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Major Quantitative Techniques for Risk Analysis in the Construction Industry – A Comparative Analysis

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Abstract
Risk analysis is one of the critical functions of the risk management process. It relies on a detailed understanding of risks and their possible implications. Construction projects, because of their large and complex nature, are plagued by a variety of risks which must be considered and responded to in order to ensure project success. This study conducts an extensive comparative analysis of major quantitative risk analysis techniques in the construction industry. The techniques discussed and comparatively analyzed in this report include: Programme Evaluation and Review Technique (PERT), Judgmental Risk Analysis Process (JRAP), Estimating Using Risk Analysis (ERA), Monte Carlo Simulation technique, Computer Aided Simulation for Project Appraisal and Review (CASPAR), Failure Modes and Effects Analysis technique (FMEA) and Advanced Programmatic Risk Analysis and Management model (APRAM). The findings highlight the fact that each risk analysis technique addresses risks in any or all of the following areas – schedule risks, budget risks or technical risks. Through comparative analysis, it has been revealed that a majority of risk analysis techniques focus on schedule or budget risks. Very little has been documented in terms of technical risk analysis techniques. In an era where clients are demanding and expecting higher quality projects and finishes, project managers must endeavor to invest time and resources to ensure that the few existing technical risk analysis techniques are developed and further refined, and that new technical risk analysis techniques are developed to suit the current construction industries requirements.

Keywords
Risk analysis, risk management, quantitative technique, comparative analysis, construction industry.

1. Introduction

Construction projects generally display many unique features such as extended project durations, technical complexities and dynamic organizational structures which clearly generate enormous risks (Wang *et al.*, 2007). These risks may not only prevent projects from being completed within the proposed time and budget constraints, but also threaten quality, safety and operational requirements (Okmen and Oztas, 2005).

Many definitions of 'risk' exist. Risk can be defined as '*the probability that an adverse event will occur during a stated period of time*' (Bowen and Edwards, 1998, p.339). Recent research tends to emphasize the double-edged nature of risks, such as 'a threat and a challenge' or '*the chance of something happening that may have a positive or negative impact on objectives*' (Wang *et al.*, 2007, p.602). In the construction industry, risks are also typically classified into a number of categories such as; social, political, economic, financial, legal, health, managerial, technical, cultural and environmental (Bowen and Edwards, 1998). At times, the construction industry has had a questionable reputation in terms of coping with project risks. Experience from past projects has often indicated less than adequate performance in terms of achieving time, cost and quality, safety and environmental targets (Perry, 1986).

Risk management has therefore become a critical part of project management and overall project success, as 'unmanaged or unmitigated risks are one of the primary causes of project failure' (Lyons and Skitmore, 2004). Risk Management aims to provide a 'systematic approach to dealing with risk through establishing appropriate contexts; identifying and analyzing risks; influencing risk decision making; and monitoring and reviewing risk responses' (Bowen and Edwards, 1998). Therefore, the concept of risk analysis and, more specifically, quantitative risk analysis techniques are critical to the successful execution of construction projects. Currently, there is very little academic literature which identifies and comparatively analyses quantitative risk analysis techniques within the construction industry.

Based on the identified research gap and problem, this study proposes to identify and comparatively analyze the most common quantitative risk analysis techniques developed for use within the construction industry and investigate possible areas for future research. In the following sections, this paper firstly introduces risk analysis in the construction industry and investigates reasons for the failure to use risk analysis techniques. Then an in-depth discussion of major risk analysis techniques is provided. Accordingly, a comparative analysis of the identified major risk analysis techniques is made. Finally, a concluding remark and recommendations are presented.

2. Risk Analaysis in the Construction Industry

2.1 Definition and Process of Risk Analysis

Risk analysis is a vital component within the overall risk management process. Risk analysis is defined by AS/NZ 4360:2004 (p.4) as '*the systematic process to understand the nature of and to deduce the level of risk which provides the basis for risk evaluation and decisions about risk treatment*.' The area of risk analysis in commercial construction is becoming more popular as competition, project size and complexity increase (Mak, 1995). Figure 1 illustrates the risk analysis function within the risk management process.

Risk analysis involves developing a detailed understanding of risk, which provides the foundation upon which informed decisions on mitigation may be based (Hull, 1990). Analysing risk allows priority areas to be targeted for mitigation and can assist in the allocation of limited resources (Akintoye and MacLeod, 1997). For example, risk analysis can be used in cost–benefit studies, which compares the costs of a particular action or project against its potential benefits. Project risk analysis in commercial construction projects requires that the approach, extent, and scope are tailored to suit the specific project (Mills, 2000).
In the early stages of a project, the emphasis may be on project evaluation in economic terms, involving the aggregation of project risks to determine the total impact on the project. More importantly for present purposes, risk analysis is helpful in developing a project design and project plans that serve to reduce uncertainty and avoid risk altogether (Chapman and Ward, 1991). Risk analysis should proceed alongside the development of the project specification in an iterative process. This implies the development of risk analysis in a learning mode, starting with an outline project specification and associated risk analysis, and moving to more detailed specification and risk analysis as the project progresses. Thus, risk analysis can

indicate early on in the project, a need for re-design, more detailed design or further investigation of aspects of the project (Chapman and Ward, 1991).

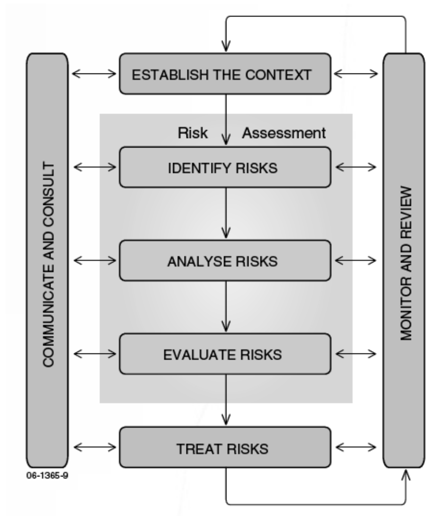

Figure 1: Risk management process (Source: AS/NZS 4360:2004, Figure 2.1)

2.2 Qualitative and Quantitative Risk Analysis

Risk identification and assessment are the primary aims of qualitative risk analysis. The objective of qualitative risk analysis is to compile the main risk sources and a description of their likely consequences (Hull, 1990). Common techniques for qualitative risk analysis include the use of risk checklists compiled from previous projects, interviewing key project participants and project team brainstorming workshops (Bowers, 1994). This initial qualitative analysis is essential in that it brings considerable benefits in terms of project understanding and potential responses to the identified risks. Qualitative risk analysis techniques will not form a focal part of this research paper.

Quantitative risk analysis usually involves more sophisticated analysis techniques. Quantitative risk analysis requires estimates of uncertainty in predicting the cost and duration of activities and a probabilistic combination of individual uncertainties. Mathematical models and analytical techniques can be useful indicators of trends and problems for attention. Their accuracy depends upon the realism of assumptions, the skill of the model and the accuracy of the historical data used. Quantitative risk analysis techniques are slowly seeing a more widespread and consistent use in the commercial construction industry, however a lack of awareness, expertise and mistrust of techniques tends to hinder widespread application (Chapman and Ward, 1991).

2.3 Major Reasons for Failure in Using Risk Analysis Techniques

Although it is obvious that risk analysis forms a critical component of the success of a construction project, many construction companies still fail to use formal risk analysis techniques. The reasons for this can be many; Chapman and Ward (1991) believe most are likely attributed to some of the following reasons:

– Lack of awareness: the company may be unfamiliar with risk analysis and unaware of its potential contribution to the project
– Lack of expertise: the company may lack the resources and expertise to carry out risk analysis techniques

- Opinion: the company may consider that a formal, detailed, quantitative analysis of project risks is not needed because risks are well understood or not large enough
- Lack of time: the company may take the view that there is not enough time to carry out risk analysis within the specified project deadlines
- Difficult to quantify risks: risk analysis may require risks to be quantified that may be perceived as too difficult to quantify
- Mistrust of risk analysis: the company may take the view that the real risks are those that are unanticipated, and these will not be included in risk analysis
- Risks will be borne by other parties: the company may take the view that risks do not need to be evaluated because they will be borne by someone else

Some of the rational and reasoning presented by Chapman & Ward is now obsolete, with attitudes changing significantly over the past twenty years. However, it is important to note that risk analysis requires more widespread and universal use in the construction industry (Bowen and Edwards, 1998).

3. Major Quantitative Risk Analysis Techniques

Several quantitative risk analysis techniques have been presented in literature to date in order to analyze potential project risks and develop appropriate risk response strategies, but only a handful are used in practice (Okmen and Oztas, 2005). Some of the major Risk Analysis techniques developed and researched in literature to date are reviewed in the following subsections.

3.1 Programme Evaluation and Review Technique (PERT)

Programme Evaluation and Review Technique **(**PERT) was originally developed in 1958 for the US Navy to tackle uncertainties involved with non-routine projects (Guikema and Imbeah, 2009). PERT requires a logically sequenced network diagram consisting of all project events and activities. Using a beta distribution, a probability distribution can be determined for each activity to represent possible durations as a result of project uncertainties (Guikema and Imbeah, 2009). This results in three estimates for each activity duration in the network diagram; optimistic, most likely and pessimistic. The mean duration for each path is the sum of the mean durations of each activity along that path, which allows the calculation of the expected project duration along with the possible variance (Chapman and Ward, 1991). Therefore it can be understood that the main objective of the PERT method is related to the scheduling of activities. The method takes into account the possible risks pertaining to an individual activity and allocates specific activity durations accordingly. PERT planning is frequently applied to schedule major commercial construction projects such as multi-storey office buildings in order to determine a critical path and schedule planning sequence.

3.2 Judgmental Risk Analysis Process (JRAP)

In 2004, another schedule risk analysis technique, Judgmental Risk Analysis Process **(**JRAP), was developed. The technique uses Monte Carlo simulation, and is unique in that it is capable of converting uncertainty to risk judgmentally in construction projects (Okmen and Oztas, 2005). JRAP involves first determining the critical risks that may affect a project's duration. The risks are assigned probability distributions using either historical data (if available), previous experience, or engineering judgment. Because historical data is not always available, one of the advantages of the JRAP technique is that it can rely on other data sources, as mentioned above. However, previous experience and engineering intuition can affect the consistency of the results obtained (Okmen and Oztas, 2005).

This method then requires the determination of the maximum and minimum durations of activities in the schedule network when the probabilities are being assigned (Okmen and Oztas, 2005). JRAP is considered a ‘pessimistic’ risk analysis approach because it assumes that the actual duration of a construction activity is greater than the most likely duration more than 50 percent of the time (Okmen and Oztas, 2005). An activity-risk factor matrix is then established using the constraint that the total influence of all risk factors on any activity in the schedule network should be 100 percent (Guikema and Imbeah, 2009). Similar in nature to the PERT technique whereby both techniques address schedule risks, JRAP is unique in that it has the ability to incorporate qualitative ‘judgmental’ data such as historical data, previous experience or engineering judgment into the analysis. However, this type of analysis strategy has additional risks associated with the subjective data used.

3.3 Estimating Using Risk Analysis (ERA)

Developed by the Hong Kong government in 1993, Estimating Using Risk Analysis (ERA) is a methodology that can be used to determine the amount of contingency required for a project by identifying uncertainties and determining the effects of the uncertainties on the project budget. ERA produces base plus contingency cost estimates during the pre-tender stage (Mak and Picken, 2000). To use ERA, a risk-free base estimate has to be prepared using the known scope. Project risks need to be identified and these are classified as either fixed or variable risks. Fixed risk events are those that either fully occur, or do not occur, whereas variable risk events are events that will definitely occur but whose extent of occurrence cannot be ascertained (Guikema and Imbeah, 2009).

An average risk allowance and a maximum risk allowance is then calculated for each risk event. With all risk events identified and the average and maximum risk allowances calculated, the average risk allowances for all events can be summed to obtain the required contingency (Mak and Picken, 2000). There are two critical assumptions in the ERA technique which must be noted; that there is only a 10 percent chance that the actual costs incurred will exceed the maximum risk allowance, and that there is a 50 percent chance that the average risk allowance will be exceeded (Mak and Picken, 2001). The ERA technique has been established to avoid traditional ‘conservatism’ in contingency estimates and over-inflated estimates. Because the technique can be carried out multiple times throughout the pre-tender period, the estimate will become more accurate as the project scope becomes more defined. ERA projects have been proven to estimate risk-based contingencies more accurately than non-ERA projects (Mak and Picken, 2001).

3.4 Monte Carlo Simulation Technique

The Monte Carlo simulation technique is one of the most popular probabilistic risk analysis techniques and has been widely applied for various types of projects. The objective of Monte Carlo simulation is to find the effect of multiple uncertainties on a value quantity of interest, such as the total project cost or project duration (Huseby and Skogen, 1992).The Monte Carlo technique is a process for developing data through the use of a random number generator (Yang, 2005). A mathematical model is constructed based on pre-specified probability distributions, which describes the possible outcomes of major cost elements (e.g., substructure, exterior walls, services) involved in a project, and determines what the overall project cost will be for each simulation replication (Akintoye and MacLeod, 1997). After a certain number of replications, the collected samples are used to derive the output distribution of the overall project cost (Yang, 2005). A ‘triple’ estimate of pessimistic, most likely and optimistic, as mentioned in the PERT technique is often adopted in the Monte Carlo technique (Chapman and Ward, 1991).

The use of random numbers implies that all identified risks are independent of one another. However, this is not the case in many construction projects. It is often the case that risks are interdependent. For example, a delay during the design stage often leads to a delay in the construction of a project. The use of the Monte Carlo technique is therefore unsuitable for projects with a significant number of interdependent risks (Huseby and Skogen, 1992). However, Monte Carlo techniques are still very common for use in project risk analysis because they provide detailed, illustrative information about risk impacts on the project cost and schedule.

3.5 Computer Aided Simulation for Project Appraisal and Review (CASPAR)

Computer Aided Simulation for Project Appraisal and Review (CASPAR) is a software program used to create investment models for all types of projects. It is a tool designed to model the interaction of time, resources, cost and revenue throughout the entire life of a project, and it has the capacity to evaluate the consequences of factors such as delays and inflation, and changes to the market or to production rates (Akintoye and MacLeod, 1997). CASPAR is usually used to appraise construction projects and is intended for use at the appraisal stage of the project life cycle where the project has not been properly defined (Merna and von Storch, 2000). The software allows the preparation of sensitivity analysis plots of cumulative frequency distributions for time and cost. The software can also simulate the effects of risks and produce sensitivity analysis of individual risks or combine the effects of project risk in a probabilistic analysis using Monte Carlo simulation (Merna and von Storch, 2000).

Sensitivity analysis is performed by changing the values of independent risk variables to predict the economic criteria of the project. The range of percentage changes in each risk variable reflects the uncertainty associated with that variable. The main limitations of sensitivity analysis are that no indication of the likely probability of occurrence of changes in key risks is given and each variable is considered independently (Merna and von Storch, 2000).

For a probability analysis using CASPAR, different values of risk variables are combined in a Monte Carlo simulation. The simulation is an iterative process, repeated a number of times. The resulting collection of outcomes is then arranged in sorted order to form a probability distribution of the result (Merna and von Storch, 2000). It is important to mention that each risk requires the definition of 'ranges', which is normally subjective in nature if no historical data is available. Therefore project members who are responsible for the original estimates should be involved in this exercise. The results of probability analysis using CASPAR are shown as frequency and cumulative frequency diagrams (Merna and von Storch, 2000).

3.6 Failure Modes and Effects Analysis Technique (FMEA)

In the design of products, services and processes it is possible to determine possible modes of failure and their effects on performance. The Failure Modes and Effects Analysis technique (FMEA) is a risk analysis technique which studies potential failures to determine their possible effects (Guikema and Imbeah, 2009). FMEA is a risk analysis technique which addresses budget, schedule and technical risks – a trait unseen in any of the above mentioned risk analysis techniques. Failures are prioritized according to how serious their consequences are, how frequently they occur and how easily they can be detected. The purpose of the FMEA is to take actions to eliminate or reduce failures, starting with the highest-priority ones (Putcha *et al.*, 2008). Ideally, FMEA begins during the earliest conceptual stages of design and continues throughout the life of the project. FMEA is typically conducted by a small team of people, ideally each who has a slightly different view of the project. The variety of perspectives that a diverse team can bring to FMEA contributes to the most successful analysis. Any one person will not be able to develop as comprehensive and valuable an FMEA as a team of people can generate (Seyed-Hosseini *et al.*, 2006).

FMEA provides ordinal, not cardinal, rankings of risks. Therefore it assists project managers to rank risks according to their likelihood and severity. However, FMEA does not provide information of the severity of one risk compared to another. That is, it does not provide cardinal rankings (Guikema and Imbeah, 2009). Cardinal ranking is critical if the allocation of scarce resources is to be optimized. If risks cannot be compared against one another, a project manager will struggle to adequately allocate the available project resources to reduce each of the risks (Guikema and Imbeah, 2009).

3.7 Advanced Programmatic Risk Analysis and Management Model (APRAM)

The Advanced Programmatic Risk Analysis and Management model APRAM was originally developed for the aerospace industry, for unmanned missions which were characterized by an 'attempt to produce a quality system, faster and at a reduced cost relative to traditional approaches' (Guikema and Imbeah, 2009). It can be noted that construction projects share very similar goals to that of those adopted by the aerospace industry, that of time, cost and quality. This technique is the only other major technique which aims to address all three of these crucial criteria, along with FMEA. APRAM can be used to manage construction project risks associated with time, cost and quality simultaneously (Guikema and Imbeah, 2009). It offers the client the opportunity to lower expected costs through optimal allocations of the residual budget and allows the client to explore all possible options for developing a facility. APRAM also provides a means of a more comprehensive risk analysis tool because it is able to reduce risk probabilities and improve technical elements of a facility, features not seen in other risk analysis techniques (Guikema and Imbeah, 2009).

APRAM involves eight distinct steps as detailed in Figure 2.

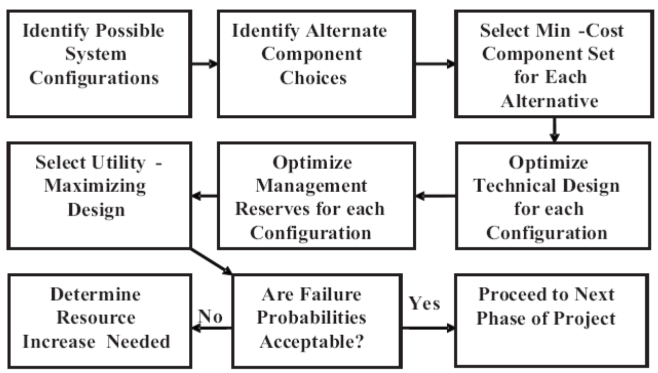

Figure 2: APRAM process (Source: Guikema and Imbeah (2009, p.773)

4. Comparative Analysis of Major Risk Analysis Techniques

In order to best understand the advantages and disadvantages of quantitative risk analysis techniques, it is wise to compare like techniques with each other. This contributes to a more developed understanding of a risk analysis techniques applications and limitations. From the above identification of major risk analysis techniques, it has been deduced that each technique aims to lessen risks in any or all of the following areas of 'schedule risks', 'budget risks' or 'technical/quality risks'. From the major techniques identified, most focus their attention to one of these three risk areas. For example, the PERT and JRAP techniques aim to address schedule risks, Monte Carlo simulation and CASPAR address schedule and budget risks, ERA addresses budget risks and FMEA and APRAM address schedule, budget and technical risks. The following subsections will comparatively analyze Risk Analysis techniques according to the risk categories addressed by each – schedule, budget or technical risks.

4.1 Schedule Risk Analysis Techniques (PERT, JRAP, MCS, CASPAR, FMEA, APRAM)

When considering the risk analysis techniques which address schedule, most of the major techniques identified rely on some form of subjective data. These are PERT, JRAP and CASPAR, FMEA and

APRAM. Subjective data can take the form of historical data, previous experience or engineering judgment (Okmen and Oztas, 2005). The major problems with subjective data are consistency and knowledge. The skill and expertise of the professional providing the subjective data will have a considerable impact on the overall results. Personal and professional bias may affect the overall risk analysis technique; therefore the collection of subjective data is best undertaken by a team of professionals, each with their own specialization and input. The only schedule risk analysis technique which differs in respect to data collection is the Monte Carlo simulation technique. The technique offers mathematical modeling and random number generation to determine the project schedule. Random number generation techniques imply that all risks are independent of one another, and generally in construction projects this is not the case. Risks are most commonly interdependent (Akintoye and MacLeod, 1997). Therefore, the Monte Carlo technique is unsuitable for projects with a significant number of interdependent risks (Huseby and Skogen, 1992). Both subjective data collection and random number generation have their merits and are widely used in schedule risk analysis. Subjective data relies upon consistent, knowledgeable and unbiased data, and random number generation relies upon a distribution value gained through simulation repetition, to arrive at an average value. Mathematical methods also require the knowledge of precise probability distribution information, mean, standard deviation and distribution shape, which may prove a problem for the untrained.

4.2 Budget Risk Analysis Techniques (ERA, Monte Carlo, CASPAR)

The risk analysis techniques identified within this study which address budget are ERA, Monte Carlo simulation and CASPAR. Once again, the Monte Carlo technique uses mathematical modeling and repetition in order to derive the output distribution of the overall project cost. The CASPAR technique is also based upon Monte Carlo simulation. The CASPAR technique improves upon the traditional Monte Carlo technique with regards to budget risk analysis because it has the ability to recognize the dynamic project environment (Akintoye and MacLeod, 1997). Huseby and Skogen (1992) are of the opinion that in a realistic model, project uncertainty must be modeled as a dynamic process in which the project manager can revise their plans as the project progresses. CASPAR is sensitive to project delays, inflation and changes to market or production rates, an improvement on the traditional Monte Carlo technique (Akintoye and MacLeod, 1997). Once again, these techniques which rely on mathematical models rely on data which may be difficult for the untrained to source or understand.

ERA takes a difference approach to budget risk analysis. It expands upon the traditional ‘cost plus contingency percentage’ method. Because the technique can be carried out multiple times throughout the pre-tender period, the estimate has the dynamic properties of CASPAR and becomes more accurate as the project scope becomes more defined (Mak and Picken, 2000). Mak and Picken (2000) are of the opinion that ERA is also useful in that it imposes a systematic and itemized discipline, which aids in financial control. ERA may be a simpler way in which companies tackle the problem of budget risk analysis because it conforms to the traditional method of base estimate plus contingency, with the added advantage of the specific identification of fixed or variable risks and their likely cost, which can be constantly updated and refined as the project scope becomes more definite.

4.3 Technical Risk Analysis Techniques (FMEA, APRAM)

The technical risk analysis techniques discovered through this research paper were FMEA and APRAM. Both approaches rely on subjective data, which poses certain risks in itself. FMEA relies on subjective data to identify all of the possible ways in which a project or project element can fail. APRAM relies on subjective data to identify possible system configurations and component choices. Once again the success of subjective data collection relies upon the skill and knowledge of the professionals undertaking this analysis.

The major difference between FMEA and APRAM as mentioned by Guikema and Imbeah (2009) is that FMEA provides only ordinal ranking of technical risks, whereas APRAM provides a cardinal rankings of technical risks. Therefore, FMEA assists project managers to rank risks according to their likelihood and severity but does not provide information of the severity of one risk compared to another. If risks cannot be compared against one another, a project manager will struggle to adequately allocate the available project resources to reduce each of the risks (Guikema and Imbeah, 2009). A notable limitation of the APRAM technique, however, is that it currently only focuses on those technical risks that can be mitigated through the allocation of monetary resources. This is not always possible, for example, some technical failures may require the integration of design and construction as a mitigation measure, an effort that depends on the project delivery approach, not specifically the allocation of resources (Guikema and Imbeah, 2009).

5. Conclusions

This literature review has explored the major types of quantitative risk analysis techniques employed within the construction industry. These techniques include PERT, JRAP, Monte Carlo Simulation, CASPAR, FMEA, APRAM and ERA. A comprehensive review of each, along with a comparative analysis of like techniques has been undertaken in order to determine areas for future research.

Risk analysis techniques traditionally attempt to address any or all of the following risks – schedule, budget and technical. For the purposes of this comparative analysis, the identified risks analysis techniques were compared against other risk analysis techniques which addressed one of these three distinct categories. Upon completion of the comparative analysis, it is evident that very little has been developed in terms of technical risk analysis techniques. Much of the literature available on risk analysis techniques focuses on either schedule or budget risks. The literature review has revealed that these risks have been thought about in depth and over a number of years, with risk analysis techniques developing into quite complex and detailed analyses. This is most likely due to the fact that that inevitably the most important project factor is money, and time (schedule) is so intrinsically linked to the budget. On the other hand, technical risks have only begun being formerly analyzed in recent times. The techniques of FMEA and APRAM have attempted to develop systematic ways to deal with the analysis of technical project risks.

The construction industry is beginning to understand the importance of delivering a high quality finish in all projects. FMEA and APRAM have taken a positive first step in the development of a risk analysis technique which addresses budget, schedule and technical risks – the further exploration and development of this idea will be crucial in the future. Further research and risk analysis technique development is highly recommended in the area of technical risk analysis in order to best eliminate and mitigate risks which affect the technical and quality aspects of a project.

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