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The Impact of Engineering Change Request (ECR) on Accuracy of Project CEAC

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Abstract

Change affects every aspect of human activity and can be one of the principal reasons for the failure of a project. In the actual "ever-changing world", where initial requirements and specifications of projects are subjected to constant modifications and might necessitate revisions of the allocated resources and re-baselining the project over and over, it is vital that project managers react appropriately to change and understand how it can influence the execution of their project, only then changes can be managed effectively.

The focus of this thesis is to get insight on the impact of Engineering Change Requests (ECRs) on final costs of dynamic and complex development projects, demonstrating the inefficiency of traditional project management practices by analyzing CEAC of twenty projects chose from an Italian supplier in automotive sector, whether these ECRs are due to financial problems of contractor or owners, change in market conditions, inadequate communication between the company and client, insufficient details, change in project specification, conflicts in contract documents or poor performance of company. The CEACs are estimated by a nonlinear regression method, which is an approach that has been gaining lots of attention since it provides an accurate estimate in early-middle stages of completion of the project.

The findings indicate that engineering change requests are identified as important causing factors to project cost overruns and therefore, there is the need for project managers to have flexibility in the project system by applying more adaptive methods to address better the uncertainty and instability in projects and to overcome the high failure rates associated with using traditional methods on modern, technology-intensive, and continuously changing projects.

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Chapter 1

Introduction

There is no engineering of a successful project without any changes; they are the rule and not the exception in product development projects because, in today's dynamic business environments, changes are necessary to stay competitive. In companies that design and produce complex products, changes and modifications often take place in the design of the product as it evolves. Many of these changes are formally initiated by the customer as new requirements, or as modified specifications or manufacturing changes. These requests, called Engineering Change Requests (ECRs) and can arises at any stage of the project life, mainly during the development phase of projects. Typically, the later they occur, the more significant the time and effort needed to implement them, and the more severe could be their negative impact on project performance [1].

Attitudes to ECR can vary broadly within an industry. As Boznak (1993) notes, engineering changes and their management can be linked to the concept of continuous product improvement. Engineering change is both an opportunity and a burden for companies, however, a survey, which examined UK firms in the mid-1990s highlighted that over 50% of the companies investigated, which both designed and manufactured products, regarded engineering changes as a major source of problems in their product development process, yet more than 60% felt that "it was possible for a well-managed EC (engineering change) process to provide a framework for improved product innovation and project realization." [2]

Implementing ECRs may affect several functions across a company, such as engineering, manufacturing, acquisitions, documentation, inventory control, accounting, etc. With the cost of completion of the project being a critical scope, it is desirable to estimate the extra cost required to implement the ECRs accurately and at the right time and subsequently, process and control them efficiently when they appear in the course of project execution. As a matter of fact, how properly a project manager (PM) can forecast potential change requests at the initial phase of a project and how well can react to this customer-driven change request often determines whether the project is delivered on time and budget.

Engineering change has grown steadily in prominence both as a critical issue for the industry and as an active academic research area and has obtained increasing popularity with the growth of concepts, such as concurrent engineering, simultaneous design, and product platform design, plus the influence of business disciplines such as configuration management. However, until now, there has been little work in specifying or detailing the importance and the influence of ECRs on project cost, therefore, in this study, I investigated the extent of the negative impact of not well-estimated extra efforts associated with emergent ECRs, on project final cost.

In terms of effort, changes can consume a considerable amount of product engineering resources. An automotive firm investigated by Boznak (1993) spent $41 million per year on the administrative processing of engineering change requests, which averaged out to $1,400 per change request. It must be remarked that none of these figures are given in context (e.g., size of the company, number of products, etc.), and thus it is hard to draw certain conclusions from them. Still, they do indicate the high costs of the engineering change process.

The cost of processing and implementing the engineering change requests in a project can be divided into tangible and intangible parts that both are very hard to assess, especially during initial stages of a project with a high degree of uncertainty. A possible solution to this problem could be to revise the project plan periodically, where project scheduling and estimated cost are modified on a short time horizon and change frequently. We, therefore, analyzed the accuracy of CEAC in twenty engineering projects, considering the application of an adaptive and short-term effort estimation process alongside the traditional project management practice.

Chapter 2

Literature Review

2.1 Engineering Change Request (ECR)

First of all, an overall look has to be taken at the phenomenon of “changes” to understand the nature of changes over the whole life cycle of a product development project.

2.1.1 Defining an ECR

An Engineering Change Request (ECR) or merely a Change Request (CR) is a set of one or more specifications related, in various ways, to a set of existing specifications. A Change Request might regard an existing and finished product development project, in which case is classified as a maintenance request, or it might concern a non-yet-developed product during one of its life cycle phases preceding the delivery. There are implied differences in the definitions which have been made in the literature. Three descriptions are as follows:

1. An engineering change request (ECR) is a modification to a component of a product after that product has entered production (Wright 1997) [3].

2. Engineering changes are the changes and modifications in forms, fits, materials, dimensions, functions, etc. of a product or a component (Huang and Mak 1999) [4].

3. Engineering change requests (ECRs) are changes to parts, drawings, or software that have already been released (Terwiesch and Loch 1999) [5].

There are some arguments with the coverage of each of these definitions. Wright's definition restricts engineering change to the production phase, and so neglects the whole range of modifications that can happen during the design and development phase of a product development life cycle. This method generates an artificial division between engineering change and "normal" product design and development work. Huang and Mak define the scope of the change, but do not comment on the timing when a change occurs. The Terwiesch and Loch definition introduce software, which is a vital part of most modern complex products, especially in the automotive industry, into the scope of engineering change as well as the idea, that a change occurs once a part, drawing or software has been released and thus handed over. It indicates that a fundamental difference between change and many other forms of iteration is that change is an active revisiting of a task that has been considered completed [6]. A weakness of the Terwiesch and Loch definition is its conflation of the change and the directive to make the change.

None of the definitions discuss the size, scope, or source of the change. An engineering change can be anything from a small revision of a diagram taking one engineer a few minutes to a significant redesign process and new software releases involving a large team of engineers working over many months or even years. Based on Terwiesch and Loch definition, Jarratt [2] provides a complete description:

"An engineering change is an alteration made to parts, drawings, or software that have already been released during the product design process. The change can be of any size or type; the change can involve any number of people and take any length of time."

2.1.2 ECRs in the Product Development Life Cycle

Virtually all texts on product development discuss the concept of the change request and product development life cycle (e.g., Otto and Wood, (2001)). Engineering change can occur throughout the entire development life cycle from the Concept phase to when a product finally goes to the Mass Production phase, even though activity varies significantly depending upon in which phase of its life cycle a project is. Change activities are also at the heart of maintaining, upgrading, and ultimately replacing complex, long-life products [2].

Inness (1994) describes the product development life cycle as moving from the 'birth' of a product idea, through design and development to production and shipping. Eventually, after a period of growth, the product matures; finally, its position can no longer be maintained and, so it is phased out: product 'death' [7].

Engineering change activity varies significantly depending upon which phase of the development life cycle an ECR arises. Figure 2.1 illustrates this point by using the generic product development process proposed by Ulrich and Eppinger (2003)[8].

Generally, changes that happen late on in the design process influence far more people than those triggered early on. Once manufacturing, suppliers, marketing, etc., are involved, the number of parties that must be informed of a change escalates dramatically. If a change request emerges after a product has entered service (e.g., due to the emergence of a fault), then the manufacturer may have to recall the product to make the required modification.

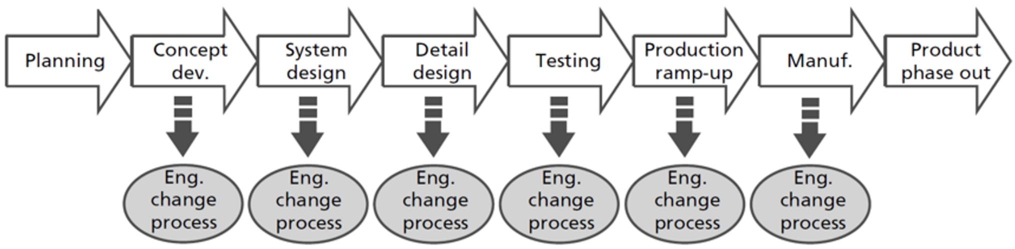

Figure 2.1: ECRs in the product development life cycle (Ulrich and Eppinger (2003))

2.1.3 Causes and Rationals of Change Requests (CR)

The causes and rationales behind change requests are complex and dependent on each other. The identified reasons and motives for CRs are divided into eight different categories, as discussed in the following.

1. Specifications and Requirements

Today's dynamic environment results in continuous changing in client demands and, consequently, changing product requirements and specifications. A subset of changes in product development is necessary to adapt products and systems to these changing requirements. This task can become very problematic when the development time of a product is the same or even longer than the rate at which the environment is changing [2]. For fast-changing specifications, it is also essential that the product meets these changes, not only during the development phase but also throughout the entire life cycle, including the complete operational phase [9].

If a product does not satisfy its specifications and has to be changed, two principally different reasons can be identified:

- Changing specifications (also often referred to as moving target)

- Incomplete or incorrect specifications

These reasons suggest that, on the one hand, the specifications for the product are really changing or, on the other hand, the specifications themselves are stable, but haven't been completely identified, well-communicated or were not correctly recognized or documented.

2. Feedbacks and Complaints

Despite all validation and verification methods, the perfect product cannot always be developed, especially when there are strict cost and schedule constraints. As an example, long-term impacts (e.g., of materials) can only partially be simulated or extrapolated, and user behavior might evolve differently than expected. Hence, a lot of changes are caused by feedback out of the field or by complaints from clients. Mainly companies with mass products in competitive markets monitor precisely the reaction of users after the introduction of the product into the market and change it for revisions according to these reactions because these changes might be crucial for long-term product success [9].

3. Complexity

The more complex a project is, the more challenging it is to control all relevant parameters and their influences on each other [2]. Often, during a development project, a reduction of complexity of the product is to be performed by modeling, which induces changes again, since modeling means a reduction of information.

4. Degree of Innovation

The success of human acting often depends on the experience of the acting persons. Even methodologically based acting is determined based on earlier experiences, as can be seen, for example, in methods like TRIZ. A critical aspect of real innovations is that at the beginning, there is a low degree of information and knowledge regarding the new technology or system and that only experience-based values can be used. The judgments rendered from the combination and extrapolation of the existing previous knowledge base need verification by an application. This subject, for example, has been confirmed by the number of incorrect cost estimations for new product development (NPD) projects with a high degree of innovation.

5. Decision Discipline

One of the primary reasons for changes in projects is the lack of discipline of engineers and managers in the decision-making process, which depends mainly on the company culture. The purpose is to establish a good balance between being quick at making decisions and passive "safety thinking."

2.1.4 Types of Change Requests

Types of CRs have been categorized considering those that start a chain of changes, as either emergent (coming from the product, e.g., errors) or being initiated from outside the product (e.g., customer requests).

1. Emergent Change Requests

Emergent changes come from the characteristics of the product itself and are raised due to the following reasons:

Error Correction

Mistakes made during design can be recognized at any point during different phases of the product life cycle by any party involved with the development of the project. Mistakes can range from a minor software coding error to issues that affect the fundamental operation of the product [2];

Safety

This is an issue "which respects no commercial boundary" [7]. Products must be changed if they do not meet safety requirements or are expected to kill, injure, damage property or cause economic damage. Producers also need to be conscious of and take actions to limit unintended uses of their products, which may be hazardous;

Change of Functionality

This change request is raised when the design does not meet its original functional requirements and specifications;

Product Quality Problems

Problems with rework and scrap can often be traced back to faulty design or incorrect manufacture and assembly instructions which cause emerging change requests in ramp-up or manufacturing phase;

2. Initiated Change Requests

Improvements, enhancements, or adaptations of a product can take on many forms. For example, a change may be initiated to decrease the cost of the product (e.g., by component standardization) or it may be undertaken to create the product complies with the standards and laws of the territories (e.g., the European Union) into which they wish to sell, so the different stakeholders that might initiate these types of change requests can be classified as follows:

Product Engineers

Designers may identify new technologies in which the product can be improved to the advantage of the customer and the company. They can further initiate changes to make up for earlier sub-optimal design, for example, in the initial concept design phase a component may be too heavy due to bad planning of the design process leaving too little time or too little resource for that particular component. A later, initiated change can improve the situation;

Suppliers

Changes requested by suppliers is becoming more popular as companies focus on their core technology and leave the development of components to external firms. Suppliers propose alterations to comply with technical standards, standardize components, or modify material specifications. Problems can occur when suppliers themselves run into problems, like when they go out of business or have issues with their supply chain. These are augmented by communication between the purchasing department and external suppliers;

Sales and Marketing Department

As well as liaising with current and potential customers, the marketing department must keep informed of market trends and developments in competitive products, hence marketing department can sometimes demand that product specifications must be modified to satisfy a particular market window of opportunity [9], or a product designed must be adapted for a specific customer for the general market [7];

Product Support

Maintenance or adjustment problems may need parts of a product to be changed which is a very complicated commercial matter as there are significant implications;

Production

Concurrent Engineering best practice should guarantee that manufacturability is a crucial issue during product design, but once production starts changes can still be inducted due to several reasons, for example, to speed up assembly operations, clarify instructions or remove the likelihood of mistakes such as a component being wrongly oriented;

Company Management

Companies may have policies that initiate change requests; for example, firms will try to pick certain suppliers to decrease overall business costs which can lead to product changes to comply with the initiative;

Legislators

Products often need to be changed and adapted to satisfy new legislation or certification requirements that can drive major project change process during different phases of the product life cycle;

Many actual CR are a mix of "pure" CR types discussed above, however, having a proper and efficient system that is capable of recognizing the different components of change requests logically is vital for controlling change requests efficiently.

2.1.5 Change Propagation

A characteristic of change is that the steps cause-change-effect are not serial but build a network, where an effect may also be a cause for new changes, and all may be somehow interconnected. Thus, a change can spread from the initially affected component or system to impact other parts of the product. The change can also spread to other products (e.g., other family members) due to common platforms, processes, and businesses (e.g., suppliers, partners, etc.). These problems can be increased by issues in the supply chain, which can create time delays in the delivery of component specifications or components, thus compressing already tight schedules or compromising the quality of the product [2].

As Williams et al. (1995) point out, the sheer number of changes and the resulting delay in the decision-making process can severely jeopardize the success of a product development project. Two authors (Fricke et al. 2000 [9]; Clarkson et al. 2001 [10]) have identified propagation as a key potential impact of implementing an engineering change. Eckert et al. (2004) [11] have identified two different types of propagation, which are depicted in Figure 2.2.

Ending Change Propagation

Consists of ripples of change, which are a small and quickly reducing volume of changes, and blossoms, which are a high number of changes that are brought to a conclusion within an expected time frame (marked by a "t" in Figure 2.2);

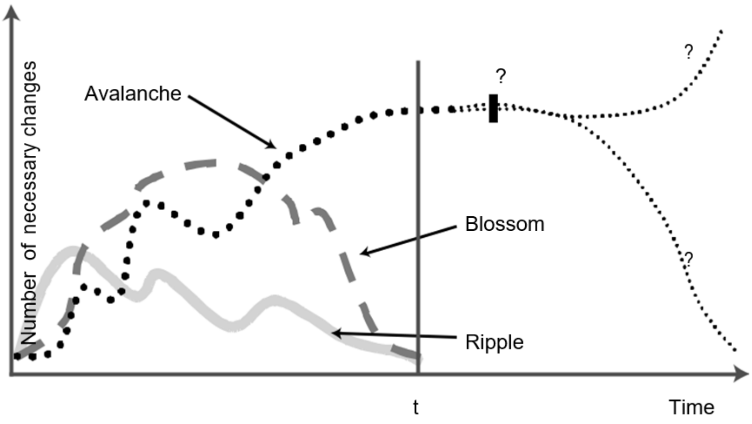

Figure 2.2: Different patterns of change propagation (Eckert (2004))

Unending Change Propagation

Characteristic of this type is an avalanche of change, which happens when a significant change starts several other major changes, and all of these cannot be brought to an adequate conclusion by a given point in time;

2.1.6 ECR and Configuration Management

Configuration Management is “a discipline, applying technical and administrative direction and surveillance to identify and document the functional and physical characteristics of a configuration item, control changes to those characteristics, record and report change processing and implementation status, and verify compliance with specified requirements”, where the item may be software or more generally a system. In software design, the term configuration management is used to describe most change-related activities [12]; however, in engineering design, a narrower view is sometimes considered concentrating on making sure that the different configurations offered by option packages are internally consistent [10].

One of the key features of Configuration Management is the control of engineering changes because uncontrolled changes will have a dramatic impact on a product’s performance and its functional and physical properties and so on the outcomes of the development project. The engineering change process is the core process of the more extensive Configuration Management process. Each change of the product or its documentation causes a change in product configuration [13]. In fact, from an approved baseline, a configuration change authority assesses the recommendation of other representatives to approve, approve with modifications, or disapprove submitted changes based on the: "total life cycle impact of the action to include cost, schedule, performance and logistics impact." [14]

Thus the processes, procedures, and users of the configuration management system play an integral role in maintaining the integrity of information throughout the life cycle by controlling changes. If users do not follow the process, errors can occur, which can cause dramatic problems to the product in the production phase and related information dissemination [15];[16]. Researchers of configuration management always find the benefits of such a controlled process of change are not always understood or realized by users [17]. Characteristics of 'configuration management' are not stable and fixed but are themselves evolving, to include the life cycle, agile approaches, and changes to strategy as well as project [14].

About 95% of UK firms that design and manufacture products have embraced a formal procedure for engineering change management (Huang and Mak 1999). Though, it must be remarked that although all companies that adopt robust Configuration Management procedures must have a formal engineering change process, this does not mean that all companies that have a structured approach to engineering changes must be following the Configuration Management system. Although the two issues are highly inter-related, they are not the same. Firms producing products of low complexity do not need a system as complicated as Configuration Management.

2.1.7 A Generic ECR Process

Different scholars have introduced different engineering change processes. They divided the process into different numbers of elements or phases. For example, Dale (1982)[18] proposed a formal method split into two steps, whereas Maull (1992)[19] suggested a process made up of five parts. A comprehensive six-step process has been suggested by Jarratt [10] which is described below and is shown in Figure 2.3.

1. A request for an engineering change must be made. Most companies

have standard forms (either electronic or on paper) that must be completed. The person responsible for managing the change requests must outline the reason for the change, the priority of the change, type of change, and perform the Impact Analysis process, which determines the components or systems are likely to be affected. This form is then sent to a change-controller who will enter it into an engineering database.

2. Potential solutions to the request for change must then be determined, but often only a single one is considered, which can be due to a diversity of reasons like time constraints, the fact that the solution is “obvious” or because engineers stop investigating once one workable solution is obtained.

3. The impact or risk of implementing each solution must then be assessed. Various factors need to be considered: e.g., the impact upon design and project schedules, how relationships with suppliers will be affected, and will a budget overrun occurs. The further through the design process a change is implemented, the more potential for disruption there is.

4. Once an appropriate solution has been determined, it must be approved. Most companies have some form of Engineering Change Board or Committee, which reviews each change, making a cost-benefit analysis for the company as a whole and then approves the implementation. The Engineering Change Board must contain a range of middle to senior ranking staff from all the critical functions connected to the project: e.g., product design, leader of the software team, supply, quality assurance, finance, product support, etc.

5. Implementation of the engineering change can either occur immediately or be phased in. Which option is followed will depend upon various factors such as the nature of the change (e.g., if it is a safety issue, then the immediate implementation must occur) and when during the project life cycle, the change is happening. Paperwork must also be updated. “One of the major problems frequently associated with ECR is that of ensuring that only current documentation is available to manufacturing areas.” [3]

6. Ultimately, after some time, the change should be reviewed to see if it achieved what was initially intended and what lessons can be learned for the future change process. The review should investigate whether the product and associated processes are functioning as expected. Often surprises can be discovered, for example, more obsolete stock than initially accounted for. Not all companies perform such a revision process accurately.

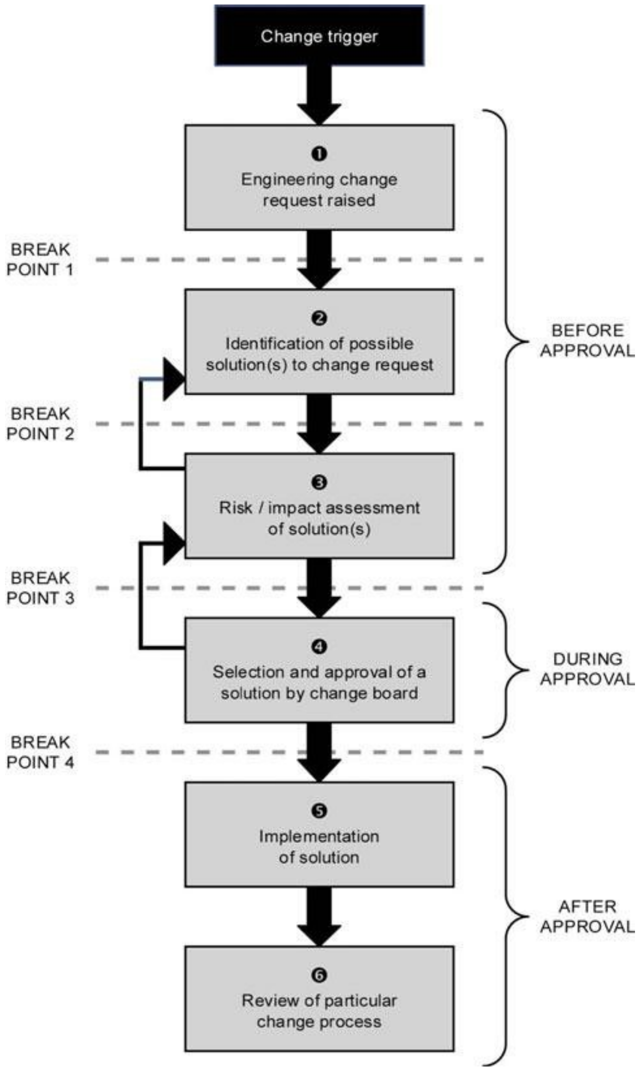

Figure 2.3: A model of a generic change process (Jarratt (2004))

There are likely iterations within the process, two of which are marked by arrows in Figure 2.3. For example, a selective solution may be too risky for the company to implement and so the process will return to Phase 2 so that other possible answers can be recognized. At the approval stage, the Engineering Change Board may suggest that more risk analysis is required and so the process will return to Phase 3. There are other possible iterative loops, but they are not marked for the sake of simplicity. The most extreme loop would be when if during the review phase, it was realized that the implemented solution had been ineffective or made circumstances worse. In such a case, the process would return to the start with a new change request being raised.

There are four breakpoints in the engineering change process displayed in Figure 2.3. At each of these points, the change process can be brought to a stop. They can be likened to the "Stage-Gate" points used by many businesses in evaluating progress during new product development projects. Breakpoint 4 is typically the juncture where an Engineering Change Order will be issued if the Engineering Change Board has confirmed a change and relevant higher authority in the organization has authorized the Board's decision. In some companies, a senior executive can overrule the Board at this point.

2.1.8 Impacts and Effects of CRs

The impact of making a change in a project is one area that has gained much coverage in academic literature. In general, change requests affect planning, scheduling, and, most importantly project costs. As discussed in precedent sections, the two main reasons for an engineering change are the elimination of a product's error or "flaw" [20] and the improvement, enhancement, or adaptation of a product. Especially the first issue can have negative impacts on a product development project, e.g., slipping schedules or overrunning budgets [21]. Changes often lead to information deficiencies of concerned persons, because the changes are not communicated immediately and adequately enough [22]. That implies that other design decisions are made based on old or out-of-date information and so in this case, the negative effects of poorly-managed change request propagates in other activities of the project.

The effects of a change, however, can be or better should be of benefit; first, changes can be performed to enhance the quality of the product, and second, a change may be implemented to save money in the long-term view. Sometimes changes are also performed to get back into the planned schedule, for example, by using more resources. This is what effects of changes should be like, and therefore it is necessary to tackle the problems coming along with change requests in engineering projects.

Generally speaking, considering the CRs with negative impact on projects, as discussed in previous parts, the later the CRs appear in the design process, the more severe will be the negative impact they have, than those triggered early on. As a project manager, when a change request is received, a series of analysis should be done, to evaluate whether it is within or outside the scope of the original project requirements as well as how it is going to impact the three constraints of the project, scope, schedule, and cost. Impact analysis is the most important step to effective change management procedure. The impact analysis should not only reveal the impacts of changes on the above three project constraints but also it should grant essential information related to the effects of changes on people, processes, quality of the project and on the operation of the company. By implementing proper impact analysis procedure one should also be able to evaluate the overall project risks, how the change is going to alter the existing risks, whether or not the project is going to face new risks and the cost associated with managing those risks.

2.1.9 Effort and Time Estimation Related to Change Requests

Using appropriate productivity and cost models connected to the specific development project, and also by reviewing historical data regarding the past projects, managers can forecast the project's effort, duration, and subsequently the cost. Budget and schedules can then be allocated in line with requirements, and the project can be started after the initial phase of the project planning. Nevertheless, after the emergence of change requests (CR), including significant changes to the specifications, revising both the functional and technical design and the project's plan becomes necessary. At this point, the company faces the challenge to assess whether resources have been correctly allocated or if the original budget is maintained, whether the associated risk is increased or diminished.

Since the requirements were changed while the work was in progress, the project has already committed a portion of those resources and generated a part of its results [23]. Hence, it is required to estimate the project's so-called "forecasts to complete," which is to say an estimate only of the resources needed starting from the moment the variation is made. The Earned Value (EV) technique is used to achieve this result. EV, a value that can be calculated at any time in the project's lifetime, is a cumulative indicator, which indicates that it outlines within itself the project's history. In the next section, I will discuss more about this project management technique and its applicability in the context of CR.

2.2 Project Management Methodologies

The basic project management terms are defined by the project management theory, and also by the international project management standards which include the standard of the Project Management Institute (PMI), the standard of the Association for Project Management called Projects in Controlled Environments 2 (PRINCE 2), and the standard of the International Project Management Association (IPMA). The Project Management Institute (2004) affirms, in its standard, that "Project management is the application of knowledge, skills, tools and techniques to project activities to meet project requirements. It is accomplished through the application and integration of the project management processes of initiating, planning, executing, monitoring and controlling, and closing" and a project as "a temporary endeavor undertaken to create a unique product, service, or result". in the following a brief interpretation of the functions are stated.

Define: To determine the main characteristics of the new project, the global vision, make market analysis, define customer requests and results to be achieved.

Plan: To determine the measures to follow for the subsequent execution of the project, the main project's activity, identifying a start and end date, subdividing the work and responsibilities, carrying out activities such as risk analysis.

Organize: To organize tools to manage resources effectively for the correct execution of the project. Organizing the project team, going to select the members and the resources that will go to set it up, calculate the costs and schedule the main activities of the project defined during the planning.

Execution: This is the main function regarding the evolution and correct realization of the project. This function is affected by the specific technique of the organization's sector.

Check: Checking that in every phase the execution of the project is in line with the objectives to be reached in terms of costs and quality, addressing potential problems by undertaking corrective actions.

Closure: Closure of project in terms of contracts, compilation of documents, ensuring that the project has been completed efficiently.

Thus, as stated by Turner, (2000), Project Management Practice is a structured approach for delivering a project, and consists of a set of processes, with each process having clearly defined resources and activities. A project management methodology will set out what an organization regards as best practice; improve inter-organizational communication; and minimize duplication of effort by having common resources, documentation, and training (Clarke, 1999).

Research by Payne and Turner (1999) has noted that project management practices can differ significantly from one project to another. Despite, Kerzner (2001) believes the best way to increase the possibility of an organization having a continuous stream of successfully managed projects is to generate a good project management methodology in-house that is flexible enough to support all projects. The project management methodologies of most organizations are fairly standard with most using a common project-management framework across the organization, often readjusted from external standards like those of the PMI.

To expand this concept, in the following paragraphs the Traditional approach, will be reviewed. Considering the purpose of the thesis, it should be clear that the following paragraph will have only an expositive aim, and the detailed study of the methodologies of Project Management adopted by the investigated company is not the purpose of this thesis.

Traditional Approach: The traditional, waterfall or sequential methodology is probably the most widespread conception of Project Management and the one suggested, this method was originally defined by Winston W. Royce in 1970, ("The Waterfall Development Methodology", 2006). It quickly gained support from managers because everything flows logically from the beginning of a project through the end, the planning of the project is done upfront and then is executed in a linear fashion, hoping there will not be any changes during the execution of projects which cause the scope change. As the name can imply, it outlines a linear and progressive method of management of the different phases of the project, widely using the concept of milestones in which the project is completed in distinct stages and moved step by step toward ultimate release to the client (Figure 2.4). The progress is mostly unidirectional and downward; every different phase of the project is treated as stand-alone, with the interchange of information between them guaranteed only by the making of formal documents. The different steps are overtaken by different people from different departments, to have a final product complete in all its features. Finally, the various steps are strictly sequential and usually, one phase is not started if the previous in the schedule is not completed.

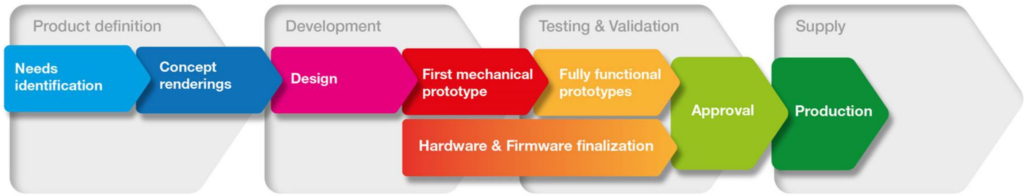

Figure 2.4: Traditional Project Management Practice

2.2.1 Traditional Cost Management

In Traditional approach, the cost of project is estimated based on a fixed scope and before the project starts. New requirements or changes requested by client mean higher costs, and since project managers estimate costs based on what they know at the project start, which is very limited and incomplete, cost overruns are very common in projects associated with high degree of change. Numerous industry studies show that companies with poorly defined project management approaches, without acceptable implementation and standardization of best practices and control methods, face greater difficulties than their competitors and requirements management related change requests are perceived as the main reasons for inaccurate cost estimates and cost control.

2.3 Earned Value Project Management

2.3.1 Background

Earned Value Management or simply EVM appeared as a financial analysis specialty in United States Government programs in the 1960s, but it has since become a significant branch of project management and cost engineering. Earned value management (EVM) is a method of project management, which facilitates project control through quantifying the technical performance of an ongoing project and providing support in forecasting final cost. Implementations of EVM can be scaled to fit projects of all sizes and complexities [24].

An overview of EVM was introduced in the Project Management Institute's first PMBOK Guide in 1987 and was expanded in subsequent editions. In the most recent edition of the PMBOK guide, EVM is listed among the general tools and techniques for processes to control project costs.

The earned value project management technique combines three critical parameters of project management: scope management, cost management, and time management to control cost-overrun and schedule delays. It requires the periodic monitoring of actual expenditures of projects and the physical scope accomplishments, and allows calculation of cost and schedule variances, along with supporting the tasks of control, analyzing, and estimating project performance indices [25].

2.3.2 EVM Key Components

EVM develops and monitors three critical dimensions for each work package and control account and to evaluate project performance; in the following, a brief description of these three parameters is presented:

Planned Value (PV)

Planned value is defined as the authorized budget assigned to scheduled work. It is the approved budget proposed for the work to be accomplished for an activity or work breakdown structure (WBS) component. This budget is allocated by phase over the life of the project, but at a given point in time, planned value defines the physical work that should have been accomplished. The total of the PV is sometimes referred to as the performance measurement baseline [26]. The total planned value for the project is also known as the budget at completion (BAC), which is the highest value of PV and the last point on the cumulative PV curve.

Earned Value (EV)

Earned value is essentially a relative effort tracking metric, which represents a measure of work accomplished expressed in terms of the budget authorized for that work. It is the budget associated with the authorized work that has been completed. The EV is often used to calculate the percent complete of a project, and project managers monitor EV, both incrementally to identify current status and cumulatively to determine the long-term performance trends.

Actual Cost (AC)

Actual cost is the realized cost incurred for the work performed on an activity during a specific period. It is the total cost incurred in accomplishing the task that the EV measured. The AC needs to correspond in definition to what was budgeted in the PV and measured in the EV (e.g., direct hours only, direct costs, or all costs including indirect costs). The AC will have no upper limit; whatever is spent to achieve the EV will be measured. This was previously called the actual cost of work performed (ACWP). Figure 2.5 uses s-curves to display the main EVM elements for a generic project.

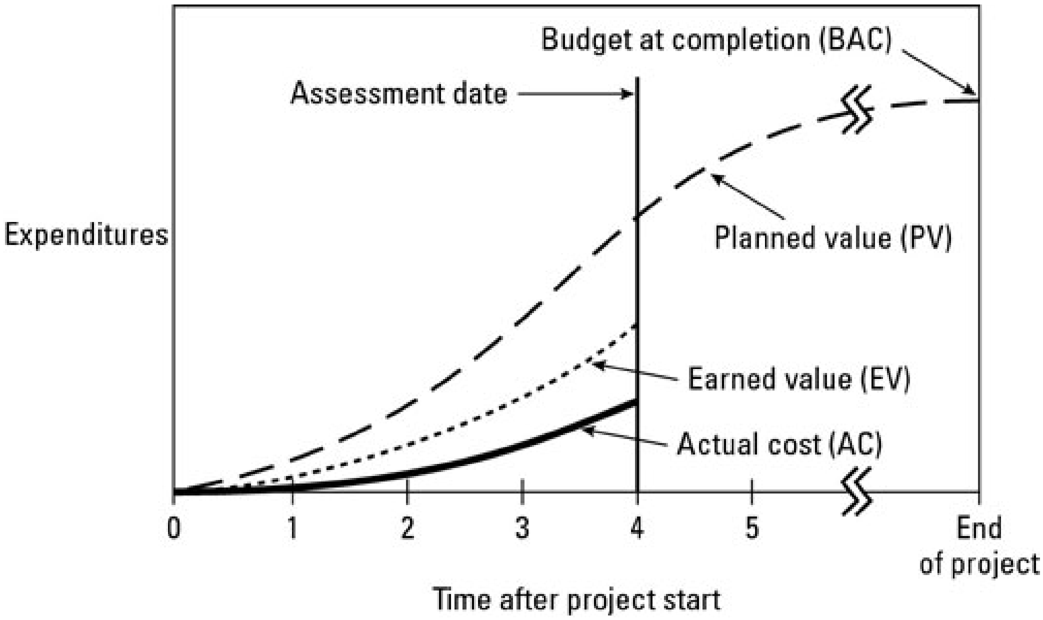

Figure 2.5: Earned Value, Planned Value, and Actual Costs

2.3.3 Earned Value Analysis (EVA)

Variance analysis is used in EVA practice to compare the baseline to the actual results and determine the cause and degree of variance to the cost baseline and finally to decide whether corrective or preventive action is required. The percentage range of acceptable deviations will tend to decrease as more work is accomplished. Cost and schedule variances are the most frequently analyzed measurements. For projects not using formal earned value analysis, similar variance analyses can be performed by comparing planned cost against the actual cost to identify variances between the cost baseline and actual project performance.

Schedule Variance

Schedule variance (SV) is a measure of schedule performance expressed as the difference between the earned value and the planned value. It is the amount by which the project is ahead or behind the scheduled delivery date, at a given point in time. It is a measure of schedule performance on a project. It is equal to the earned value (EV) minus the planned value (PV), as shown by Eqn. 2.1. The EVA schedule variance is a useful metric that can indicate when a project is falling behind or is ahead of its baseline schedule. The EVA scheduled variance will ultimately equal zero when the project is completed because all of the planned values will have been earned [27].

$$SV = EV - PV \tag{2.1}$$

Cost Variance

Cost variance (CV) is the amount of budget deficit or surplus at a given point in time, expressed as the difference between earned value and the actual cost. It is a measure of cost performance on a project. It is equal to the earned value (EV) minus the actual cost (AC), as shown by Eqn. 2.2. The cost variance at the end of the project will be the difference between the budget at completion (BAC) and the actual amount spent. The CV is particularly critical because it indicates the relationship of physical performance to the costs paid. A negative CV is often severe for the project to recover.

$$CV = EV - AC \tag{2.2}$$

Schedule Performance Index

The schedule performance index (SPI) is a measure of schedule efficiency expressed as the ratio of earned value to planned value. It measures how efficiently the project team is accomplishing the work. It is sometimes used in conjunction with the cost performance index (CPI) to forecast the final project completion estimates. The SPI is equal to the ratio of the EV to the PV (Eqn. 2.3).

$$SPI = EV/PV \tag{2.3}$$

Cost Performance Index

The cost performance index (CPI) is a measure of the cost efficiency of budgeted resources, expressed as a ratio of earned value to actual cost. It is considered the most critical EVA metric and measures the cost efficiency for the work completed. The CPI is equal to the ratio of the EV to the AC (Eqn. 2.4).

$$CPI = EV/AC \tag{2.4}$$

2.3.4 Estimating Cost at Completion

In Earned Value Analysis (EVA), the Cost Estimate At Completion, usually abbreviated as CEAC, is the estimation of the final cost of an ongoing project considering the current progress and performance of the project. Thus, it is a forward-looking tool to help Project Managers (PMs) with the task of making timely and appropriate decisions about cost outcome of their in-progress projects [28] which allows objective monitoring of actual project status, and tracking of deviations by comparing it with the project baseline.

CEAC can be developed using different cost estimating approaches like traditional index-based (IB) approaches or regression-based approaches [29] ; [30]. IB approaches are more simple-to-use, however, they have three inherent limitations, as follows: (1) reliance on the past performance only, (2) unreliable CEAC in early stages of the project life because of few available EVM information, and (3) no count of forecasting statistics [31]; [32].

To overcome the stated deficiencies of the IB approach and to generate more reliable CEAC, linear or nonlinear regression-based analysis has been valued as an alternative to traditional IB approaches to develop regression-based models [29]. Although implementing the curve fitting methods and regression techniques are more sophisticated compared to the IB-based method, their accuracy regarding the CEAC calculation will be improved significantly, and thus this technique will provide more reliable forecasts early into the project life [33]. In the nonlinear regression approach, the sigmoid functions are used as the growth models better describe the nonlinear relationship between the input and output variable and produce the s-shaped curve of this cumulative cost. These methodologies extend the application limits of the traditional index-based methods and overcome the three previously mentioned limitations. In the literature, growth models with nonlinear regression have been widely applied to study cumulative cost growth [29]. In the next two following parts, I will explain more about these methods regarding the calculation of CEAC.

CEAC Calculation with Traditional Index-Based Approach

In the EVM theory and practice, the calculation of CEAC is done by using the critical parameters of EVM which were discussed in previous sections, which are the planned value (PV), actual cost (AC), earned value (EV), and budget at completion (BAC). Cost estimate st completion is computed by extrapolating the actual project cost performance to the end of the project life by summing up two factors, Eqn. 2.5, which are: the Actual Cost (AC) of work performed at Actual Time (AT) and the estimated cost of the remaining work. The second part of the equation is a difference between the Budget at Completion (BAC) and the Earned Value (EV) adjusted by a Performance Index (PI), which is a measure of cost efficiency of budgeted resources [34].

$$CEAC(x) = AC(x) + (BAC - EV(x))/PI(x) \tag{2.5}$$

Performance Index or PI is set based on project status and risks and as Zwikael [32] stated, this choice is related to assumptions introduced by PMs, from an optimistic assumption that all the past cost variations will be diminished in the future so that their projects can be accomplished within the BAC to a pessimistic one that the variations will continue at the rate observed so far [35]. PMI [34] presents four PIs to correct the remaining BAC (Table 2.1) with different assumptions associated with actual project performance.

Performance Index	PI Formula	Assumptions on future cost performance
Cost Performance Index, CPI	EV/AC	The same as past cost performance
Critical Ratio, CR	CPI*SPI	Influenced additionally by past schedule performance
Composite index , CI	$0.8PI + 0.2SPI$	Influenced jointly in some proportion by both cost and schedule performances

Table 2.1: EVM PIs and Assumptions (PMI, 2011)

The most commonly used PI among these indexes is the Cost Performance Index (CPI), which assumes that past cost performance is the best indicator of future cost performance as a reasonable estimate. The second row of the table 2.1 demonstrates that by using a product of CPI and Schedule Performance Index (SPI), an estimate can be obtained by considering both project cost and time performance which is the project Critical Ratio (CR) and can be a ceiling CEAC to reflect both cost deviation and schedule progress and can be seen as an indicator of the overall project health [35].

Regarding this matter, a prior analysis performed on defense projects showed that a cumulative value of CPI stabilizes when the project is almost 20% complete, and the estimated cost does not change by more than 10% percent from that point in time to completion [36]. The EVM community received this finding as a rule of thumb and generalized it as being applicable for all types of projects. Nevertheless, recent studies doubted this finding attributing it only to large-scaled and long duration defense projects [37]; [38]. They investigated whether the PI stability existed and discovered that most projects from other industries (e.g., construction) with relatively small budgets and short duration achieved the PI stability by the second half portion of the project life.

To overcome these limitations inherent with the IB approach, the regression based procedures have been winning more approval by practitioners. We will discuss more this method in the following section.

CEAC Calculation with Regression-Based Approach

Several methods based on regression analysis have been gaining acceptance as valuable methods to support the cost-estimating activity as an alternative to the index-based approach [39]. The main characteristic of these methods is that they describe a linear or nonlinear statistical relationship between input (predictor variable) and an output (response variable) through their parameters [40]. In these analyses, a dependent variable (typically the AC) is regressed against an independent variable (usually time) to calculate the CEAC.

The regression model can be either linear or nonlinear to represent the respective relationship between the response and predictor [41]. The parameters of a regression model determined through a regression analysis represent the behavior of a project concerning the entire life cycle. Besides, even though the effort required to perform the regression-based computation is more significant compared with the relatively simple index-based cost-forecasting method, it yields better estimates early in the project life [36]and Heise 1993; Tracy 2005) while the index-based approach is likely to be unreliable.

Growth Models

Growth models represent situations inherent to data with a growth pattern, in which the growth rate monotonically grows to a maximum before it steadily declines to zero (Seber and Wild 1989) and is the fundamental concepts associated with Regression-based methods. This behavior is well-described by an s-shaped or sigmoidal models that are widely used in curve-fitting and forecasting of population growth.

In Project Management, S-curves are used to graphically demonstrate cumulative progress of work, expressed in units of costs, labor hours, efforts, progress percentage, etc., plotted against time (PMI, 2008). The s-like form of this curve depicts work progress, which has a lower rate at the beginning and end and a higher rate in the middle (steeper pattern) and is characterized by the position of the point of inflection, which is the time at which the growth rate is the greatest. Figure 2.6 shows the typical characteristics of growth models.

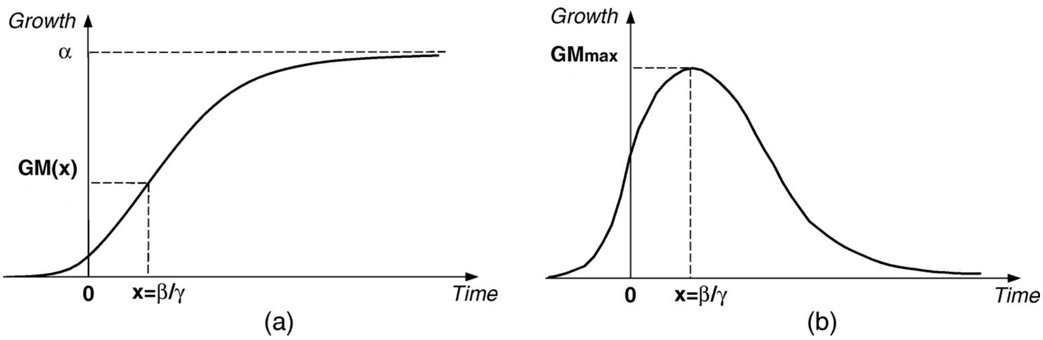

Figure 2.6: Characteristics of an S-shaped Growth Model: (a) Cumulative Growth Curve; (b) Growth Rate Curve

Many growth models can be used to describe the sigmoidal behavior of the cost of a project, depending on whether their functional form and parameters reflect the nature of the project and satisfy the s-shaped pattern and its requirements or not. The mathematical characteristics of these models are common. They all have an α value, which is a parameter that represents the asymptotic project final cost as time (x) approaches infinity (which in never obtained). In other words, as a project tends to its completion, there is less work left to perform, and the closing phase is a typical slow-paced approach to the final cost (the α-asymptote). The β parameter is the $y - intercept$ indicating an initial budget size, and the γ represents a scale parameter that directs the cost growth rate (GR).

The formula for the computation of the CEAC is Eqn. 2.6, which assumes the values of the growth model today (AT) and when a project is 100% complete. This formula is similar to the traditional method used in the IB approach in Eqn. 2.5 because both equations have AC. Though, in Eqn. 2.6 the remaining portion of the CEAC is calculated based on the non-linear growth model results, whereas in Eqn. 2.5 PI corrects the remaining portion of the BAC.

$$CEAC(x) = AC(x) + [GrowthModel(1.0) - GrowthModel(x)](BAC) \quad (2.6)$$

After developing the appropriate growth model, by substituting the three parameters for the Eqn. 2.6, one should calculate the value for the growth model in $x = 1.0$ in which the time is 100% complete, and it approaches its α-asymptote. For the growth model x, the predictor variable is the to-date value of the time increment. These two values are calculated by using the equation of the growth model selected, and their difference represents the estimated portion of BAC required to complete a project, which is, in turn, added to the current AC incurred to calculate the final CEAC.

Chapter 3

Data Collection

Document review is used as the method of data collection to collect required quantitative data of the research by reviewing the existing documents of the company. This method is an efficient and effective way of gathering data as documents are manageable and are the practical resource to get qualified data from the past. Apart from strengthening and supporting the research by providing supplementary research data document review has been identified as one of the beneficial methods to gather quantitative research data.

For the comparative study of the impact of Engineering Change Requests (ECR) on the CEAC of a project, twenty projects were selected from an R&D center of an Italian supplier of high-tech components in automotive industry, from which eleven projects are completed and delivered, and the rests are ongoing projects. All the project are analyzed in their early-middle stages of their life. In Table 3.1, the list of projects and their actual status can be seen. They are all small to medium-scale projects with a duration varying from 16 to 42 months and an average BAC of 1 million euros (with an average of 120 FTE). The projects are mainly human resource-based R&D projects with the almost constant and significantly small cost of material compared to human resource costs, so in this study, the Full-time equivalent (FTE) is used as a unit of cost for the analysis of projects.

Number	*Project Name*	*Duration(months)*	*Status*
1	A	18	*Finished*
2	B	23	*Ongoing*
3	C	31	*Finished*
4	D	18	*Finished*
5	E	19	*Finished*
6	F	27	*Ongoing*
7	G	30	*Finished*
8	H	42	*Ongoing*
9	I	31	*Ongoing*
10	J	35	*Finished*
11	K	30	*Finished*
12	L	16	*Ongoing*
13	M	25	*Finished*
14	N	15	*Ongoing*
15	O	36	*Ongoing*
16	P	28	*Ongoing*
17	Q	23	*Finished*
18	R	19	*Finished*
19	S	21	*Finished*
20	T	23	*Ongoing*

Table 3.1: List of projects

The data were collected from different documents associated with every project. In the next section, I will explain more about the how each set of data required for the CEAC analysis, was collected.

3.1 Variability of Project Planned value

Project Planned Value (PV) and Planned Duration (PD) are the first elements of earned value management, which in the investigated company, are recorded in the planning document of the project in which the approved value of the work to be completed in a given time is indicated. Since the nature of the most phases of these projects are uncertain and variable, with the scopes not fully defined, so the project can not benefit from detailed cost calculations due to frequent changes. Instead, lightweight estimation methods are used to generate a not-so-reliable forecast of project labor costs, which can then be adjusted as changes arise. Therefore although the principal approach practiced by the company is the Traditional approach (Waterfall Approach), in phases of project which are associated with a huge number of change requests, the PMs start to re-baseline the projects following more adaptive methods. Therefore, somehow the company is applying a kind of hybrid project management methodology, depending on the type of project and the amount of change requested later on by the client, in order to capture the impact of change requests (CRs) on all constraints of projects.

In this regard, every project has two sets of planned Value, Initial Planned Values, which are the values estimated by PMs, based on the traditional practices at initial phase of project, before it stars, and, Revised Planned Values which are the effort estimated in a more adoptive way, leading to cost re-baselining, consisting the extra effort for implementation of CRs which is done every trimester. The main reason for the presence of these two different sets of planned effort data is nothing but the existence of many change requests and the dynamic and complex environment of projects which require a predefined set of revisions in order to take into account new features or changed requirements requested by the clients. These two differently estimated planned values are explained in the following.

3.1.1 Project Initial Planned Value

Plan Cost Management, as defined in the PMBOK Guide is the process of defining how the project costs will be estimated, budgeted, managed, monitored, and controlled. The key benefit of this process is that it provides guidance and direction on how the project costs will be managed throughout the project [42]. Planned Value is the estimated cost before actually doing the work, which also serves as a baseline of the project and are forecasted by different approaches like, the expert judgment, top-down approach, bottom-up approach, analogy and many more. Total Planned Value for the project is also known as Budget at Completion (BAC). According to the PMBOK Guide,

"Planned Value (PV) is the authorized budget assigned to work to be accomplished for an activity or WBS component."

This Value represents the offered value by the company to the client at the phase of Project buy-in (Offer phase) and comes from the budget determining process which is the process of aggregating the estimated costs of individual activities or work packages to establish an authorized cost baseline (PMBOK Guide 2015)[42]. In the planning document, PV is called the Initial Planned Value, shortly Initial-PV, and it is calculated on a task by task basis and summed to produce the project's total PV for the entire duration of project, exerting the traditional method. It covers the project estimates in the unit of FTE cost plus a not-so-reliable estimated amount of contingency reserve for ECRs that the company receives from clients for potential upcoming Change Requests (CRs) that the project managers are assured about at the beginning of the project based on historical data, which is usually is underestimated by a very high percentage error. Eqn. 3.1 shows how the Initial-PV is calculated for the projects.

$$Initial - PV = Offered\ Value + Change\ Request\ Contingency \tag{3.1}$$

In the past, the planned value was also called the Budgeted Cost of Work Scheduled (BCWS). Information about the hierarchical reflection of all the work in the project in terms of deliverables that identifies work packages to be accomplished (WBS) by each team of the R&D department is also illustrated in this document.

The main part of data was extracted from a very extensive database, which is called the project's Initiative or project's Spending Curve, in which the growth pattern of cost (FTE) during the implementation of the project is defined monthly, divided by team and by various sites. Figure 3.1 depicts some part of this database, from which I extract the input data for my calculation. The project cost baseline then will be changed based on the project status during the process of cost control and monitoring.

		2018												2019											
		Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4		
		1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
	Customer Milestone				Supplier Nomination			PT								AV			PS				SOP		
	Design phases	offer																							
	Release and deliverables									SW1				SW2											
	SW Validation														Full validation										
TOT	Product Validation																Delta PV								
560	SW architect			0.1	0.1	0.75	0.5	0.5	0.25	0.25	0.15	0.15	0.15	0.1		0.1		0.1		0.1		0.1		0.1	
152	SW Architect India						0.1	0.15	0.15	0.15	0.1	0.1	0.1	0.1											
320	SW reference/Integrator				0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.1											
960	SW Appl						0.5	1	1	0.5	1	1	0.5	0.5											
560	SW RTE						0.5	1	1	1															
176	SW Network				0.1	0.5	0.5																		
48	SW WDF						0.3																		
240	SW PTF DIAG/Bootloader								0.5	0.5	0.5														
0	SW OS/WD/LP/AUTOSAR																								
80	SW IO					0.5																			
2384	**TOT SW DEV**	0	0	0	0.3	1.2	2	2.2	2.7	2.3	1.7	1.2	0.7	0.6	0.3	0.2	0.2	0.2	0.1	0	0	0	0	0	0
256	SIL India									0.5	0.5	0.5		0.1											
256	SW PTF India						0.1	0.5	0.5	0.5															
512	**TOT SW India**	**0**	**0**	**0**	**0**	**0**	**0.1**	**0.5**	**0.5**	**1**	**0.5**	**0.5**	**0**	**0.1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
395.2	HW Ref Des			0.2	0.25	0.25	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.12	0.1	0.1	0.05							
0	HW Des																								
0	Layout																								
0	Hw Thermal																								
0	HW Antipinch																								
0	HW Prof Leader																								
0	HW Customer Interface																								
395.2	**TOT HW DEV**	**0**	**0**	**0.2**	**0.25**	**0.25**	**0.2**	**0.2**	**0.1**	**0.1**	**0.2**	**0.2**	**0.2**	**0.2**	**0.12**	**0.1**	**0.1**	**0.05**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
80	M Des				**0.05**	**0.05**	**0.1**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**												
264	**PRD VAL**														0.5	0.5	0.35	0.3							
1088	SW Validation													0.6	1.4	2	2	0.8							
240	PVR and HIL engineer					0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1					
1328	**TOT SW VAL**	**0**	**0**	**0**	**0**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.7**	**1.5**	**2.1**	**2.1**	**0.9**	**0.1**	**0.1**	**0**	**0**	**0**	**0**	**0**
640	**SW Validation INDIA**														**1.2**	**1.5**	**0.8**	**0.5**							
272	Functional Safety (only R&D) - architect									0.5	0.5	0.5	0.2												
240	Functional Safety (only R&D) - HW									0.2	0.1	0.1	0.2	0.2	**0.2**	**0.2**	**0.2**	**0.1**							
272	Functional Safety (only R&D) - SW													**0.3**	0.4	0.4	0.4	0.1	0.1						
320	Functional Safety (only R&D) - SW validation													**0.4**	**0.5**	**0.5**	**0.3**	**0.2**	**0.1**						
112	Functional Safety (only R&D) - product validation													**0.2**	**0.2**	**0.1**	**0.1**	**0.1**							
1216	**TOT Functional Safety (only R&D)**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0.7**	**0.6**	**0.6**	**0.4**	**1.1**	**1.3**	**1.2**	**1**	**0.5**	**0.2**	**0**	**0**	**0**	**0**	**0**	**0**
0	FSM																								
512	CPE				0.2	0.2	0.1	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1		
120	Res Engineer																			0.25	0.25	0.25			
0	Project Management																								

Input R&D Scenario | Expenses_investments A | **R&D Effort_ Spending Curve A** | R&D effort - summary | Simulators Details

Figure 3.1: A part of Spending Curve of project A

3.1.2 Project Revised Planned Value

Cost estimates (Initial-PV) should be reviewed and refined during the project to reflect additional detail as it becomes available during the project execution. The accuracy of a project estimate will increase as the project progresses through the project life cycle. For example, a project in the initiation phase may have a rough order of magnitude (ROM) estimate in the range of −25% to +75%. Later in the project, as more information becomes known, definitive estimates could narrow the range of accuracy to −5% to +10%. In some organizations, there are guidelines for when such refinements can be made and the degree of confidence or accuracy that is expected [26].

In the investigated company, the planned value of each project is revised every four months to reflect the change in project requirements and its initial scope, mainly due to the change requests (CRs) demanded during the implementation of project, considering the actual costs spent to date. The new planned value in which, the change requests play the leading role, is called the Revised Planned Value (Revised-PV) in the company documents, is calculated by the Eqn. 3.2.

$$Revised - PV = (Initial - PV) + Extra\ Costs\ of\ CRs \tag{3.2}$$

3.2 Project Actual Cost

The actual cost of a project or the real effort spent is an other element of earned value management and is defined as the total cost incurred for the actual work completed to date. According to the PMBOK Guide, Actual Cost (AC) is the realized cost incurred for the work performed on an activity during a specific period. It is the total cost incurred in accomplishing the task that the EV measured. The AC needs to correspond in definition to what was budgeted in the PV and measured in the EV (e.g., direct hours only, direct costs only, or all costs including indirect costs). The AC will have no upper limit; whatever is spent to achieve the EV will be measured [42]. Actual Cost is also known as the Actual Cost of Work Performed (ACWP).

In the case of project monitoring and controlling, tracking the team's time-sheet is necessary to help boost the project productivity, so the actual effort spent on every activity of the projects is collected through a customdesigned system used by the company which is called DEC Evo. DEC Evo. is a multi-use tool, that is designed mainly to keep track of the time that teams are working on every project, and all members of teams fill it on a daily basis, representing the hour worked on every projects' activities and sub-activities defined and controlled by the team leader and project managers (PMs) for every project. In Figure 3.2, a part of this web-based system, is depicted.

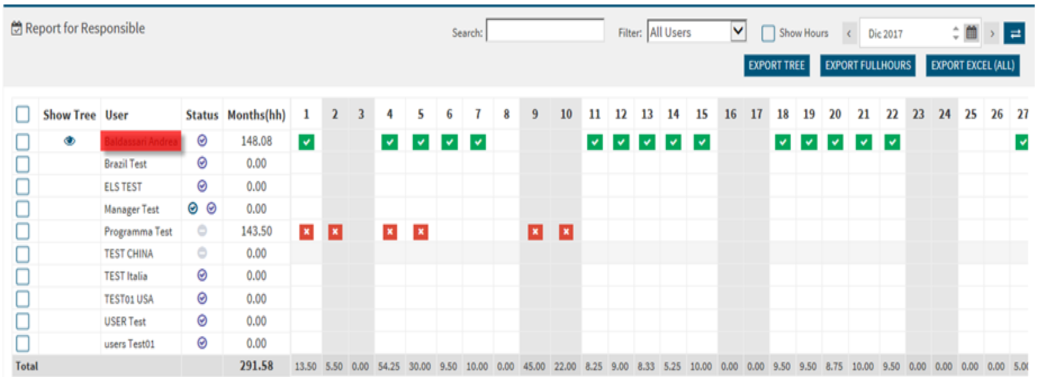

Figure 3.2: Actual Cost (Effort) Collection by DEC Evo. System

3.3 General Characteristics of Implemented CRs

In the investigated company, the nature of the change requests (CRs), are closer to Jarratt [2] definition, as software development is one of the most important part of development projects and is the part which incurs the major part of CRs after any release to the client. Regarding the size of these CRs, the relative documents imply that they can differ from a small revision in a part of software release to significant changes that can take several months to implement and like many ECRs they show the step-change-cause-effect, meaning that they usually start from a change in software release and then lead to a network of changes in the work of other teams (Hardware, Mechanical Design, Validation, etc.,).

The sheer number of the change requests initiate from the client and are considered as external CRs, which can arise during any phases of the project life cycle but mainly occur during the design phase and increase to the maximum number in the development phase. The leading causes of great part o the CRs in the analyzed projects, as mentioned before, are related to the high degree of complexity of the products and the continuous change of client demands relating to the requirements and specifications of products which constantly change the project initial scope.

Unfortunately due to the lack of a system capable of managing and controlling the change requests, it is not possible to precisely measure and distinguish the exact amount of effort put on the implementation of "Emergent Changes", which include, as defined in previous chapters, activities of error correction and bug fixing from the effort spent on the "Initiated Changes", which are changes that target improvements and adoption of product almost always requesting by the clients.

3.3.1 Impact Analysis of Change Requests

There are 5 core steps in a change management process in the projects, which are Identifying/Receiving the change request, Reviewing the change request, Impact assessment, approval of the change request, Implementing the change request, and closing the change request (figure 3.3). There are numerous methods to analyze and evaluate the risks and impacts of an engineering change request. The approach with which the investigated company performs the impact analysis on its ECRs is “Change Impact and Risk Analysis,” which is the most common method used to analyze and assess risks. In this approach, which is mainly based on the Failure Modes and Effects Analysis (FMEA), performing the impact analysis looks for potential side effects caused by a change request on the product's characteristics, which could lead to further changes. So, the result of this analysis is a list of potential effects that have to be supervised in the case of changing that characteristic.

In the next step, based on the type and size of the change request, each team begins to forecast the amount of extra effort required to perform the CR by using different techniques. The most common techniques applied by teams are first the "Analogy Technique", which estimates the effort through comparison with similar projects., and second is the "Expertise", in which the intuition and experiences of PM from other projects build the basis of the effort estimation.

Figure 3.3: Change Management Process

Chapter 4

Methodology

This section explains the methodology used for the calculation of CEACs regarding the analysis of CRs impact on the final cost of completion of ongoing projects.

The cost-forecasting method used in this analysis is based on a modified index-based formula estimating the expected cost for the remaining work with an appropriate growth model through nonlinear regression curve-fitting. The CEAC formula used in this study interpolates the parameters of the growth models found through the nonlinear regression analysis to overcome the limitation of the IB method. One of the most essential properties of EVM cost estimating approaches is the timeliness of estimation, meaning that the forecasted cost should be reliable and accurate over a certain period or entire project life. From a practical perspective, PMs may be more concerned about timeliness in cost forecasting as it implies reliability in cost forecasting and provides a project team with warning signals about the final cost outcome [43].

Vandevoorde and Vanhoucke (2006) reported timeliness analysis of this methodology concerning the accuracy of estimates, and De Marco and Narbev (2014) performed also the analysis of the precision timeliness, as a property describing more accurate and precise CEAC over the three forecast stages [44], [35]. Thus, this approach is more accurate and precise in all early, middle, and late-stage estimates than the conventional IB approach. From a practical perspective, this may be of great importance to PMs as it implies the reliability of the cost forecast process.

Since almost half of analyzed projects are ongoing projects that are continuously subjected to significant adjustments and cost and scope re-baselining, the earned scheduled (ES) concept, which also takes into consideration the project work progress, will not be integrated in the CEAC methodology adopted in this research.

In Project Management, cumulative progress of work, represented in units of costs, efforts, labor hours, progress percentage, etc., plotted against time are displayed graphically by S-curves (PMI, 2008) [26]. The S-like shape of this curve represents perfectly the pattern of work progress in the analyzed projects, which has a lower rate at the beginning and end and a higher rate in the middle [35]. This behavior, as discussed before, is well-described by the sigmoidal patterns that we use for curve-fitting and forecasting of CEAC.

To attain this purpose, this analysis is performed in two steps. First, I combine the two planned values (Initial-PV, Revised-PV), which I fully-described them in the Data Collection chapter, with AC data versus time to find the proper growth model fitting the data, and then determine their parameters required for the computation of CEACs. Second, by inserting the growth model parameters, I apply the CEAC equation (Eqn. 2.6).

4.1 Developing the Growth Model

In this analysis, for every project, the curve-fitting process was performed twice, once by extrapolating initial planned values (Initial-PVs) versus time and the second time by considering the revised planned values (Revised-PVs) versus time points. To generate the regression-based nonlinear growth model that is used to fit the cumulative cost S-shaped curve line of the projects, the collected data was adjusted and normalized as the following steps:

Step 1.

Time points, which represent the predictor variable (x) of the growth model, are normalized to unity, that assumes the project is 100% time completed (i.e., PD=1.00) and then each next time point is a cumulated portion of this unity with the final time point representing planned duration of the project. Each time point (x), has two corresponding cost points, which are the response variables (y_1, y_2).

Step 2.

Actual Costs (ACs) are normalized to unity twice, once by considering initial planned values and second time by considering revised planned values, from time 0 to Actual Time (AT) which are the two response variables (y_1, y_2) of the two curve-fitting processes.

Step 3.

Initial planned values (Initial-PVs) are normalized to unity at the time range from AT to PD (i.e., $BAC_1 = 1.00$).

Step 4.

Planned values (Revised-PVs), are also normalized to unity in the same way, at the time range from AT to PD (i.e., $BAC_2 = 1.00$).

Table 4.1 provides a part of the original analyzed database, showing the absolute values for project A, the time values (column Time Point), and costs data (columns Initial-PV, Revised-PV, and AC). Then these time points are normalized to unity (assuming PD = 18 is 1.00) and Initial-PV, Revised-PV, and AC values are also normalized to unity, once assuming $BAC_1 = 69.399$ FTE is 1.00, and then assuming $BAC_2 = 93.450$ FTE is 1.00. These normalized time (variable x) and costs (variable y_1, y_2) points are then reported down on the columns Predictor and Response 1 and Response 2 in the presented table and are input data for the nonlinear regression analysis to run the curve-fitting process. The AC–PV values are combined values of AC from time zero ($x = 0$) to AT first with Initial-PV from AT to $BAC_1 = 69.399$, and then with Revised-PV from AT to $BAC_2 = 93.450$. To compute the early-middle stage, CEACs for Project A, month 9, is chosen as the time for the final cost estimation.

Month	Time Point (months)	Predictor	Initial-PV	Initial-PV Cumulative	Revised-PV	Revised-PV Cumulative	AC	AC Cumulative	Response 1 (AC-Initial PV normalized to BAC)	Response 2 (AC-Revised PV normalized to BAC)
Apr-18	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
May-18	1	0.056	3.738	3.738	0.000	0.000	0.000	0.000	0.000	0.000
Jun-18	2	0.111	5.988	9.725	2.100	2.100	1.852	1.852	0.027	0.020
Jul-18	3	0.167	7.238	16.963	3.250	5.350	4.784	6.636	0.096	0.071
Aug-18	4	0.222	6.944	23.906	5.250	10.600	3.442	10.078	0.145	0.108
Sep-18	5	0.278	7.188	31.094	9.350	19.950	4.980	15.058	0.217	0.161
Oct-18	6	0.333	9.100	40.194	10.700	30.650	7.169	22.227	0.320	0.238
Nov-18	7	0.389	6.850	47.044	13.150	43.800	12.258	34.484	0.497	0.369
Dec-18	8	0.444	4.200	51.244	9.350	53.150	14.766	49.250	0.710	0.527
Jan-19	9	0.500	3.175	54.419	6.500	59.650	7.097	56.347	0.812	0.603
Feb-19	10	0.556	2.800	57.219	7.250	66.900			0.824	0.716
Mar-19	11	0.611	2.840	60.059	5.750	72.650			0.865	0.777
Apr-19	12	0.667	1.970	62.029	4.550	77.200			0.894	0.826
May-19	13	0.722	1.800	63.829	9.400	86.600			0.920	0.927
Jun-19	14	0.778	1.500	65.329	3.500	90.100			0.941	0.964
Jul-19	15	0.833	1.750	67.079	1.650	91.750			0.967	0.982
Aug-19	16	0.889	0.870	67.949	1.200	92.950			0.979	0.995
Sep-19	17	0.944	0.950	68.899	0.500	93.450			0.993	1.000
Oct-19	18	1.000	0.500	69.399	0.000	93.450			1.000	1.000
Nov-19	19	–	–	–	–	–	–	–	–	–

Figure 4.1: Normalized predictor and response values for Project A

4.2 Implementing Nonlinear Regression on Data

Minitab® software tool is used for the task of curve-fitting. Minitab® is a statistical software that provides a simple, effective way to input statistical data, manipulate them, identify trends and patterns, and then extrapolate answers to the problem at hand.

Nonlinear regression is a powerful method that provides the most flexible curve-fitting functionality compared to linear regression. The trick is to find the nonlinear function that best fits the S-shaped curve of the projects costs growth considering their behavior. Fortunately, Minitab provides tools to make this task easier. Defining an equation for the S-curve model needs discussing some issues relevant to nonlinear regression analysis. Unlike linear regression, for applying nonlinear regression on a data set, we need to supply starting values for the model parameters and an algorithm for the approximation of these values [40].

Nevertheless, there is no standard procedure to help us define reliable starting values, so establishing a good set of these values in nonlinear curve-fitting is a difficult task because of the presence of a nonlinear relationship between the predictor and the response variables, unless one knows the starting values of the model parameters based on prior information (e.g., previous historical data, EVM data, variables relationship). To determine the values of these parameters, both linear and nonlinear regression use the least-squares (LS) method of approximation. The most common assumption in curve-fitting is that data points are randomly scattered around an ideal curve with the distribute following Gaussian distribution [40]. With these concerns, the LS approach minimizes the sum of the squared errors (SSE, the difference between the estimated values and actual input values of the parameters) of the vertical distances of the points from a curve [39].

The analysis reported in this thesis applies a Gauss-Newton algorithm for this iterative approximation, which converges not heavily depending on the starting values (Bates and Watts, 1988). The iteration process continues until the algorithm converges to determine the parameter values within the specified tolerance on the minimum SSE [40].

The important task is to find the nonlinear function that best fits the specific curve in our data. After entering data for all twenty projects in Minitab, to find the best nonlinear function that describe the inherent growth pattern in the data set, I applied three types of growth models, as follows: (1) Gompertz model (GM), (2) logistic model (LM) and (3) Weibull model (WM), which all belong to family of sigmoidal models and have broad application in many fields associated with population growth studies. Figure 4.2 depicts the function's catalog of Minitab software from which we applied the three mentioned functions. Figure 4.3 presents their generic cumulative distribution functions (CDF) and also provides the parameterized CDF equations that are used for curve-fitting and forecasting.

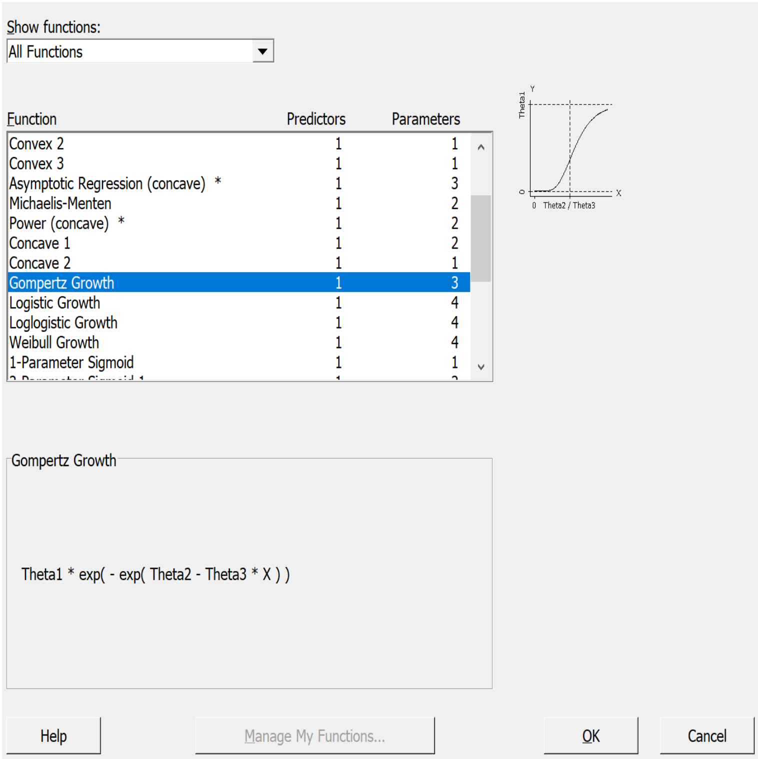

Figure 4.2: Minitab Software; Nonlinear Functions Catalog

Property	Logistic	Gompertz	Weibull
Generic CDF	$\alpha/[1+\beta e(-kx)]$ (Seber and Wild 1989)	$\alpha e\{-e[-k(x-\gamma)]\}$ (Seber and Wild 1989)	$1-e\{-[(x-\gamma)/\delta]^{\beta}\}$ (Hines and Montgomery 1990)
Parameterized CDF	$LM(x) = {}^{\alpha}/_{[1+e(\beta-\gamma x)]}$	$GM(x) = \alpha e[-e(\beta-\gamma x)]$	$WM(x) = \alpha\{1-e[-({}^{x}/_{\gamma})^{\delta}]\}$
Inflection Point	$x = {}^{\beta}/_{\gamma}$ $LM(x) = {}^{\alpha}/_{2}$	$x = {}^{\beta}/_{\gamma}$ $GM(x) = {}^{\alpha}/_{e}$	$x = ({}^{1}/_{\gamma})(\delta - {}^{1}/_{\delta})^{1/\delta}$ $WM(x) = 1-e[-(1-\delta^{-1})]$
Symmetry	Symmetrical	Asymmetrical	Flexible
Maximum Growth Rate	${}^{\alpha\gamma}/_{4}$	${}^{\alpha\gamma}/_{e}$	${}^{1}/_{\gamma}$
Parameters	$\alpha = asymptote$ $\beta = y-intercept$ $\gamma = scale$	$\alpha = asymptote$ $\beta = y-intercept$ $\gamma = scale$	$\alpha = asymptote$ $\delta = shape$ $\gamma = scale$

Figure 4.3: Growth Models and Mathematical Properties

In the next step, Minitab displays the following dialog (Figure 4.4), and so we need to select the starting values for each parameter in the function.

The initial values of these parameters are set as 1.00 with a confidence level of 95%. This selection is made based on the fact that the values of predictor and response variables are normalized to one and regarding issues related to defining initial values of the growth model parameters and the Gauss-Newton approximation algorithm discussed above.

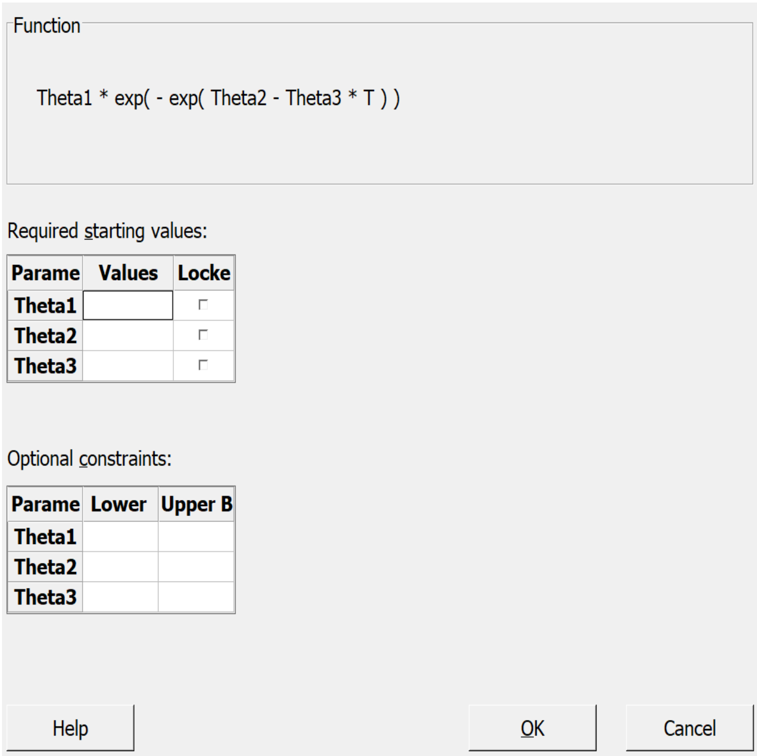

Figure 4.4: Minitab Software; Setting Initial Values

Cost expenditure behavior of the studied R&D projects can be described by all of these growth models because they all have functional patterns and parameters that best describe the cost pattern of projects. As discussed before, during the initial stages of a project, the progress is typically slow-paced, and by midlife, the project implementation progress speeds up, increasing the work rate to a maximum, and finally decreases during the completion phase. A mutual mathematical feature of these models is that they all have an α-asymptote value, a β parameter and, a γ value. The differences in mathematical properties and behaviors render these models applicable to a variety of fields, as presented in a diverse and large body of literature (Bates and Watts 1988; Seber and Wild 1989) [40][45].

4.2.1 Interpretation of Nonlinear Regression Results

In the nonlinear regression output of Minitab software, S can be found in the Summary of Model section, which is a statistic that provides an overall measure of how well the model fits our data. S is known both as the standard error of the regression and as the standard error of the estimate and represents the average distance that the observed values fall from the regression line. S is in the units of the dependent variable, and the smaller amounts are better because it signifies that the distances between the data points and the fitted values are smaller and so the observations are closer to the fitted line (Figure 4.5).

Summary

Iterations	17
Final SSE	0.0195002
DFE	20
MSE	0.0009750
S	0.0312252

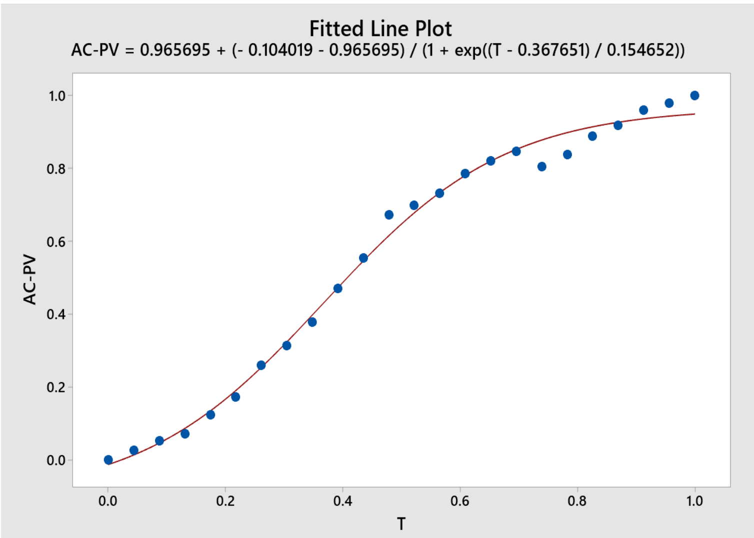

Figure 4.5: Minitab Software; Fitted Line Plot and Standard Error (S)

Figure 4.6 demonstrates a part of the outputs (projects A to J) of nonlinear regression analysis for all data by applying three mentioned functions. In the next step, the Logistic Model (LM) is selected as the best and the most accurate model for curve-fitting as it has the least Standard Error (S) for most of the project and also based on the fact that when it comes to LM model it is always the same best model for both Initial-PV-AC and Revised-PV-AC data whereas for other models does not act in the same manner.

	AC-Initial PV						AC-Revised PV					
	GGM		LM		Weibull		GGM		LM		Weibull	
A	Iterations	20	Iterations	12	Iterations	20	Iterations	9	Iterations	12	Iterations	16
	Final SSE	0.043104	Final SSE	0.023724	Final SSE	0.021977	Final SSE	0.015145	Final SSE	0.0184968	Final SSE	0.0161233
	DFE	16	DFE	15	DFE	14	DFE	16	DFE	15	DFE	14
	MSE	0.002694	MSE	0.001582	MSE	0.00157	MSE	0.000947	MSE	0.0012331	MSE	0.0011517
	S	**0.051904**	**S**	**0.039769**	**S**	**0.03962**	**S**	**0.030766**	**S**	**0.0351158**	**S**	**0.0339362**
B	Iterations	28	Iterations	43	Iterations	28	Iterations	20	Iterations	10	Iterations	182
	Final SSE	0.328157	Final SSE	0.285927	Final SSE	0.255116	Final SSE	0.002332	Final SSE	0.0016709	Final SSE	0.0013468
	DFE	21	DFE	20	DFE	19	DFE	21	DFE	20	DFE	19
	MSE	0.015627	MSE	0.014296	MSE	0.013427	MSE	0.000111	MSE	0.0000835	MSE	0.0000709
	S	**0.125006**	**S**	**0.119567**	**S**	**0.115876**	**S**	**0.010537**	**S**	**0.0091404**	**S**	**0.0084194**
C	Iterations	17	Iterations	12	Iterations	20	Iterations	12	Iterations	11	Iterations	14
	Final SSE	0.072679	Final SSE	0.044868	Final SSE	0.040879	Final SSE	0.010143	Final SSE	0.0098738	Final SSE	0.0093209
	DFE	29	DFE	28	DFE	27	DFE	29	DFE	28	DFE	27
	MSE	0.002506	MSE	0.001602	MSE	0.001514	MSE	0.000350	MSE	0.0003526	MSE	0.0003452
	S	**0.050062**	**S**	**0.04003**	**S**	**0.038911**	**S**	**0.018702**	**S**	**0.0187786**	**S**	**0.0185801**
D	Iterations	14	Iterations	10	Iterations	18	Iterations	10	Iterations	14	Iterations	16
	Final SSE	0.012369	Final SSE	0.006012	Final SSE	0.006841	Final SSE	0.043459	Final SSE	0.0361842	Final SSE	0.038807
	DFE	16	DFE	15	DFE	14	DFE	16	DFE	15	DFE	14
	MSE	0.000773	MSE	0.000401	MSE	0.000489	MSE	0.002716	MSE	0.002412	MSE	0.002772
	S	**0.027804**	**S**	**0.02002**	**S**	**0.022105**	**S**	**0.052117**	**S**	**0.049115**	**S**	**0.0526491**
E	Iterations	14	Iterations	10	Iterations	18	Iterations	11	Iterations	12	Iterations	16
	Final SSE	0.007372	Final SSE	0.006478	Final SSE	0.006187	Final SSE	0.008272	Final SSE	0.0112551	Final SSE	0.0081884
	DFE	17	DFE	16	DFE	15	DFE	17	DFE	16	DFE	15
	MSE	0.000434	MSE	0.000405	MSE	0.000412	MSE	0.000487	MSE	0.000703	MSE	0.000546
	S	**0.020824**	**S**	**0.020122**	**S**	**0.020309**	**S**	**0.022058**	**S**	**0.0265225**	**S**	**0.0233643**
F	Iterations	13	Iterations	13	Iterations	20	Iterations	12	Iterations	13	Iterations	17
	Final SSE	0.044264	Final SSE	0.026992	Final SSE	0.028326	Final SSE	0.033507	Final SSE	0.0217706	Final SSE	0.0238251
	DFE	25	DFE	24	DFE	23	DFE	25	DFE	24	DFE	23
	MSE	0.001771	MSE	0.001125	MSE	0.001232	MSE	0.001340	MSE	0.000907	MSE	0.001036
	S	**0.042078**	**S**	**0.033536**	**S**	**0.035094**	**S**	**0.03661**	**S**	**0.0301182**	**S**	**0.032185**
G	Iterations	15	Iterations	15	Iterations	21	Iterations	14	Iterations	15	Iterations	18
	Final SSE	0.091188	Final SSE	0.068848	Final SSE	0.066944	Final SSE	0.053966	Final SSE	0.0385165	Final SSE	0.0390413
	DFE	28	DFE	27	DFE	26	DFE	28	DFE	27	DFE	26
	MSE	0.003257	MSE	0.00255	MSE	0.002575	MSE	0.001927	MSE	0.001427	MSE	0.001502
	S	**0.057068**	**S**	**0.050497**	**S**	**0.050742**	**S**	**0.043902**	**S**	**0.0377695**	**S**	**0.0387504**
H	Iterations	12	Iterations	12	Iterations	16	Iterations	12	Iterations	15	Iterations	19
	Final SSE	0.042877	Final SSE	0.030584	Final SSE	0.038919	Final SSE	0.100109	Final SSE	0.0743487	Final SSE	0.0829337
	DFE	40	DFE	39	DFE	38	DFE	40	DFE	39	DFE	38
	MSE	0.001072	MSE	0.000784	MSE	0.001024	MSE	0.002503	MSE	0.0019064	MSE	0.0021825
	S	**0.03274**	**S**	**0.028003**	**S**	**0.032003**	**S**	**0.050027**	**S**	**0.0436621**	**S**	**0.0467169**
I	Iterations	8	Iterations	200	Iterations	200	Iterations	13	Iterations	13	Iterations	14
	Final SSE	0.119479	Final SSE	0.102403	Final SSE	0.144932	Final SSE	0.059414	Final SSE	0.0497012	Final SSE	0.0516304
	DFE	29	DFE	28	DFE	27	DFE	29	DFE	28	DFE	27
	MSE	0.00412	MSE	0.003657	MSE	0.005368	MSE	0.002049	MSE	0.001775	MSE	0.0019122
	S	**0.064187**	**S**	**0.060475**	**S**	**0.073266**	**S**	**0.045263**	**S**	**0.0421313**	**S**	**0.0437292**
J	Iterations	14	Iterations	11	Iterations	16	Iterations	10	Iterations	11	Iterations	16
	Final SSE	0.015551	Final SSE	0.011044	Final SSE	0.009933	Final SSE	0.009047	Final SSE	0.0064249	Final SSE	0.0057784
	DFE	33	DFE	32	DFE	31	DFE	33	DFE	32	DFE	31
	MSE	0.000471	MSE	0.000345	MSE	0.00032	MSE	0.000274	MSE	0.0002008	MSE	0.0001864
	S	**0.021708**	**S**	**0.018578**	**S**	**0.0179**	**S**	**0.016558**	**S**	**0.0141696**	**S**	**0.0136528**

Figure 4.6: Output of Nonlinear Regression, Project: A to J

LM is a common S-shape (sigmoid curve), which is one of the most widely used S-shaped growth models because of its simplicity and analytic tractability (Seber and Wild 1989), it is normally distributed and has the inflection point at 50% of total growth at $x = \frac{\beta}{\gamma}$ with cumulated growth $LM(x) = \frac{\alpha}{2}$ when the cost expenditure rate reaches its maximum at $LM_{max} = \frac{\alpha\gamma}{4}$. LM generic function is given in Eqn. 4.1. In Eqn. 4.1 the predictor x represents normalized time points with its maximum value equal to 1.00 (100% time-complete); i.e., the PD of a project. The corresponding value of the response variable is normalized points of the combined-to-date AC (from a project beginning to AT) and Initial-PV and Revised-PV (from AT and onto 100%) with their maximum values BAC_1 and BAC_2 of 1.00. The α parameter is the future value asymptote of the model which indicates the final cost (which is never reached) as the time (x) tends to infinity. The β parameter represents the $y-intercept$ which represents the initial size of the project cost, and γ is a scale parameter that governs the rate of growth. The next task will be to determine the three parameters for the LM nonlinear equation by employing the combined data set of AC and PVs with respect to time points for the model-fitting.

$$LM(x) = \frac{\alpha}{[1 + \exp(\beta - \gamma x)]} \tag{4.1}$$

4.3 Calculating the projects CEACs

To compute the CEAC for the projects the Eqn. 2.6 is applied, which assumes the values of the growth model when a project is to-date (AT) and 100% complete. This formula is similar to the classical Index-Based (IB) formula in Eqn. 2.5, with the difference that Eqn. 2.5 corrects the remaining portion of the BAC by Performance Indexes (PIs). Trahan (2009) [46] presents the generic form of Eqn. 2.6 and developed the nonlinear growth model by regressing the response values of the AC for the entire project life cycle against the corresponding time increments. Unlike the approach of Trahan (2009), in this analysis first the values of Initial-PV and AC and then the values of Revised-PV and AC are combined as explained previously in step 1-4.

By obtaining the three parameters of the LM equations (LM_1,LM_2) by the curve-fitting procedures, the values for the growth models in $x = 1.0$ in which the time is 100% complete and also in $x = AT$ were computed by using the Eqn. 4.1 and their difference represents the estimated portion of BAC (BAC_1,BAC_2) needed to complete a project, which is in turn added to the current-to-date AC incurred to compute the final CEACs ($CEAC_1$,$CEAC_2$).

4.4 ECRs and Accuracy of CEACs

In order to assess the influence of CRs on the quality of project CEACs, the forecasted costs (CEACs) are evaluated based on "Accuracy" criteria, which is the most often used and important criteria to carry out this analysis [47].

Here to confirm the negative impact of CRs on project cost, and demonstrate the limited reliability of Initial-PV, the CEACs accuracy is measured for the eleven finished projects with available CAC (cost at completion), by calculating a percentage error (PE) and the mean absolute percentage error (MAPE), which measure the size of the error in percentage terms.

PEs, (PE_1,PE_2) are determined by Eqn. 4.2 and 4.3, in which the CAC which is the project cost at completion, is subtracted from both computed CEACs, which are our experimental values and then is expressed as a percentage of CAC. The negative percentages reveal the underestimation of effort required to accomplish the projects considering the potential upcoming CRs, at the initial phase of project, and the positive percentages suggest overestimation of effort.

$$PE_{1i}(\%) = \frac{CEAC_{1i} - CAC}{CAC}100\% \tag{4.2}$$

$$PE_{2i}(\%) = \frac{CEAC_{2i} - CAC}{CAC}100\% \tag{4.3}$$

MAPEs are applied to calculate the average of the absolute values of differences between the experimental values and the accepted value, which in this analysis are $CEAC_1$, $CEAC_2$ and, CAC, over all the examined finished projects [40]. Eqn. 4.4 and 4.5 are used to compute these measures.

$$MAPE_1\% = \frac{100\%}{n}\sum_{i=1}^{n}\frac{|CEAC_{1i} - CAC_i|}{CAC_i} = \frac{1}{n}\sum_{i=1}^{n}|PE_{1i}|\,\% \tag{4.4}$$

$$MAPE_2\% = \frac{100\%}{n}\sum_{i=1}^{n}\frac{|CEAC_{2i} - CAC_i|}{CAC_i} = \frac{1}{n}\sum_{i=1}^{n}|PE_{2i}|\,\% \tag{4.5}$$

Where n is the number of finished projects, that in this research is $n = 11$.

4.5 ECRs and Precision of CEACs

To investigate the narrowness of the forecast error, we adopted the precision criterion which measures the Standard Deviation (SD), as an indicator of a statistical dispersion of the values of prediction errors from the average forecast within the population [45]. Eqn. 4.6 and 4.7 are used in order to obtain SDs, which exerts the square root of the variance (the average of the squared differences between the PE of an individual project and mean of the PEs) for both $CEACs_1$ and $CEACs_2$. A smaller value of SD shows that cost estimates calculated by a particular model are closer to its Mean Percentage Error (MPE) and, therefore, produce more precise CEACs.

$$SD_1\% = \sqrt{\frac{\sum_{i=1}^{n} (PE_{1i} - MAPE_1)^2}{n}}\% \tag{4.6}$$

$$SD_2\% = \sqrt{\frac{\sum_{i=1}^{n} (PE_{2i} - MAPE_2)^2}{n}}\% \tag{4.7}$$

4.5.1 Sample Application

In this part, I describe the stepped procedure using the EVM data of Project A which was demonstrated in Figure 4.1 to forecast CEACs when the project is in its middle stage of completion. The first step is to determine the values of the three LM parameters by the nonlinear regression curve fitting. To estimate CEACs for Project A, month 9 ($PD = 18$) is taken as the time for the middle stage estimation time ($AT = 9$). The requirements that should take into account when running the nonlinear regression are introduced in the previous sections.

The Minitab's fitted line plots for project A for both AC-Initial PV and AC-Revised PV analysis are shown in Figures 4.7 and 4.8.

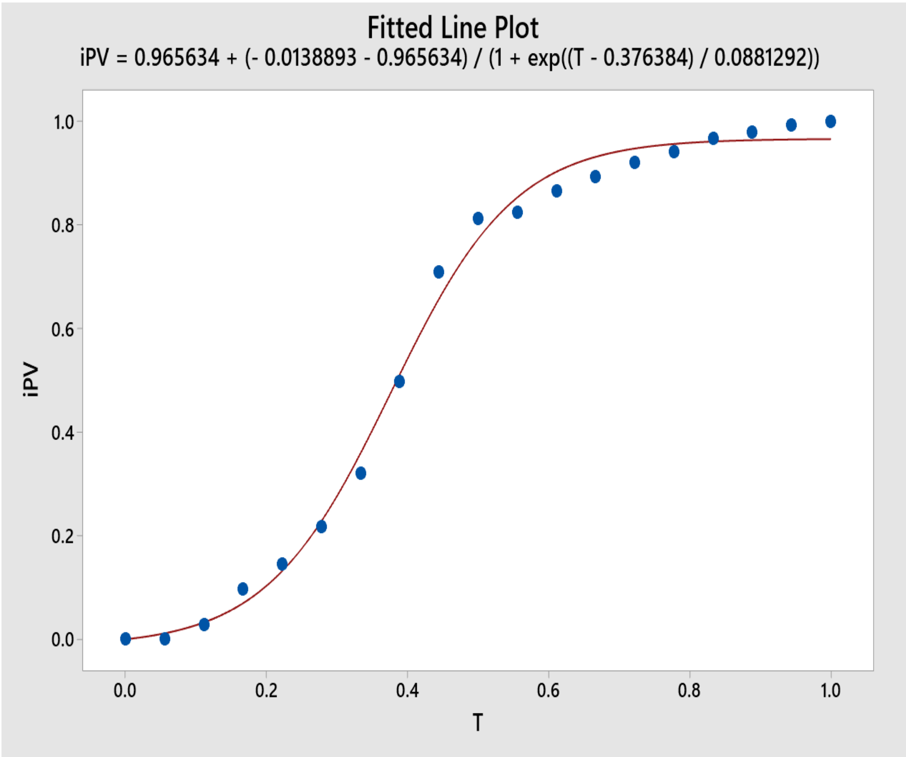

Figure 4.7: Minitab's fitted line plots for project A; AC-Initial PV

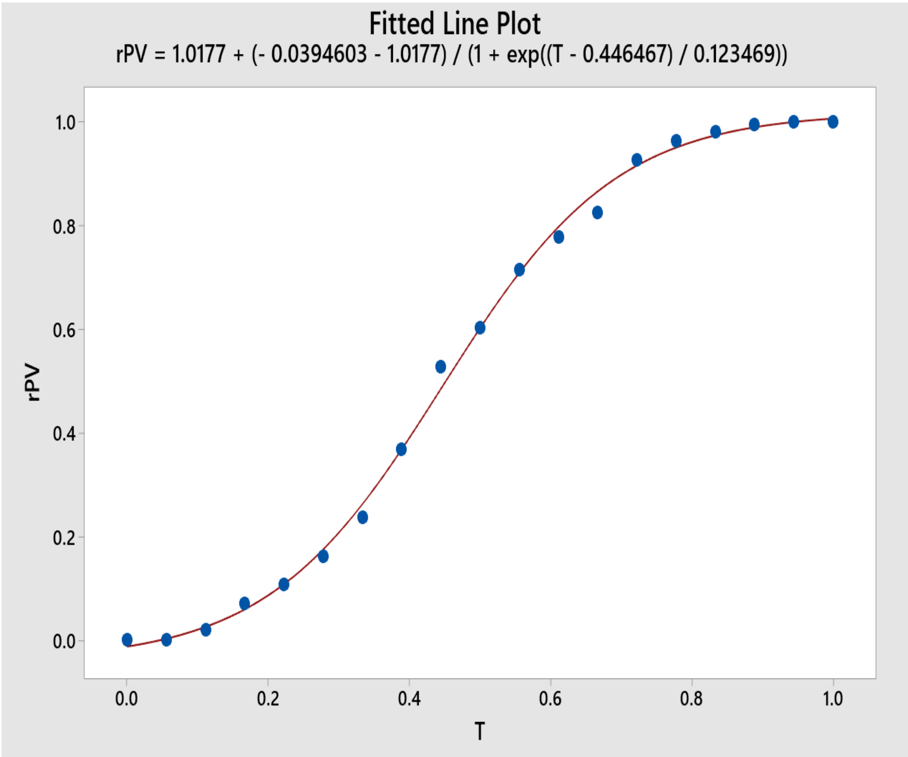

Figure 4.8: Minitab's fitted line plots for project A; AC-Revised PV

The LM equations generated by Minitab® for the EVM data of Project A is presented in Eqn. 4.8 for AC-Initial PV data and Eqn. 4.9 for AC-Revised PV data. To calculate CEACs for the middle stage, nine months into the project execution when x is 0.500 (Table 4.1), these LM equations result is 0.722 by considering the AC-Initial PV values (or 77.23% of the project BAC_1) and 0.602 by considering the AC-Revised PV values (or 60.19% of the project BAC_2).

$$LM_1(x) = \frac{0.965634 + (-0.0138893 - 0.965634)}{(1 + \exp((x - 0.376384)/0.0881292))} \tag{4.8}$$

$$LM_2(x) = \frac{1.0177 + (-0.0394603 - 1.0177)}{(1 + \exp((x - 0.446467)/0.123469))} \tag{4.9}$$

The values of three parameters for each LM equation are reported in Table 4.5.1 and by interpretation of the values we can see that the ratio of the β parameter to the γ parameter for LM_1, which presents time percent complete point ($x = \frac{\beta}{\gamma}$) when the cost growth rate is maximum which is 45.47% for Project A with resulting cumulative cost of 68.01% ($LM(x) = \frac{\alpha}{2}$) of the BAC_1 and the same ratio for LM_2 is equal to 59.65% with resulting cumulative cost of 77.59%. Finally, α_1 and α_2, the asymptote values of 1.004 for AC-Initial PV data implies that, as Project A tends to infinity, it will experience a 0.36% cost overrun and as for AC-Revised PV data alpha is 1.160 which means that the project will have about 16.01% cost overrun.

Project A	α	β	γ
$LM_1(x)$	1.004	6.680	14.693
$LM_2(x)$	1.160	3.607	6.046

In the next step, the project CEACs are calculated for the case when $x = 1.00$ (100% time complete), in order to adjust the remaining amount of the project BACs (BAC_1,BAC_2) by the difference of the two values of LM (for both LM_1,LM_2), considering the time point when the project is 100% complete and at $x = 0.500$. So first, $LM_1(1.00) = 0.965$ and $LM_2(1.00) = 1.006$ are computed and then we use Eqn. 2.6 to calculate $CEAC_1$ and $CEAC_2$. The described analysis determines the project $CEAC_1 = 69.708$ FTE and $CEAC_2 = 94.095$ FTE with $PE_1 = -25.41\%$ which means that the cost o project A is underestimated at initial offer by this amount and $PE_2 = 0.69\%$ meaning that by estimating the final cost based on more reliable PV (Revised-PV) we will overestimate the CEAC of project by 0.69% which is negligible comparing to -25.41% .

Chapter 5

Results and Conclusions

This chapter presents the numerical results of cost at completion forecasts for the twenty studied projects and also provides the accuracy and precision analysis of the estimates reflecting the impacts of CRs, in early stage of completion, on the project's final cost. The outcomes of CEACs calculation, based on nonlinear regression approach, are exhibited in Table 5.1.

$Project$	$CEAC_1$	$CEAC_2$	$Project$	$CEAC_1$	$CEAC_2$
A	69.708	94.095	K	139.622	141.481
B	48.275	64.955	L	14.118	18.944
C	265.501	307.823	M	15.885	21.295
D	54.128	80.108	N	16.083	27.667
E	186.087	210.468	O	37.644	45.464
F	39.988	43.882	P	57.516	69.051
G	336.959	357.048	Q	6.256	10.719
H	92.621	101.139	R	15.407	22.770
I	462.942	488.781	S	30.103	41.532
J	67.904	78.545	T	40.389	56.230

Table 5.1: CEACs Results

And Table 5.2 allows an assessment of the impact of CRs on projects CEACs, through the accuracy framework proposed in previous chapter,by calculating PE_{2i} (Eqn. 4.3), considering the Revised-CEACs ($CEAC_{2i}$), in comparison with the PE_{1i} (Eqn. 4.2) corresponding to the Initial-CEACs ($CEAC_{1i}$), for the finished projects.

$Project$	$CEAC_1$	PE_1	$CEAC_2$	PE_2
A	69.708	-25.41%	94.095	0.69%
C	265.501	-17.79%	307.823	-4.68%
D	54.128	-39.45%	80.108	-10.39%
E	186.087	-14.34%	210.468	-3.12%
G	336.959	-4.34%	357.048	1.36%
J	67.904	-18.65%	78.545	-5.90%
K	139.622	-8.23%	141.481	-7.01%
M	15.885	-29.08%	21.295	-4.92%
Q	6.256	-44.39%	10.719	-4.72%
R	15.407	-33.01%	22.770	-1.00%
S	30.103	-28.16%	41.532	-0.88%

Table 5.2: CEACs Accuracy results ($PE\%$)

The present findings show that all of Initial-CEACs, provide PEs above 10.00 for most of the projects, whereas the Revised-CEACs generate PEs equal or less that 10.00 for all of the cases (plus two positive PE_2s), demonstrated by Figure 5.1. Closer to zero line values of PE in the chart imply more accurate estimates. The main conclusion that can be drawn is that CEACs results computed by revised data, which are the planned values that incorporate the influential change factor more precisely, are more accurate than those calculated by the initial planned values, meaning that revising the estimated cost of project and adapting cost management methods to fit the special nature of projects subjected to changes, uncertainty and complexity, create more reliable data of estimated final cost, and so improve the projects cost performance during the execution and increase the accuracy of CEAC.

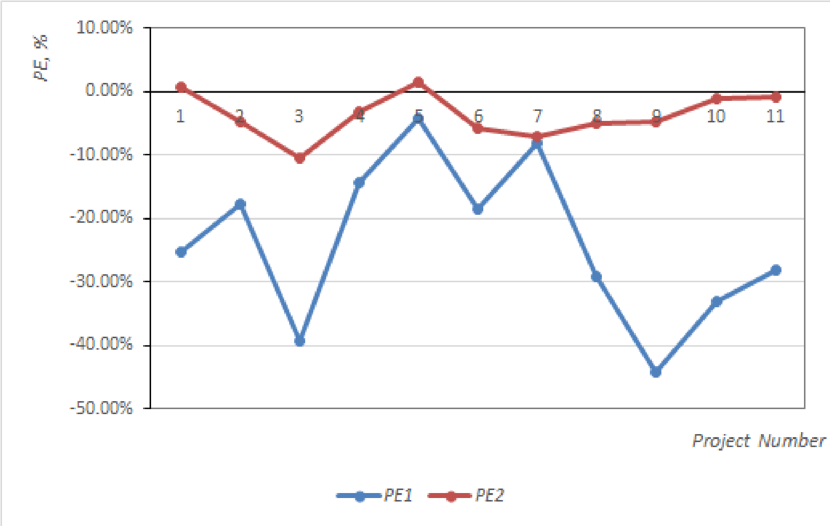

Figure 5.1: Impact of CRs on CEAC Accuracy

Table 5.3 provides the CEACs accuracy and precision, calculated by Eqn. 4.4, 4.5, 4.6 and, 4.7, revealing that cost estimates based on revised data, are more accurate (in MAPE) and precise (in SD) than those of Initial-CEACs.

	$CEAC_1$	$CEAC_2$
$Accuracy\ (MAPE, \%)$	23.90%	4.06%
$Precision\ (SD, \%)$	49.27%	8.45%

Table 5.3: CEACs Accuracy and Precision

On average, integration of CRs impact on planned value of projects and consequently on CEAC calculation, improves the cost estimates from $MAPE = 23.90\%$ to 4.06% in early phases of projects execution. More generally, these findings are consistent with research purpose, in providing evidence on the topic that poor estimates of effort are frequently accountable for disclosing incorrect information on project cost performance, and as changes are unavoidable and unpredictable during the development of most projects, there is a need to investigate and better understand the impact of requirement changes or in general Change Requests on development projects in terms of effort.

By these analyses, it was attempted to find out to what extent the ECRs can play an important role affecting the behavior of project cost and how applying pure traditional project management practice, without project re-baselining, in projects where continuous changes are taken, can not be the best answer. Project Managers should particularly take account of the environment surrounding the project they are dealing with, together with many other factors. Indeed, this is only an example to specify one of the elements that should lead to the optimal choice of the methodology for project management. However, identifying all those factors leading to the appropriate approach, for which several articles and books have been written, is not the aim of this work.

However, until the date, there is no research that can guarantee which technique can be the most suitable in the cost estimation process. Accordingly, many researches have been studying the most appropriate method that can be implemented. Choosing the right cost estimation technique is essential to ensure the result is accurate. Different approaches applied in the cost estimation techniques might produce different accuracy of the result. There are few researches have been carried out to integrate more than one technique, which is called the hybrid technique, like the case we analyzed. Yet, no one can claim which technique is the best. The most critical matter is to choose the right technique which fits the type of project. Accepting the fact that you will have and need changes during the implementation of projects, you aspire to have fewer changes, to front-load changes, to manage necessary changes more effectively, to perform the changes efficiently in terms of time, cost, and resources, and more importantly to learn continuously from implemented changes. Future investigations are necessary to conduct more effort estimation studies in the context of dynamic and changing development projects, that besides size and other factors, also take into account Engineering Change Request as an influential factor.

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