THE EFFECTS OF CHANGE ORDERS
ON PRODUCTIVITY

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ABSTRACT

The Effects of Change Orders on Productivity

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It is generally recognized that change orders issued during construction can create disruptions in job momentum and in orderly sequences of performance and, as such, reduce job morale. Nevertheless, the effects of change orders on productivity are often underrated or completely unrecognized by many owners, design professionals, and even some contractors. Currently, productivity losses on labour resulting from change orders are quantified after the fact, usually using the classical 'differential method' of cost calculation. The differential method, however, can be performed only if adequate cost and progress records are available.

In an effort to identify the effects of change orders on productivity and to provide an alternate method of calculation, 90 cases drawn from 57 projects are examined in a comprehensive field investigation. In all cases examined, the contractor experienced productivity losses due to change orders.

The cases are studied to determine reasons for and sources of the productivity losses and factors influencing

the loss. A statistical analysis is performed on data collected from the cases. The results indicate a significant direct correlation between the labour component of change orders and the resulting loss of productivity for civil/architectural work and electrical/mechanical work. Models are then developed to estimate loss of productivity due to change orders incurred both independently and in combination with other major causes of productivity loss.

In appropriate cases experiencing greater than 10% to 15% in change orders, these models can be used to estimate productivity losses of labour at the micro level. Such losses could be utilized in preparing or evaluating claims for additional compensation, in projecting manpower requirements and in updating schedules of work affected by change orders. The results are not intended to be applied directly to macro productivity or overall construction costs.

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CHAPTER I

INTRODUCTION

1.1 GENERAL

In recent years, a great deal of attention has been directed toward the impact of delays and other disruptions on project cost and time. Conservative estimates have put the yearly costs of delays and disruptions at more than one billion dollars [1], approximately 2% of the total Canadian construction volume (1986) of 63 billion dollars [2]. Such costs (referred to hereinafter as 'impact costs') are not direct costs of changed and altered work, but rather additional costs incurred in the performance of work affected by the delays and disruptions.

As such, impact costs originate with isolated problems and then spread unabated through the project, like ripples on a pond. Although the problem can be identified as a source of specific additional cost, the effect does not stop there but creates expanding ripples which adversely affect seemingly unrelated activities. It is generally recognized that impact costs can result from a number of construction problems, including: change orders; late and inadequate supply of information; late delivery of owner-supplied equipment and/or material; poor scheduling and coordination; changed subsurface conditions; labour disruptions; acceleration; restricted access to site; and contractors' inefficiencies.

Earlier studies [3,4,5] have identified change orders as one of the most common and significant causes of impact costs. In fact, change orders are always a major consideration in the administration of construction projects [6,7]. The question of whether a particular variation or alteration to the work warrants an extra or change to the contract often causes disagreement between owners and contractors. Such situations, however, usually involve questions of fact and contract interpretation which have been previously addressed by others [8,9,10,11]. Impact of change orders, on the other hand, is an area of particular concern and one in which little research has been done.

It is generally accepted that large, untimely, and numerous change orders can disrupt progress of the work and reduce productivity. The effects of change orders on productivity, however, are not completely understood by design professionals and particularly by owners, who often make far-reaching decisions regarding quality and completeness of the design and issuance of change orders. Too often owners do not provide design professionals with sufficient time and/or monies to prepare a complete design of acceptable quality. And, owners often cannot make up their minds about the requirements of the final product, believing changes can be readily made in the field as construction progresses.

In practice, many owners and design professionals underrate or completely refuse to recognize productivity losses resulting from change orders and, as such, equate impact losses with contractors' underestimating, inefficiencies, and risks assumed under the terms of the contract. Such underrating or refusal of impact costs stems not only from the obscure relationship between causes of impact and their effect, but also from the difficulty in determining impact costs in advance of the loss and contractors' inability to properly substantiate and quantify their losses.

While most owners insist on knowing the impact cost of proposed change orders prior to authorizing their performance, contractors prefer to submit single, all-encompassing impact cost calculations upon completion of the job. Such calculations are usually submitted on the basis that impact costs can be neither isolated for each change order nor calculated accurately in advance due to the interdependency of construction activities. In fact, few contractors maintain adequate job records to allow evaluation of impact costs for each change order. In addition, some contractors do not realize that they have incurred impact costs until the final profit and loss statements indicate a sizeable loss.

For the purpose of quantification, impact costs may be broadly classified into two categories: 1) time-related, and 2) productivity-related [1]. Time-related costs are those associated mainly with extended duration, i.e., extension of the project beyond the original contractual completion date. Once the equitable time extension (owing to the contractor) has been established, quantification of time-related costs is a relatively straightforward exercise [11,12,13]. Research carried out by Fondahl [14], and expanded upon by Revay [15], has led to a reliable method for evaluating time extensions.

Productivity-related costs are those resulting from productivity losses. For the purpose of the present research, loss of productivity can be defined as "the decline in labour efficiency due to specific causes from the level which could have been achieved except for the cause(s) under examination" [1]. Unlike time-related costs, productivity-related costs can be rarely established accurately simply because it is difficult to demonstrate what costs would have been incurred without the inefficiency.

The 'differential cost' calculation [1,16,17] is the preferred method of quantifying loss of productivity as it compares productivity achieved by the contractor during a normal, unimpacted period to that of the impacted period. This differential calculation, however, can be performed only after the fact and then only if accurate data on physical progress and labour cost is available. Therefore, contractors commonly calculate impact costs simply by subtracting their planned costs from their actual costs. Owners and courts of law, however, do not look favourably upon such a calculation because it does not take into account contractors' inefficiencies, and risks assumed by them under the contract.

Industry-wide studies are also used to estimate loss of productivity. In recent years, a number of studies have been published in which average percentage factors for loss of productivity have been computed using historical data. Such studies are available for a number of causes of impact including overtime [18,19,20,21], overmanning [22,23,24], congestion of trades [23], and climatic effects [25,26,27].

However, there are no published productivity studies related to change orders. In fact, there has been no study, empirical or otherwise, dealing with impact of change orders on productivity. It is believed that the present study not only clarifies but creates a greater awareness of the extent to which change orders adversely affect productivity. It is also believed that relationships between the labour content of change orders and loss of productivity developed herein are useful for estimating loss of productivity when a differential cost calculation is not possible.

1.2 CONSTRUCTION PRODUCTIVITY

The welfare of the national economy, as well as that of individual businesses, is widely recognized as being dependent on the productivity of its people. Productivity in the construction industry is particularly important as construction is a major sector of the economy. Also, construction productivity influences the competitiveness of many industries vis-à-vis that portion of the selling price of manufactured products which covers the capital cost of the manufacturing facility. Moreover, construction is labour-intensive and its products generally unrepetitive and, unlike capital-intensive industries with standardized products, its overall productivity is particularly influenced by the numerous factors that affect the efficiency of its labour.

In general, productivity measures the efficiency with which resources (inputs) are utilized in producing goods and/or services (outputs). Although there are various definitions [28], productivity is usually defined as a ratio of the output of the production process to one or more of the associated inputs (i.e., Productivity = Output/Input) [29]. A variety of related productivity measures have been developed which unfortunately contribute to the misunderstanding and confusion surrounding productivity [30]. It should be realized, however, that no one measure is the right or the best measure because productivity measures serve a wide range of purposes. As such, choice of a particular measurement depends on the purpose to which it is to be used.

To obtain partial productivity measures, ratios of output to single classes of input are calculated. For example, the ratio of output to assets represents capital productivity while the ratio of output to labour (cost or quantity) represents labour productivity. By combining two or more classes of input with appropriate weighing factors and dividing the combined measure of input by output, multiple-factor productivity can be established. Although measurement of multiple-factor productivity is necessary to determine an efficient balance between various factors of production, comparisons of such productivity factors are questionable because there are no generally accepted weighing factors.

Output in the construction industry is usually expressed as some physical achievement. Measurement of output is relatively straightforward with one-product types of operations (e.g., tons of steel). However, the exercise becomes complicated when dealing with multi-component outputs (e.g., a completed structure) because product values have to be either adjusted by price indices or developed from physical quantities combined with price weights. Also, measurement of output must consider changes unrelated to the associated input(s), such as changes in quality of the final product.

To measure output on a particular project, three methods are commonly used: 1) estimated percent complete [31], 2) physical measurement [31,32], and 3) earned value [31,32]. With the estimated percent complete method, percentages of work activities that have been done are subjectively evaluated with respect to their total scope. The physical measurement method involves counting or measuring the number of units of work completed (e.g., metres of pipe and cubic metres of concrete). When work items are numerous and have intermediate steps, physical measurement is not practical. With the widely used earned value method, portions of the total value of the work activity are credited or 'earned' as the work is completed. Earned value is typically expressed in labour-hours so that work items of different units can be readily combined to permit calculation of a single output for a number of different activities.

Productivity ratios can be established on a global (macro) scale and on a discrete (micro) level. Macro productivity expresses the degree of accomplishment of the desired result, i.e., effectiveness, whereas micro productivity refers to how well particular resources are utilized to accomplish results, i.e., efficiency.

In construction, the input portion of both macro and micro productivity measures may be expressed in terms of labour, money, equipment or material. Input is usually measured with respect to labour not only because construction is labour-intensive but also because labour is the most variable input. As pointed out by Revay [30], macro productivity is best expressed as a function of labour cost (i.e., labour-dollars per unit of completed structure) and micro productivity ought to be expressed in terms of labour hours (i.e., labour-hours per unit of individual task or activity).

As with other measures of productivity, the purpose of the analysis dictates which measurement is to be employed. Owners are more interested in macro productivity since total labour costs are usually determined more by the effectiveness with which labour is utilized than the efficiency of labour itself. Conversely, contractors measure productivity at the micro level for purposes of future estimating and evaluating productivity improvement techniques.

To quantify loss of productivity, measurements are usually made at the micro level as most causes of impact affect the rate at which labour performs specific tasks or groups of tasks (i.e., labour efficiency) and not the contractor's entire method of operation (i.e., labour effectiveness). Accordingly, in the present study productivity is measured at the micro level with respect to labour.

1.3 SCOPE AND OBJECTIVES OF THE RESEARCH

The main objective of the present research is to examine the effects of change orders on productivity, both qualitatively and quantitatively. The qualitative examination is to document the reasons why change orders, individually and cumulatively, affect productivity and to identify the corresponding sources of productivity loss. The qualitative aspect of the research is the essential prerequisite for understanding the quantitative analysis and interpreting its results. As such, the quantitative analysis is to determine relationships, if any, between change orders and loss of productivity. Well-established statistical techniques are used 1) to identify a change order parameter that has significant statistical correlation with loss of productivity, and 2) to develop models for estimating productivity losses resulting from change orders. In essence, the quantitative analysis is equivalent to an industry-wide study as it is based on data from actual projects.

Other objectives of the present research are: identification of factors influencing negatively the effects of change orders on productivity and, accordingly, development of recommendations to minimize such effects.

The present study is carried out by examining a large number of different types of contracts performed on a variety of construction projects. Relevant data has been collected from 84 separate contracts carried out mainly in Canada within the last 10 years. In total, the value of the 84 contracts is in excess of $220,000,000. These contracts were carried out on 57 independent projects comprising various types of buildings and industrial facilities. The value of each project ranges from a few million dollars to several hundred million dollars.

With one exception, all projects were completed under the 'traditional' contracting method [33] with a lump-sum or unit-price contract awarded on the basis of a competitive bid process to the lowest qualified bidder. None of the contracts examined were originally intended to be performed in a 'fast-track' mode, although a number were actually carried out essentially under 'fast-track' circumstances as a result of design changes and delays in supplying information.

Excluded from the present study are the following: 'one-of-a-kind', unusually complex and highly specialized industrial projects such as nuclear power plants; offshore exploration structures; megaprojects, of any type; and heavy civil engineering-construction projects such as highways, tunnels, bridges, rail and marine ports.

1.4 THESIS LAYOUT

Chapter II presents a literature review of previous work done in the areas of factors affecting productivity and impact costs.

Chapter III describes the methodology used in the present research. Therein, reasons for utilizing the case study approach are enumerated, and methods used to collect and analyze the data as well as to identify causes of impact are described in detail.

In Chapter IV, the qualitative results of the field investigation are presented, including accounts of the effects of individual and cumulative change orders on productivity. Factors that negatively influence the effect of change orders on productivity are also outlined.

Statistical analysis of the data, including interpretation and description of the significance of the results, is presented in Chapter V.

In Chapter VI, conclusions are made, followed by remarks on the application of the results and then by recommendations for industry practice and for further research.

CHAPTER II

LITERATURE REVIEW

2.1 INTRODUCTION

Construction productivity has been the subject of considerable research in recent years [3,34,35,36,37,38,39]. Such research can be divided into two broad categories: 1) that aimed at examining and quantifying various factors affecting productivity [3,4,19,23,25,40,41,42,43], which is reviewed in this chapter, and 2) that directed toward productivity improvement [37,44,45,46,47,48,49,50].

A review of the present literature reveals that numerous factors influence construction productivity, including delays and disruptions which usually have significant adverse effects. It also reveals that change orders are a major cause of delays and disruptions and, thus, productivity losses. Previous research, however, has not examined the effects of change orders on productivity and empirical data for loss of productivity caused by delays, disruptions, and particularly change orders, is scarce.

2.2 FACTORS AFFECTING PRODUCTIVITY

There is almost an endless list of factors which can be identified as affecting productivity. As a result, related research has concentrated mainly on the influence of certain factors on productivity, and there have been few attempts to integrate the complex array of productivity factors into a comprehensive model. Indeed, previous research directed toward integrated productivity models, such as Adrian's Method of Productivity Delay Model [51], Kellogg's Hierarchic Model [52], and Clapp's Integrated Model [53], has dealt with measurement of multiple-factor productivity as opposed to modelling of individual factors affecting productivity. Nevertheless, factors affecting productivity can be grouped into: 1) extraneous, 2) labour, and 3) management.

2.2.1 Extraneous

Extraneous factors are those over which management has little or no control, such as: project location; project size; project type; regulations; and unions. Project location determines not only the climatic conditions and labour availability, but also whether a camp is necessary. It has been reported [30] that urban projects enjoy levels of productivity 10% - 15% higher than rural projects on which camps are necessary.

Project size is a significant factor affecting productivity for a number of reasons. The sheer physical size of large projects directly results in extended on-site travel; longer and, hence, less efficient lines of communication; an increased number of conflicts due to increase in personnel; and decreased availability of skilled labour.

Large projects, by nature, are more susceptible to motivational problems than smaller projects. Research by Borcherding and Garner [40] has identified numerous factors, some inherent to large projects and others, which are common, that strain workers' performance and result in demotivation.

Large projects on which the scope is not sufficiently defined are often carried out under cost-reimbursable contracts. It has been reported [36] that productivity on such projects averages 30% - 40% lower than on fixed-price contracts.

It is generally recognized that the type of project influences labour productivity, mainly because of variations in the complexity of the work. Degree of complexity affects both the ability of labour to understand the work and the repetitiveness of the operations.

Government regulations related to building codes, occupational safety and health codes, environment and affirmative action can have an effect on productivity.

Research by Jansma and Borcherding [54] indicates that changes in the regulatory requirements for nuclear power plants has led to increases in the range of 30% - 60% for concrete unit rates (MH/CY) over a period from 1968 to 1979. According to the authors, such productivity decreases have occurred due to removal of control from those closest to the work (i.e., demotivation), decreased engineering lead time, and change orders.

2.2.2 Labour

Various factors related directly to labour productivity include skill, availability, and attitude. Whether an adequate supply of skilled workers is available depends on apprentice-training programs and the level of local work activity. When demand for labour is high, due to say a megaproject or an expanding-area economy, workers are drawn from a less qualified pool and high turnover may be a problem. In such instances productivity suffers accordingly.

Although skill of trained workers essentially remains constant throughout the project, productivity of individuals and of the work force as a whole generally improves during the project due to the 'learning curve' effect. Learning curve theory applies to work activities which are repetitious, continuous, and essentially identical (i.e., repeat operations). For such operations, several mathematical models have been developed to describe increases in productivity as a function of the number of units produced [41,55,56,57].

The third major labour-related factor affecting productivity is the attitude of labour itself. Attitude is determined by the inherent attitude of the individual arriving at the work place and, more importantly, by conditions which create motivation and demotivation in the worker toward the job [1]. Previous research [40] reveals that labour motivation is governed somewhat by the work environment, but mainly by numerous factors affecting productivity that fall under the control of management.

2.2.3 Management

In general, management is responsible for delivering the project within the objectives of cost, time, and quality. Successful management implies completion of the project within good customer relations as well as effective and efficient utilization of resources.

Because management has control over so many job-related factors, their practices significantly influence the level of productivity attainable by the work force and the motivation of the work force. Field observations by Olson [58] indicate that labour inefficiencies are more closely related to management failures than any other single source. Adrian [44] suggests that management-related factors account for approximately one-third of nonproductive time on typical construction projects.

Of the various management functions, planning and communication are widely recognized as having a major influence on productivity. Indeed, all projects require formal and detailed planning because of their relatively short duration and requirement for often limited resources. To maximize productivity, planning should ensure that work crews are able to build up job rhythm which can be sustained without interruption throughout the course of the project. As such, proper project planning entails many functions, including: development of overall job organization; efficient sequencing of project phases; development of Work Breakdown Structure and contract packages; scheduling of work activities; and scheduling of material resources including labour, equipment, and material.

Previous research [59] indicates that job morale and productivity are closely related to the amount and quality of communication occurring between management and workers. As such, communication refers to transfer of information and instructions which is effective only when accurate, complete, and understood by the recipient. Good communication also means that individuals are constantly advised of what is expected of them and that there is feedback and a mechanism for measuring performance against expectations.

Quality of construction drawings has been cited as a typical example of good versus bad communication [60]. Incomplete and inadequate drawings lack sufficient detail for execution of the work making it difficult for foremen to plan and procure material properly. While foremen spend extra time trying to interpret the intent of the A/E's, crews are waiting idly for instructions. Incomplete and inadequate drawings require revisions and change orders which, in turn, often result in further delays and loss of productivity.

Clearly, on-site supervisors play an important role in transferring information and instructions to the work force. Research by Hinze and Kuechenmeister [61] indicates that the ability to communicate is the most significant attribute of productive foremen. Their research indicates that productive foremen are fair in their dealings with crew members without compromising on production goals and workmanship. Samuelson reports [62] a strong relationship between formen's methods of handling their crews and crew productivity and safety performance.

Consideration also must be given to the ratio of foremen to craftsmen. An unnecessarily high ratio of foremen to craftsmen increases the cost of work, while insufficient supervision results in decreased productivity [42].

It is also recognized that management practices may have a further influence on productivity through their effect on worker satisfaction and motivation [63,64].

Many of the studies [65,66,67,68] on satisfaction and motivation in construction are based on models developed by Maslow and Herzberg which attempt to identify specific factors motivating individuals. According to Maslow [69], individuals are motivated by five basic categories of human needs: 1) psychological, 2) safety, 3) social, 4) self-esteem, and 5) self-actualization. Maslow argues that these needs are arranged hierarchically, and individuals become motivated by a higher need once the lower need is satisfied. Herzberg's theory of motivation [70], although similar to Maslow's, deals with different job-related factors that result in feelings of satisfaction and dissatisfaction among workers. Factors affecting satisfaction (e.g., achievement, growth, responsibility, work itself, and recognition) are referred to as motivators while factors which may cause job dissatisfaction (e.g., supervision, security, working conditions, and interpersonal relations) are referred to as hygiene factors.

By applying Maslow's hierarchy of needs to the construction industry, Schrader [65] identified improved communication and involvement of workers with management as appropriate means to motivate construction workers. Hazeltine [66], using Maslow's need theory, concluded that the potential for productivity improvement through motivation was often limited by inadequate and inappropriate management actions.

Referring to Herzberg's model, Borcherding and Oglesby [67,68] explored the relationships between job satisfaction, job dissatisfaction, and productivity. According to Herzberg's theory, high job satisfaction leads to greater productivity. However, Borcherding and Oglesby [67] found that a reverse relationship prevailed in construction, namely, a productive job created high job satisfaction while a non-productive job, or one which fell behind schedule, produced dissatisfaction. The authors also found that satisfaction among craftsmen occurred when the workers could "point with pride to an accomplished task" and through "identification of building a physical structure". Rework necessitated by change orders was found to decrease worker morale usually resulting in loss of productivity. With respect to job dissatisfaction, Borcherding and Oglesby [68] found that much of it resulted from poor management practices and job conditions beyond control of the workers.

Whether efforts directed toward improving job satisfaction are effective means of increasing labour productivity has been questioned by some authors [71,72]. The research, however, leaves little doubt that satisfaction, challenge and productivity are closely intertwined and that poor management practices result in dissatisfaction causing individuals to lower their work efforts (i.e., productivity).

Borcherding and Oglesby [67] found one of the major differences in job satisfaction between workers and management to be their perspective of the effects of change orders. Their research indicated that management was not concerned with the effects of change orders on morale and productivity as long as the company continues to "make money on changes". However, without accurate and timely productivity-reporting mechanisms, management does not know whether the change orders have affected productivity until the job is complete and it is too late to take corrective action.

The findings of Borcherding and Oglesby's research into job satisfaction and dissatisfaction are supported by a later study by Borcherding with others [40,73,74] on 12 large U.S. energy projects, mainly nuclear power plants. During interviews, foremen identified lack of engineering information, material and tool unavailability, and rework as major productivity problems [74], while craftsmen identified material and tool unavailability, rework, and crew discontinuity as significant causes of productivity loss and demotivation [40,73]. To increase productivity and motivation, the authors recommend management increase engineering lead time, improve communications, and improve planning and scheduling systems.

The quantitative results of Borcherding's research [40,73,74] have been cited [60] as an example of the extent to which management practices can affect productivity. However, it is important to realize that in Borcherding's research productivity losses were estimated by craftsmen themselves, as opposed to measured by the researchers, for the purpose of relative comparisons, and the research was limited to cost-reimbursable contracts carried out on large, complex projects characterized by lengthy schedule delays, disruptions, and cost overruns. It is also important to realize that the recommendations made apply specifically to nuclear power plant construction and probably cannot be extrapolated as means for productivity improvement for the entire industry. Their research, however, does provide empirical evidence that schedule delays and disruptions result in productivity loss and demotivation.

Due to limitations of Maslow's and Herzberg's theories, behavioural scientists have developed other theories to explain motivation of individuals. In recent years, the expectancy theory [75] has become one of the more generally accepted. According to the expectancy theory, motivation is a combined function of the individual's expectations concerning future outcomes and the value they place on those outcomes. In other words, expectancy theory deals with the individual's aspiration that: 1) his effort will result in success of the task (i.e., performance, and 2) his performance will result in rewards. Under the expectancy theory, obstacles to performance affect motivation and, hence, productivity. Based on the expectancy theory, Laufer and Jenkins [63] concluded that management should direct motivational improvement efforts toward development of reward systems and involvement of workers in productivity improvement programs.

2.3 QUANTIFICATION OF FACTORS AFFECTING PRODUCTIVITY

Although previous studies [40,63,65,66,67] clearly establish a link between management practices, motivation, and productivity, few attempts have been made to quantify the effect of particular management practices on productivity.

Logcher and Collins [43] analyzed the effect of management strategies on labour productivity for tile-laying on five construction sites in the U.S. The results indicate a direct relationship between productivity and such factors as crew coordination and delays attributable to management. The sample size, however, is insufficient for prediction purposes.

Based on his firsthand experiences on over 1500 construction projects, Hohns [76] developed a chart showing ranges and expected values of inefficiencies for various job conditions and management practices. The results, shown in

Table 2.1, clearly demonstrate the effect of management practices and decisions on productivity. However, the factors are too general and insufficient background information is provided to be used for quantification of productivity loss.

For various job conditions affecting productivity, published tables are available based on statistical averages of actual historical data. Published tables are frequently used to quantify loss of productivity for scheduled overtime [18,19,20,21], overmanning [22,23,24], congestion of trades [23], remobilization [22], and weather [25,26,27].

Scheduled overtime refers to the continuing utilization of labour for more than 40 hours per week, i.e., extended work days and/or weekends. It is used to attract workmen to a project for reasons such as location, job conditions, nature of the work, and in attempts to accelerate completion dates and make up for lost time due to delays. Depending on the particular circumstances, loss of productivity occurs as a result of scheduled overtime due to a number of reasons, including: fatigue; demotivation; absenteeism; reduction of work pace; accidents; turnover of labour; and supervision problems [77]. The factors most commonly used today to estimate loss of productivity due to overtime are those pre pared by the Construction Users' Anti-Inflation Roundtable [19], shown in Figure 2.1.

Overmanning occurs when more workers are placed in a given area than that area can efficiently accommodate. Acceleration, additional scope of work and attempts to make up for loss of productivity are common reasons for overmanning. Typically, overmanning is associated with increases in crew size and deployment of additional crews. As more workers are added to a crew of normal size, each new worker increases crew productivity less than the previous one. Overmanning creates inefficiencies due also to physical conflict, competition for same resources, fewer productive workers drawn from labour pools, dilution of supervisory control and, in general, demotivation. The effect of overmanning on productivity, as reported by the Office of the Chief of Engineers, U.S. Army [23], is shown in Figure 2.2 and, as reported by Foster Wheeler [22], in Figure 2.3.

Acceleration results in congestion of trades (or activity stacking) when activities, which are normally scheduled sequentially, are performed concurrently in a given area. Congestion of trades may also occur when workers are prematurely moved to another area due to a disruption. The effect on productivity of congestion of trades, measured as a percentage of additional workers to the normal level, is shown in Figure 2.4 [23].

For unplanned disruptions and temporary suspensions of individual operations which require crews to remobilize, Foster Wheeler [22] has developed an inefficiency curve, shown in Figure 2.5. Unfortunately, this curve does not take into account the loss of productive rhythm and demotivation resulting from prematurely moving the crew. For repeat operations, learning curve models can be used to calculate loss of productivity flowing from unplanned delays and disruptions [41,78], as shown in Figure 2.6.

Kappaz [24] has presented a number of different methods for evaluating the effect of scope changes on schedule for large engineering-construction projects. Although his methodology is not readily applicable to small projects and contracts within a large project, Kappaz does recognize the need to consider the cumulative effect of changes which singly may appear to have no significant impact. The relationship between work force density and productivity, as developed by Kappaz, is shown in Figure 2.7.

2.4 IMPACT-RELATED STUDIES

In recent years, various studies have been carried out to identify the major factors causing loss of productivity and delays in the construction industry [3,4,5]. Generally, the purpose of such studies is to identify areas to which further research and management attention should be directed.

A recent study, commissioned by an advisory group to the Minister of Regional Expansion and conducted at the

Centre for Building Studies [4], surveyed the construction industry to determine the major factors impairing productivity. Respondents were asked to rank factors within particular categories and each category in order of importance. Based on the rankings, all factors were analyzed collectively.

As expected, the most important factors cited by contractors were related to labour and their unions, namely, restrictive union rules and labour opposition to productivity improvements. Owners and labour union officials emphasized factors related mainly to design and procurement and, to a lesser extent, construction management. In particular, the latter pointed to design changes as the single most important factor impairing construction productivity.

It should be admitted that the aforementioned study has been criticized because it does not differentiate between micro and macro productivity. According to Revay [30], union rules are essentially macro factors that impair the effectiveness with which labour is utilized and, as such, they are not comparable with design changes which affect labour efficiency (i.e., micro productivity). A review of the contractors' responses, however, indicates that contractors, like owners and labour unions, feel lack of information and design changes are the most important factors affecting micro productivity.

Another recent study in the U.S., jointly undertaken by the National Electrical Contractors' Association (NECA) and Mechanical Contractors' Association (MCA) [3], addresses the impact of schedule delays and disruptions on cost and time. The results are based on a survey of electrical and mechanical subcontractors in the U.S. from whom there were 71 responses. Contractors were requested to report data from completed projects on which a significant schedule disruption had caused a loss of labour productivity and other unanticipated labour costs.

Electrical and mechanical contractors reported a total overrun of 30% on prime costs (excluding home office overhead and profit), 67% of which was attributable to overruns in labour cost. As shown in Figure 2.8, 44% of the labour cost overrun was due to loss of productivity. The total loss of productivity, expressed as a percentage of the original estimated labour costs, was 21% and 24% for electrical and mechanical contractors respectively.

Contractors surveyed in the NECA/MCA study considered lack of proper coordination as the major cause of schedule disruptions and delays, followed by various factors related to lack of information and change orders. Essentially, all causes ranked by the contractors were conditions beyond their control.

With respect to the effects of schedule delays and disruptions, the contractors ranked factors relating to loss of productivity, i.e., loss of productive rhythm, redundant mobilization, and demotivation, as being the most significant. However, loss of productive rhythm and demotivation are essentially impossible to quantify for individual delays and disruptions, and neither published tables nor previous empirical research exists for these factors. In fact, the widely recognized causes of loss of productivity (i.e., overmanning, loss of learning curve, and congestion), for which published tables are available [22,23,78] and frequently used to quantify such losses, were ranked lower by the contractors.

The results of the NECA/MCA study suggest, first, that quantification of productivity losses on delayed and disrupted projects should be an 'after-the-fact' calculation done on a global basis, as opposed to estimates done at the time of each particular disruption and, secondly, that published tables for loss of productivity must take into account loss of productive rhythm and demotivation of the workers.

In an earlier study reported by Baldwin et al. [5], general contractors ranked design changes as the most important factor influencing progress, behind weather, labour supply, and subcontractors. While architects and engineers (A/E's) ranked design changes significantly lower, thus indicating that A/E's underrate the effects of design changes on progress.

Thamhain and Wilemon [79] conducted a field survey of over 300 project leaders to determine the most significant reasons for schedule and budget overruns. Results of the survey revealed that both project managers and senior management viewed customer- and management-initiated changes as a major cause of overruns. Similarly, A/E's and construction management on several U.S. nuclear power plants, in interviews, ranked change orders as the highest impact area that may cause delays if not handled properly [80].

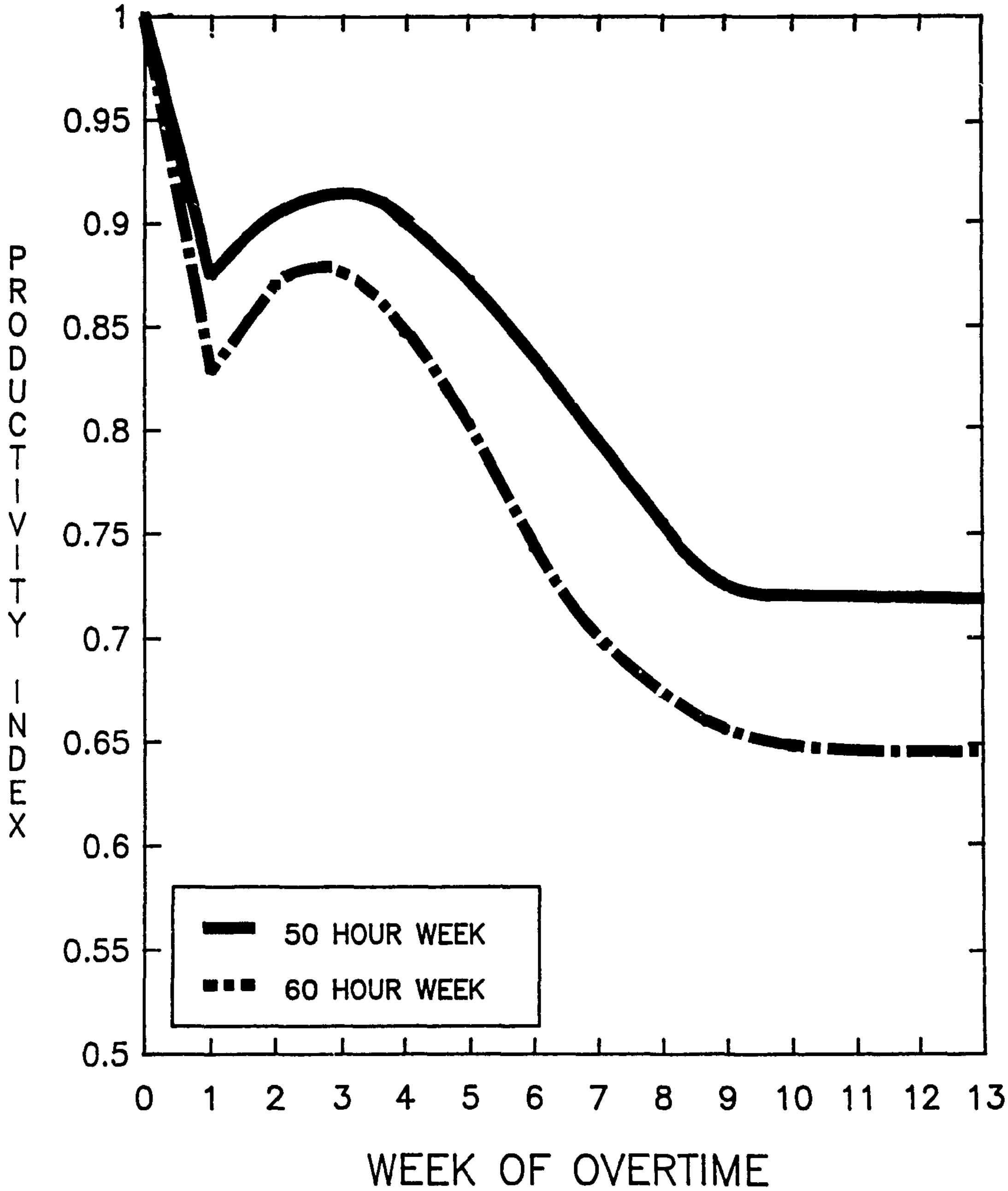


FIGURE 2.1 - EFFECT OF CUMULATIVE OVERTIME ON PRODUCTIVITY - (Ref. 19)

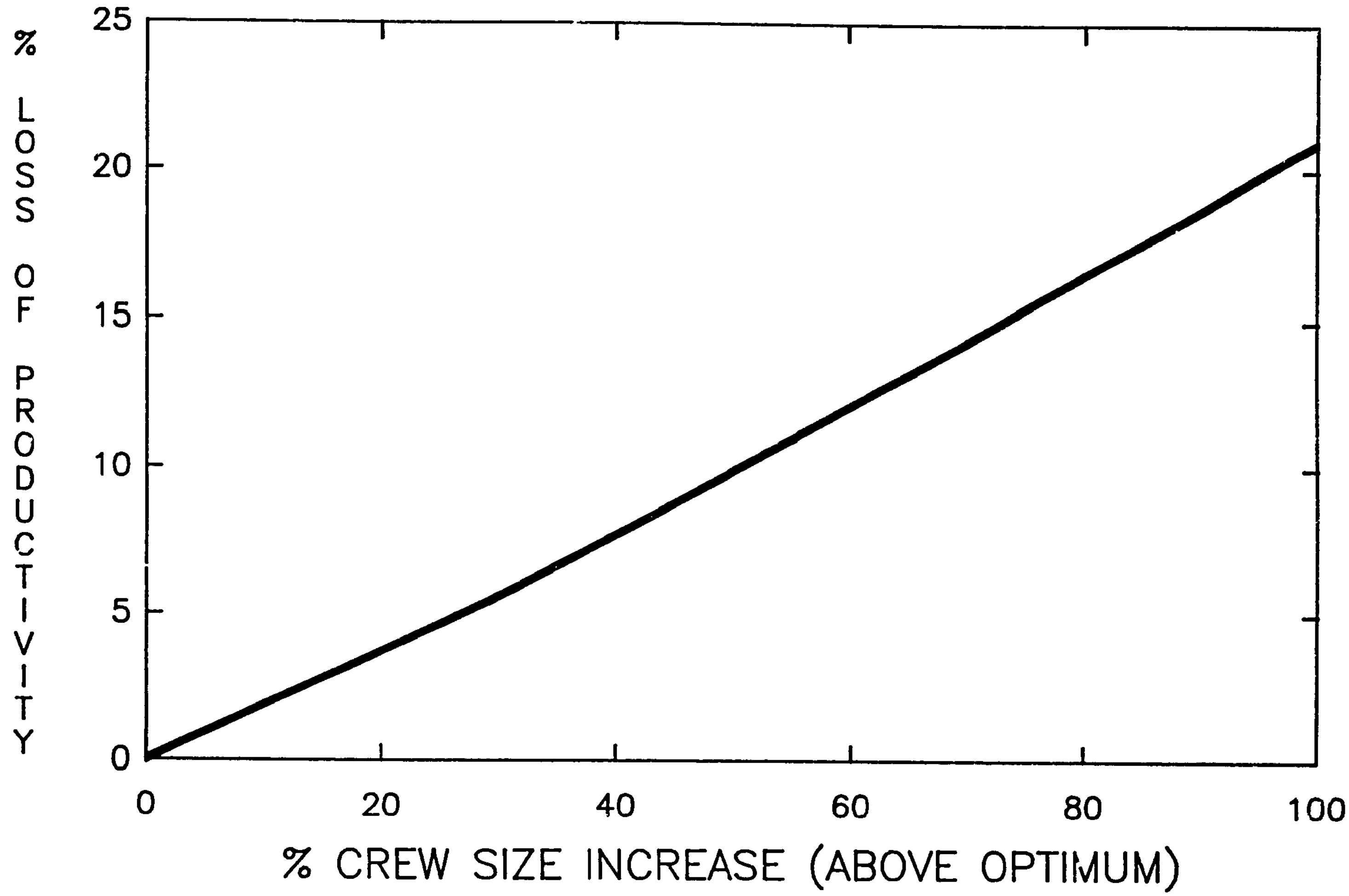


FIGURE 2.2 - EFFECT OF CREW SIZE INCREASL ON PRODUCTIVITY - (Ref. 23)

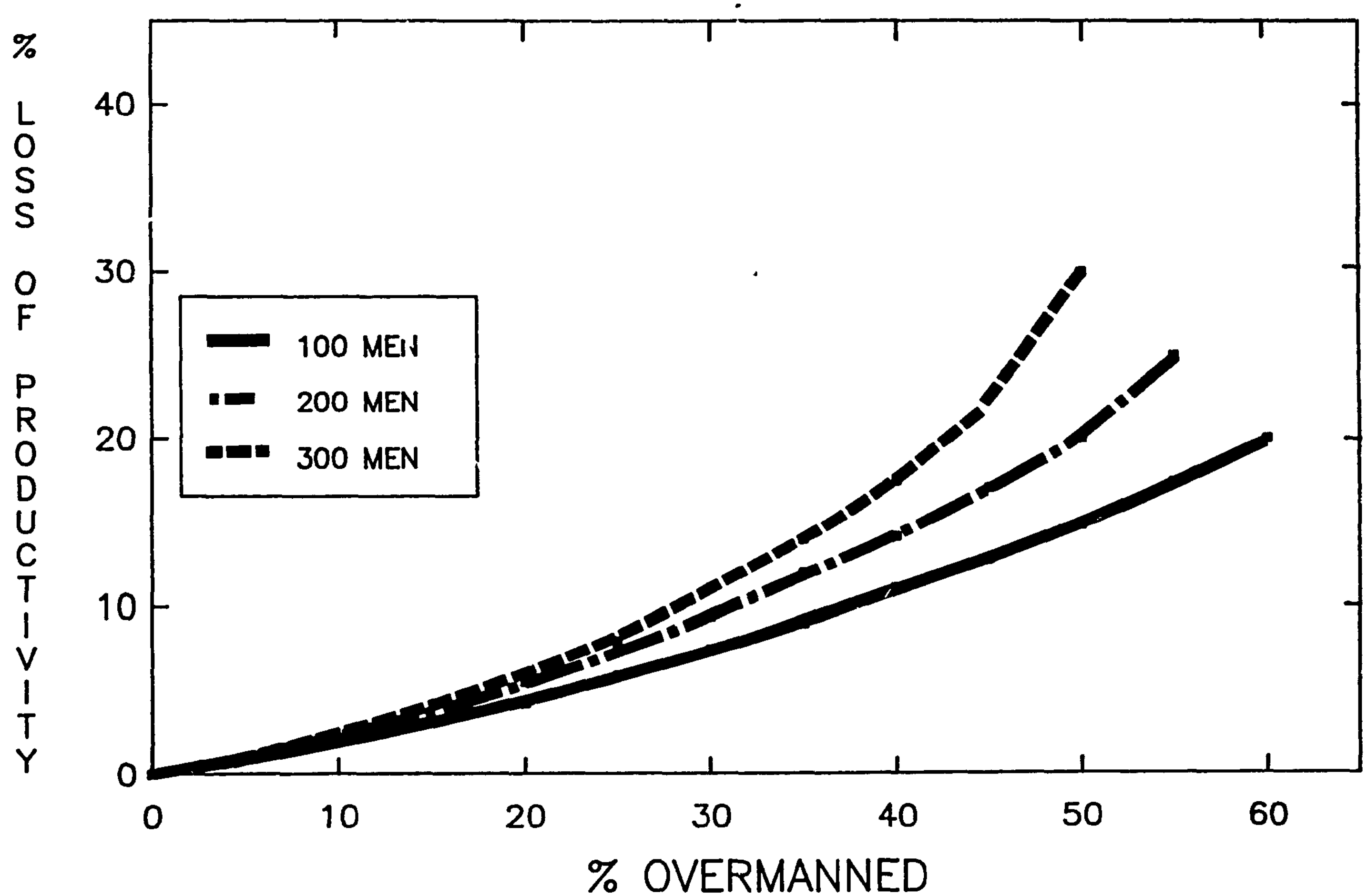


FIGURE 2.3 - EFFECT OF OVERMANNING ON PRODUCTIVITY - (Ref. 22)

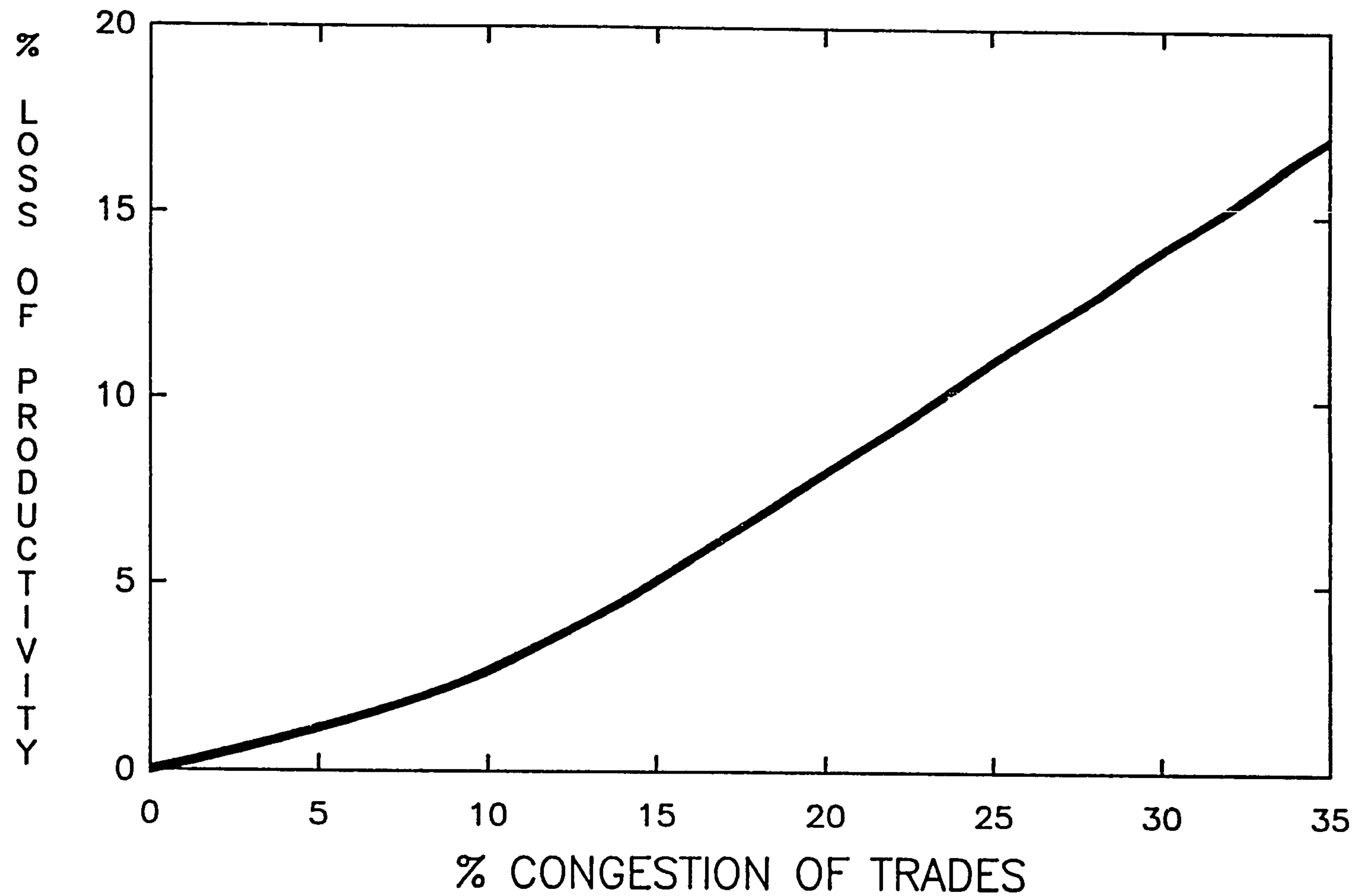


FIGURE 2.4 - EFFECT OF CONGESTION OF TRADES ON PRODUCTIVITY - (Ref. 23)

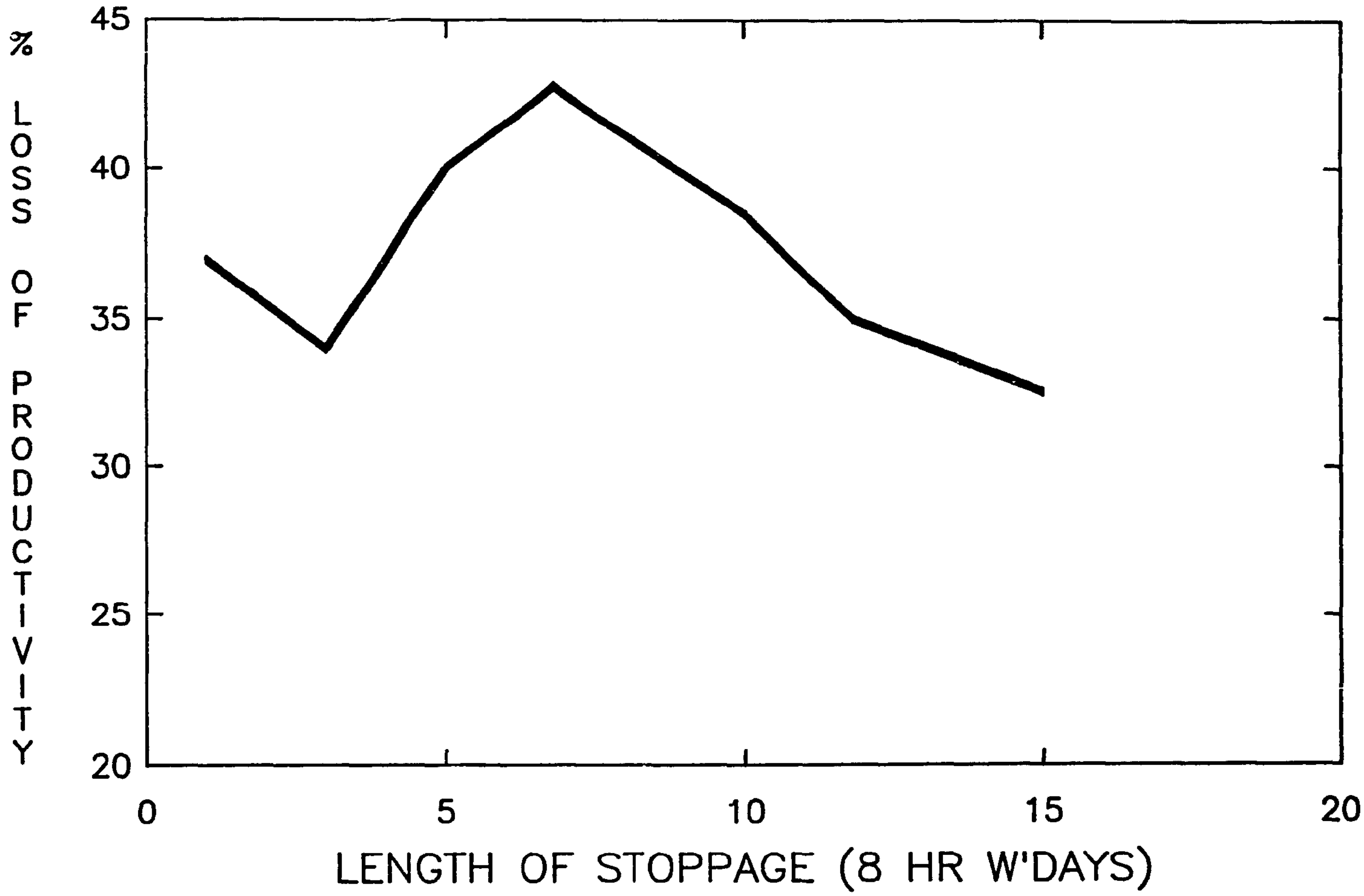


FIGURE 2.5 - EFFECT OF REMOBILIZATION ON PRODUCTIVITY - (Ref. 22)

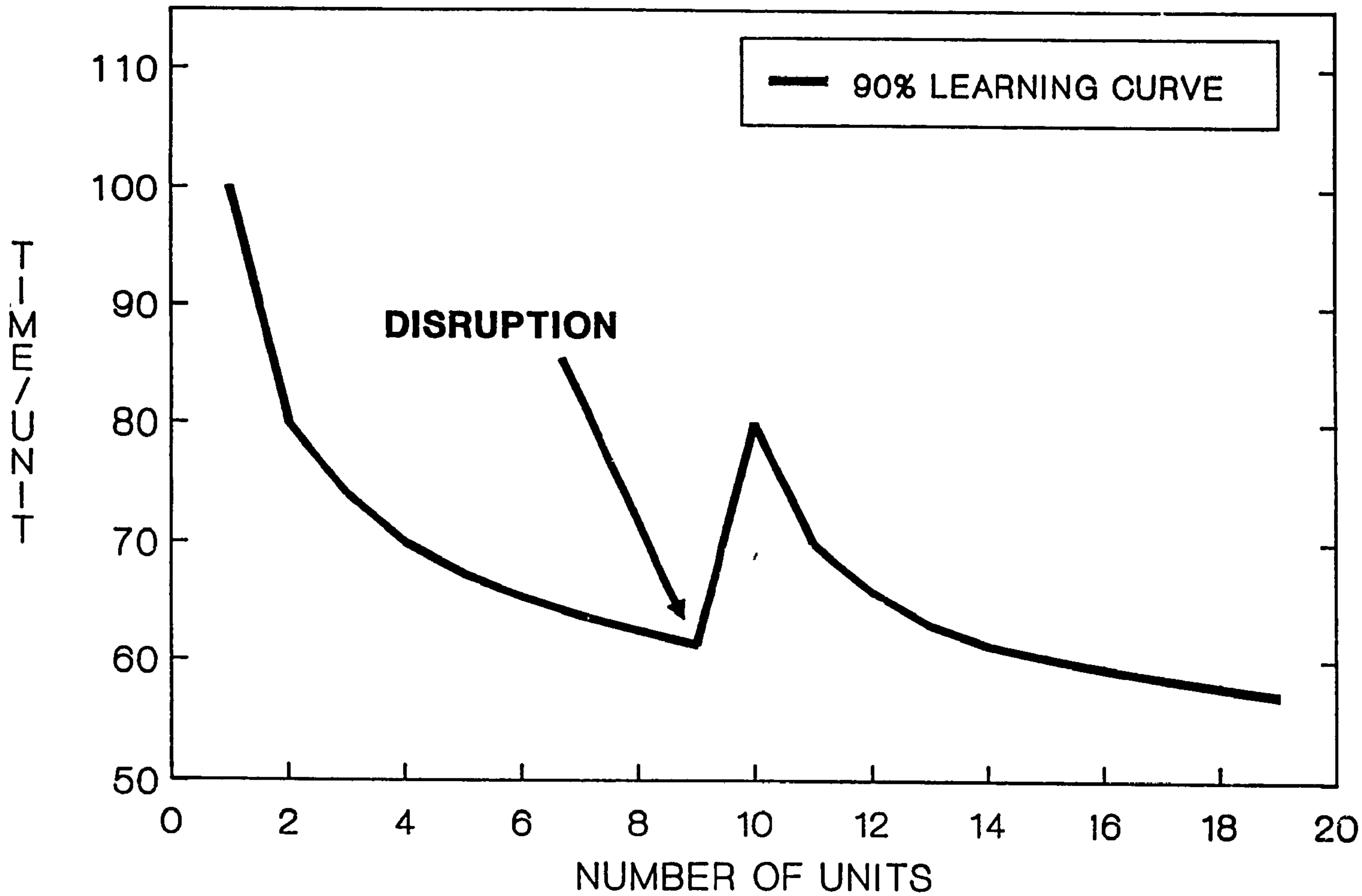


FIGURE 2.6 - EFFECT OF A DISRUPTION ON LEARNING CURVE

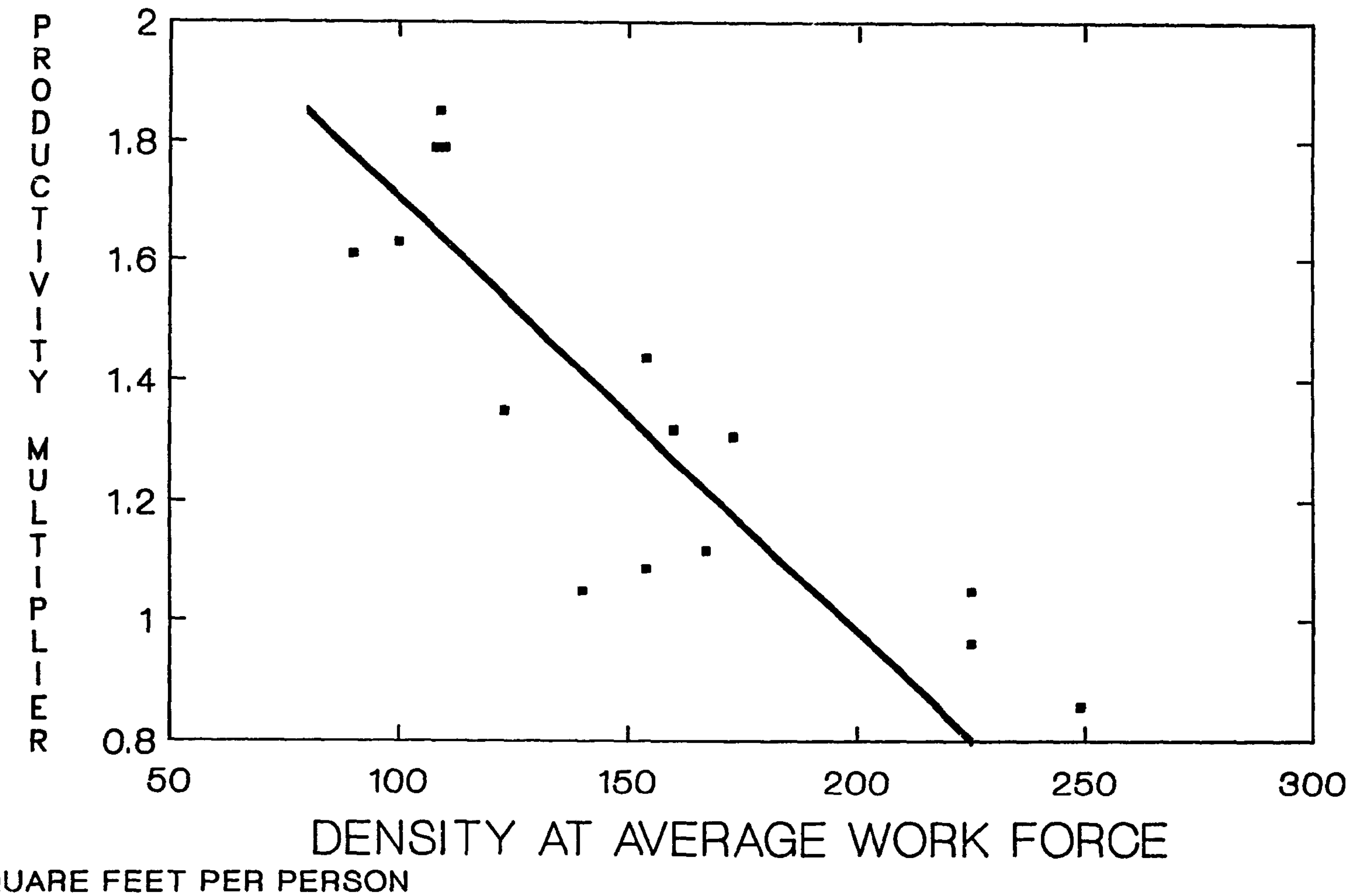


FIGURE 2.7 - EFFECT OF DENSITY AT AVERAGE WORK FORCE ON PRODUCTIVITY (Ref. 24)

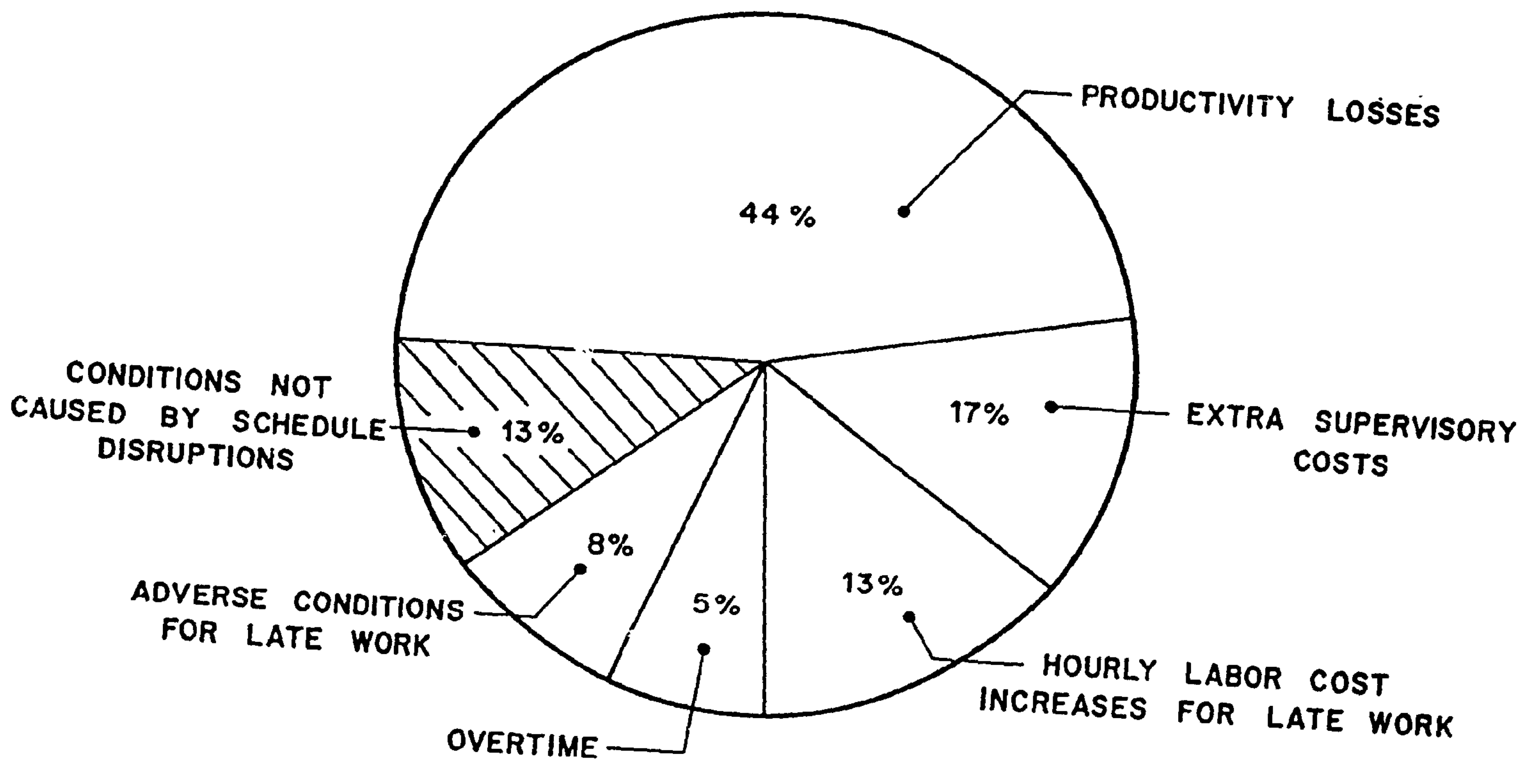


FIGURE 2.8 - BREAKDOWN OF LABOUR COST OVERRUN ON ELECTRICAL AND MECHANICAL CONTRACTS - (Ref. 3)

Types of Impact	Inefficiency* Range	Inefficiency* Expected
1) Poor Management		
(a) Problems in Layout	115-250	130
(b) Foreman with Less than Normal Loyalty or Ability	110-200	115
(c) Poor Quality Superintendent	105-180	140
(d) Lack of Tools	110-200	130
(e) Lack of Material	100-200	140
(f) Lack of Direction(s)	100-250	135
(g) Lack of Full-Time Project Manager on Site	100-140	110
(h) Sour Job (one with no profit or worse)	110-200	115
(i) Lack of Decision Making (by Owner, Architect, Engineer, Contractor, or Subcontractor)	120-190	130
(j) Lack of Planning	60-500	150
(k) Attitude of Company (by Owner, Architect, Engineer, Contractor, or Subcontractor)	110-115	
2) Inadequate and/or Incomplete Drawings		
(a) If 10% or less of the completed drawings are bad	100-170	120
(b) If 30% or less of the completed drawings are bad	110-180	135
(c) If 60% or less of the completed drawings are bad	120-210	160
3) Interference		
(a) Remove Operation Underway & Redo	160-210	170
(b) Remove Operation Completed & Redo	170-300	210
(c) Do A (Above) More than Once	190-290	210
(d) Do B (Above) More than Once	200-310	240
(e) Stop Work, Move Men for Hold Less than Five Days	140-220	155
(f) Stop Work, Move Men for Hold More than Five Days	140-225	175
(g) Continual Stop/Start	165-210	175
(h) Over Inspection	120-240	140
(i) Under Inspection	80-220	110
(j) Malice in Inspection	150-260	160
(k) Implies Acceleration	100-120	108
(l) Suspension of Less than 25% of Work	105-140	110
(m) Stretch Task Out 20% Longer	115-160	125
(n) Stretch Task Out 50% Longer	115-180	140
(o) Stretch Task Out 100% Longer	115-230	160
(p) Work 6-day Week	105-130	120
(q) Work 10-hour Days	105-140	120
(r) Work 6 Ten-hour Days	105-155	120
(s) Schedule Trades Too Closely		
Two in One Area	110-160	130
More Than Two	120-180	140

*Percent Increase in Labour-Hours to Perform Task

TABLE 2.1 - EFFECTS OF MANAGEMENT PRACTICES ON PRODUCTIVITY - (Ref. 76)

CHAPTER III

METHODOLOGY

3.1 INTRODUCTION

In the early stages of this research program it became apparent that detailed review and comprehensive analysis of a relatively large number of cases were the most appropriate means of examining the qualitative and quantitative effects of change orders on productivity. In previous impact-related studies [3,4,5], information was obtained from questionnaires completed by contractors, owners, A/E's, and labour officials.

Although technical surveys usually provide a tangible amount of data which can be readily analyzed, such surveys do not permit researchers to examine the particular circumstances of each case and to analyze the project data in detail. Additionally, success of surveys depends on the number of responses received. Thus, the low response rate (less than 1%) of the NECA/MCA study [3] discourages the use of surveys to collect data for future impact-related studies.

The case study approach utilized in the present research, as opposed to the survey approach, allows extensive examination of the project history and permits analysis of productivity. Indeed, a sound knowledge of the project history is required to determine how change orders individually and cumulatively can affect productivity. Additionally, to examine the relationship between change orders and loss of productivity, it is necessary to analyze the change orders and calculate the corresponding loss of productivity for each case.

3.2 METHOD OF INVESTIGATION

To obtain information for the case studies, a field investigation was conducted over a period of 18 months at Revay and Associates Limited of Montreal, a professional construction management consulting firm specializing in the preparation and evaluation of construction claims. From various contracts analyzed by the firm, 84 contracts were identified on which the contractor had experienced loss of productivity as a result of change orders. Out of the 84 contracts, 5 were divided into 2 or more separate work packages to be examined independently, thus, a total of 90 cases were analyzed. Information was collected from contractors' claims (prepared by the firm on behalf of contractors), claim evaluations (carried out on behalf of owners) and expert reports (prepared for presentation in courts or arbitration) and from corresponding job files.

For each case, the field investigation consisted of several steps. First, the contract was classified according to type of work and type of construction. For the purpose of the present research, two basic types of work were considered: 1) electrical and mechanical work (i.e., fine motor trades), and 2) civil and architectural work (i.e., gross motor trades). Also, two basic types of construction were considered: 1) commercial and institutional building construction, and 2) industrial construction. Thereafter, three categories were chosen: electrical/mechanical contracts on building projects (Appendix A), electrical/mechanical contracts on industrial projects (Appendix B), and civil/architectural contracts on building and industrial projects (Appendix C).

Secondly, data on raw project facts was collected to provide background information. As shown in Tables A.1, B.1 and C.1 of Appendices A, B and C respectively, data was collected on the following: type of project; type of work; type of contractor; type of contract; original contract amount; value of approved change orders; original contract duration; actual contract duration; and number of change orders. Table 3.1 summarizes project data on the 90 cases examined.

Thirdly, the project history and related analyses carried out by the firm were examined to assess causes of impact, as explained in Section 3.3, and to identify qualitative effects of change orders on productivity and factors influencing the effects of change orders on productivity, as reported in Chapter IV - Qualitative Results of Field Investigation.

Fourthly, project data on labour-hour expenditure, physical progress, and change orders was collected for analysis of change orders and calculation of productivity loss. These steps are explained in Sections 3.4 and 3.5 respectively.

3.3 ASSESSMENT OF THE CAUSES OF IMPACT

To examine the statistical relationship between change orders and loss of productivity, it is necessary to ensure that all causes of impact are taken into consideration. Consequently, it is not only necessary to identify potential problems but also to assess the impact of such problems on productivity.

In practice, various methods are used to evaluate impact of problems arising on construction projects. Both period-by-period and cumulative productivity analyses are used to determine the extent to which particular problems affect productivity [1,81,82]. Network analysis techniques are frequently used to evaluate causes of impact [83,84,85,86]. By comparing as-planned and as-built schedules, it may be possible to identify and assess the effects of poor coordination and scheduling, changes in sequence, acceleration, and late delivery of equipment, material, or supply of information. Similarily, comparisons of planned and actual manpower histograms and physical progress curves provide knowledge of delays, change orders and acceleration [81,84,87].

Since courts of law require contractors to prove causation, such analyses are frequently undertaken in claim situations with a view to establishing connection between the problems and the resulting impact costs. By examining the analyses included in claims and expert reports, and the related project documentation, it is possible to study and classify the impact of the various problems.

For the purpose of the present research, causes of impact under examination are classified as: 1) major causes of productivity-related impact, 2) minor causes of productivity-related impact, and 3) causes of delay-related impact, as shown in Tables A.3, B.3 and C.3 of Appendices A, B and C respectively. Causes of impact not under examination were excluded from the present research as explained in Section 3.5.3.

Major causes of productivity-related impact are defined as acts and failures to act by owners and A/E's which resulted in a significant productivity loss for an extended period of the work. Major causes of productivity-related impact frequently identified in the cases include: change orders; inadequate scheduling and coordination by owners, general contractors, and construction managers; acceleration; changes in sequence; late supply of information, equipment, or material; increased complexity of the work; and the ripple-effect of change orders issued to other contractors.

Minor causes of productivity-related impact are defined as acts or omissions which adversely affected productivity for a relatively short period of the work. Minor causes of productivity-related impact identified in the cases include: priority changes; untimely responses to queries; late approval of shop drawings; late delivery of equipment or material; and impeded access to the site. Acts or omissions which resulted in delays without giving rise to productivity losses included: unavailability of site; late completion of preceding work; reinstallation of equipment; and late issuance of construction drawings.

To account for causes of impact other than change orders, the cases are categorized according to the number of major causes of productivity-related impact. As shown in Tables A.3, B.3 and C.3 of Appendices A, B and C respectively, Type 1 refers to cases in which change orders are the only major cause of productivity-related impact. Type 2 refers to cases in which productivity-related impact resulted from change orders and one additional major cause, while Type 3 refers to cases in which change orders and more than one additional major cause resulted in productivity-related impact.

3.4 MEASUREMENT OF CHANGE ORDERS

To examine the statistical relationship between change orders and loss of productivity, it is necessary to quantify these two variables. Since there is no standard single measurement for qualifying change orders, the following measurements (shown in Tables A.2, B.2 and C.2 of Appendices A, B and C respectively) have been considered:

$$1.\ \text{Frequency} = \frac{\text{Number of Change Orders}}{\text{Contract Duration (Months)}} \qquad \ldots\ 3.1$$

$$2.\ \text{Average Size} = \frac{\text{Change Order Hours}}{\text{Number of Change Orders}} \qquad \ldots\ 3.2$$

$$3.\ \text{Percentage (\%)} = \frac{\text{Change Order Hours}}{\text{Actual Contract Hours}} \times 100 \qquad \ldots\ 3.3$$

Change order hours are the total additional labour-hours directly required to perform the changed work. As such, change order hours do not include unproductive labour-hours reimbursed through change orders, and other items such as overtime premiums, engineering, and site supervision. Actual contract hours are the labour-hours spent by contractor on the original scope of work (i.e., excluding direct hours spent on changes).

In many of the cases examined, actual hours spent by the contractor on change order work are not available. Consequently, earned change order hours, obtained from estimates prepared by either the contractor or the owner, are utilized. In such instances, actual contract hours are calculated by subtracting earned change order hours from actual total hours, thus, any productivity loss on the change orders themselves is included indirectly in the actual contract hours. To avoid overstating the change order hours in fewer than 10 cases, large changes issued prior to start of the work (e.g., changes from the tender to the construction drawings) were considered to be part of the original scope of the work. Hence, labour-hours for these charges are added to earned hours of the original scope of work. This was done where such changes were readily accommodated into the contractor's plan without affecting productivity.

Although the productivity-related impact of an individual change order depends on various factors, and such impact will vary from change to change, it is beyond the scope of the present research to investigate each individual situation in the 90 cases examined. Therefore, the measurements may include change orders that have not adversely affected, or may have even improved, productivity. Nevertheless, it is believed that all change orders ought to be considered to account for their cumulative effect. Also, since measurements which include all change orders are easily determined, models based on such measurements could be readily used on future projects.

3.5 CALCULATION OF LOSS OF PRODUCTIVITY

All contractor claims and expert reports examined under the present study include a calculation for loss of productivity. Since expert reports put forth independent and unbiased evaluations of impact costs (or time extensions), calculations for loss of productivity presented in such reports are considered reliable for the purpose of the present research.

Claims, on the other hand, are generally assertions of a right to additional compensation, based on interpretation of the facts and calculations most favourable to contractors. As such, claims may not take into account contractors' inefficiencies and underestimating. Consequently, productivity losses identified in claim submissions have been reassessed according to the procedure shown in Figure 3.1.

As previously stated in Chapter I, loss of productivity is best calculated using the differential method because it is based on the level of productivity achieved by the contractor during an unimpacted period of the job. To establish whether the differential cost method is applicable, the following guidelines [1,16] are normally considered:

1 - The unaffected work is representative both in complexity and method of execution of the work which was impacted by the causes under examination;

2 - The difference between the actual productivity of the impacted work and the normal productivity resulted solely from the causes under examination;

3 - All work analyzed must have been impacted by the cause in question;

4 - The normal productivity of the unaffected work is portable and is valid; it allows for all applicable risks and/or inherent shortcomings of the contractor, and represents a sufficiently large percentage of the entire job to allow reasonable confidence in the comparison.

Often, a considerable amount of investigation is required to determine whether these guidelines can be met. Where a differential method of cost calculation is deemed applicable, it is then necessary to determine whether accurate data on physical progress and labour-hour expenditure is available. If not, either the modified or the total cost approach must be utilized, as explained in Section 3.5.2.

3.5.1 Differential Cost Calculation

The first step of the differential method of cost calculation is to establish the contractor's productivity on the original scope of work. For such a measurement, productivity is expressed as the ratio of physical progress or earned value to actual input of labour. An example of monthly earned and actual contract hours and the corresponding productivity is shown in Figure 3.2. By definition, ratios of less than one represent better than estimated productivity and vice versa.

The next step is to determine the time frame of an unimpeded (i.e., normal) period of work, that requires sound knowledge based on the job history. Normal productivity, for the purpose of the analysis, is considered to be that level of productivity the contractor could have maintained if not for the interferences of the owners and A/E's. The normal period, expressed in percentage of physical progress, is shown in column (3) of Tables A.2, B.2 and C.2 of Appendices A, B and C respectively.

Based on this normal productivity, normal hours to complete the entire job (shown in Tables A.2, B.2 and C.2 of Appendices A, B and C respectively) are calculated, taking into consideration variations in productivity due to the 'learning curve effect'. As such, the learning curve effect refers to the gradual increase in productivity that occurs as workers become familiar with job conditions and as methods and organization of the job are refined. Normally, productivity increases to a maximum level at a time between 15% - 20% of physical completion that is maintained up to about 90% completion. At the end of the job, productivity generally declines somewhat.

Such variations in productivity are quantitatively described by learning curve factors, where values greater than one represent decreased productivity and vice versa. These factors can be utilized to calculate labour-hours required for the entire job from levels of productivity achieved during given periods. In accordance with common industry practice, the present research utilizes the learning curve factors presented in Table 3.2 to calculate normal hours from normal productivity.

To standardize the loss of productivity calculation, earned hours (shown in column (5) of Tables A.2, B.2 and C.2 of Appendices A, B and C respectively) are equated with normal hours. As such, earned hours represent the labour-hours that the contractor would have utilized to complete the original scope of work except for the specific causes of the impact under examination.

3.5.2 Modified and Total Cost Approaches

When the differential method of cost calculation is not possible, it is usual to revert to the contractor's estimate (shown in column (1) of Tables A.2, B.2 and C.2 of Appendices A, B and C respectively) to calculate loss of productivity. Under the modified cost approach [16,17], two methods are used to evaluate the contractor's estimate.

In one method, the contractor's tender is compared with tenders submitted by other bidders. Where the difference is less than 3% - 5% between the average of the next three lowest tenders and that of the contractor the estimate is considered valid. Otherwise, the estimate is corrected, as follows:

$$ME = CE \times \frac{AVE}{CT} \qquad \ldots 3.4$$

in which:

ME = modified estimate (labour-hours),

CE = contractor's estimate (labour-hours),

AVE = average of next three tenders ($), and

CT = contractor's tender ($).

In one case examined there was a significant difference between the contractor's tender and the average of the next three tenders; nevertheless, the actual material costs remained within the estimate, thus the underestimating was entirely in the labour component of the estimate. Accordingly, an amount equal to the value of the difference between the tenders was added to the labour component as follows:

$$ME = CE + \frac{AVE - CT}{RATE} \qquad \ldots 3.5$$

in which:

ME = modified estimate (labour-hours),

CE = contractor's estimate (labour-hours),

AVE = average of next three tenders ($),

CT = contractor's tender ($), and

RATE = cost of labour ($ per labour-hour).

In the second method of the modified cost approach, the contractor's estimate is compared with an estimate prepared using published estimating tables. When this theoretical estimate is greater than the contractor's estimate by more than 3% - 5%, then the contractor's estimate is adjusted to equal the theoretical estimate.

When the contractor's estimate is reasonable, or when it is not possible to use alternate methods, the total cost approach [17,88] is adopted (i.e., the values estimated by the contractor are assumed to be 'normal').

A measure of the accuracy of the contractor's estimate for the original scope of work, commonly referred to as the site-experience factor, is calculated as the ratio of the so-calculated normal cost to the contractor's estimate. Site-experience factors (shown in column (7) of Tables A.2, B.2 and C.2 of Appendices A, B and C respectively) greater than one imply that the contractor underestimated the scope of work and vice versa.

It should be mentioned that the 'normal' cost developed through the modified cost approach is likely to be conservative. Indeed, in competitive bidding there is always a low bidder, but it does not necessarily mean that he has underestimated the resources required to carry out the work. Contractors who have significantly underbid their competition may stay within their estimate simply by directing greater attention toward planning and cost control.

3.5.3 Exclusion of Causes of Impact Not Under Examination

Prior to calculating loss of productivity for the causes under examination, it is necessary to exclude unproductive hours resulting from other causes. Contractor inefficiencies, such as repairing deficiencies and labour disruptions, and inefficiencies due to inclement weather are excluded from the examination. As shown in Figure 3.1, unproductive labour-hours attributable to such causes are simply subtracted from actual contract hours.

Based on a ratio of output to input, the productivity index (PI) attained by contractors on the original scope of work (shown in column (8) of Tables A.2, B.2 and C.2 of Appendices A, B and C respectively) is calculated as follows:

$$PI = \frac{E}{A} \qquad \ldots 3.6$$

in which:

PI = productivity index,

E = earned (or normal) contract hours, and

A = actual contract hours.

The unproductive labour-hours attributable to the causes of impact under examination expressed as a percentage of labour-hours spent on original contract work, referred to herein as percentage loss of productivity (shown in column (9) of Tables A.2, B.2 and C.2 of Appendices A, B and C respectively), is calculated as follows:

$$LP = \frac{A - E}{A} \times 100\% \qquad \ldots 3.7$$

OR

$$LP = (1 - PI) \times 100\% \qquad \ldots 3.8$$

in which:

LP = loss of productivity (%),

A = actual contract hours,

E = earned contract hours, and

PI = productivity index.

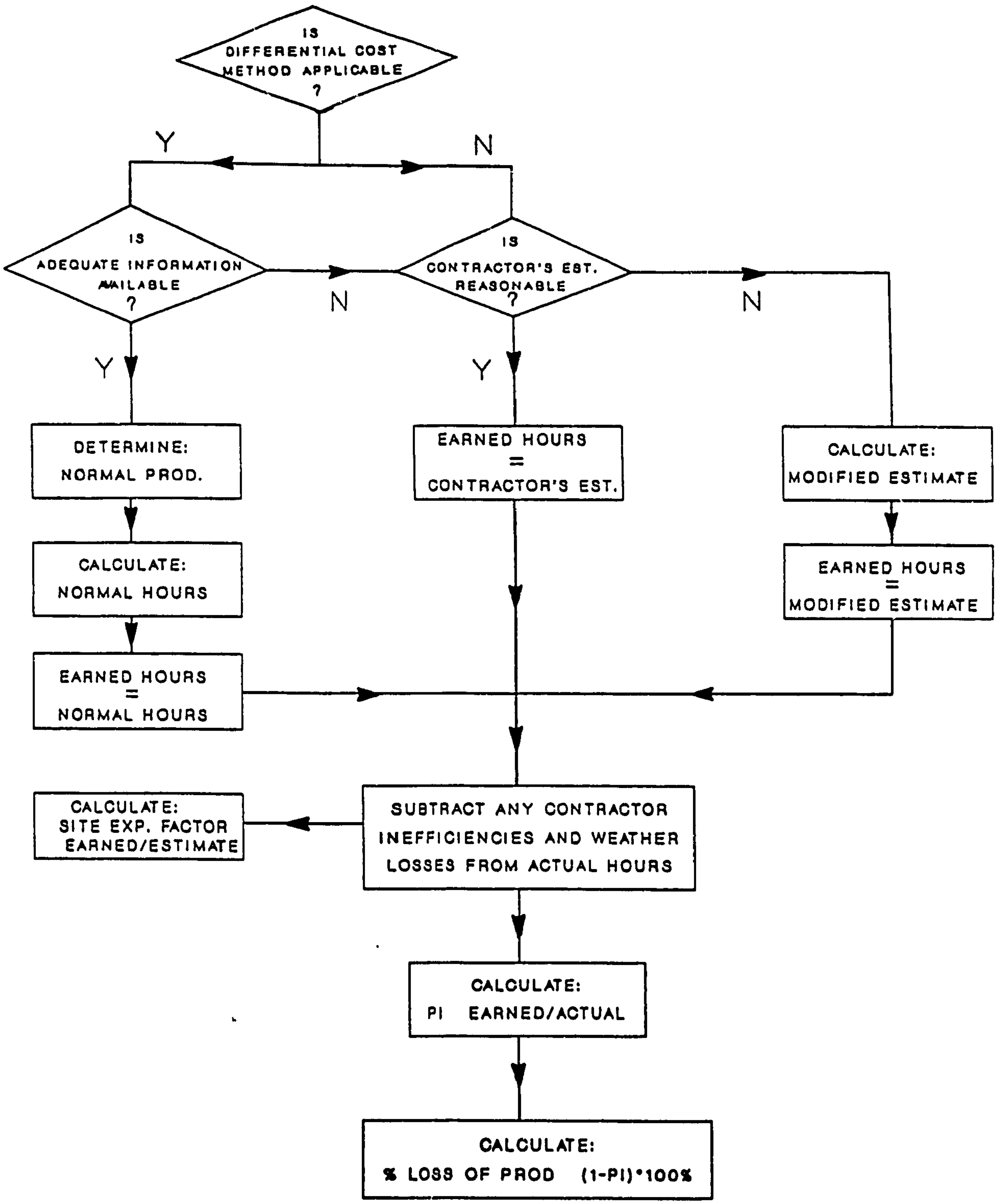


FIGURE 3.1 - METHODOLOGY FOR CALCULATION OF PRODUCTIVITY LOSS

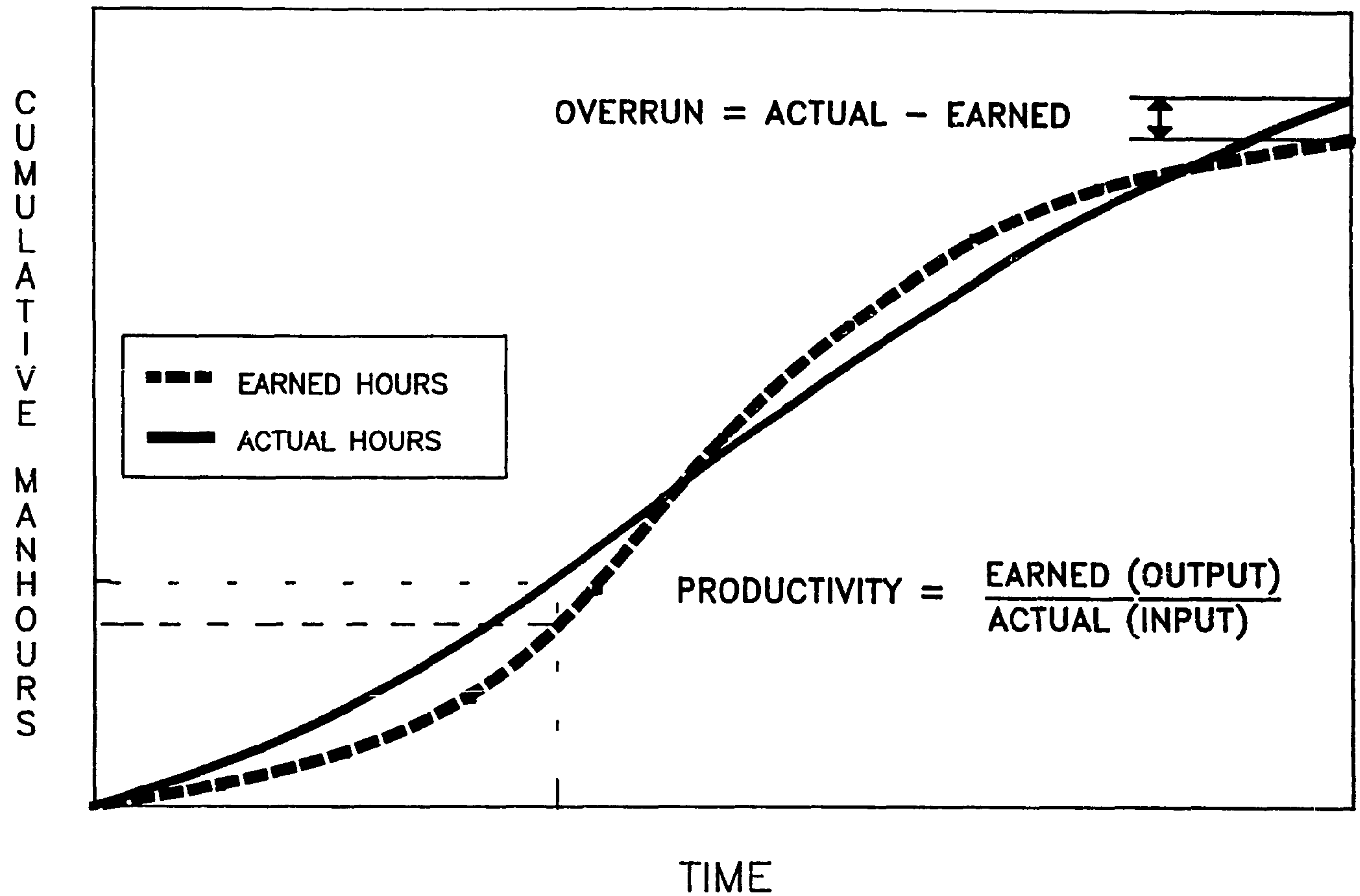


FIGURE 3.2 - EARNED VS. ACTUAL LABOUR-HOURS

CATEGORY	TYPE OF WORK	TYPE OF CONSTRUCTION	VALUE OF ORIGINAL CONTRACT	VALUE OF CHANGE ORDERS	TOTAL ACTUAL LABOUR-HOURS
1	ELEC/MECH	BUILDING	$ 72,374,000	$22,822,000	2518588
2	ELEC/MECH	INDUSTRIAL	$107,508,000	$33,163,000	3378892
3	CIVIL/ARCH	BLDG & IND	$ 42,285,000	$ 9,696,000	1418720
		TOTAL	$222,167,000	$65,681,000	7316200

TABLE 3.1 - PROJECT DATA SUMMARY

PHYSICAL PROGRESS AT TIME OF UNIMPACTED PERIOD	LEARNING CURVE FACTOR
0% - 5%	1.7
6% - 10%	1.4
11% - 15%	1.2
16% - 90%	0.9
91% - 95%	1.0
96% - 100%	1.2

TABLE 3.2 - LEARNING CURVE FACTORS

CHAPTER IV

QUALITATIVE RESULTS OF FIELD INVESTIGATION

4.1 INTRODUCTION

The qualitative investigation of the chronology of the 90 cases, and the related analyses contained in the source documents identified: the reasons why change orders affect productivity; the significant and recurring sources of productivity losses triggered by change orders; the general correlation between change orders and loss of productivity; and the factors negatively influencing impact of change orders on productivity. The results of this qualitative examination, as documented in this chapter, establish a basis for the quantitative analysis described in Chapter V and provide awareness and understanding of the effects of change orders on productivity.

4.2 EFFECTS OF INDIVIDUAL CHANGE ORDERS

The most frequently encountered effects of individual change orders were found to be disruptions and delays. In general, disruptions occurred when workers were prematurely moved from one task to another, and disruptions resulted in delays to the completion of only a portion of the affected activities. Other causes of impact, however, often delayed performance of entire activities. Impacts relating to this second group are referred to as 'delays' herein. In the cases examined, delays and disruptions were found to result from changes requested by owners and A/E's, which put the affected work on 'hold', and design errors and omissions, which prevented performance of the affected work. In both instances, work could not have proceeded until a solution was found to the problem or perhaps even until a change order was issued.

Similar to studies conducted by others [3,23], the following disruption-causing occurrences were identified in the present research: stop-and-go operations; out-of-sequence work; and learning-curve-related losses. When activities were disrupted, stop-and-go operations occurred as crews moved elsewhere to new tasks. Regardless of the competency of the supervision and the attitude of the labour force, loss of productivity was found to be inevitable in such situations. Non-productive time resulting directly from such relocations included: time before the decision was made to move on to the next step; packing of tools; return of materials to storage; movement to new location; familiarization with new work; unpacking of tools; obtaining new materials; and crews relocating again at a later date to complete the disrupted work. A comparison of the productive time remaining in a working day following a typical relocation with that of a normal working day is shown in Figure 4.1. Although not confirmed by the present research, a previous study [22] indicates that productivity losses resulting from such disruptions would have increased with the duration of the work stoppage, particularly when crews required a second orientation period.

Out-of-sequence work occurred when disruptions forced contractors to perform work in a sequence different from that originally planned, as shown in Figure 4.2. Revised sequences which were illogical and uneconomical, resulted in productivity losses on the affected activities. More importantly, out-of-sequence work and stop-and-go operations interrupted job rhythm resulting in productivity losses on affected activities and, more importantly, even on unchanged activities (i.e., activities indirectly affected by changes).

In some instances, delays and disruptions deprived contractors from benefiting from the learning curve because contractors were prevented from keeping crews on repetitive tasks, were forced to lay off workers then rehire and retrain them as work became available. The effect of a disruption on a typical learning curve is shown in Figure 2.6. In accordance with previous findings [41,55], learning curve losses associated with disruptions were generally found to be related to task orientation rather than acquisition of skills necessary to perform the work.

As shown in Figure 4.3, the extent of delays was dependent on the time taken to issue appropriate instructions to proceed and the time required to organize and perform the work outlined in the change orders. Delay-related losses of productivity typically occurred when activities had to be performed under inclement weather conditions (e.g., winter) and out of sequence. The effect of a delay on the project completion depended on whether the delay was on the critical path or a path made critical by the delay, and on the effects the delay had on resource utilization.

4.3 CUMULATIVE EFFECTS OF CHANGE ORDERS

As stated in the previous section, it was found that individual change orders disrupted and delayed performance of affected activities and often those indirectly affected, resulting in loss of productivity. In approximately 65% of the cases examined, change orders were found to have a significant cumulative effect on performance of the work. Generally, such an effect was experienced when change order hours exceeded 10% - 15% of the earned (or normal) contract hours which is the maximum level of changes which contractors generally maintain they can accommodate without affecting their work.

Cumulatively, delays and disruptions to individual work activities caused by change orders were found to bring about gradual deterioration of original schedules. From comparisons of the as-planned and the as-built schedules, it was found that orderly sequences of operations were broken down into several, perhaps isolated, activities due to delays and disruptions. For example, in one case (Case #1 of electrical/mechanical contracts on building construction - Appendix A), the contractor sent the construction manager a letter which stated:

> "You mention increasing the crew so as to accomplish this. Even an elementary examination of the job reveals that more men will do little or nothing to improve this condition because this is not where the problem lies. Our crew was reduced to a minimum of electricians. This is not because there was a shortage of men but because we continually ran into bottlenecks and couldn't proceed further in any intelligent patterns caused largely by changes."

In such cases, operations were completed in a piecemeal manner over an extended period, as shown in Figure 4.4. In cases of severe disruptions, scheduling was found to be the function of the release of approved change orders and drawing revisions, instead of normal construction logic and economics. Similar to other impact-related studies [3,40,67,68,69], productivity and work force motivation were found to be significantly affected in cases where progress was continually disrupted by change orders.

In the cases examined, it was found that normal gains in job rhythm which occur as work progresses were often either not encountered or lost due to the cumulative effect of change orders. Such losses of job rhythm significantly reduced labour motivation and productivity on the delayed and disrupted activities. Similarly, normal gains in productivity due to the learning curve effect were either lost or never encountered on delayed and disrupted activities. Due to the interdependency among construction operations, losses in job rhythm and learning curve had a ripple-effect on the productivity of activities indirectly affected by change orders.

Delays, disruptions and additional work created by change orders often resulted in unbalanced crews. Crews composed of the wrong number or skill of workers occurred, clearly increasing cost of the operation and reducing productivity of the crew in question. When crew members changed frequently, the supervisory influence of foremen over crew members and, thus, crew productivity was reduced. Crew productivity decreased when foremen that normally perform manual work (i.e., working formen) became instead involved in replanning and coordinating the work affected by change orders.

Generally, the cases examined were bid on the basis of using a fixed number of tradesmen. In approximately 25% of the cases examined, change orders resulted in unplanned fluctuations in manpower levels. Consequently, layoffs, rehiring and retraining of workers occurred, adversely affecting productivity.

As shown in Tables A.3, B.3 and C.3 of Appendices A, B and C respectively, the contractor was forced to accelerate the work in 26 of the 90 cases examined. And, in 73% of such cases, the acceleration was due to the owner's refusal to grant an extension of time for delays (Figure 4.5). Additional work created by change orders and advancement of planned completion dates are only attributable for 15% and 12% of the accelerated cases.

In the 26 cases, the various steps taken to accelerate the work are all generally recognized as demotivators, i.e., giving rise to productivity losses [17,19,23]. As shown in Figure 4.6, additional manpower and scheduled overtime were employed in 88% and 59% of the accelerated cases, respectively. In approximately 46% of the 26 cases, acceleration resulted in congestion of trades, which was detrimental to productivity due to the inherent interference among trades. Multiple shifts were utilized in 19% of such cases. Except on severely congested job sites, employment of additional manpower was the least costly method of accelerating performance of the work. In about 10% of the cases examined, productivity was significantly affected by the decision to start an operation prior to obtaining all required information or clarifications.

On unaccelerated jobs examined in the present research, completion dates were extended by an average of 75% which compares well with the 87% reported in the NECA/MCA study [3]. On accelerated jobs, completion dates were extended by an average of 25% only, thus indicating that acceleration can be effective in reducing the duration of otherwise delayed and disrupted projects. Clearly a large portion of this reduction resulted directly from the particular steps implemented to increase the work pace, although some time saving was attributable to the increased desire and committment of all parties to complete the work as expeditiously as possible. It was not possible to identify, in the cases examined, the extent to which each factor contributed to a reduction of the extended duration.

Lack of information was identified as a cause of impact in all cases experiencing cumulative effects of change orders. Under this category, the following causes were identified: late issuance of construction drawings; late approval of shop drawings; untimely response to requests for clarifications; and, most commonly, insufficient details on drawings. When proper clarifications and drawing revisions were issued in time to permit procurement of materials and scheduling of the affected activities, impact on productivity turned out to be negligible. Conversely, when lack of information disrupted progress of the work, productivity was affected significantly. The latter instances, however, were generally found to be those in which change orders were issued for missing and changed work. Accordingly, for the purposes of the present research, lack of information was considered to be an effect of change orders, as opposed to an additional cause of impact.

Generally, it was found that relations among contractors, owners and A/E's were adversely affected by change orders. Pricing of change orders, by nature, is always a potential source of disagreement between the parties. Frequent and severe disagreements were found to result in increased processing time of the change orders and generally gave rise to bad relations between the parties. Delays in processing of change orders served to magnify their impact and poor relations between the parties clearly affected communication and the flow of information necessary for contractors to maintain progress. On one project (electrical/mechanical cases Nos. 6, 7 & 8 on building Construction - Appendix A) disagreements over productivity rates for work outlined in change orders culminated in an incident whereby the contractor requested the construction manager's representative be replaced. At the request of the project manager, both the contractor and the construction manager brought in new representatives. Thus, valuable time was lost while they became familiar with the scope of the work and job conditions.

In more than 50% of the cases examined, it was evident that requesting, estimating, negotiating, and carrying out change orders required considerable effort on the part of site management. Additional personnel were employed to help with the increased workload in about 10% of such cases. In the remaining cases, the processing and administration of change orders interfered with the planning and coordination of responsibilities of contractors' site management. In particular, overloading of contractors' field engineers with extensive change order administrative duties prevented them from providing technical support to working crews which, in turn, affected crew productivity.

In approximately 15% of the cases examined, it was found that contractors were forced to produce drawing revisions themselves where the contract documents lacked sufficient details for the execution of the work. Not only did such a practice place unwarranted responsibilities on contractors in general and additional work on contractors' projects engineers in particular, but lack of engineering support also adversely affected labour productivity.

The cumulative effects of change orders on productivity were evident when the actual, earned and change order hours were plotted cumulatively. From such graphs, which were plotted for roughly 40% of the cases examined, two general trends were identified. In approximately 20% of these cases, earned and actual cumulative curves were fairly uniform but with increasing deviation. Such a trend, shown in Figure 4.7, indicates that the contractor did not carry out the work as tendered because he underestimated the scope of work and/or because the conditions and requirements turned out to be different from those originally anticipated. In the cases examined, an increasing deviation between earned and actual curves was generally found to be the result of a continuous stream of design changes, errors and omissions rather than underestimating.

In the remaining 80% of such cases, actual and earned curves were parallel for a while (usually at the beginning) indicating a period of normal, unimpacted productivity. Then, the slope of the actual curve suddenly changed with the earned curve following in a less pronounced manner, as shown in Figure 4.8. Such a change marks the start of a period of impact and decreased productivity.

This analysis identified a number of significant trends:

1 - The frequency of change orders at the beginning of the job was generally low compared to later periods;

2 - Normal, unimpacted periods were usually at the beginning of the job;

3 - The amount of change order work performed during normal periods was less than 15%;

4 - In each case, productivity decreased as percentage of change orders increased;

5 - Unlike normal projects where productivity increases due to the learning curve effect, productivity in these cases generally decreased as the job progressed;

6 - Productivity losses during impacted periods were usually greater than 25%;

7 - The time spent on carrying out changed work during impacted periods ranged from 15% to more than 100% of original contract work.

In a number of instances the need for the change was not recognized until either: 1) a short time prior to the start of the affected activity, or 2) during performance of the affected activity. Consequently, it was not possible to incorporate the changed work into the original work without delaying completion of the given activity. In the first instance, the entire activity was delayed and then performed out of sequence. In the second instance, the activity was partially completed and then finished out of sequence at a later date with additional loss of productivity due to the stop-and-go operation.

Productivity losses associated with stop-and-go operations and working out of sequence usually occur later in the job when crews return to perform the approved change order work and complete the disrupted activities. Accordingly, productivity analyses in those cases indicated higher percentages of productivity losses during later periods of the job. And, loss of productivity increased with the number of disruptions (i.e., frequency and severity of change orders).

In the cases with cumulative change orders, it was found that the work started with an incomplete and inadequate design which was corrected or 'fixed up' as the contractor progressively encountered each deficiency. In a hypothetical worst case, a contractor repeatedly performs 50% of an activity, and is then forced to move on to the next activity due to a design deficiency or a pending change order. Halfway through the job, the contractor could have performed 50% of all activities and, as such, carried out 50% of the physical progress (i.e, earned 50% of the contract hours). At that time, the job appears to be on schedule and the contractor might even be experiencing the anticipated level of productivity. However, he still has to complete the disrupted activities and the associated change order work which require remobilization, out-of-sequence work and additional contract time. Consequently, the job cannot possibly be finished on the planned completion date without acceleration which, in turn, leads to further productivity losses. Although none of the examined cases fit the above scenario exactly, it is representative of a number of them.

In approximately 15% of the cases examined, physical progress was overreported during the early stages of the job. Such overreporting was found to be the result of inaccurate progress measurements and 'front-end loading' by contractors to increase the value of initial progress payments. As a consequence of this overreporting, the work remaining for completion would have been understated and productivity achieved by contractors in the early stages of the job would have been overstated.

If the job was originally underestimated by the contractor, such overreporting generally resulted in acceleration and/or late project completion. Because contractors usually employ manpower according to their original estimate, underestimated jobs were undermanned during early stages resulting in less than planned progress. Due to overreporting of progress in the early stages, such undermanning and lack of progress was not recognized until it was too late to bring the project back on schedule without some form of acceleration. In such cases acceleration combined with the impact of the change orders resulted in substantial productivity losses and additional financial burden during later stages of the job that was in excess of the amount of underestimating. In at least three of the cases examined, the financial burden of the impact costs combined with that of the underestimating was enough to force the contractor into bankruptcy or prevent him from completing the job. Clearly, such situations are not in the best interests of either contractors or owners.

In Case #19 of the civil/architectural contracts (Appendix C), productivity of successive operations was affected by design changes and by variations in actual quantities. The number of tradesmen per crew and the number of crews assigned to each activity depends upon: 1) crew productivity, 2) quantity of work, and 3) required rate of progress of other operations. Consequently, proper scheduling and resource allocation are necessary to ensure a continuous and balanced flow of operations. As such, changes in design and quantity variations were found to upset the smooth flow of operations resulting in idle time, stop-and-go operations, and slowdowns in the rate of progress of successive operations.

4.4 FACTORS INFLUENCING THE EFFECTS OF CHANGE ORDERS ON PRODUCTIVITY

The effect of individual change orders was generally found to depend on the timing of the instruction to proceed in relation to the planned start of the affected activity. As shown in Figure 4.9, instructions to proceed (or approvals) were issued at four different times in relation to the planned start of the affected activity. In Case A, the change order was issued and approved in advance of the planned start allowing the contractor time to plan for the changed or additional work and to procure the required additional material. In such an instance, completion of the affected activity was probably delayed by the additional time required to carry out the change order work. In Case B, the change notice was issued, but work not authorized prior to the scheduled start of the affected activity. Consequently, start of the activity was delayed. In Case C, the change was ordered during performance of the affected activity resulting in disruption of the work and delay in its completion. In Case D, the change order was issued following completion of the affected activity necessitating additional work or rework. In Cases B, C and D, subsequent activities were often delayed, disrupted or performed out of sequence.

Timing of the instruction to proceed, in turn, was generally found to be related to the origin of the change order and its processing time. It is generally recognized that change orders usually originate from: 1) design errors and omissions, and 2) owner and A/E requests for changes to the original design. In the cases examined, change orders for design errors and omissions were initiated by A/E's during finalization and review of the design and, more commonly, by contractors during takeoff of material quantities, planning, and layout of the work and performance of the affected work. Changes requested by owners and A/E's were generally issued throughout the job, although owner changes often originated once the related work was completed.

In the cases examined, procedures for processing change orders varied from one project to another. However, processing time was generally found to include: 1) preparation and issuance of contemplated change notices and revised drawings by A/E, 2) preparation and submission of quotation by contractor, and 3) evaluation and approval of contractor's quotation by owner and/or A/E. In some cases, processing times of change orders and, thus, their effects on productivity were minimized by issuing verbal instructions to proceed with the work outlined in the change notice prior to finalization of pricing. In such instances, change order work was reimbursed either on a cost-plus basis or according to lump sum and unit prices agreed upon at a later date.

Other factors which the present research identifies as influencing the effect of change orders on productivity include:

- complexity of work;
- interdependencies among activities;
- intensity of work (i.e., tightness of schedule);

- frequency and severity of design errors and omissions;

- response time of A/E's to contractors' requests for clarifications and instructions;

- management practices of contractors including use and updating of schedules, ability to coordinate and integrate change order work into contract work, procedures adopted to motivate the work force, and cost and progress control procedures;

- relations and communication between the various parties; and

- inspection and supervision by A/E's.

The frequency in which such factors negatively influenced the effects of change orders on productivity in the 90 cases examined is shown in Figure 4.10.

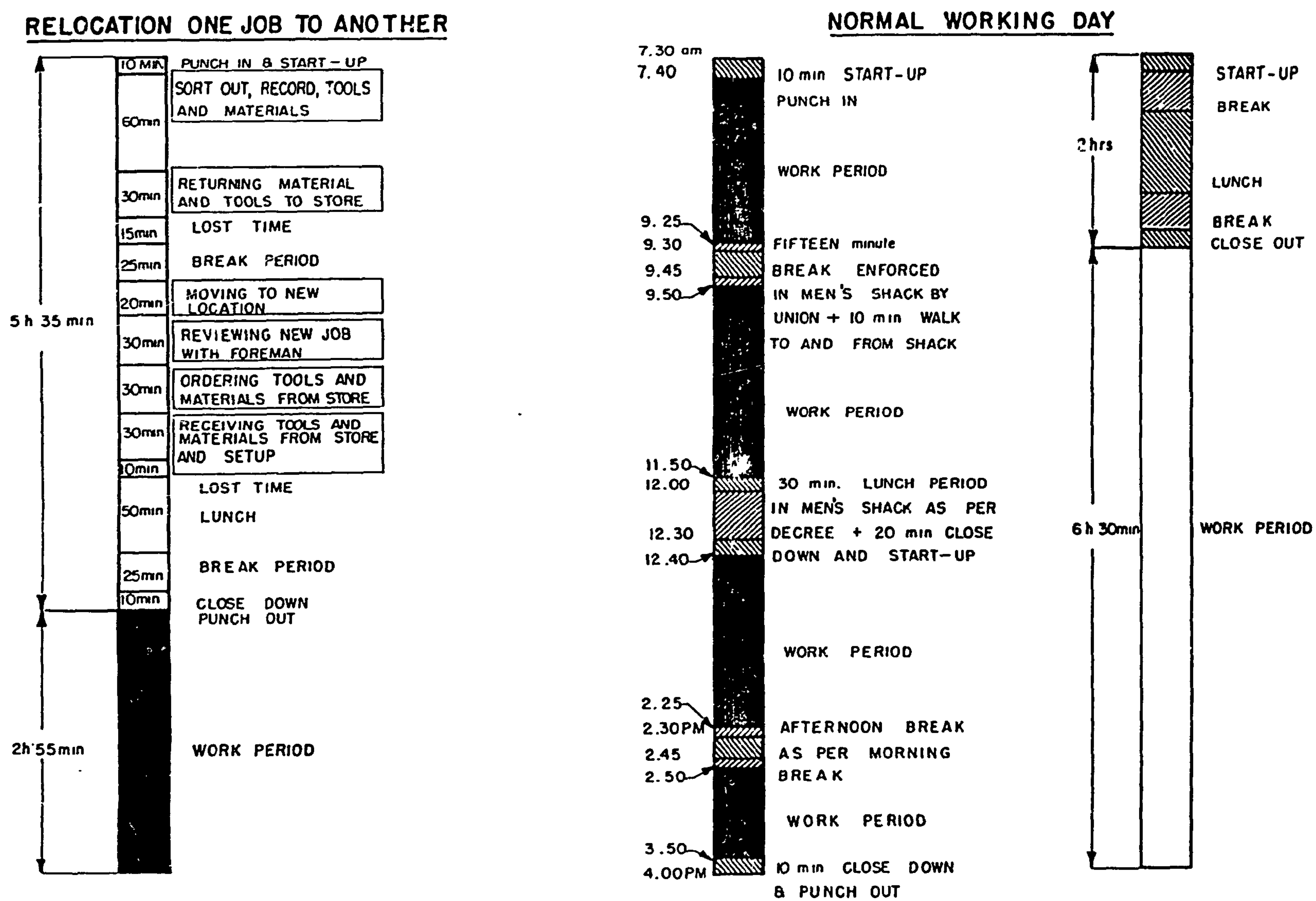


FIGURE 4.1 - COMPARISON OF PRODUCTIVE TIME ON NORMAL VS. DISRUPTED WORKING DAY

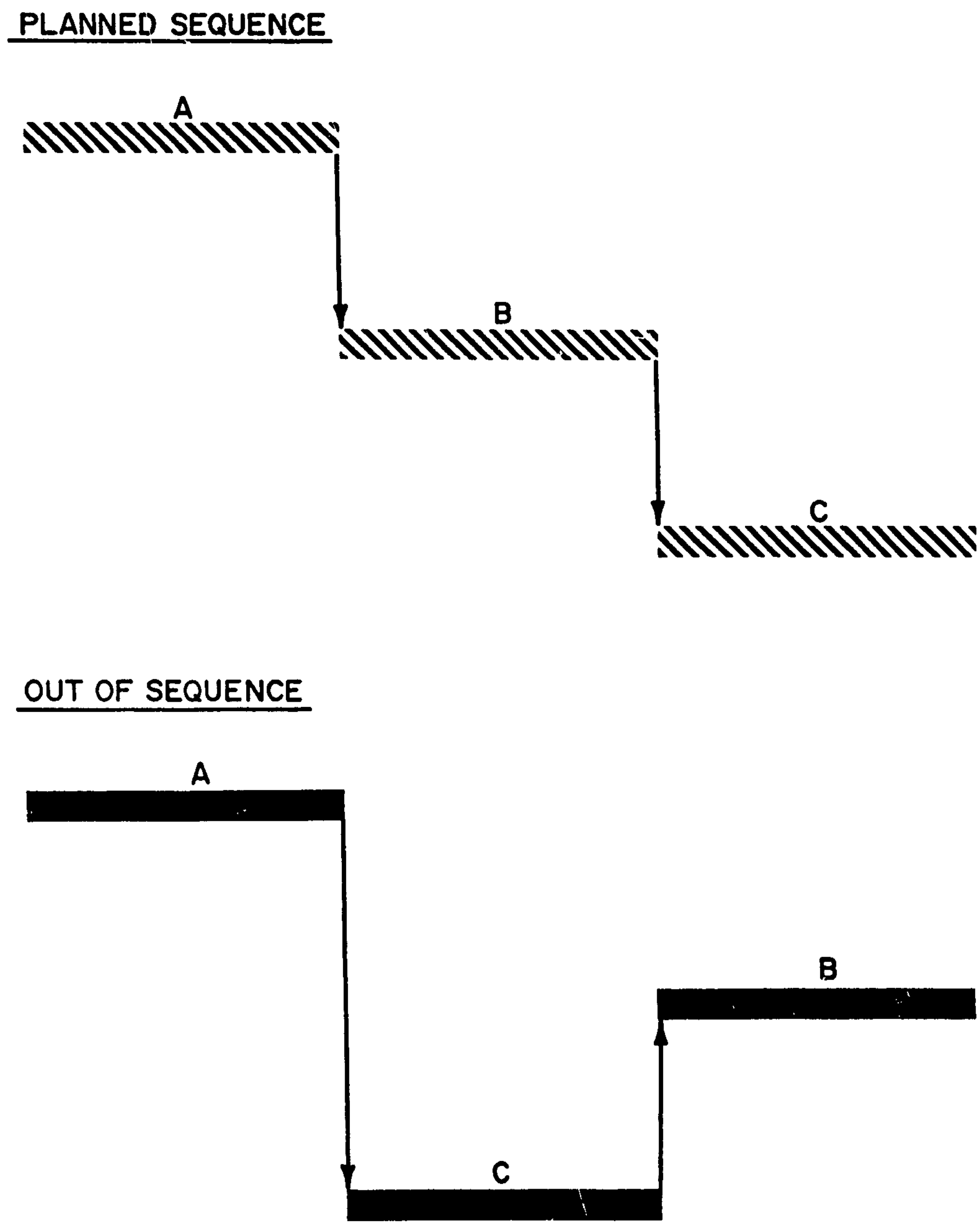


FIGURE 4.2 - OUT-OF-SEQUENCE WORK

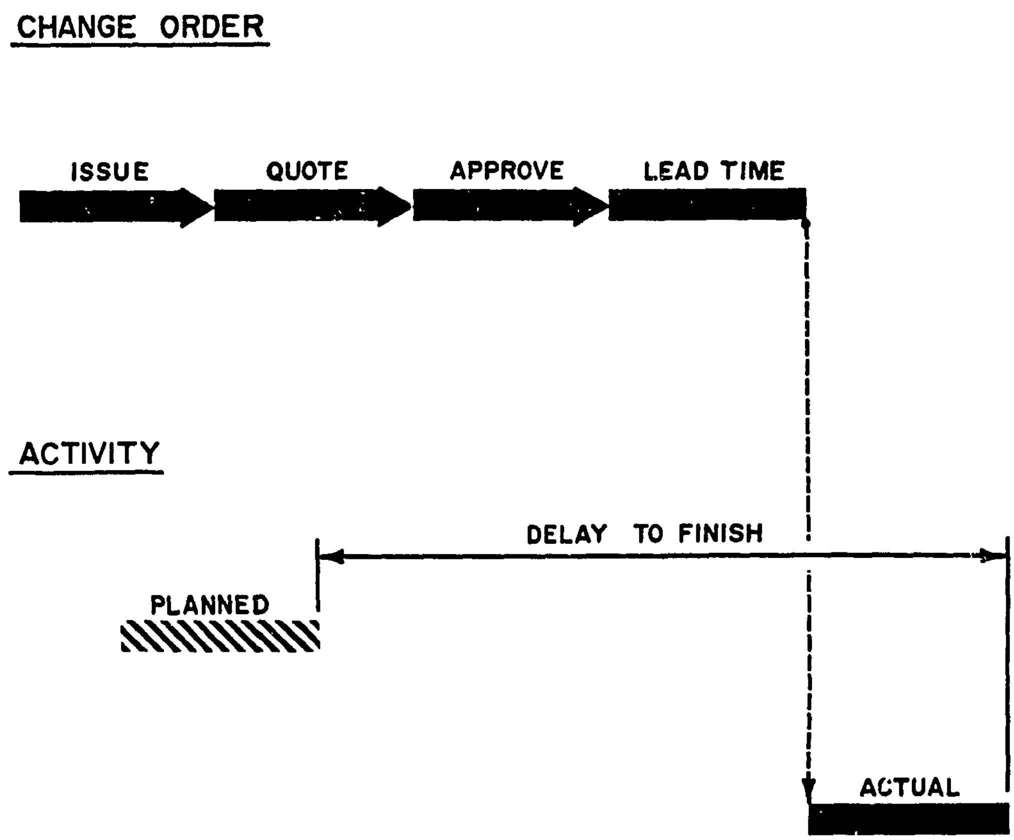


FIGURE 4.3 - DELAYS CAUSED BY CHANGE ORDERS

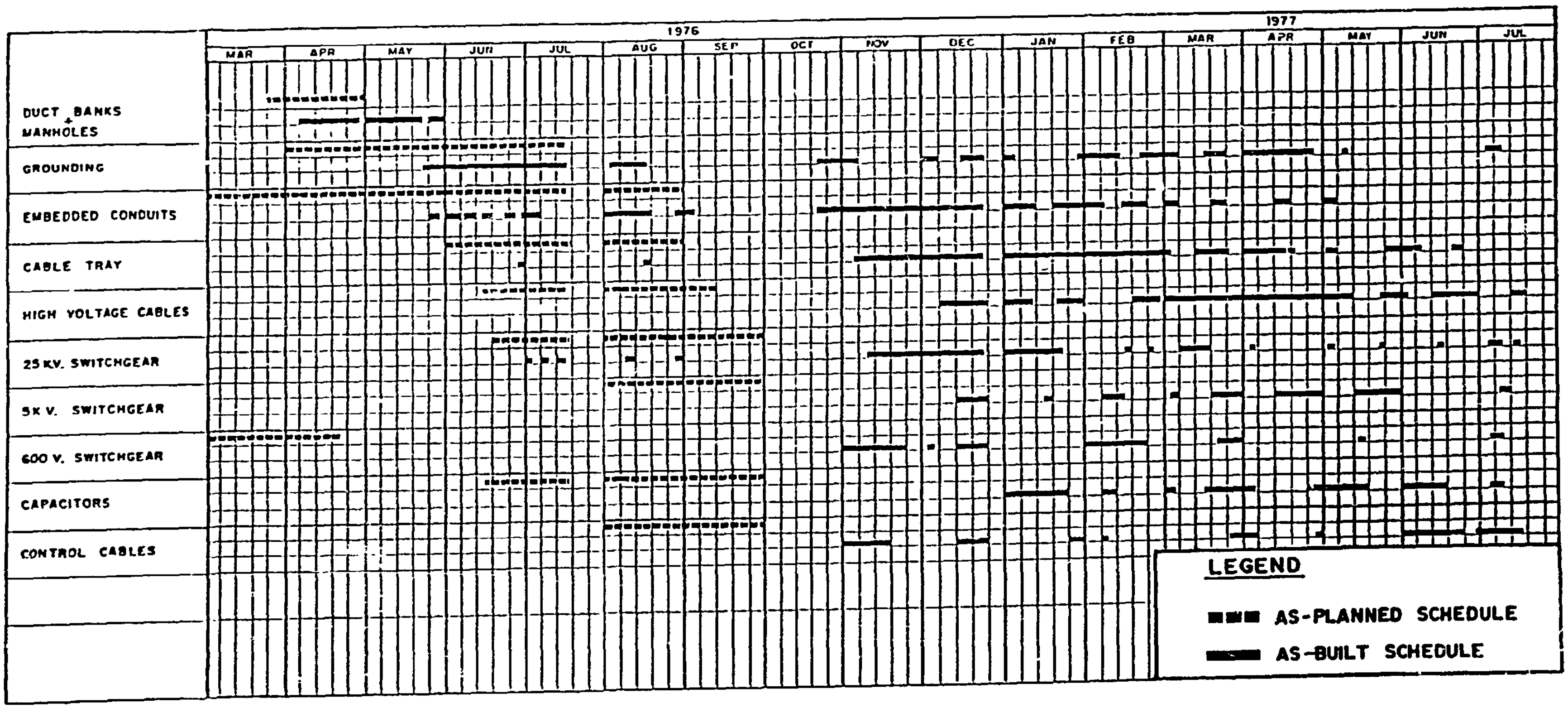


FIGURE 4.4 - AS-PLANNED VS. AS-BUILT SCHEDULE COMPARSION (CASE #8 - APPENDIX A)

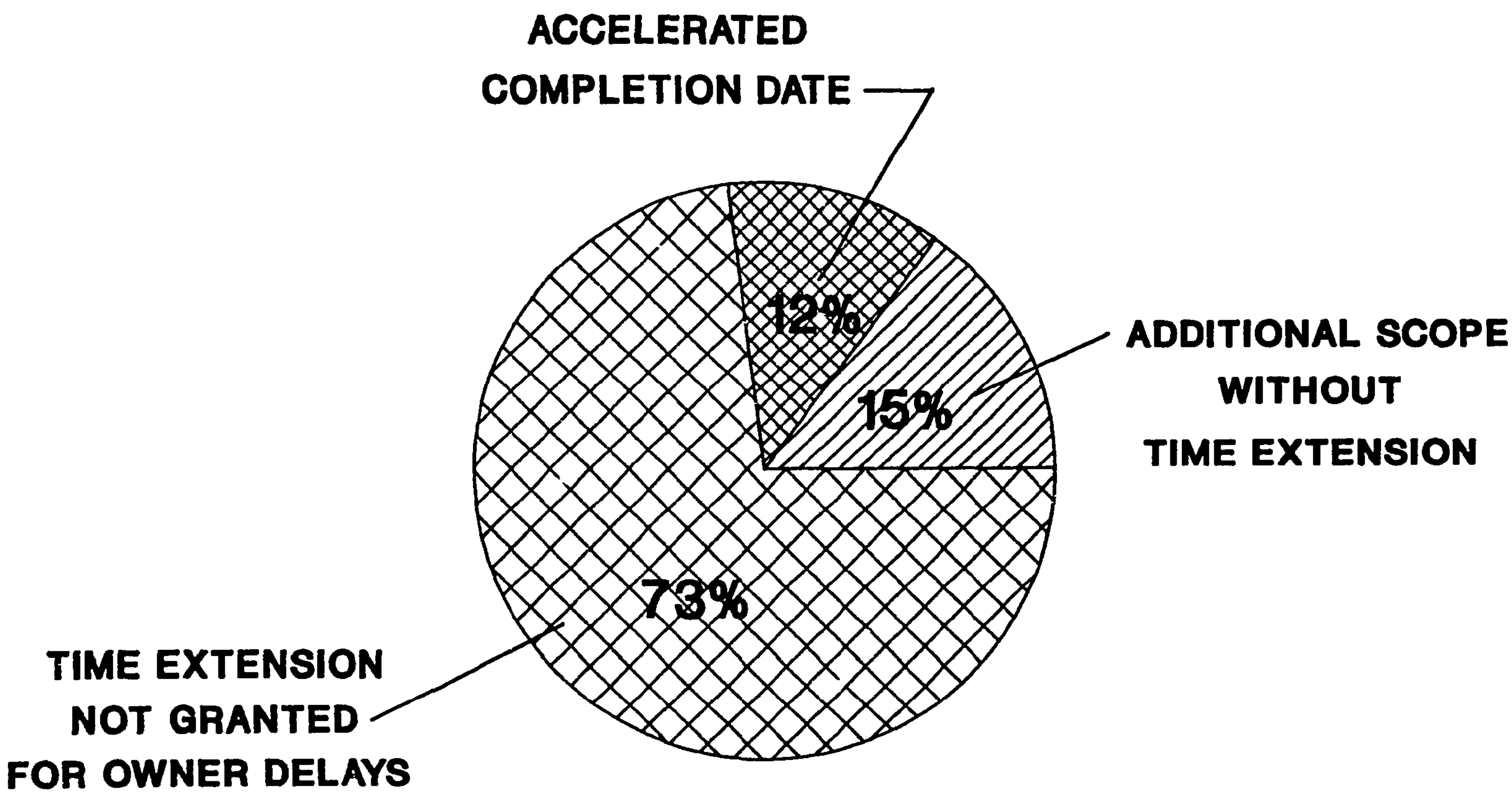


FIGURE 4.5 - BREAKDOWN OF CAUSES OF ACCELERATION

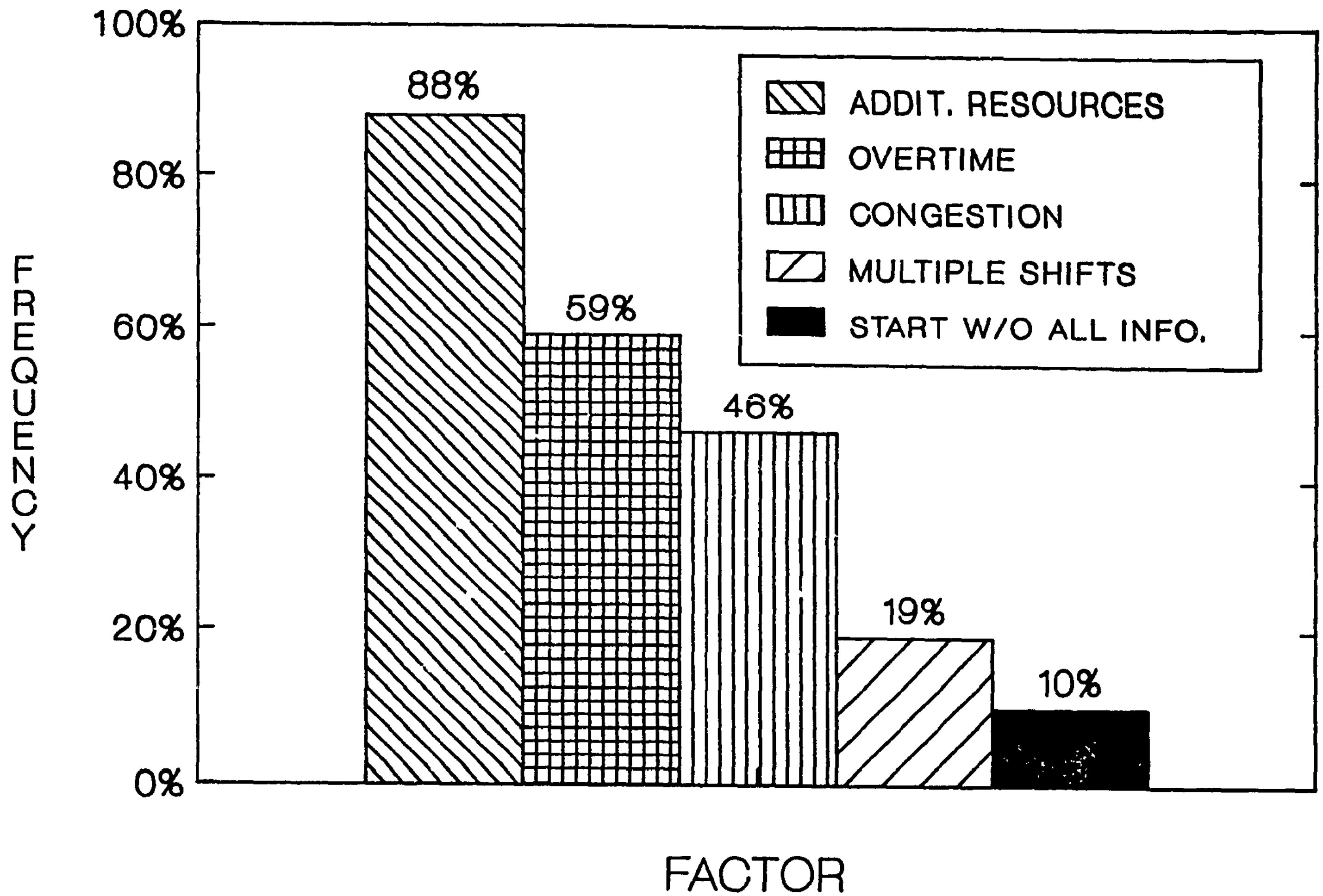


FIGURE 4.6 - FORMS OF ACCELERATION

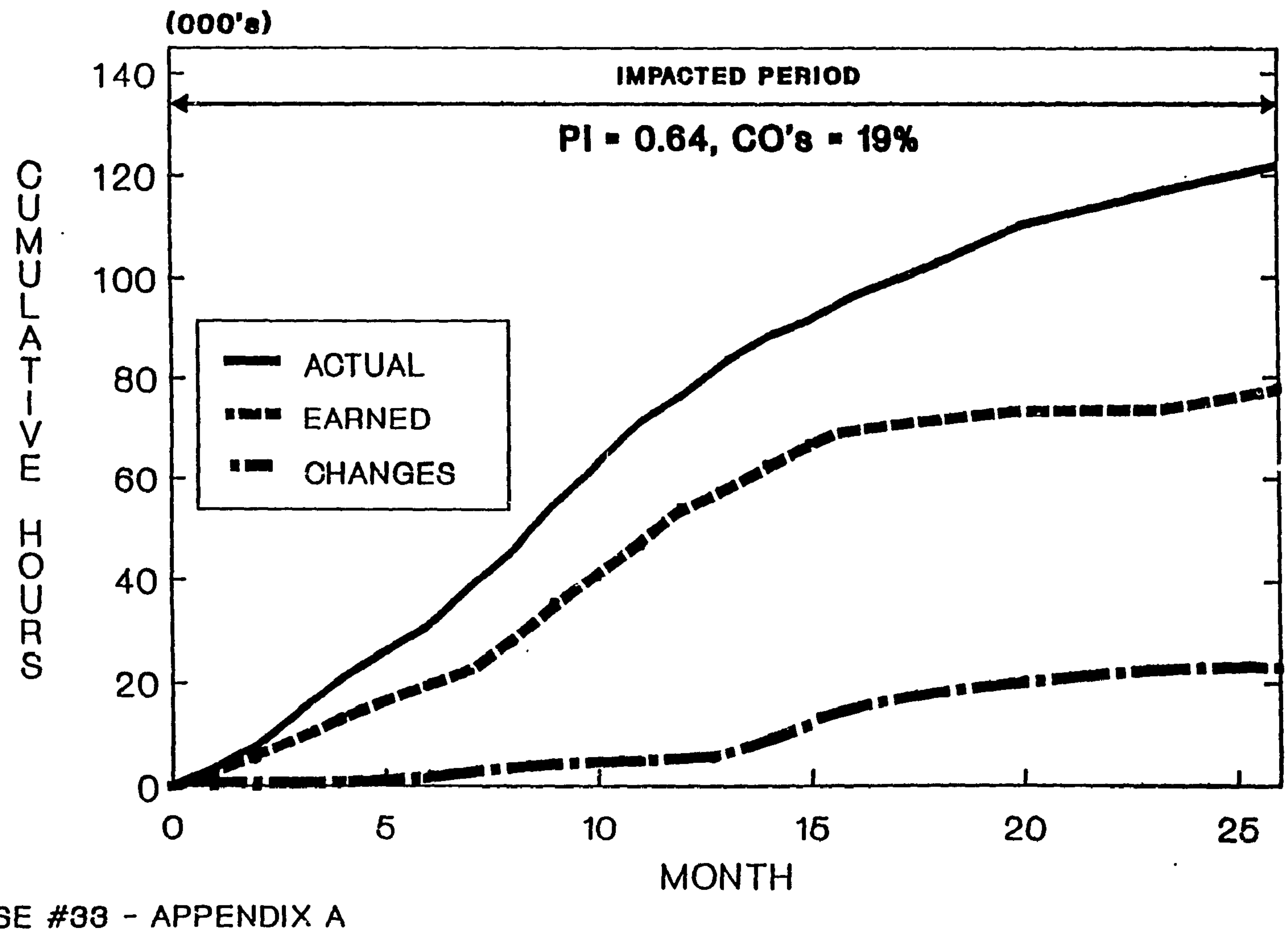
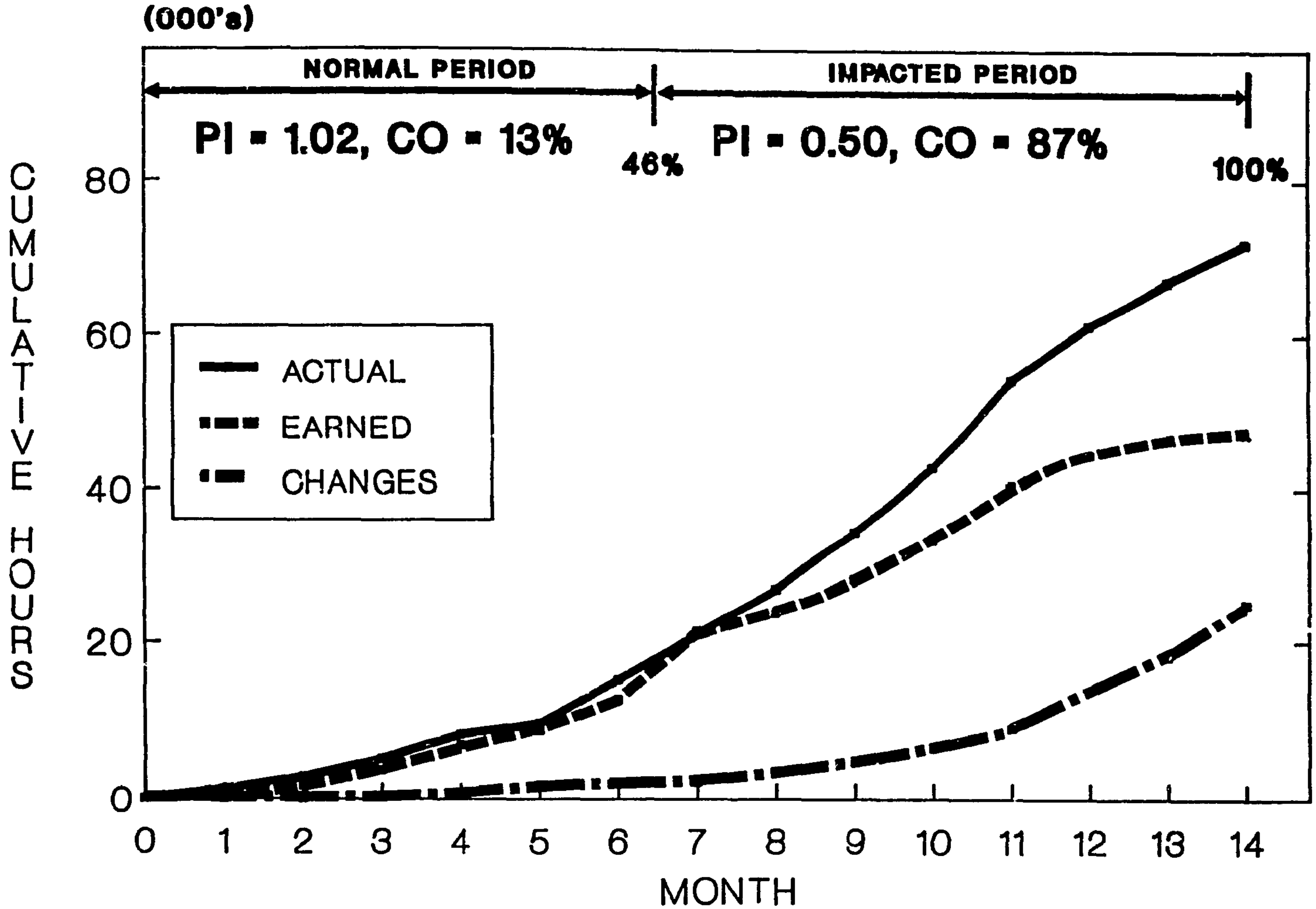


FIGURE 4.7 - CUMULATIVE EARNED VS. ACTUAL LABOUR-HOURS:
NO NORMAL PERIOD



CASE #5 - APPENDIX B

FIGURE 4.8 - CUMULATIVE EARNED VS. ACTUAL LABOUR-HOURS: NORMAL PERIOD

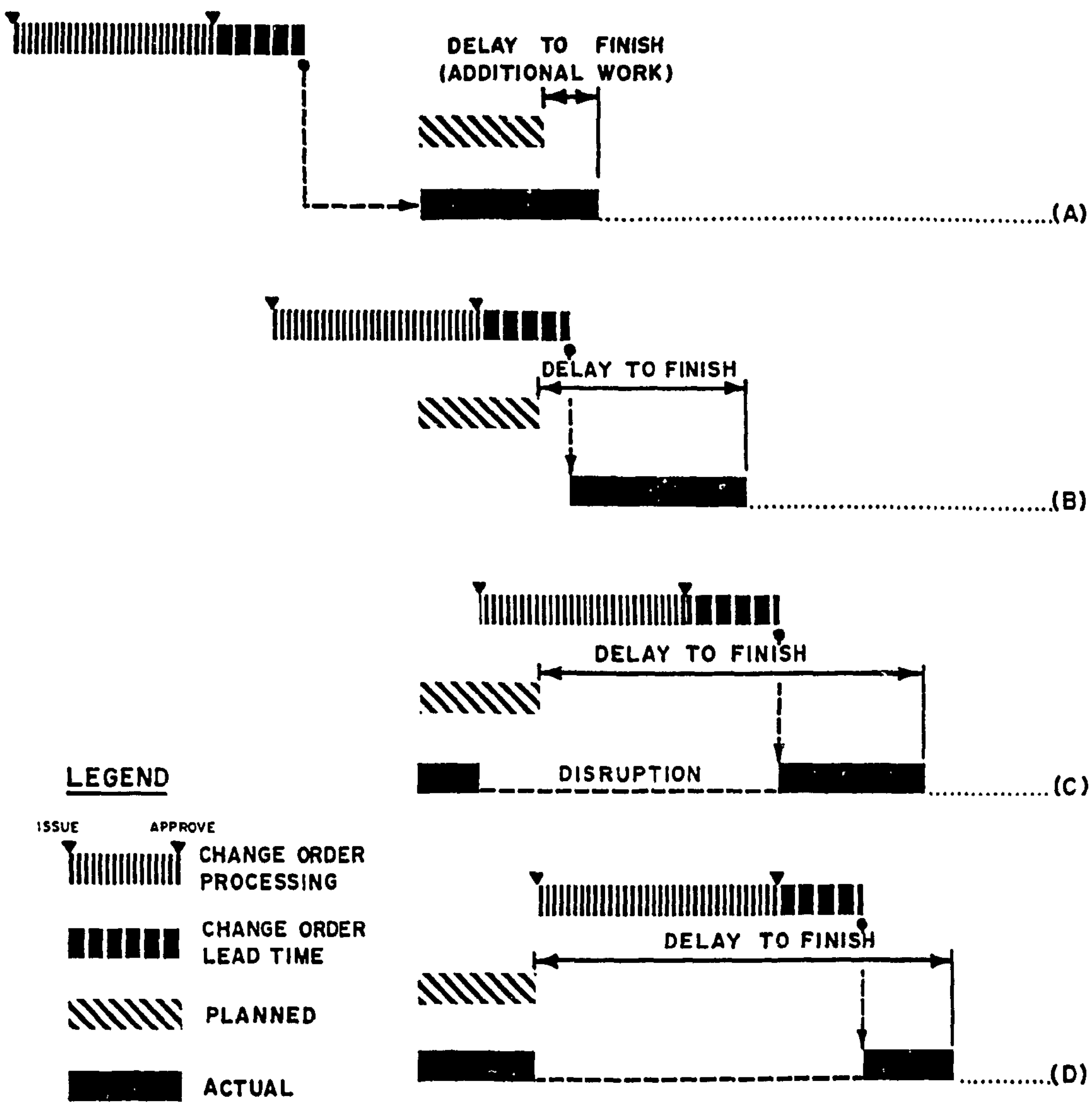


FIGURE 4.9 - TIMING OF INSTRUCTION TO PROCEED IN RELATION TO START OF AFFECTED ACTIVITY

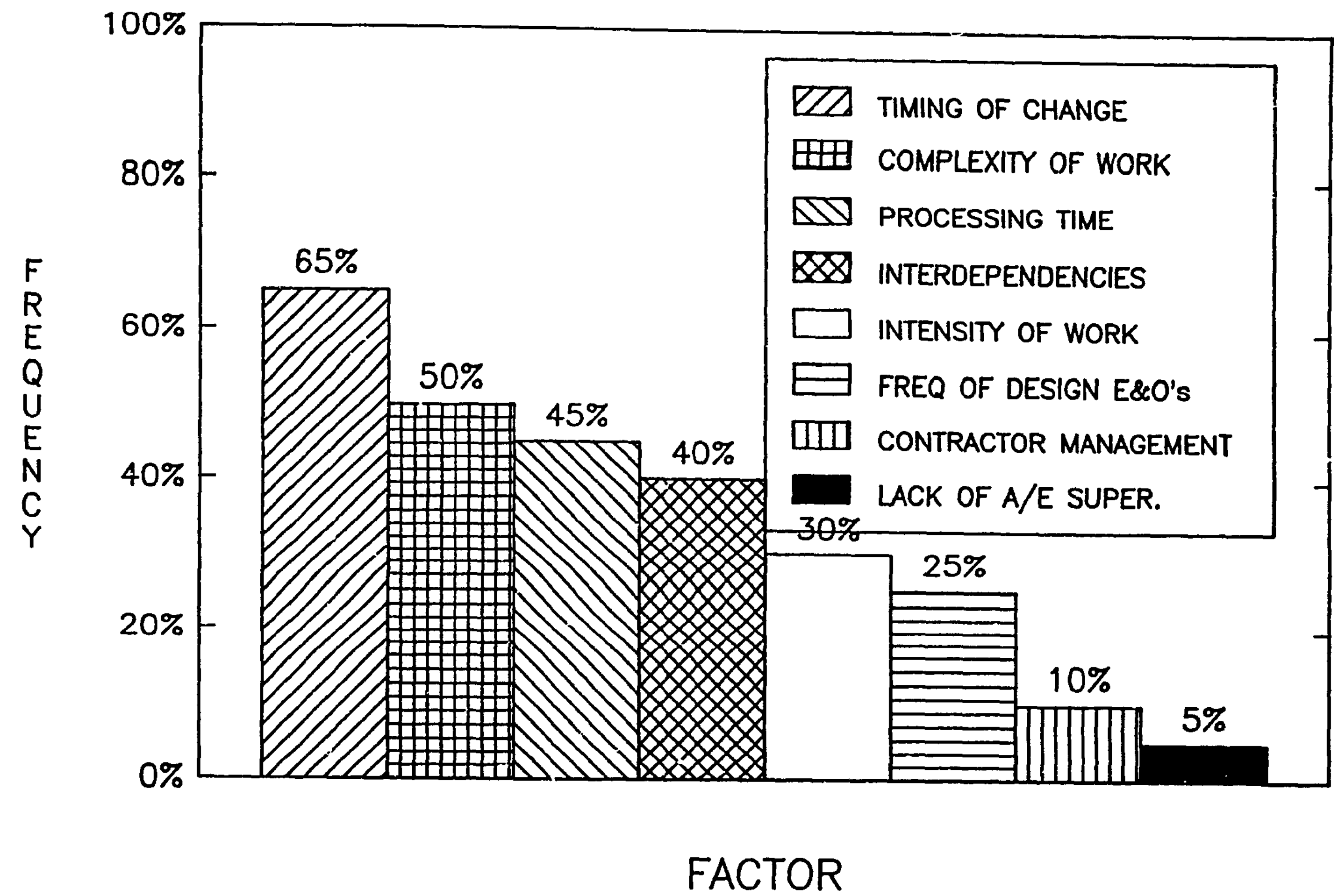


FIGURE 4.10 - FACTORS NEGATIVELY INFLUENCING CHANGE ORDER IMPACT

CHAPTER V

QUANTITATIVE RESULTS OF FIELD INVESTIGATION

5.1 STATISTICAL ANALYSIS

To develop the correlation between change orders and loss of productivity, statistical analysis was performed on data from the 90 cases examined in the present study. The method of least squares or regression analysis [90,91] was used to examine dependency of productivity loss on change orders. A commercially available software package "Statgraphics" [92] was employed to carry out the regression analysis.

As explained in Chapter III, change orders were quantified according to three measurements: 1) frequency, 2) average size, and 3) percentage. To identify which of these measures, if any, correlate with loss of productivity, a linear regression analysis was performed for percentage loss of productivity (i.e., unproductive labour-hours due to cause of impact under examination expressed as a percentage of labour-hours spent on original contract work) on each measure. The resulting coefficients of correlation are shown in Table 5.1 for each category.

In particular, Type 1 cases in each category yielded a high correlation between percentage change orders (i.e., labour-hours spent carrying out changed work expressed as a percentage of labour-hours spent on original contract work) and percentage loss of productivity. In fact, percentage change orders yielded consistently positive correlations for Type 2 and Type 3 cases also, while these results varied considerably (i.e., from -0.79 to +0.93) for average size and frequency of change orders. As shown in Table 5.1 the weighted average coefficients of correlation for percentage change orders was more than triple those for average size and frequency. Accordingly, subsequent analyses concentrated on examining relationships between percentage change orders and percentage loss of productivity.

Prior to conducting further analyses, residuals of the linear regressions of percentage loss of productivity on percentage change orders were reviewed to identify outliers (i.e., points which lie more than three or four standard deviations from the mean of the residuals). In the data from the 90 cases examined, a number of outliers were identified which were not consistent with the rest of the data. Upon careful examination of the circumstances surrounding the corresponding cases, three outliers were rejected. Case #14 of electrical/mechanical contracts on building construction (Appendix A), which displayed a high loss of productivity for the level of change orders, was rejected because inadequate coordination and scheduling appeared to have resulted in an unusually large loss of productivity and the percentage of change orders was less than 1%.

Case #21 of electrical/mechanical contracts on industrial construction (Appendix B), which experienced a relatively low loss of productivity, was rejected because the nature of the work differed substantially from others in the same category. Case #20 of civil/architectural contracts (Appendix C), which experienced a relatively high loss of productivity, was rejected because the contractor's estimate could not be substantiated and the causes of impact could not be accurately assessed due to insufficient information on the project history.

Following the rejection of outliers, linear and non-linear regression analyses were performed for the eight categories. The results, summarized in Table 5.2, indicated that relationships between change orders and loss of productivity are best described by linear models. Coefficients of correlation were found to be greater for linear than non-linear regression for Type 1 and Type 2 cases of electrical/ mechanical contracts on both building and industrial construction and Type 2 cases of civil/architectural contracts. For Type 3 cases of electrical/mechanical contracts on both building and industrial construction and Type 1 cases of civil/architectural contracts, nonlinear coefficients were found to be greater than or equal to those of linear regression. For these categories, however, differences between the linear and nonlinear coefficients of correlation were less than 3%, and there were significantly fewer observations. The difference in predicted loss of productivity between the linear and nonlinear models of these categories was less than 4% for values of change orders up to 50%.

As shown in Table 5.2, regression coefficients of Type 1 and Type 2 cases for electrical/mechanical contracts on building construction are similar to those of the corresponding categories on industrial construction. Therefore, linear regression analysis was performed for Type 1, Type 2, and Type 3 cases of electrical/mechanical contracts on building and industrial construction combined, the results of which are summarized in Table 5.3.

5.2 DISCUSSION OF RESULTS

As mentioned in the previous section, labour-hours spent on carrying out changed work expressed as a percentage of the labour-hours spent on the original contract work were found to have the highest correlation with loss of productivity among the various change order measurements examined. As shown in Table 5.1, values of correlation coefficients for percentage change orders obtained by linear regression analyses ranged from +0.15 to +0.90 with a weighted average of +0.60. A direct correlation was expected between these variables as increases in the amount of change orders would generally increase the extent of delays and frequency of disruptions which, in turn, would decrease productivity.

Because the number of unproductive labour-hours depends on the extent of delays and frequency of disruptions, it was expected that loss of productivity would also vary directly in relation to the number of change orders. Accordingly, frequency of change orders was expected to correlate positively with loss of productivity. However, values of correlation coefficients obtained from linear regressions of percentage loss of productivity on frequency of change orders ranged from -0.57 to +0.93 with a weighted average of +0.13. Such a wide range of values and the relatively low weighted average indicated no general correlation between these two variables. Therefore, the number of change orders issued is not an accurate indication of the number of delays and disruptions, partially because single change notices often contain more than one design change.

Similarly, values of correlation coefficients for average size of change orders ranged from -0.79 to +0.60 with a weighted average of +0.18, indicating no general correlation between the two variables. Such results were expected as average size of change orders would not be representative of either the significance or frequency of change orders (i.e., two change orders with an average size of five labour-hours would not be expected to have similar effects on productivity as two hundred change orders of the same average size).

In comparing results of the linear and nonlinear regression analyses, it was found that linear models best describe relationships between percentage change orders and percentage loss of productivity. Although there are no similar studies to enable direct comparison with the findings of the present study, various impact-related studies conducted by others [18,20,22,23,24] have found linear and near-linear relationships.

The U.S. Army Corps of Engineers [23] has reported linear relationships for the effects of overmanning and congestion of trades (for levels greater than 10%) on productivity. Similarly, research by Kappaz [24] has revealed a straight-line relationship between density of average work force and productivity, with a coefficient of correlation of 0.81, and Foster Wheeler's research [22] has revealed a near-linear relationship for overmanning of 100 men at levels above 10%. A number of studies [18,20] have found near-linear relationships between scheduled overtime and loss of productivity. Thus, a linear relationship between change orders and productivity is compatible with those of other causes of productivity loss.

High percentages of change orders, however, could be seen to have a compound effect on productivity and, as such, result in nonlinear relationships. Nonlinear trends may indeed apply to percentages of change orders greater than those examined in the present research (i.e., greater than 50% - 60%).

For practical purposes, the results of linear regressions of both Type 1 and Type 2 cases of electrical/ mechancial contracts on building construction were equal to those of industrial construction. For example, at 40% change orders there is no difference in predicted loss of productivity between the combined results and those of each individual category for Type 1 cases. The difference for Type 2 cases at this percentage change orders is only 3% for building construction and 1% for industrial construction.

Unlike Type 1 and Type 2 cases, results of the relatively small sample of Type 3 cases of electrical/ mechanical contracts differ substantially from building to industrial construction. However, to increase the sample size and hence the accuracy of the results, data for these two types of construction has been combined similarly to what was done for Type 1 and Type 2 cases of electrical/ mechanical contracts.

Results of linear regression analysis for electrical/mechanical contracts on building and industrial construction combined are depicted graphically in Figures 5.1 to 5.3. Results of the analysis for civil/architectural contracts on building and industrial construction combined are presented in Figures 5.4 and 5.5.

As shown in Figures 5.1 and 5.4, coefficients of correlation between percentage change orders and percentage loss of productivity for Type 1 cases of electrical/mechanical contracts and of civil/architectural contracts were 0.88 and 0.82, respectively. Considering the nature of these variables and the sample sizes, such coefficients indicate significant correlation. In both instances, the standard error of estimate was less than 4%.

As expected, coefficients of correlation for Type 2 and Type 3 cases were lower than those for Type 1 cases due to the varying effects that additional causes of impact have on productivity. As shown in Figures 5.2 and 5.5, Type 2 cases of electrical/mechanical contracts and civil/architectural contracts yielded coefficients of correlation of 0.76 and 0.74, respectively, indicating a relatively strong correlation. Type 3 cases of electrical/mechanical contracts yielded a relatively weak correlation of 0.34, however, the regression line does follow the trend depicted in Type 1 and Type 2 cases. By definition, standard errors of estimates for Type 2 and Type 3 cases increased as coefficients of correlation decreased, although such errors were less than 6%.

In Figures 5.1 to 5.5 inclusive, 95% confidence intervals (shown by the inner dotted lines) and 95% prediction limits (indicated by the outer dotted lines) are shown for the regression analysis. Confidence intervals relate to standard estimates of error and, as such, to the variance in the observed data. Prediction limits define the limits in which future observations are expected to lie and are related to the scatter of the observed data. Due to a relatively strong correlation and low standard estimates of error in the present data, the confidence intervals are relatively narrow. The wider prediction limits (i.e., up to 10% for Type 1 and Type 2 cases) indicate that change orders have somewhat varying effects on productivity and, as such, no one curve could take into account the particular circumstances of all projects.

Due to the nature of linear regression analysis, the regression lines for Type 1 cases did not pass through the origin of the x-y axis. In reality, loss of productivity for Type 1 cases equals zero when percentage change orders equals zero. As mentioned in Chapter IV, change orders were generally found to have a cumulative effect on productivity when their labour-hours exceeded 10% of the earned (or normal) contract hours, which corresponds to the level that contractors generally maintain they can accommodate without affecting their work. Below such a level, loss of productivity depends entirely on the particular circumstances of the individual change, and any additional causes of impact.

Therefore, the statistical models developed in the present research should only be used to predict loss of productivity when change order hours exceed 10% of earned contract hours. As shown in Table 5.4, exclusion of those cases in which change order hours amounted to less than 10% of the earned contract hours, for practical purposes, does not change the results of the regression analyses.

For the above-mentioned reasons, no attempt has been made to fit the models to levels of change orders below 10% (of earned hours). Such models, however, would likely follow one of the two trends shown in Figure 5.6.

As shown in Figures 5.7 and 5.8, additional major causes of productivity-related impact were found, as expected, to have a cumulative negative effect on productivity. As shown in Figure 5.7, loss of productivity on electrical/mechanical contracts was increased between 14% (at 10% change orders) and 11% (at 60% change orders) by one additional major cause and between 24% (at 10% change orders) and 20% (at 60% change orders) by two additional major causes. For civil/architectural contracts, one additional major cause increased loss of productivity by a constant 8% over the range of change orders examined, as shown in Figure 5.8. Based on extrapolation, two additional major causes would be expected to increase loss of productivity by 14%.

These results, however, do not imply that the effect of additional major causes decreases or remains constant as the level of change orders increases. In fact, the productivity losses of such causes, when measured with respect to productive labour-hours, increase with the level of change orders, due to the combined effect that changes and additional major causes have on productivity.

Measured against the productive labour-hours, loss of productivity due to one additional major cause increased from 14% (at 10% change orders) to 17% (at 60% change orders) on electrical/mechanical contracts, as shown in Figure 5.9. Similarly, loss of productivity due to two additional major causes increased from 27% to 31%, as shown in Figure 5.10. For civil/architectural contracts, loss of productivity measured with respect to the productive hours increased from 9% (at 10% change orders) to 11% (at 60% change orders) due to one additional major cause and from 16% to 19% due to two additional major causes, as shown in Figures 5.11 and 5.12 respectively.

As expected, results of the regression analyses differed between the two types of work examined because of differences in the level of skill required to perform the work and in the complexity of the work. As shown in Figure

5.13, loss of productivity for Type 1 cases was greater on electrical/mechanical work (i.e., fine motor skills) than on civil/architectural work (i.e., gross motor skills) increasing to a difference of 10% at 60% change orders. As shown in Figure 5.14, loss of productivity was greater for Type 2 cases of electrical/mechanical contracts by 6% at 8% change orders, increasing to a difference of 13% at 60% change orders. For Type 3 cases, loss of productivity, would be expected to be 10% greater for electrical/ mechanical contracts at 8% change orders and 16% greater at 60% change orders, as shown in Figure 5.15.

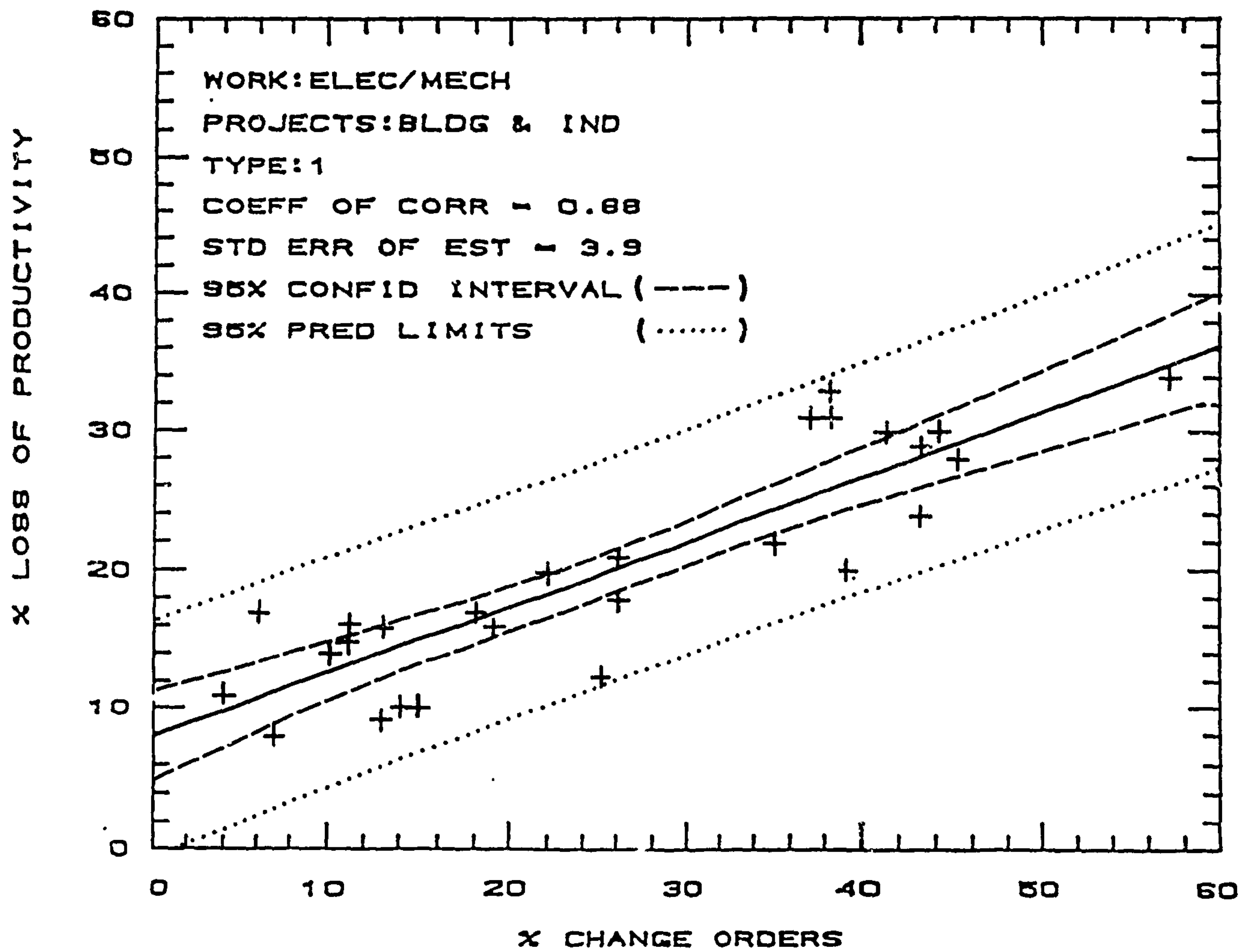


FIGURE 5.1 - CHANGE ORDERS VS. LOSS OF PRODUCTIVITY:
ELECTRICAL/MECHANICAL CONTRACTS - TYPE 1

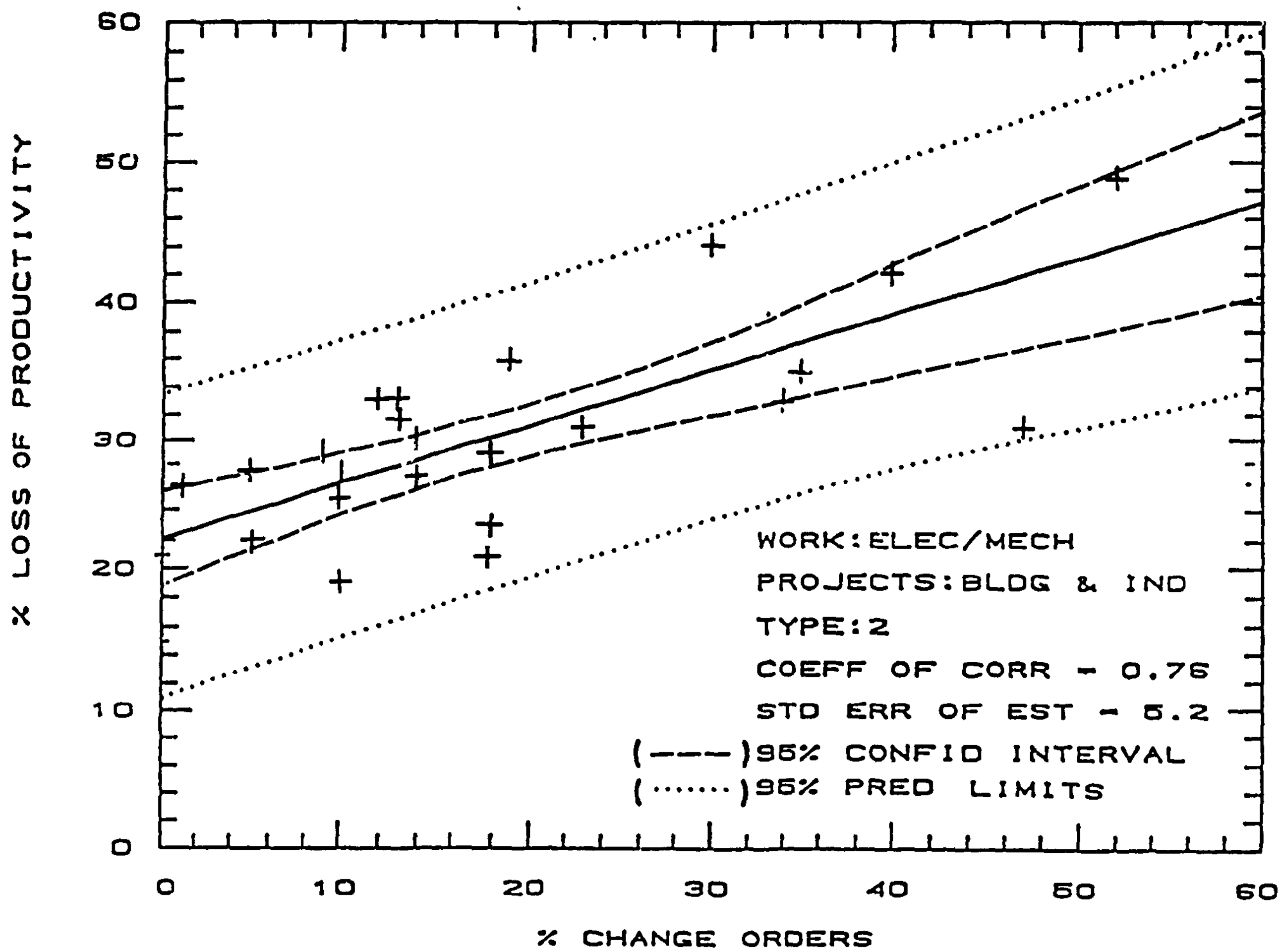


FIGURE 5.2 - CHANGE ORDERS VS. LOSS OF PRODUCTIVITY:

ELECTRICAL/MECHANICAL CONTRACTS - TYPE 2

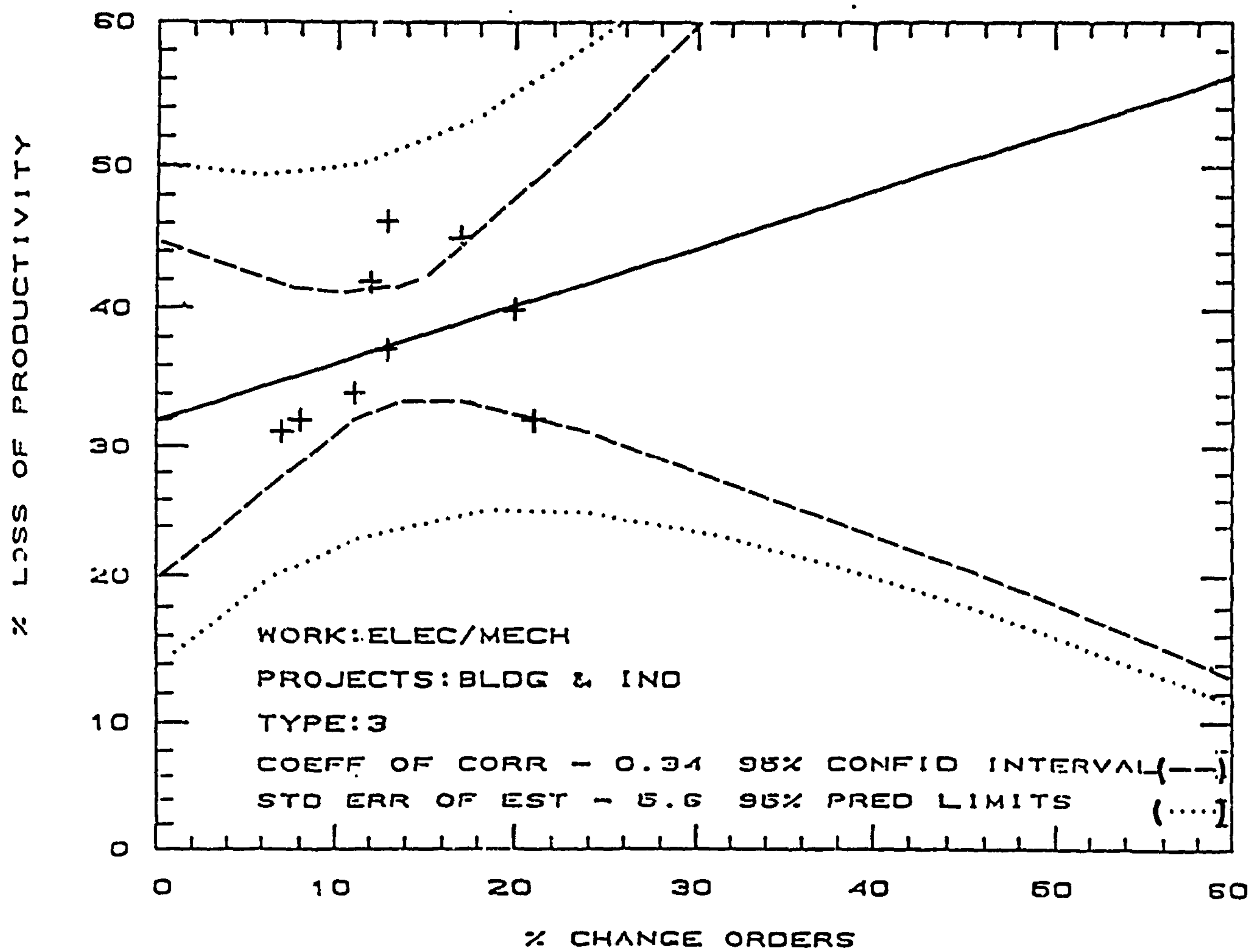


FIGURE 5.3 - CHANGE ORDERS VS. LOSS OF PRODUCTIVITY:

ELECTRICAL/MECHANICAL CONTRACTS - TYPE 3

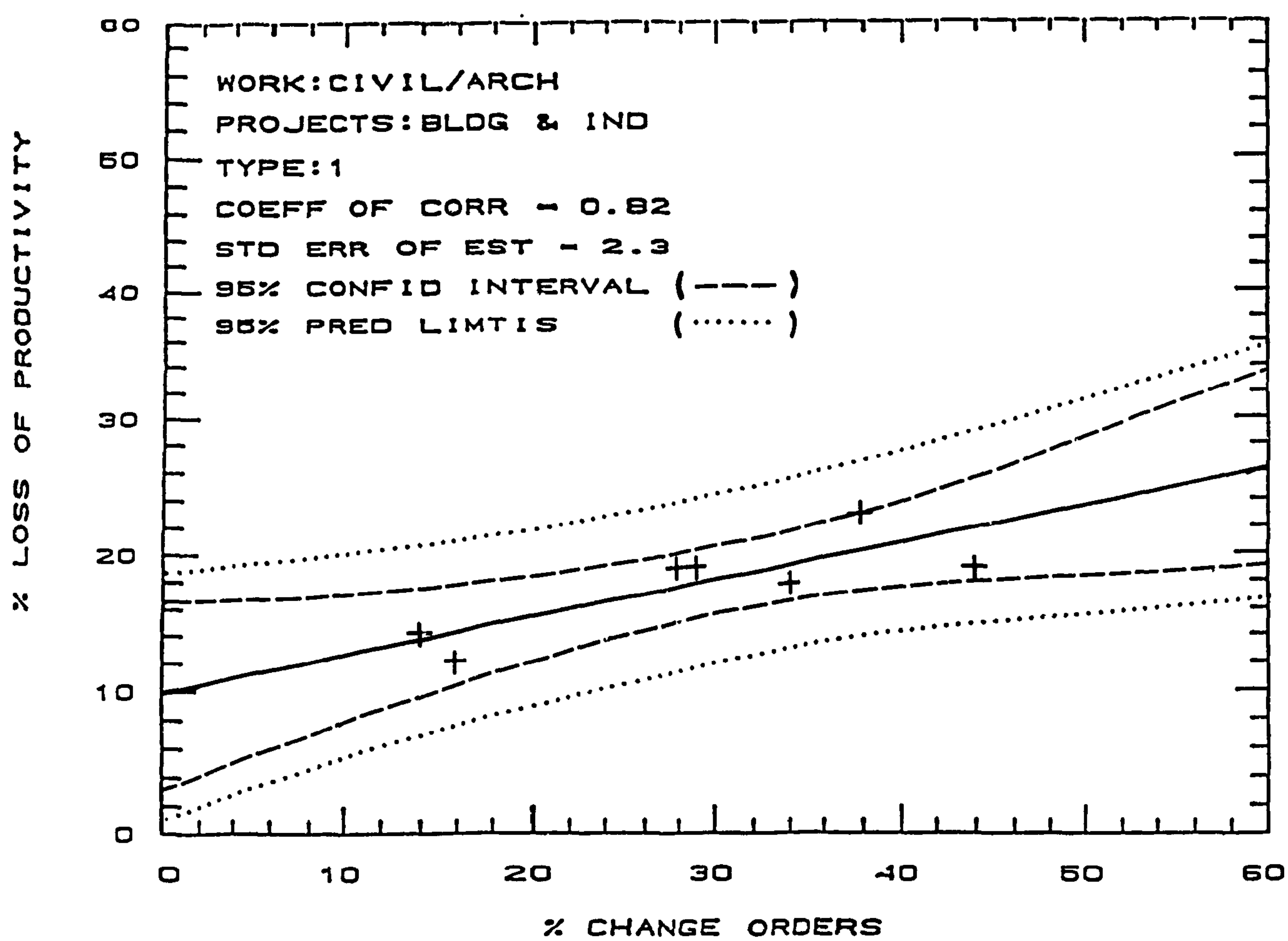


FIGURE 5.4 - CHANGE ORDERS VS. LOSS OF PRODUCTIVITY:
CIVIL/ARCHITECTURAL CONTRACTS - TYPE 1

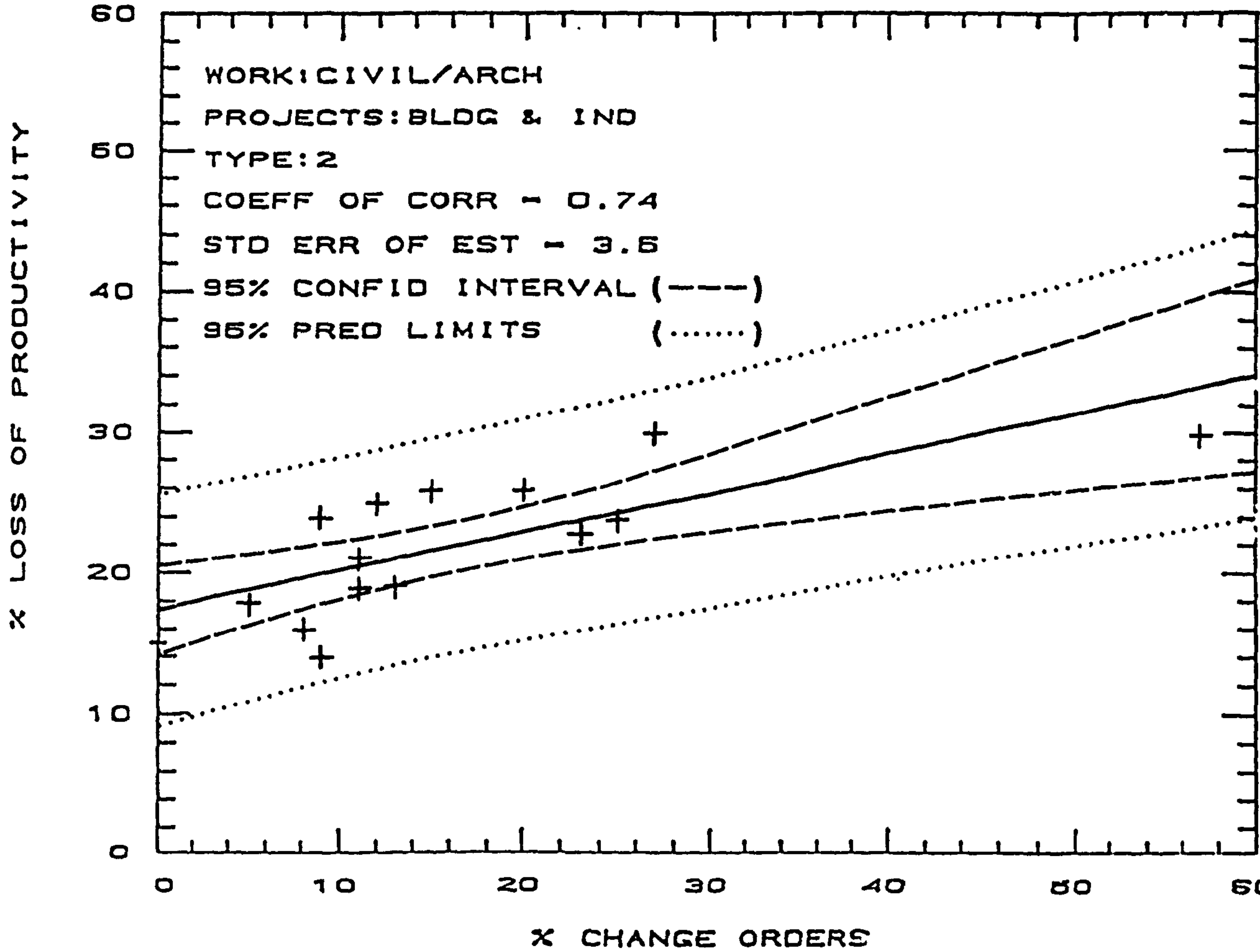


FIGURE 5.5 - CHANGE ORDERS VS. LOSS OF PRODUCTIVITY:
CIVIL/ARCHITECTURAL CONTRACTS - TYPE 2

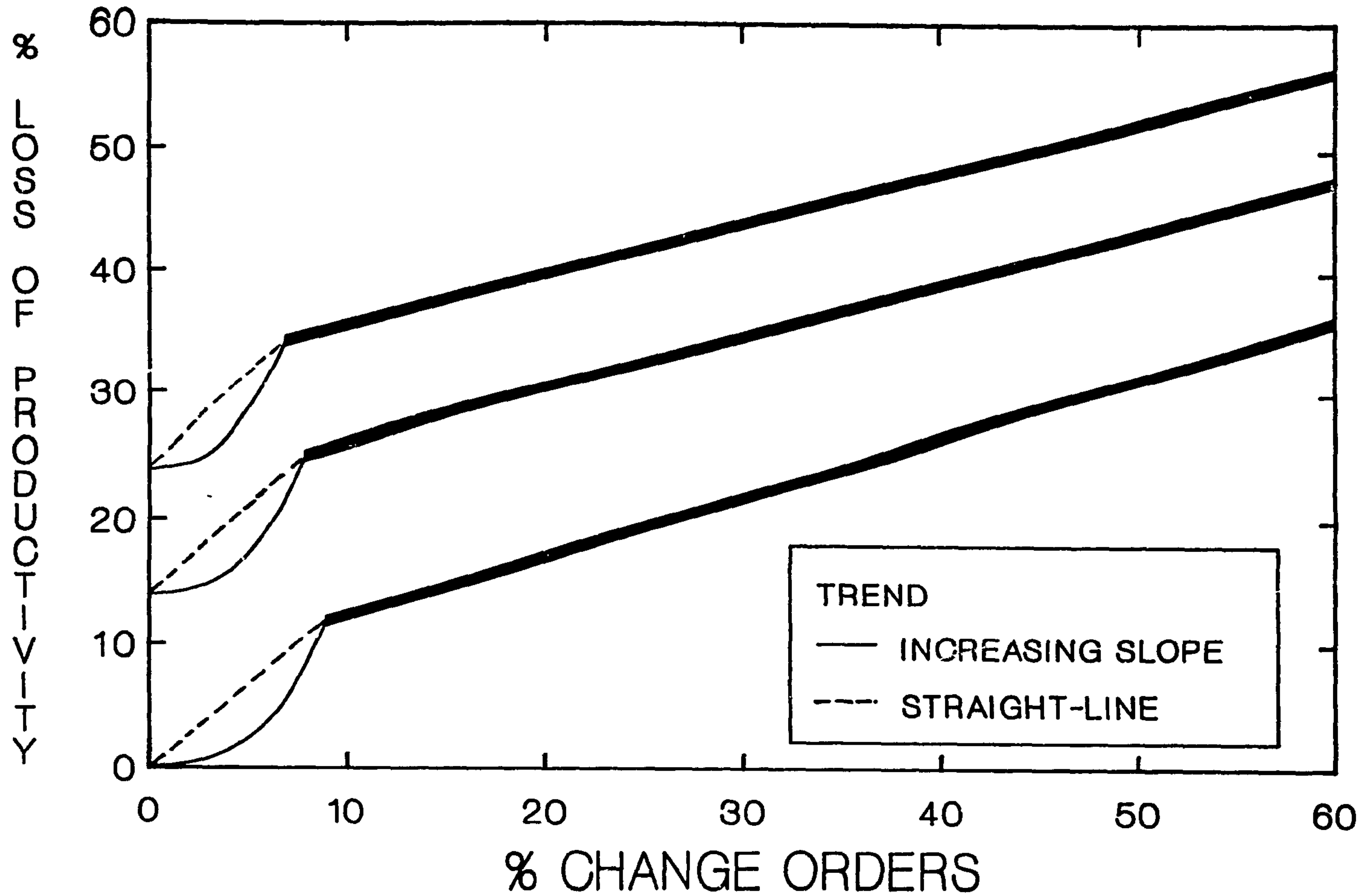


FIGURE 5.6 - CHANGE ORDERS VS. LOSS OF PRODUCTIVITY: CHANGE ORDER HOURS BELOW 10% OF EARNED CONTRACT HOURS

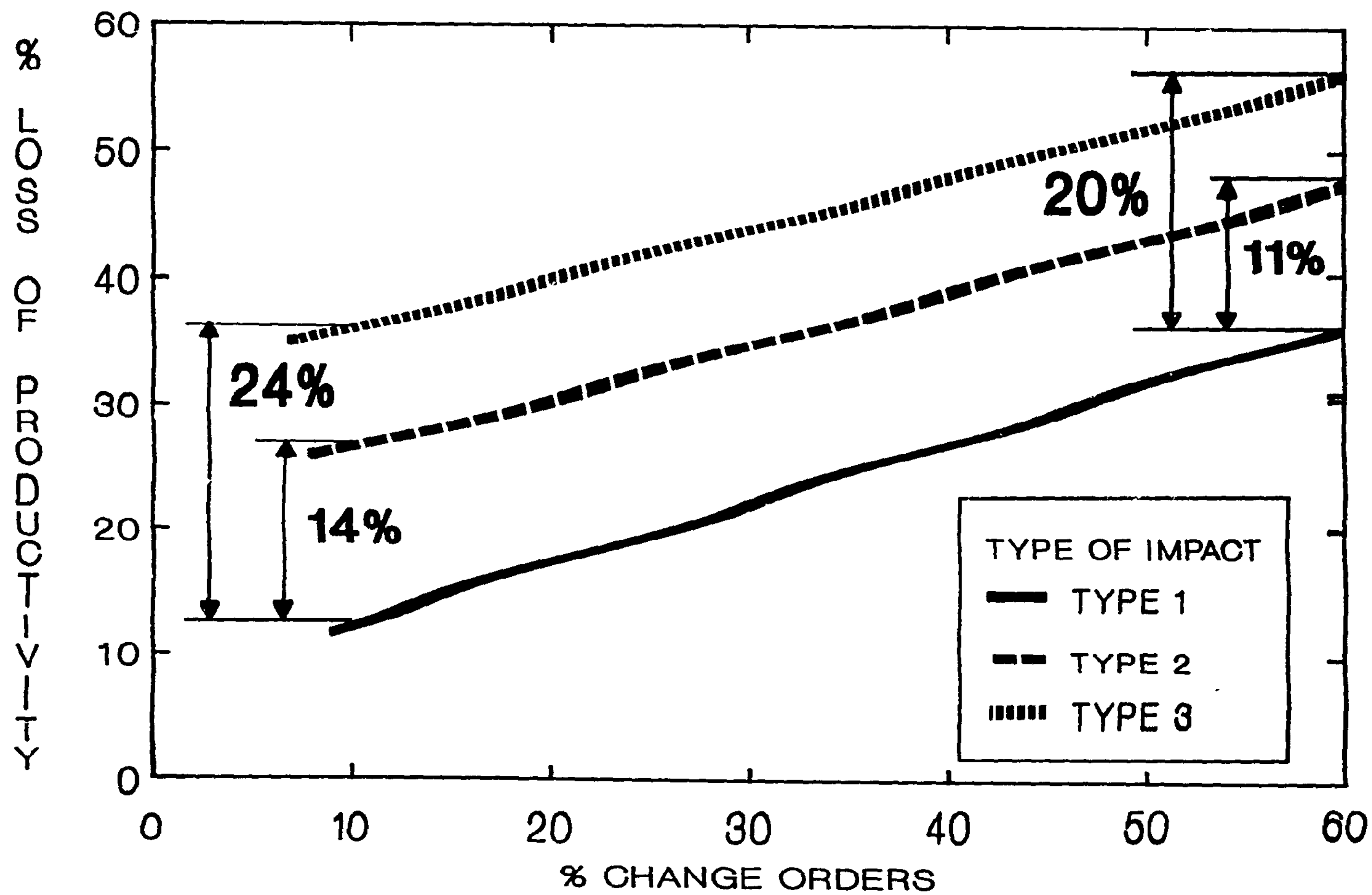


FIGURE 5.7 - CHANGE ORDERS VS. LOSS OF PRODUCTIVITY: ELECTRICAL/MECHANICAL CONTRACTS - TYPES 1, 2 & 3

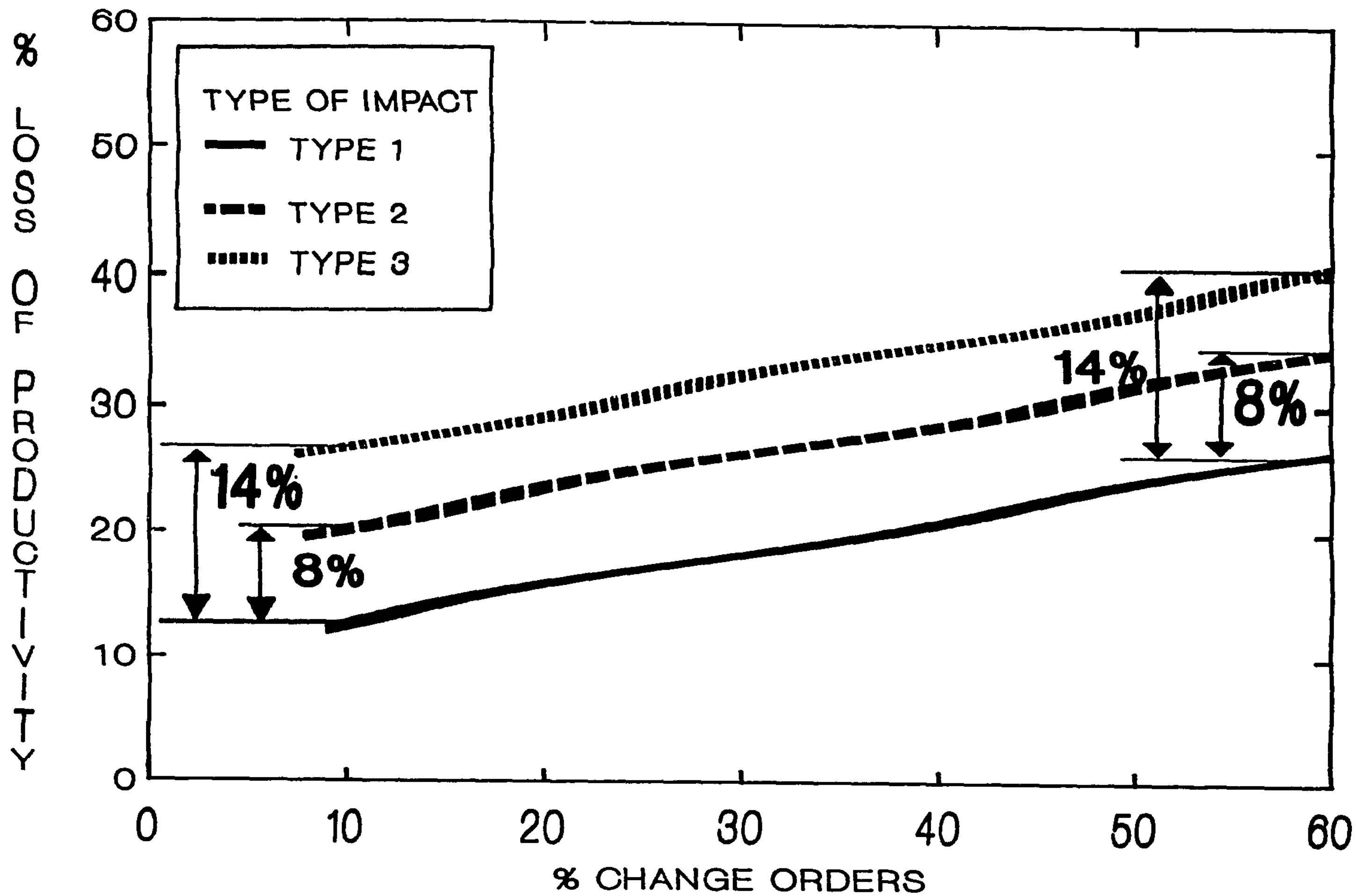


FIGURE 5.8 - CHANGE ORDERS VS. LOSS OF PRODUCTIVITY:
CIVIL/ARCHITECTURAL CONTRACTS - TYPES 1, 2 & 3

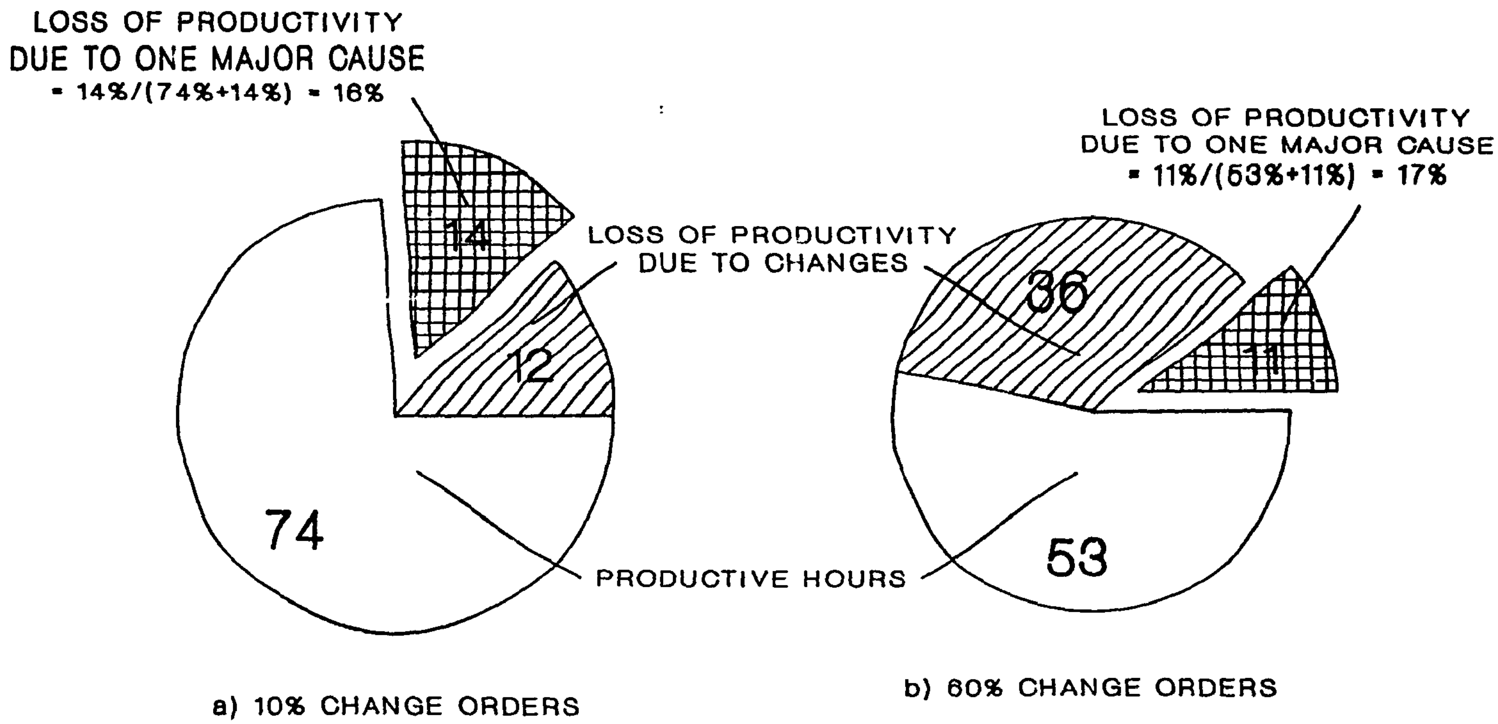


FIGURE 5.9 - BREAKDOWN OF LABOUR-HOURS:
ELECTRICAL/MECHANICAL CONTRACTS - TYPE 2

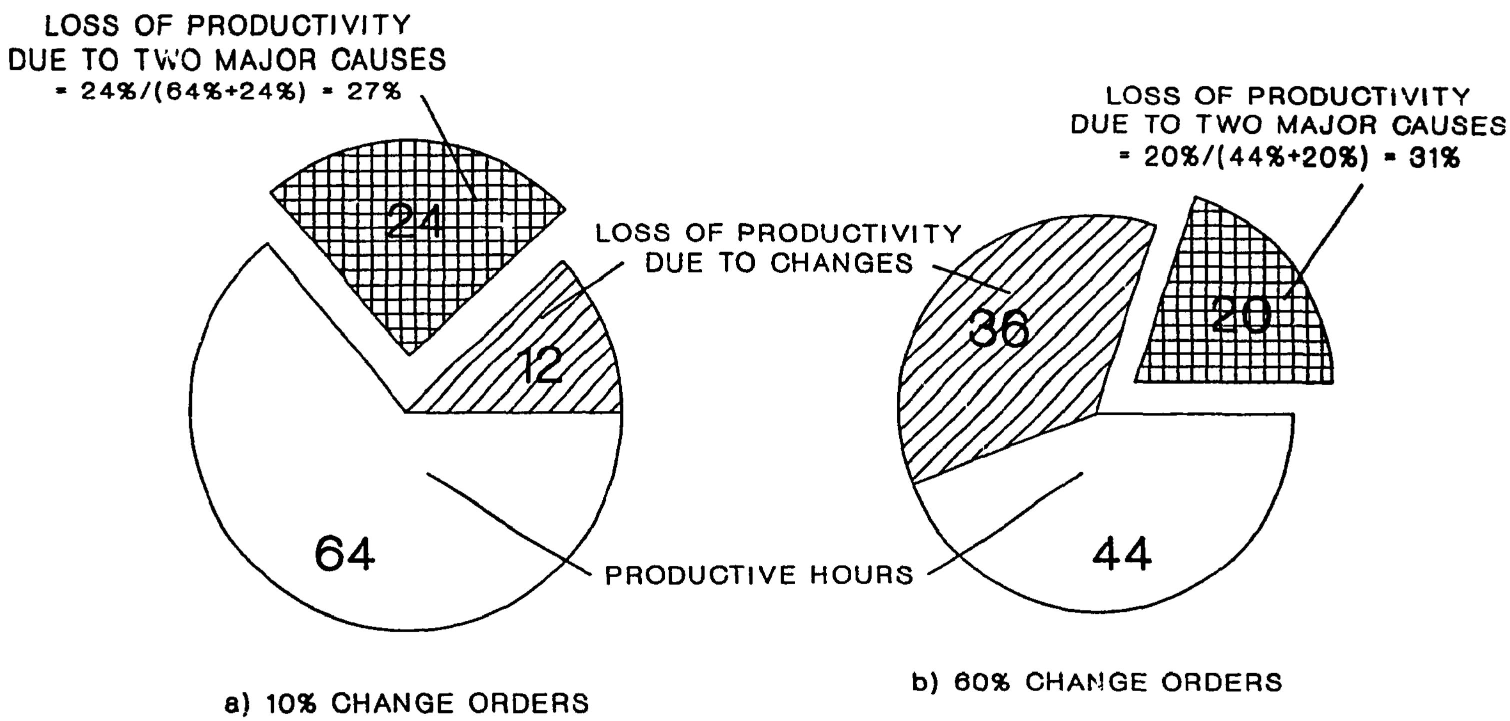
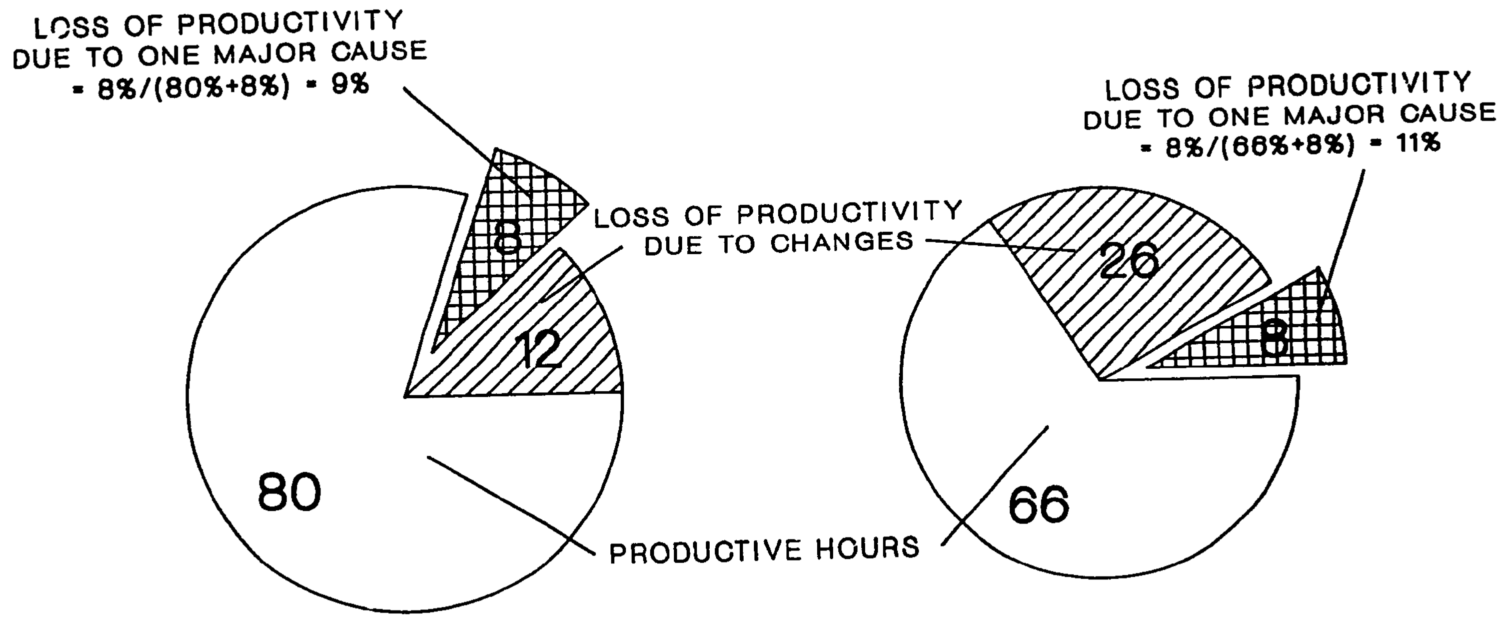


FIGURE 5.10 - BREAKDOWN OF LABOUR-HOURS:
ELECTRICAL/MECHANICAL CONTRACTS - TYPE 3



a) 10% CHANGE ORDERS

b) 60% CHANGE ORDERS

FIGURE 5.11 - BREAKDOWN OF LABOUR-HOURS:
CIVIL/ARCHITECTURAL CONTRACTS - TYPE 2

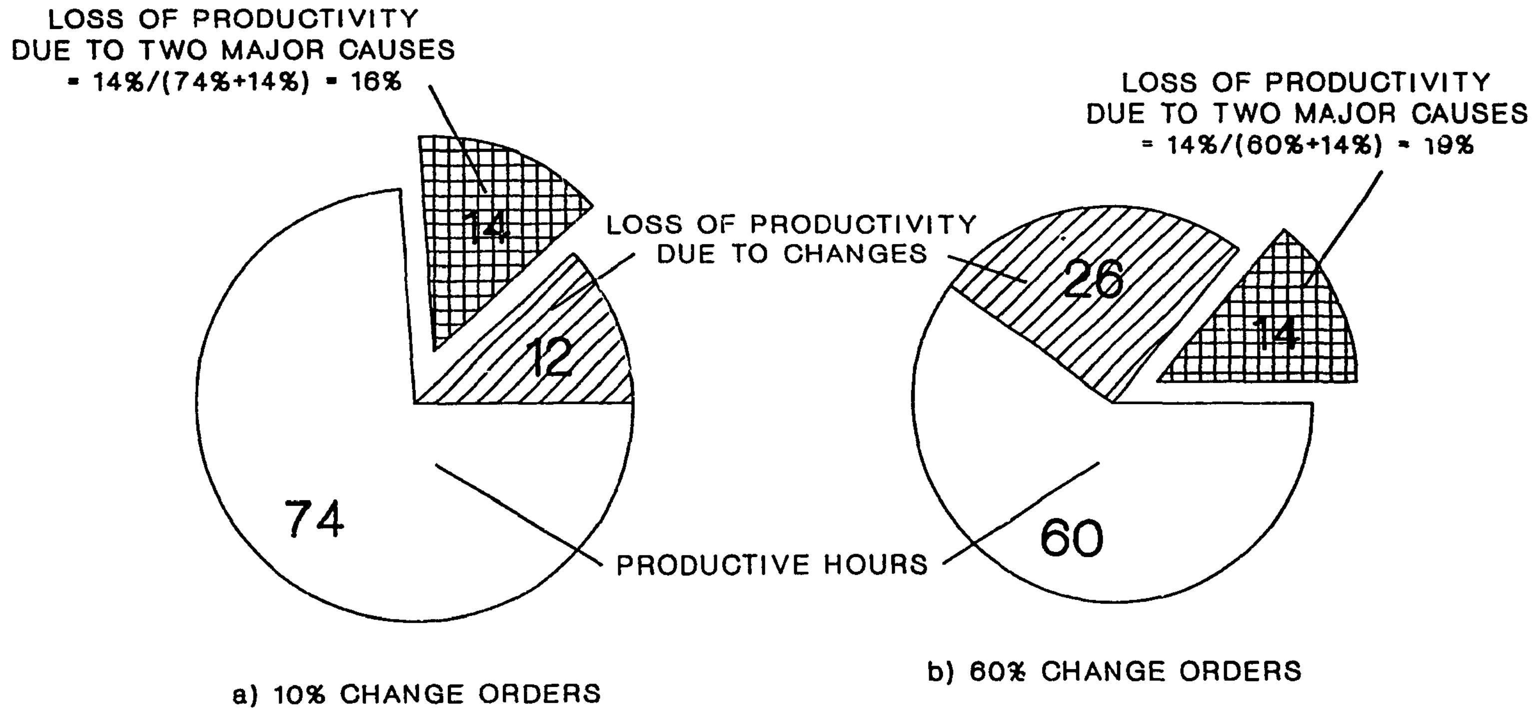


FIGURE 5.12 - BREAKDOWN OF LABOUR-HOURS:
CIVIL/ARCHITECTURAL CONTRACTS - TYPE 3

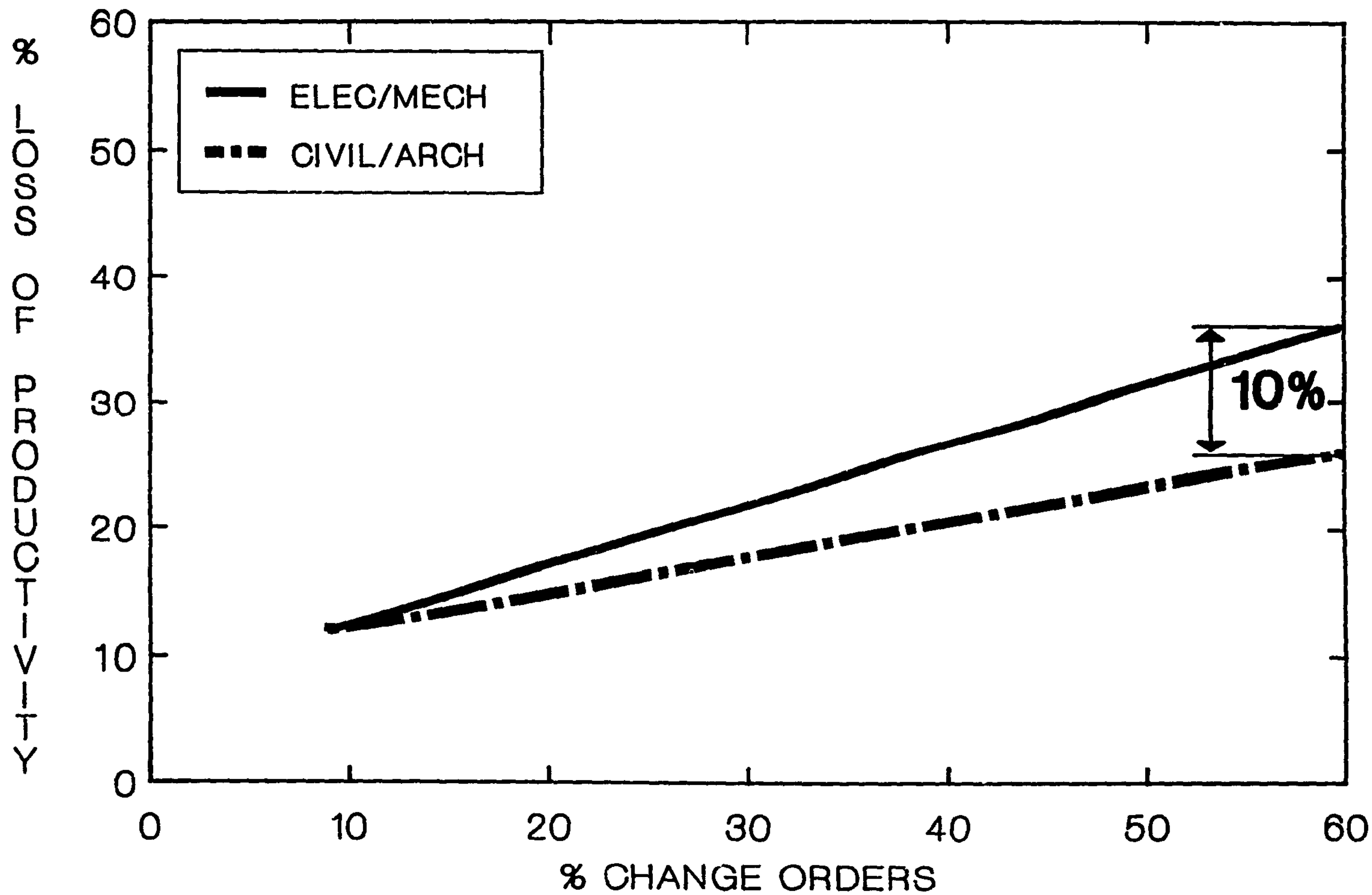


FIGURE 5.13 - CHANGE ORDERS VS. LOSS OF PRODUCTIVITY: ELECTRICAL/MECHANICAL CONTRACTS AND CIVIL/ARCHITECTURAL CONTRACTS - TYPE 2

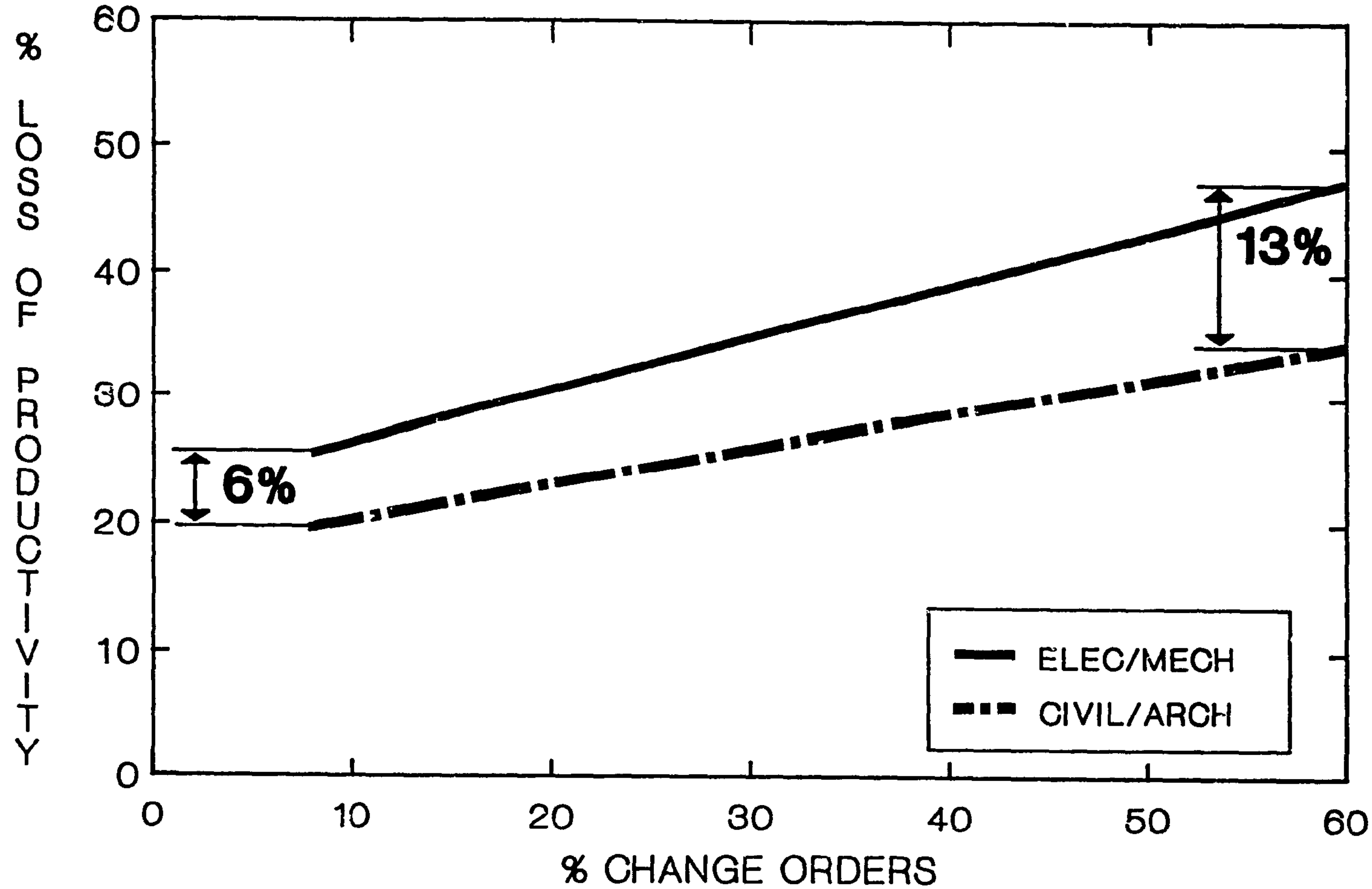


FIGURE 5.14 - CHANGE ORDERS VS. LOSS OF PRODUCTIVITY: ELECTRICAL/MECHANICAL CONTRACTS AND CIVIL/ARCHITECTURAL CONTRACTS - TYPE 2

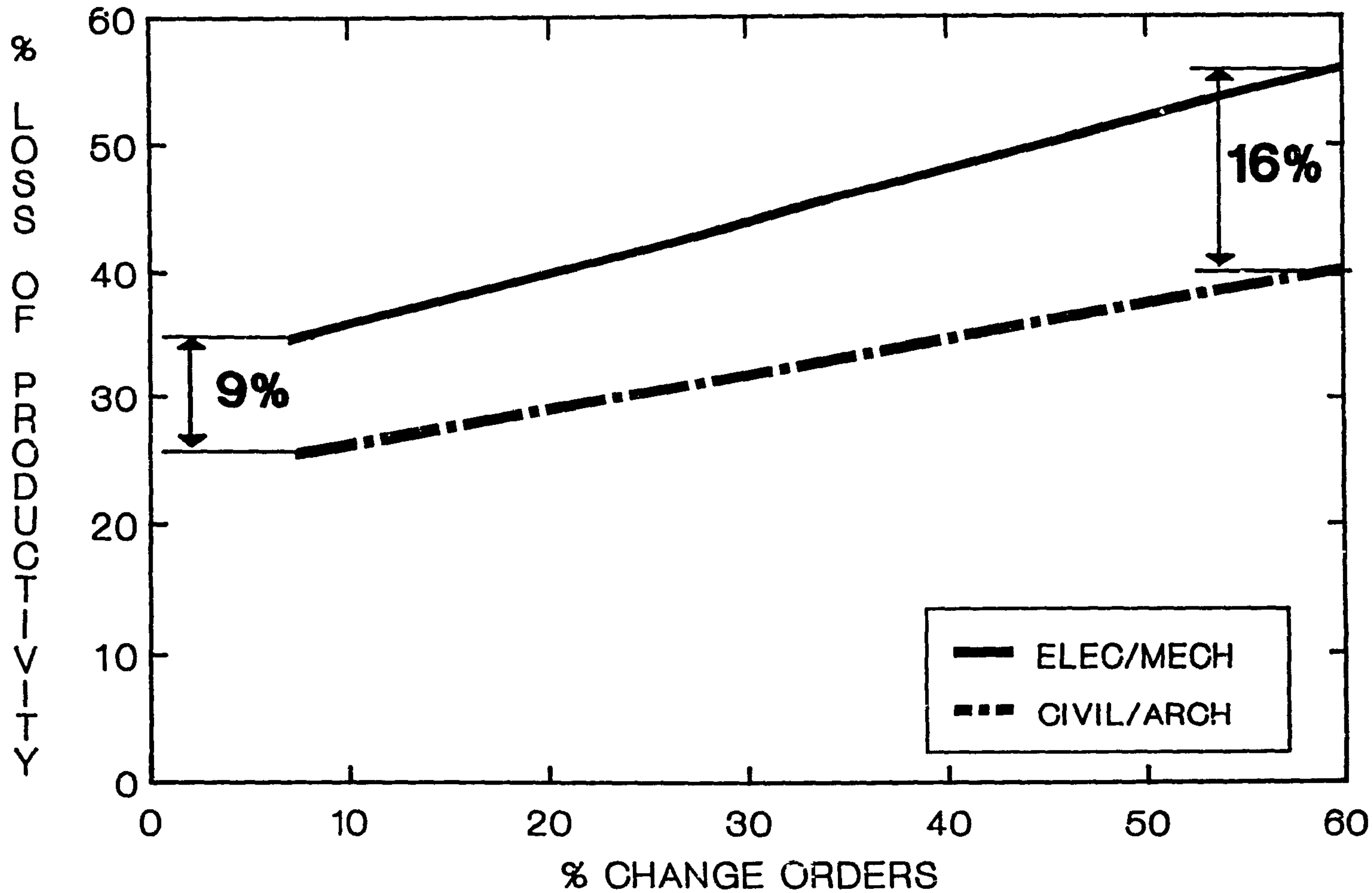


FIGURE 5.15 - CHANGE ORDERS VS. LOSS OF PRODUCTIVITY: ELECTRICAL/MECHANICAL CONTRACTS AND CIVIL/ARCHITECTURAL CONTRACTS - TYPE 3

CHANGE ORDER MEASUREMENT	COEFFICIENT OF CORRELATION								
	ELEC/MECH BUILDING PROJECTS			ELEC/MECH INDUSTRIAL FACILITIES			CIVIL/ARCH BLDGS & IND		WEIGHTED
	TYPE 1	TYPE 2	TYPE 3	TYPE 1	TYPE 2	TYPE 3	TYPE 1	TYPE 2	AVERAGE
PERCENTAGE	0.9	0.33	0.15	0.9	0.4	0.81	0.82	0.52	0.6
AVERAGE SIZE	0.2	0.17	0.31	-0.22	0.25	-0.79	0.6	0.08	0.18
FREQUENCY	0.18	0.7	-0.6	0.61	0.02	0.93	0.49	0.67	0.13

TABLE 5.1 - LINEAR REGRESSION OF PERCENTAGE LOSS OF PRODUCTIVITY ON CHANGE ORDER MEASUREMENTS

CATEGORY		# OF OBSERVATIONS			LINEAR REGRESSION				NONLINEAR REGRESSION			
TYPE OF WORK	TYPE OF IMPACT	TOTAL	OUT-LIERS	NET	Y-AXIS INTERCEPT (a)	SLOPE OF LINE (b)	COEFF. OF CORREL.	STD. EST. OF ERR.	COEFFICIENTS (a)	COEFFICIENTS (b)	COEFF. OF CORREL.	STD. EST. OF ERR.
E/M BLDG	1	17		17	6.3	0.52	0.9	4.1	2.2	0.03	0.88	0.23
E/M BLDG	2	12	1	11	21.5	0.48	0.71	4.3	3.06	0.02	0.68	0.18
E/M BLDG	3	6		6	35.6	0.16	0.15	5.9	3.57	0.00	0.15	0.16
E/M IND	1	11		11	9.2	0.44	0.9	3.3	2.35	0.02	0.87	0.2
E/M IND	2	16	1	15	23.6	0.37	0.71	5.6	3.2	0.01	0.69	0.17
E/M IND	3	4		4	18.9	2.13	0.81	4.8	2.98	0.06	0.83	0.12
C/A	1	7		7	9.8	0:27	0.82	2.3	2.37	0.02	0.83	0.12
C/A	2	16	1	15	17.4	0.28	0.74	3.5	2.86	0.01	0.71	0.18
C/A	3	1		1								

NOTE: EQUATION OF LINEAR REGRESSION LINE = a + bx

EQUATION OF NONLINEAR REGRESSION LINE = exp (a + bx)

TABLE 5.2 - LINEAR AND NONLINEAR REGRESSION OF PERCENTAGE LOSS OF PRODUCTIVITY ON PERCENTAGE CHANGE ORDERS

TYPE	# OF OBSERVATIONS			Y-AXIS	SLOPE OF LINE (b)	COEFF. OF CORREL.	STD. EST. OF ERROR
	TOTAL	OUTLIERS	NET	INTERCEPT (a)			
1	28		28	8	.47	.88	3.9
2	28	2	26	22	.42	.68	5.2
3	10		10	32	.40	.34	5.6

NOTE: EQUATION OF REGRESSION LINE = $a + bx$

TABLE 5.3 - LINEAR REGRESSION OF PERCENTAGE LOSS OF PRODUCTIVITY ON PERCENTAGE CHANGE ORDERS FOR ELECTRICAL/MECHANICAL CONTRACTS ON BUILDING AND INDUSTRIAL CONSTRUCTION

			RESULTS OF STATISTICAL ANALYSIS FOR CHANGE ORDER HOURS GREATER THAN 10% OF EARNED CONTRACT HOURS				COMPARSION OF RESULTS WITH THOSE OF ALL CASES — ESTIMATED LOSS OF PRODUCTIVITY					
							@ 10% CHANGE ORDERS			@ 60% CHANGE ORDERS		
TYPE OF WORK	TYPE OF IMPACT	NUMBER OF CASES	Y-AXIS INTERCEPT (a)	SLOPE OF LINE (b)	COEFF. OF CORREL.	STD. EST. OF ERR.	CASES >10% (1)	ALL CASES (2)	DIFF. (2-1)	CASES >10% (3)	ALL CASES (4)	DIFF. (4-3)
E/M	1	25	7.1	0.5	0.88	3.9	12%	12%	0%	37%	36%	1%
E/M	2	20	23.7	0.37	0.68	5.3	27%	26%	-1%	46%	47%	1%
C/A	2	13	18.2	0.25	0.69	3.7	21%	20%	-1%	33%	34%	1%

NOTE: EQUATION OF REGRESSION LINE = a + bx

TABLE 5.4 - LINEAR REGRESSION OF PERCENTAGE LOSS OF PRODUCTIVITY ON PERCENTAGE CHANGE ORDERS - CHANGE ORDER HOURS ABOVE 10% of EARNED CONTRACT HOURS

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY AND CONCLUSIONS

Based on the 90 cases examined in the present research, the following conclusions can be drawn:

(1) The majority of change orders are issued for design errors and omissions and owner- and A/E-required changes, which are generally the result of inadequate and incomplete designs.

(2) Individual change orders which disrupt and delay progress of the work adversely affect productivity of the contractor's labour force due to: stop-and-go operations; out-of-sequence work; and loss in benefiting from the learning curve.

(3) Due to the interdependency of construction operations, change orders have a ripple-effect on productivity of unchanged activities.

(4) Change orders have a detrimental and cumulative effect on labour productivity when total labour-hours spent

on change orders exceed 10% - 15% of the earned (or normal) labour-hours for the original contract work.

(5) Cumulatively, change orders result in the following causes of productivity loss: stop-and-go operations; out-of-sequence work; loss in productive rhythm; demotivation of work force; loss in learning curve; unbalanced crews; excessive manpower fluctuations; unbalancing of successive operations; lack of management and engineering support; and acceleration when equitable time extensions are not granted.

(6) Productivity losses resulting from change orders are experienced mainly during later periods of the job when the majority of change order work is carried out and the delayed and disrupted activities have to be completed. As a result, completion of projects, which at the outset were on schedule and within the anticipated level of productivity, might be delayed significantly as productivity decreases and manpower is diverted to change order work toward the end of the job.

(7) As a consequence of disruptions, additional work and productivity losses created by change orders, project completion dates may be significantly extended. On average, completion dates for the contracts analyzed were extended by 75% when unaccelerated and 25% when accelerated. Thus, additional productivity-related impact costs of well-planned acceleration programs are partially offset by savings in field and home office overhead costs.

(8) Scheduling and coordination of the work are the major factors affecting productivity, particularly on electrical and mechanical work in building construction as such work depends on completion of necessarily preceding work by other trades. Delays, disruptions and additional work resulting from change orders bring about a gradual deterioration of original schedules and, as such, render continuous scheduling and effective coordination not only more difficult and time-consuming, but increasingly more important.

(9) The effect of individual change orders on both productivity and project completion depends, to a great extent, on the timing of the instruction to proceed in relation to the planned start of the affected activity. Progress of the work is adversely affected when change orders are not issued and approved with adequate lead time for material procurement prior to the start of the affected activity.

(10) On delayed and disrupted projects, productivity losses due to individual change orders cannot be accurately estimated in advance. Productivity losses are best calculated on a global basis, after the fact and, when accurate data on physical progress is available, by comparing impacted and unimpacted periods of work (i.e., using the differential method of cost calculation).

(11) Total change order labour-hours expressed as a percentage of total labour-hours spent on original contract work directly correlate with percentage loss of productivity on contract work. As such, relationships between change orders and loss of productivity are best described by linear rather than nonlinear models, and the correlations are relatively strong.

(12) The level of productivity losses flowing from change orders is affected by the type of work (i.e., fine versus gross motor skills), but not by the type of construction (i.e., buildings versus industrial facilities). Productivity losses are higher for electrical/mechanical work (i.e., fine motor skills) than civil/architectural work (i.e., gross motor skills), and differences increase with the level of change orders.

(13) Additional major causes of productivity-related impact, such as acceleration and inadequate scheduling and coordination, have a cumulative negative effect on productivity. One such additional cause can be expected to increase productivity losses between 11% and 14% on electrical/mechanical work and 8% on civil/architectural work. Two such additional causes can be expected to increase productivity losses between 20% and 24% on electrical/mechanical work and 14% on civil/architectural work.

6.2 APPLICATION OF QUANTITATIVE RESULTS

As previously mentioned, productivity losses are best quantified using the differential cost method of calculation because it compares the level of productivity achieved by the contractor during a normal, unimpacted period to that of the impacted period. Such a calculation, however, requires accurate data on labour-hour expenditure and physical progress. In practice, many contractors do not maintain adequate records for a differential cost calculation, and on severely delayed and disrupted projects a representative normal period may not exist. In fact, differential cost calculations were not possible for these reasons on more than 60% of the cases examined in the present research.

Consequently, it is often necessary to calculate loss of productivity using industry averages or estimated values. When change orders have adversely affected productivity, losses can be estimated from the models developed in the present research. The effects of change orders on productivity are shown for electrical/mechanical work in Figure 6.1 and for civil/architectural work in Figure 6.2. Figure 6.3 depicts the results of these two types of work based on a 45/55 ratio, being the ratio of labour-hours expanded by the corresponding trades in the Canadian non-residential construction industry [93]. The models shown in Figure 6.3 could be used to estimate overall productivity losses on combined contracts and entire projects when a specific breakdown of trades is not known.

Estimates of productivity loss from the models developed in the present research could be used by contractors in preparing claims for additional compensation and by owners in budgeting for and evaluating contractors' claims. Such estimates could also be used by managers (i.e., owners and contractors) to evaluate contemplated change orders, to estimate manpower loading levels required to meet project completion dates, to establish realistic activity durations when updating schedules, and to perform cost-benefit analyses of proposed acceleration programs.

Although predictions obtained from these models are approximations which do not account for specific circumstances of a particular job, it is well established in courts of law that precise calculation of loss of productivity is not essential for recovery [94]. Courts, however, do require strict proof of causation or connection between cause and effect. Therefore, in claim situations, results of the models developed in the present research, as with any other industry averages, are best supported by expert analysis of the specific facts which establish causation.

To estimate productivity losses on change orders with the models shown in Figures 6.1, 6.2 and 6.3, two measures have to be determined: 1) total actual, or earned in the absence of actual, hours for the change order work, and 2) total hours spent by the contractor on both the changed and original contract work. From total actual hours, actual contract hours are calculated by subtracting change order hours and any unproductive hours attributable to contractor inefficiencies, such as repairing deficiencies and labour disruption, and inclement weather. Percentage change orders is then calculated by dividing change order hours by actual contract hours and multiplying the result by 100. Estimated percentage loss of productivity on the original contract work is obtained directly from the appropriate model according to the number of additional major causes of productivity-related impact. A detailed investigation of the project history, however, may be necessary to determine whether there were any additional such causes. The amount of unproductive hours on the original contract work is calculated by multiplying percentage loss of productivity by actual contract hours, and dividing by 100.

Approximate productivity losses of contemplated changes can be estimated using the models shown in Figures 6.1, 6.2 and 6.3 by apportioning the productivity loss associated with the anticipated total percentage of change orders to each contemplated change. To estimate such losses, percentage change orders is calculated as total anticipated change order hours divided by earned contract hours, and multiplied by 100. Percentage loss of productivity on earned contract hours is equal to the percentage loss of productivity obtained directly from the appropriate model multiplied by a factor from Table 6.1 to account for substitution of earned for actual contract hours. The total loss of productive hours, calculated as percentage loss of productivity multiplied by earned contract hours divided by 100, are then apportioned to each contemplated change. If necessary, an adjustment could be made at the end of the contract based on the actual percentage of change orders.

Alternatively, productivity losses of contemplated changes can be estimated from the models developed in the present research by calculating the incremental increase in percentage loss of productivity associated with each additional change order. Similar to the above-mentioned approach, percentage change orders and percentage loss of productivity would be measured with respect to earned contract hours with an adjustment factor applied to the percentage loss of productivity obtained from the appropriate model. These factors, shown in Table 6.1, are developed from the regression equation for loss of productivity as follows:

$$\%LP = a' + b\ \%CO$$

$$\frac{LP}{A} = a + b\ \frac{CO}{A}$$

$$\frac{LP}{A}\ \frac{A}{E} = a\ \frac{A}{E} + b\ \frac{CO}{A}\ \frac{A}{E}$$

$$\frac{LP}{E} = a\ \frac{(E + LP)}{E} + b\ \frac{CO}{E}$$

$$\frac{LP}{E} = a + a\frac{LP}{E} + b\frac{CO}{E}$$

$$\frac{LP}{E}(1-a) = a + b\frac{CO}{E}$$

$$\frac{LP}{E} = \left(a + b\frac{CO}{E}\right)\frac{1}{1-a} \qquad \ldots\ 6.2$$

in which:

%LP = percentage loss of productivity = LP/A x 100

%CO = percentage change orders = CO/A x 100

LP = loss of productivity (hours)

A = actual contract hours = E + LP

E = earned contract hours

CO = change order hours

a' = Y-intercept of regression line (%)

a = Y-intercept of regression line = a'/100

b = slope of line of regression line

$\frac{1}{1-a}$ = adjustment factor

6.3 RECOMMENDATIONS FOR INDUSTRY PRACTICE

Since change orders have a significant effect on productivity, it is recommended that the following be considered:

(1) Although it is not possible to completely eliminate change orders on fixed-price contracts, sufficient money and time ought to be allocated to the design stage to ensure an accurate, well-coordinated and completed design that reflects the owner's needs and requirements. Sections of the job and specific activities that cannot be completely

designed prior to tendering should be identified in the tender package and preferably bid on a provisional sum basis (i.e., cash allowance).

(2) Since the effect of an individual change order depends upon its timing, all parties should direct their efforts toward identifying, processing and approving change orders as expeditiously as possible to minimize their impact. Procedures and time periods for processing change orders should be written into construction contracts. Authorizations to proceed, prior to the finalization of the formal change order, ought to be encouraged. Additionally, contracts should always provide authority to proceed with disputed work, without depriving the contractor from pursuing a subsequent claim.

(3) When a change cannot be efficiently scheduled into the contract work, it may be beneficial, particularly on industrial projects, to establish a 'rover crew' to work specifically on rework and limited extra work on a time-and-material basis as opposed to shifting men among crews and adjusting manpower levels. When necessary, such crews ought to work night shifts to avoid congestion with other trades.

(4) Owner-supplied schedules ought to be realistic and practical and prepared with regard to the necessary sequencing and resource requirements. When utilizing the professional construction management approach, construction manag-

ers must take a leading role in scheduling and coordinating work of the various trades rather than leaving the trades to coordinate the work among themselves.

(5) On all projects, and in particular those delayed or disrupted, adequate tools and techniques should be employed to accurately measure productivity and schedule performance.

6.4 RECOMMENDATIONS FOR FURTHER RESEARCH

It is believed the present research will create a greater awareness and understanding among contractors and, more importantly, among owners, design professionals and construction managers of the extent to which change orders adversely affect productivity. To fully understand the change order process, however, further research is needed in a number of areas. During the course of the present research, the following areas were identified as pertinent topics worthy of further studies:

1 - Sources of Change Orders: Although it is generally recognized that most change orders arise as a result of design errors and omissions and owner-requested changes, the sources or underlying reasons for such changes are not clearly understood. Based on such a study, procedures and recommendations could be developed to minimize the occurrence, and thus impact, of change orders.

2 - Cost/Benefit Analyses of Design Review and Coordination: In many of the cases examined, additional design reviews by design professionals and owners would have clearly decreased the occurrence of changes during construction. Similarly, a number of cases, particularly electrical and mechanical, would have experienced less changes had there been proper coordination of the various design disciplines. It is reccmmended that further research be conducted to determine the frequency of projects delayed and disrupted by incomplete and inadequate design, and the additional costs of added design review and coordination. Such costs ought to be weighted against the additional costs of performing changed work and impact costs incurred by contractors (and owners).

3 - Minimizing Impact Costs: The present research has identified a number of factors influencing the impact of change orders, but more research is required to develop practical guidelines which would help contractors minimize the impact of changes and, in general, other causes of productivity losses.

4 - Quantification of Factors Influencing the Impact of Change Orders on Productivity: In examining the relationship between percentage change orders and percentage loss of productivity, only major additional causes of productivity-related impact were considered. No attempt has been made in the present research to quantitatively take into account

either minor additional causes of productivity-related impact (Tables A.2, B.2 and C.2 of Appendices A, B and C respectively) or the factors negatively influencing the productivity loss. If such influences were considered in the statistical analysis then it is likely that the correlation between percentage loss of productivity and percentage change orders would be even stronger. To increase the accuracy of these models, it is recommended that further research quantitatively examine the effect of such factors.

5 - Effects of Change Orders on Macro Productivity: In the present research the effects of change orders are considered only on the productivity of labour at the micro level. It is recommended that further research examine the overall effects of change orders on a macro basis. Such research should examine the effects on the total project cost to the owner including costs of design, contract administration, loss of revenue, financing, labour, material, equipment, supervision and overhead. The results of such a study would enable owners to make better decisions regarding design and contemplated changes.

6 - Change Orders in Design-Construct Projects: All of the cases examined herein were competitively bid based on drawings prepared by A/E's on behalf of the owner. Further research needs to be done to determine whether change orders are less frequent and less severe in design-construct projects as well as the costs and benefits of such an approach.

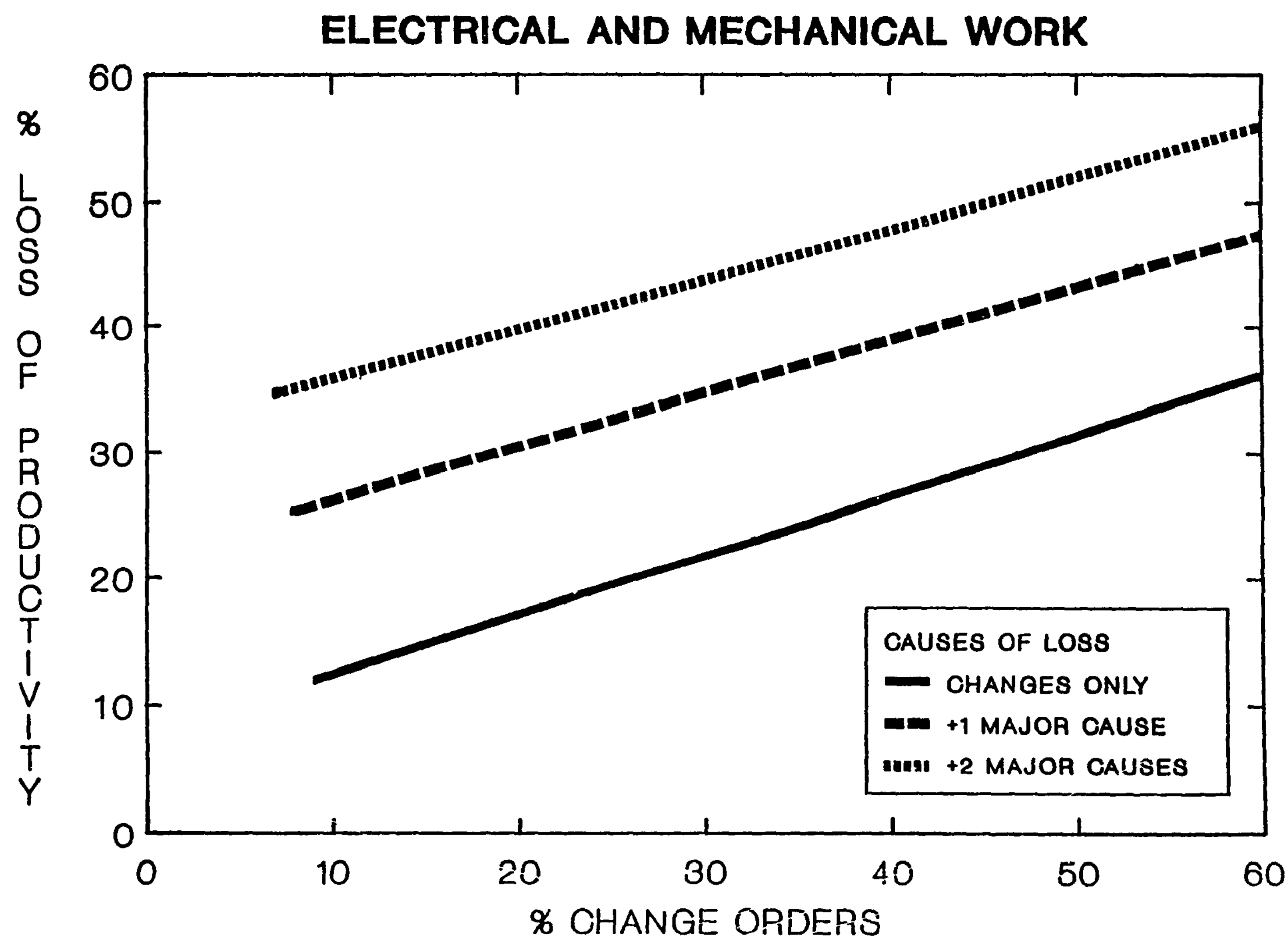


FIGURE 6.1 - EFFECTS OF CHANGE ORDERS ON PRODUCTIVITY: ELECTRICAL/MECHANICAL WORK

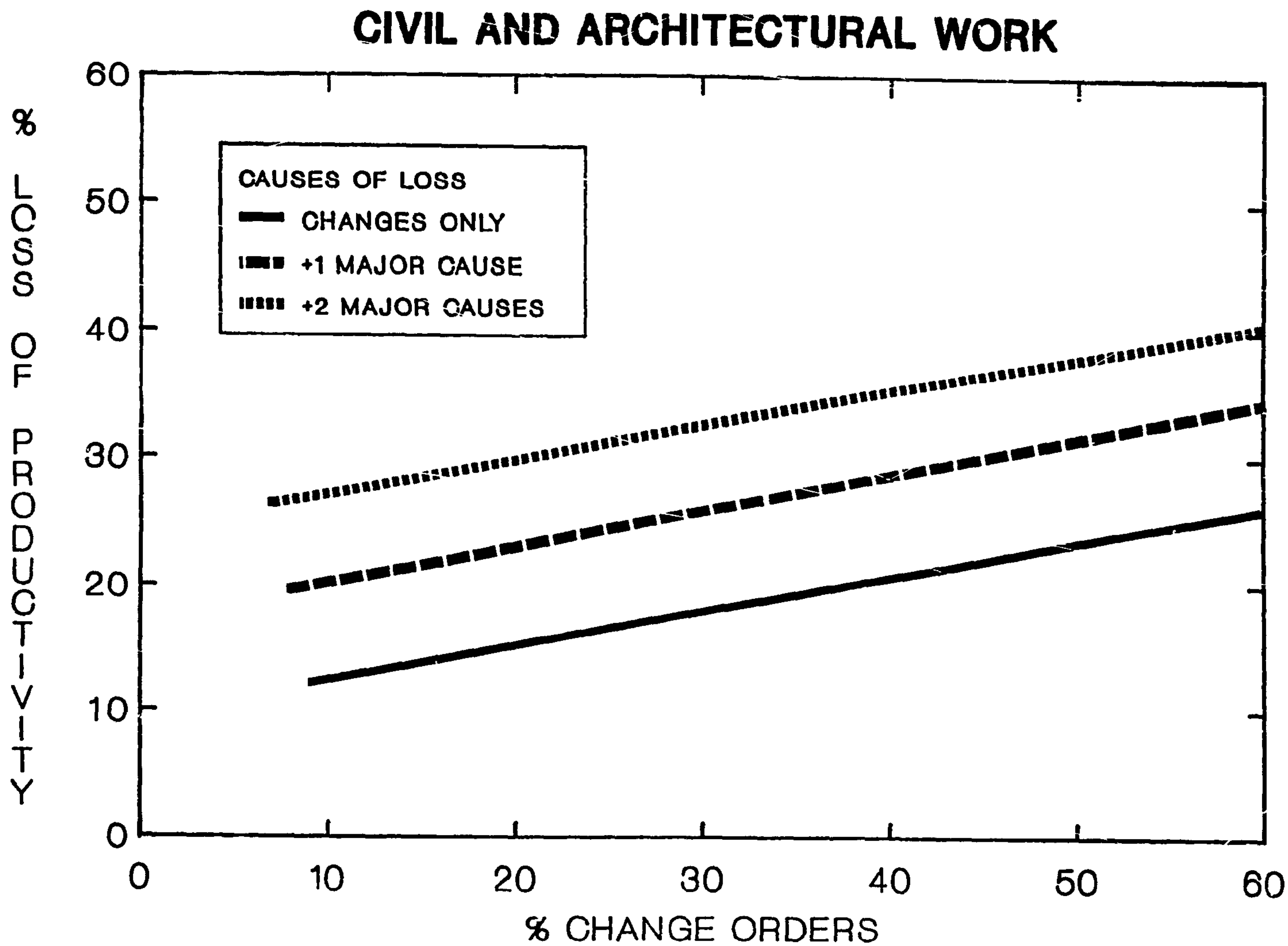


FIGURE 6.2 - EFFECTS OF CHANGE ORDERS ON PRODUCTIVITY: CIVIL/ARCHITECTURAL WORK

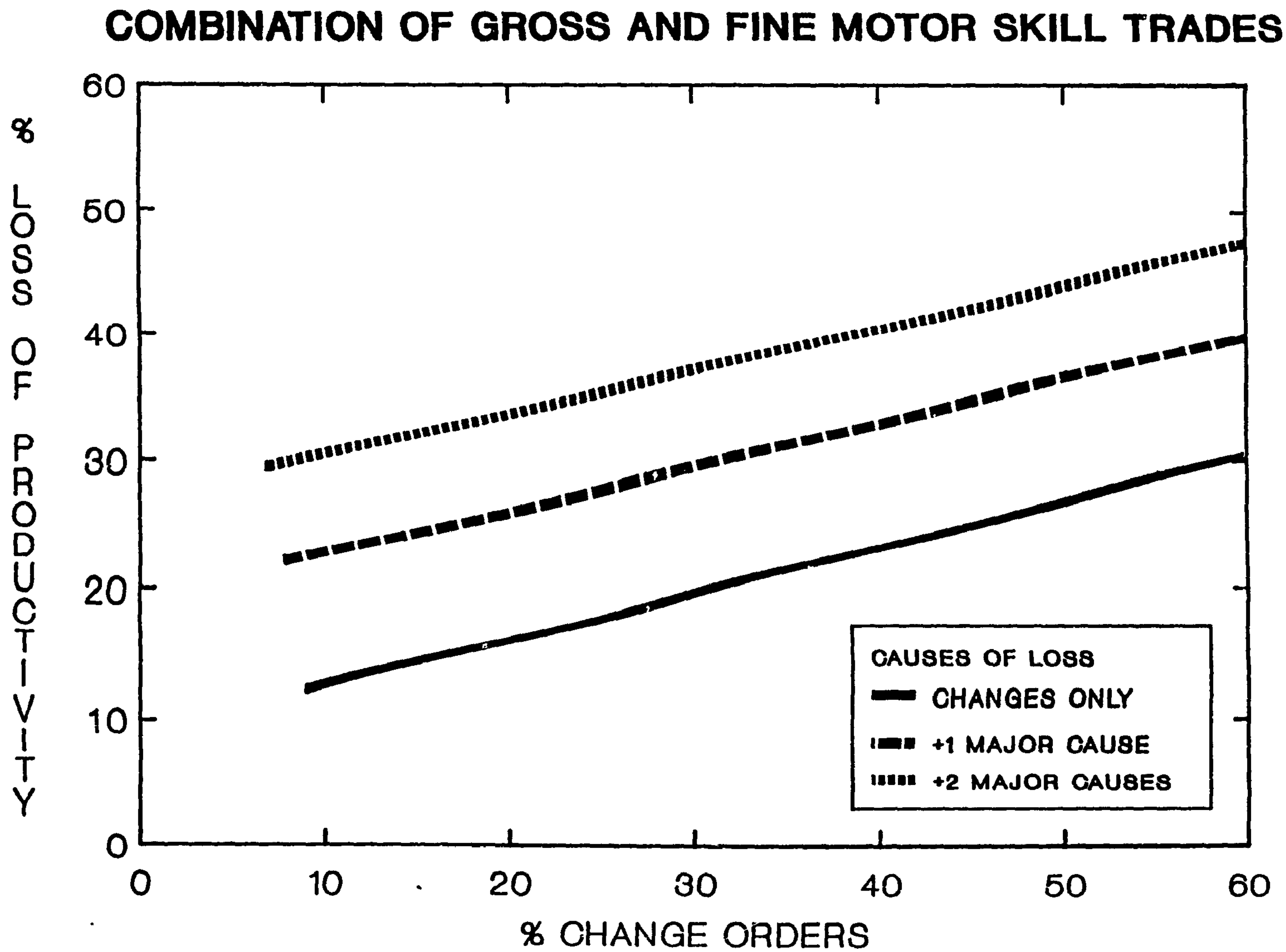


FIGURE 6.3 - EFFECTS OF CHANGE ORDERS ON PRODUCTIVITY: COMBINATION OF GROSS AND FINE MOTOR SKILL TRADES

TYPE OF WORK	TYPE OF IMPACT	ADJUSTMENT FACTOR
ELEC/MECH	CHANGES ONLY	1.1
ELEC/MECH	+1 MAJOR CAUSE	1.3
ELEC/MECH	+2 MAJOR CAUSES	1.5
CIVIL/ARCH	CHANGES ONLY	1.1
CIVIL/ARCH	+1 MAJOR CAUSE	1.2
CIVIL/ARCH	+2 MAJOR CAUSES	1.3

TABLE 6.1 - ADJUSTMENT FACTOR FOR ESTIMATING PRODUCTIVITY LOSSES WITH RESPECT TO EARNED CONTRACT HOURS

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APPENDICES

#	TYPE OF PROJECT	TYPE OF WORK	TYPE OF CONTRACTOR	TYPE OF CONTRACT	VALUE OF ORIGINAL CONTRACT	VALUE OF CHANGE ORDERS	ORIGINAL DURATION (MONTHS)	ACTUAL DURATION (MONTHS)	% EXTENDED DURATION	NUMBER CHANGE ORDERS	MAJOR CAUSE OF CHANGE ORDERS
1	Health Centre	Elec	Prime	LS	$537,000	$200,000	12	26	127	76	Incomplete Design
2	Airport Terminal (Ex./Re.)	Elec	Sub	LS	$1,800,000	$350,000	28	31	11	125	Incomplete Design
3	Office Complex	Elec	Sub	LS	$6,615,000	$4,550,000	17	27	59	137	Design Changes
4	Office Complex	Elec	Sub	LS			17	27	59	77	Design Changes
5	Office Complex	Elec	Sub	LS			17	27	59	114	Design Changes
6	Office Complex	Mech	Prime	LS	$4,889,000	$390,000	15	26	70	195	Incomplete Design
7	Office Complex	Elec	Prime	LS	$7,100,000	$1,500,000	15	26	72	250	Incomplete Design
8	Office Complex	Elec	Prime	LS	$1,399,000	$100,000	10	14	35	50	Incomplete Design
9	Processing Facility	Elec	Prime	LS	$1,055,000	$435,000	7	16	129	62	Incomplete Design (New Technology)
10	Processing Facility	Elec	Prime	LS	$4,394,000	$1,687,000	24	24	0	203	Incomplete Design (New Technology)
11	Courthouse	Mech	Sub	LS	$1,825,000	$258,000	23	26	11	100	Defective Design (New Technology)
12	Hospital	Mech	Sub	LS	$2,359,000	$100,000	16	30	88	54	Design Changes
13	Hospital	Mech	Sub	LS	$473,000	$5,000	10	18	80	15	Design Changes
14	Hospital	Elec	Sub	LS	$1,650,000	$83,000	16	28	75	73	Design Changes
15	School Renovations	Elec	Prime	LS	$460,000	$50,000	6	10	85	10	Design Changes
16	University Bldg. (Ex./Re.)	Elec	Prime	LS	$1,465,000	$262,000	14	17	21	86	Design Changes; Unforseen Conditions
17	Hospital Renovations	Mech	Sub	LS	$1,450,000	$331,000	12	22	83	91	Design Changes
18	Arena	Mech	Prime	LS	$5,700,000	$1,600,000	17	18	6	50	Design Changes
19	Office Building	Mech	Prime	LS	$1,070,000	$275,000	6	9	68	12	Design Changes
20	Airport Terminal	Mech	Prime	LS	$458,000	$150,000	14	27	100	29	Design Changes
21	Airport Terminal	Mech	Prime	LS	$1,751,000	$1,258,000	9	15	76	21	Unforseen Conditions
22	Airport Terminal	Mech	Prime	LS	$317,000	$17,000	11	19	76	7	Design Changes
23	Airport Terminal	Mech	Sub	LS	$463,000	$100,000	5	14	200	40	Design Changes
24	Airport Terminal	Mech	Sub	LS	$815,000	$294,000	14	28	100	50	Design Changes
25	Airport Terminal	Mech	Sub	LS	$600,000	$120,000	10	20	111	50	Design Changes
26	Airport Terminal (Ex./Re.)	Mech	Sub	LS	$2,878,000	$750,000	13	19	46	169	Incomplete Design
27	Residential Complex	Mech	Prime	LS	$1,724,000	$425,000	22	26	18	41	Design Changes
28	Hotel	Elec	Prime	LS	$2,326,000	$250,000	17	17	0	68	Design Changes
29	Hotel	Elec	Prime	LS	$3,318,000	$700,000	16	18	13	91	Design Changes
30	Museum	Elec	Sub	LS	$1,658,000	$0	11	23	109	0	
31	Museum	Mech	Sub	LS	$1,600,000	$0	11	24	118	0	
32	Museum	Mech	Sub	LS	$246,000	$0	11	18	64	0	
33	Processing Facility	Elec	Prime	LS	$2,251,000	$6,321,000	15	26	70	107	Incomplete Design
34	Hospital	Mech	Sub	LS	$5,000,000	$210,000	24	32	33	75	Incomplete Design
35	Processing Facility	Mech	Prime	LS	$2,725,000	$71,000	9	17	89	120	Incomplete Design
				TOTALS	$72,375,000	$22,822,000					

TABLE A.1 - ELECTRICAL/MECHANICAL CONTRACTS ON BUILDING CONSTRUCTION: BACKGROUND INFORMATION

#	TYPE OF PROJECT	CALCULATION OF PRODUCTIVITY LOSS									MEASUREMENT OF CHANGE ORDERS				
		ORIGINAL ESTIMATE HOURS	MODIFIED ESTIMATE HOURS	NORMAL PERIOD (% PROGRESS)	NORMAL HOURS	EARNED HOURS	SITE EXPERIENCE FACTOR	ACTUAL HOURS	PI	% LOSS OF PROD.	NUMBER	FREQUENCY	HOURS	AVERAGE SIZE	%
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1	Health Centre	17211				17211	1.00	24440	0.70	30	76	3	9933	131	41
2	Airport Terminal (Ex./Re.)	27970		7%-22%	45600	45600	1.63	78280	0.58	42	125	4	9727	78	12
3	Office Complex	35260		0%-20%	37500	37500	1.06	53700	0.70	30	137	5	23850	174	44
4	Office Complex	64560		0%-44%	66300	66300	1.03	80600	0.82	18	77	3	21150	275	26
5	Office Complex	45880		10%-60%	47350	47350	1.03	53800	0.88	12	114	4	13450	118	25
6	Office Complex			16%-71%	107600	107600		127850	0.84	16	195	8	14625	75	11
7	Office Complex			27%-54%	136540	136540		216500	0.63	37	250	10	29200	117	13
8	Office Complex			0%-25%	18600	18600		26067	0.71	29	50	4	2287	46	9
9	Processing Facility	16567				16567	1.00	24834	0.67	33	62	4	9452	152	38
10	Processing Facility	140000	154000			154000	1.10	225130	0.68	32	203	8	48360	238	21
11	Courthouse	19500	19845			19845	1.02	28700	0.69	31	100	4	6500	65	23
12	Hospital	41050	44500			44500	1.08	56900	0.78	22	54	2	2600	48	5
13	Hospital	9200	11400			11400	1.24	15350	0.74	26	15	1	100	7	1
14	Hospital	26000	36000			36000	1.38	63000	0.57	43	73	3	800	11	1
15	School Renovations	7900		0%-48%	10500	10500	1.33	12200	0.86	14	10	1	1200	120	10
16	University Bldg. (Ex./Re.)	16900	21000			21000	1.24	35288	0.60	40	86	5	7185	84	20
17	Hospital Renovations	22000	33000			33000	1.50	43300	0.76	24	91	4	18700	205	43
18	Arena	34400				34400	1.00	38000	0.91	9	50	3	4880	98	13
19	Office Building	13600				13600	1.00	15120	0.90	10	12	1	2270	189	15
20	Airport Terminal	14000	32400			32400	2.31	42200	0.77	23	29	1	7500	259	16
21	Airport Terminal	61500	61500			61500	1.00	88500	0.69	31	21	1	33500	1595	38
22	Airport Terminal	10335	28700			28700	2.78	39200	0.73	27	7	0	2000	286	5
23	Airport Terminal	11410	16000			16000	1.40	19000	0.84	16	40	3	3600	90	19
24	Airport Terminal	12000	27000			27000	2.25	34500	0.78	22	50	2	12000	240	35
25	Airport Terminal	20640	32500			32500	1.57	36000	0.90	10	50	3	5000	100	14
26	Airport Terminal (Ex./Re.)	41000				41000	1.00	48200	0.85	15	169	9	5100	30	11
27	Residential Complex	44000		0%-36%	44000	44000	1.00	80500	0.55	45	41	2	13800	337	17
28	Hotel	32300		0%-35%	37700	37700	1.17	55750	0.68	32	68	4	4300	63	8
29	Hotel	39500		0%-43%	61600	61600	1.56	88300	0.70	30	91	5	12300	135	14
30	Museum	18000				18000	1.00	21100	0.85	15	0	0	0	0	0
31	Museum	12850		56%-93%	16000	16000	1.24	20200	0.79	21	0	0	0	0	0
32	Museum	2325		15%-70%	3200	3200	1.38	4100	0.78	22	0	0	0	0	0
33	Processing Facility	78000				78000	1.00	121990	0.64	36	107	4	22890	214	19
34	Hospital	145000				145000	1.00	162500	0.89	11	75	2	6250	83	4
35	Processing Facility	35000				35000	1.00	53000	0.66	34	120	7	30000	250	57
					TOTALS	1549113		2134079					384509		

TABLE A.2 - ELECTRICAL/MECHANICAL CONTRACTS ON BUILDING CONSTRUCTION:

CALCULATION OF PRODUCTIVITY LOSS AND MEASUREMENT OF CHANGE ORDERS

#	TYPE OF PROJECT	TYPE OF IMPACT	MAJOR CAUSES OF PRODUCTIVITY-RELATED IMPACT				MINOR CAUSES OF PRODUCTIVITY-RELATED IMPACT	CAUSES OF DELAY-RELATED IMPACT ONLY
			CHANGE ORDERS	INADEQUATE COORD. & SCHEDULING	ACCEL-ERATION	OTHERS		
1	Health Centre	1	X				Untimely Approval of Shop Drwgs.	
2	Airport Terminal (Ex./Re.)	3	X		X	Impeded Access; Changing Priorities		
3	Office Complex	1	X				Changing Priorities	
4	Office Complex	1	X				Changing Priorities	
5	Office Complex	1	X				Changing Priorities	
6	Office Complex	1	X				Poor Coord. & Sched., Changing Priorities, Late Issue of D	
7	Office Complex	3	X	X	X		Late Issue of Drwgs., Changing Priorities	
8	Office Complex	2	X	X			Late Issue of Drwgs., Changing Priorities	
9	Processing Facility	1	X				Untimely Approval of Shop Drwgs; Late Del. of Equip./Mtl.	Unavailability of Site
10	Processing Facility	3	X	X	X		Untimely Approval of Shop Drwgs; Changing Priorities	Late Issue of Drwgs.
11	Courthouse	2	X		X		Untimely Responses	Changed Subsurface Condit.
12	Hospital	2	X	X			Late Delivery of Equipment	
13	Hospital	2	X	X			Late Delivery of Equipment	
14	Hospital	2	X	X			Late Delivery of Equipment	
15	School Renovations	1	X					
16	University Bldg. (Ex./Re.)	3	X	X	X		Changing Priorities	Late Completion of Structure
17	Hospital Renovations	1	X				Late Issue of Drwgs., Slow Responses	
18	Arena	1	X					Late Completion of Struct.
19	Office Building	1	X					
20	Airport Terminal	2	X	X				Late Issue of Drawings
21	Airport Terminal	1	X				Late Issue of Drawings	Lack of Acces
22	Airport Terminal	2	X	X			Late Issue of Drawings	Lack of Access
23	Airport Terminal	1	X				Late Issue of Drawings	
24	Airport Terminal	1	X				Late Issue of Drawings	
25	Airport Terminal	1	X				Late Issue of Drwgs., Late Del. of Equip.	
26	Airport Terminal (Ex./Re.)	1	X				Late Issue of Drwgs., Lack of Access	
27	Residential Complex	3	X	X	X		Hot Works	
28	Hotel	3	X	X	X			
29	Hotel	2	X	X				Impeded Access
30	Museum	2				Ripple-Effect of Change to Structure		
31	Museum	2				Ripple-Effect of Change to Structure		
32	Museum	2				Ripple-Effect of Change to Structure		
33	Processing Facility	2	X	X			Late Del. of Equip., Delay in Approval of Shop Drwgs.	
34	Hospital	1	X					
35	Processing Facility	1	X				Poor Coordination & Scheduling	

TABLE A.3 - ELECTRICAL/MECHANICAL CONTRACTS ON BUILDING CONSTRUCTION:

ASSESSMENT OF CAUSES OF IMPACT

#	TYPE OF PROJECT	TYPE OF WORK	TYPE OF CONTRACTOR	TYPE OF CONTRACT	VALUE OF ORIGINAL CONTRACT	VALUE OF CHANGE ORDERS	ORIGINAL DURATION (MONTHS)	ACTUAL DURATION (MONTHS)	% EXTENDED DURATION	NUMBER CHANGE ORDERS	MAJOR CAUSE OF CHANGE ORDERS
1	Chemical Plant	Mech	Prime	LS	$8,029,000	$1,650,000	15	14	-7	230	Design Changes
2	Chemical Plant	Mech	Prime	LS	$3,220,000	$1,094,000	14	15	7	260	Design Changes
3	Chemical Plant	Mech	Prime	LS	$1,850,000	$331,000	8	9	13	50	Design Changes
4	Chemical Plant	Elec	Prime	LS			8	9	13	55	Incomplete Design
5	Coal Preparation Plant	Elec	Sub	LS	$1,476,000	$1,540,000	10	14	40	322	Incomplete Design
6	Recalcining Plant	Mech	Prime	LS	$1,948,000	$400,000	7	11	57	200	Design Changes (New Technology)
7	Thermal Power Plant	Mech	Prime	LS	$2,046,000	$200,000	14	14	0	100	Design Changes
8	Sewage Treatment Plant	Mech	Sub	LS	$5,560,000	$250,000	8	12	44	200	Incomplete Design
9	Pulp Mill Exepansion	Mech	Prime	UP	$745,000	$1,410,000	6	11	83		Design Changes
10	Elevator Terminal	Elec	Prime	LS	$1,034,000	$710,000	5	20	300	92	Design Changes
11	Thermal Power Plant	Mech	Prime	LS	$2,293,000	$200,000	13	17	27	150	Late/Incomplete Design
12	Thermal Power Plant	Elec	Prime	LS/UP	$4,960,000	$250,000	14	16	11	250	Late/Incomplete Design
13	Mineral Smelter	Elec	Prime	LS	$1,920,000	$690,000	10	16	60	124	Design Errors& Omissions
14	Cement Plant	Elec	Prime	LS	$4,801,000	$3,565,000	15	22	47	75	Design Errors& Omissions
15	Sewage Treatment Plant	Elec	Sub	LS	$1,694,000	$300,000	15	23	53	100	Design Errors& Omissions
16	Automotive Plant	Mech	Sub	LS	$16,880,000	$1,000,000	14	16	14		Incomplete Design
17	Steel Plant Expansion	M/E	Prime	LS	$12,410,000	$2,800,000	10	20	100	150	Design Changes
18	Water Filtration Plant	Elec	Sub	LS/UP	$4,506,000	$8,857,000	22	37	66	25	Design Changes
19	Food Processing Plant	M/E	Prime	LS	$8,362,000	$1,745,000	6	12	100	700	Design Errors & Omissions
20	Food Processing Plant	M/E	Prime	LS	$5,715,000	$1,567,000	6	15	173	2150	Design E & O; Defective Parts
21	Rock Crusher	M/E	Prime	LS	$1,165,000	$300,000	3	3	-15	65	Design E & O
22	Cement Crusher	Mech	Prime	LS	$300,000	$25,000	1	3	88	140	Design Changes
23	Oil Refinery	M/E	Prime	LS	$2,900,000	$340,000	12	18	50		Design Changes
24	Aluminum Plant	Mech	Sub	LS	$1,362,000	$1,000,000	5	5	0	110	Design Changes
25	Aluminum Plant	Elec	Sub	LS/UP	$297,000	$330,000	6	10	67		Design Changes
26	Aluminum Plant	Elec	Sub	LS/UP	$439,000	$625,000	8	10	25		Design Changes
27	Aluminum Plant	Elec	Sub	LS	$718,000	$674,000	6	8	41	170	Design Changes
28	Brewery Plant Expansion	Mech	Prime	LS	$476,000	$150,000	2	5	150	104	Incomplete Design
29	Chemical Plant	Mech	Prime	LS	$7,118,000	$500,000	5	6	20		Late Design Completion
30	Chemical Plant	Elec	Prime	LS			6	6	0		Late Design Completion
31	Cement Plant	Mech	Prime	LS	$3,264,000	$660,000	6	6	0	70	Rework of Defective Equip.
				TOTALS	$107,508,000	$33,183,000					

TABLE B.1 - ELECTRICAL/MECHANICAL CONTRACTS ON INDUSTRIAL CONSTRUCTION:

BACKGROUND INFORMATION

#	TYPE OF PROJECT	CALCULATION OF PRODUCTIVITY LOSS									MEASUREMENT OF CHANGE ORDERS				
		ORIGINAL ESTIMATE HOURS	MODIFIED ESTIMATE HOURS	NORMAL PERIOD (% PROGRESS)	NORMAL HOURS	EARNED HOURS	SITE EXPERIENCE FACTOR	ACTUAL HOURS	PI	% LOSS OF PROD.	NUMBER	FREQUENCY	HOURS	AVERAGE SIZE	%
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1	Chemical Plant	83400		0%-45%	154000	154000	2.43	224000	0.69	31	230	16	16000	70	7
2	Chemical Plant	40200		0%-45%	40900	40900	1.02	51900	0.79	21	260	17	13400	52	26
3	Chemical Plant	18000		0%-37%	17865	17865	0.99	20679	0.86	14	50	6	2100	42	10
4	Chemical Plant	8000		0%-79%	9392	9392	1.17	12828	0.73	27	55	6	1850	34	14
5	Coal Preparation Plant			0% 46%.	46621	46621		71887	0.65	35	322	23	25000	78	35
6	Recalcining Plant	23800	25000			25000	1.05	31150	0.80	20	200	18	12000	60	39
7	Thermal Power Plant	37100		41%-70%	48000	48000	1.29	59451	0.81	19	100	7	5882	59	10
8	Sewage Treatment Plant	56776			56776	56776	1.00	68500	0.83	17	200	17	4388	22	6
9	Pulp Mill Expansion	47000	47000			47000	1.00	67700	0.69	31		0	32000		47
10	Elevator Terminal	25000	45000			45000	1.80	67677	0.66	34	92	5	7523	82	11
11	Thermal Power Plant	32800	45950			45950	1.40	68486	0.67	33	150	9	8000	53	12
12	Thermal Power Plant	51230	53671			53671	1.05	79873	0.67	33	250	16	10000	40	13
13	Mineral Smelter	36280	43000			43000	1.18	54700	0.79	21	124	8	10000	81	18
14	Cement Plant	68475	95000			95068	1.39	141304	0.67	33	75	3	47400	632	34
15	Sewage Treatment Plant	14050		40%-78%	21100	21100	1.50	29743	0.71	29	100	4	5264	53	18
16	Automotive Plant	96200	108213			108213	1.12	149133	0.73	27		0	15000		10
17	Steel Plant Expansion	557000				557000	1.00	661600	0.84	16	150	8	83000	553	13
18	Water Filtration Plant	174700			173000	173000	0.99	207932	0.83	17	25	1	37000	1480	18
19	Food Processing Plant	140000				140000	1.00	213500	0.66	34	700	58	23000	33	11
20	Food Processing Plant	86000	102000			102000	1.19	189000	0.54	46	2150	143	25500	12	13
21	Rock Crusher					6050		7530	0.80	20	65	24	4000	62	53
22	Cement Crusher					3300		4400	0.75	25	140	56	450	3	10
23	Oil Refinery	84800	109233			109233	1.29	119112	0.92	8		0	8150		7
24	Aluminum Plant	14529	17000			17000	1.17	33300	0.51	49	110	22	17200	156	52
25	Aluminum Plant	8500	10000			10000	1.18	14000	0.71	29		0	6075		43
26	Aluminum Plant	14250	15700			15700	1.10	21900	0.72	28		0	9850		45
27	Aluminum Plant	23000	33800			33800	1.47	57800	0.58	42	170	22	23000	135	40
28	Brewery Plant Expansion	9000		20%-70%	7313	7313	0.86	10675	0.69	31	104	21	4000	38	37
29	Chemical Plant	19960	15250			15250	0.76	22500	0.68	32		0	3000		13
30	[illegible]mical Plant	9000	9500			9500	1.06	16900	0.56	44		0	5000		30
31	[illegible]nt Plant	62500	88000			88000	1.41	110500	0.80	20	70	12	24200	346	22
					TOTALS	2144702		2889660					489232		

TABLE B.2 - ELECTRICAL/MECHANICAL CONTRACTS ON INDUSTRIAL CONSTRUCTION:

CALCULATION OF PRODUCTIVITY LOSS AND MEASUREMENT OF CHANGE ORDERS

#	TYPE OF PROJECT	TYPE OF IMPACT	MAJOR CAUSES OF PRODUCTIVITY-RELATED IMPACT: CHANGE ORDERS	INADEQUATE COORD. & SCHEDULING	ACCEL-ERATION	OTHERS	MINOR CAUSES OF PRODUCTIVITY-RELATED IMPACT	CAUSES OF DELAY-RELATED IMPACT ONLY
1	Chemical Plant	3	X		X	Change in Sequence (Work by Systems,	Late Delivery of Material	
2	Chemical Plant	1	X				Late Delivery of Material	Reinstallation of Equip.
3	Chemical Plant	1	X				Late Del. of Mtl. & Completion of Piperacks	
4	Chemical Plant	2	X			Late Delivery of Equip., Mtl. & Info.		
5	Coal Preparation Plant	2	X		X		Late Issue of Drawings; Untimely Responses	
6	Recalcining Plant	1	X					
7	Thermal Power Plant	2	X		X		Late Issue of Drawings	
8	Sewage Treatment Plant	1	X				Untimely Responses	
9	Pulp Mill Expansion	2	X		X			Late Issue of Drwgs. & Del.
10	Elevator Terminal	3	X	X	X		Late Del. of Equip./Mtl.; Changing Priorities	
11	Thermal Power Plant	2	X			Late Release of Drwgs., Info. & Work	Late Del. of Equip./Mtl.; Changing Priorities	
12	Thermal Power Plant	2	X			Late Release of Drwgs., Info. & Work	Late Del. of Equip./Mtl.; Changing Priorities	
13	Mineral Smelter	2	X		X		Priorities Requested by Owner	Late Issue of Drwgs. & Del.
14	Cement Plant	2	X	X				
15	Sewage Treatment Plant	2	X			Equipment Interfacing Problems	Late Del. of Equip.; Untimely Responses	Late Completion of Structure
16	Automotive Plant	2	X		X			Late Completion of Structure
17	Steel Plant Expansion	1	X				Impeded Access	
18	Water Filtration Plant	1	X				Impeded Access (Late Compl. of Structure)	
19	Food Processing Plant	3	X	X		Increased Complexity & Overdemanding	Late Delivery of Equipment	
20	Food Processing Plant	3	X	X		Increased Complexity & Overdemanding	Late Delivery of Equipment	
21	Rock Crusher	2	X		X		Late Delivery of Equipment	
22	Cement Crusher	2	X			Interferences & Obstructions		Late Availability of Site
23	Oil Refinery	1	X				Late Del. of Equip.; Changing Priorities	
24	Aluminum Plant	2	X		X		Late Issue of Drwgs. & Del. of Mtl.	
25	Aluminum Plant	1	X				Impeded Access	
26	Aluminum Plant	1	X					
27	Aluminum Plant	2	X		X		Late Delivery of Material	
28	Brewery Plant Expansion	1	X				Late Issue of Drwgs. & Del. of Mtl.	
29	Chemical Plant	2	X		X		Problems with Speciality Items	Late Completion of Civil/Str.
30	Chemical Plant	2	X		X		Late Delivery of Equipment	
31	Cement Plant	1	X				Late Delivery of Equipment	

TABLE B.3 - ELECTRICAL/MECHANICAL CONTRACTS ON INDUSTRIAL CONSTRUCTION: ASSESSMENT OF CAUSES OF IMPACT

#	TYPE OF PROJECT	TYPE OF WORK	TYPE OF CONTRACTOR	TYPE OF CONTRACT	VALUE OF ORIGINAL CONTRACT	VALUE OF CHANGE ORDERS	ORIGINAL DURATION (MONTHS)	ACTUAL DURATION (MONTHS)	% EXTENDED DURATION	NUMBER CHANGE ORDERS	MAJOR CAUSE OF CHANGE ORDERS
1	Educational Residences	Concrete	Prime	LS	$1,310,000	$200,000	8	14	133	13	Design Changes
2	Educational Residences	Masonry	Prime	LS			6	14	133	10	Design Changes
3	Educational Residences	Concrete	Prime	LS	$2,000,000	$200,000	12	15	25	12	Design Changes
4	Educational Residences	Masonry	Prime	LS			12	15	25	11	Design Changes
5	Educational Residences	Masonry	Prime	UP	$260,000	$60,000	6	10	58	10	Design Changes
6	Educational Residences	Drywall	Prime	LS	$320,000	$40,000	2	11	450	20	Design Changes
7	Educational Residences	Drywall	Prime	LS	$430,000	$50,000	6	11	83	25	Design Changes
8	University Building	Concrete	Prime	UP	$3,760,000	$450,000	10	16	63		Late/Incomplete Design
9	Residences	Masonry	Prime	LS	$3,675,000	$1,000,000	15	20	38	235	Design Changes
10	School Renovations	Arch	GC	LS	$3,780,000	$240,000	6	10	67	20	Unforeseen Conditions; Design Changes
11	Processing Facility	Masonry	Prime	LS	$1,970,000	$890,000	16	21	32	253	Incomplete Design
12	Airport Terminal	Asbestos	Sub	LS	$300,000	$200,000	13	19	46	25	Unforeseen Conditions
13	Airport Terminal	Str/Arch	GC	LS	$2,200,000	$290,000	9	20	122	46	Design Changes
14	Museum	Drywall	Sub	LS	$80,000	$0	3	9	183	0	
15	Public Building	Roof	Sub	LS	$1,980,000	$400,000	8	8	0	100	Design Changes
16	Bridge Reconstruction	Concrete	GC	LS	$2,000,000	$350,000	10	21	110		Unforeseen Conditions; Design Changes
17	Industrial Plant	Concrete	Prime	LS	$940,000	$120,000	10	10	0	65	Design Changes
18	Cement Plant	Civil	GC	LS	$6,400,000	$350,000	12	12	0	75	Design Changes
19	Hydro Dam Refurbishment	Concrete	GC	UP	$760,000	$235,000	2	4	75	10	Change in Scope & Quantity Variations
20	Pulp Mill Expansion	Concrete	Prime	LS	$2,700,000	$60,000	5	7	40	100	Late/Incomplete Design
21	Thermal Power Plant	S/Steel	Prime	LS	$1,820,000	$400,000	10	18	80		Design Changes
22	Mill Building	Concrete	GC	UP	$1,000,000	$830,000	9	9	0	190	Change in Scope & Design Changes
23	Mill Building	Concrete	GC	UP	$1,400,000	$830,000	9	9	0		Change in Scope & Design Changes
24	Mill Building	S/Steel	Sub	LS	$3,200,000	$2,500,000	9	9	0	150	Design Changes
				TOTALS	$42,285,000	$9,896,000					

TABLE C.1 - CIVIL/ARCHITECTURAL CONTRACTS ON BUILDING AND INDUSTRIAL CONSTRUCTION: BACKGROUND INFORMATION

#	TYPE OF PROJECT	CALCULATION OF PRODUCTIVITY LOSS									MEASUREMENT OF CHANGE ORDERS				
		ORIGINAL ESTIMATE HOURS	MODIFIED ESTIMATE HOURS	NORMAL PERIOD (% PROGRESS)	NORMAL HOURS	EARNED HOURS	SITE EXPERIENCE FACTOR	ACTUAL HOURS	PI	% LOSS OF PROD.	NUMBER	FREQUENCY	HOURS	AVERAGE SIZE	%
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1	Educational Residences	20808		30%-62%	27750	27750	1.33	37700	0.74	26	13	1	5800	446	15
2	Educational Residences	11250		42%-70%	14250	14250	1.27	17600	0.81	19	10	1	1900	190	11
3	Educational Residences	23200		73%-96%	23000	23000	0.99	26800	0.86	14	12	1	2300	192	9
4	Educational Residences	40300		0%-60%	52000	52000	1.29	63220	0.82	18	11	1	3000	273	5
5	Educational Residences					15000		19800	0.76	24	10	1	1700	170	9
6	Educational Residences			42%	13000	13000		15450	0.84	16	20	2	1300	65	8
7	Educational Residences			42%	12300	12300		15250	0.81	19	25	2	2000	80	13
8	University Building	86500		7%-25%	88500	88500	1.02	132200	0.67	33		8	10350		8
9	Residences	13166			13160	131600	1.00	179000	0.74	26	235	12	35000	149	20
10	School Renovations					20000		26000	0.77	23	20	2	6000	300	23
11	Processing Facility	74500		0%-80%	79300	79300	1.06	97200	0.82	18	253	12	32800	130	34
12	Airport Terminal					6200		8900	0.70	30	25	1	5100	204	57
13	Airport Terminal			39%	30500	30500		35500	0.86	14	48	2	5000	109	14
14	Museum					2900		3400	0.85	15	0	0	0		0
15	Public Building					17400		21500	0.81	19	100	13	9400	94	44
16	Bridge Reconstruction					35000		43000	0.81	19		0	12000		28
17	Industrial Plant	52000		45%-55%	52000	52000	1.00	69000	0.75	25	65	7	8000	123	12
18	Cement Plant	74500		8%-27%		105000	1.41	133000	0.79	21	75	6	14200	189	11
19	Hydro Dam Refurbishment					19500		25500	0.76	24	10	3	6500	650	25
20	Pulp Mill Expansion					14000		22500	0.62	38	100	14	2700	27	12
21	Thermal Power Plant			0%-15%	25000	25000		35600	0.70	30		0	9600		27
22	Mill Building	36800	44000			44000	1.20	57000	0.77	23	190	22	21500	113	38
23	Mill Building	40600	48000			48000	1.18	59000	0.81	19		0	17000		29
24	Mill Building	44300	46800			46800	1.06	53150	0.88	12	150	18	8300	55	16
				TOTALS		923000		1197270					221450		

TABLE C.2 - CIVIL/ARCHITECTURAL CONTRACTS ON BUILDING AND INDUSTRIAL CONSTRUCTION:

CALCULATION OF PRODUCTIVITY LOSS AND MEASUREMENT OF CHANGE ORDERS

#	TYPE OF PROJECT	TYPE OF IMPACT	MAJOR CAUSES OF PRODUCTIVITY-RELATED IMPACT: CHANGE ORDERS	INADEQUATE COORD. & SCHEDULING	ACCEL-ERATION	OTHERS	MINOR CAUSES OF PRODUCTIVITY-RELATED IMPACT	CAUSES OF DELAY-RELATED IMPACT ONLY
1	Educational Residences	2	X			Dimensional Discrepancies		
2	Educational Residences	2	X			Ripple-Effect of Delays to Structure; Dim. Discrep.	Late Delivery of Material	
3	Educational Residences	2	X			Ripple-Effect of Delays to Structure; Dim. Discrep.		Late Approval of Shop Drwgs
4	Educational Residences	2	X			Ripple-Effect of Delays to Structure; Dim. Discrep.		
5	Educational Residences	2	X			Ripple-Effect of Delays to Structure; Dim. Discrep.		
6	Educational Residences	2	X			Ripple-Effect of Delays to Structure; Dim. Discrep.		
7	Educational Residences	2	X			Ripple-Effect of Delays to Structure; Dim. Discrep.		
8	University Building	3	X		X	Late Flow of Info.; Ineffic. Crane Oper.; Increased		
9	Residences	2	X		X	Qty. of Small-Sized Rebar	Interferences by Others; Late Del. of Mtl.	Late Completion of Struct.
10	School Renovations	2	X		X			
11	Processing Facility	1	X				Lack of Master Schedule	Late Completion of Struct.
12	Airport Terminal	2	X			Increased Difficulty	Late Issue of Drwgs.; Impeded Access	
13	Airport Terminal	1	X				Late Approval of Shop Drwg.; Untimely Responses	
14	Museum	2				Ripple-Effect of Changes and Delays to Structure		
15	Public Building	1				Mtl. Deficiencies & Poor Sequence of Delivery	Changes	
16	Bridge Reconstruction	1	X					
17	Industrial Plant	2	X		X		Late Delivery of Material	Unavailability of Site
18	Cement Plant	2	X		X			
19	Hydro Dam Refurbishment	2	X		X			
20	Pulp Mill Expansion	2	X	X				
21	Thermal Power Plant	2	X		X			
22	Mill Building	1	X				Winter	
23	Mill Building	1	X				Winter	
24	Mill Building	1	X					

TABLE C.3 - CIVIL/ARCHITECTURAL CONTRACTS ON BUILDING AND INDUSTRIAL CONSTRUCTION:

ASSESSMENT OF CAUSES OF IMPACT