QUALITATIVE AND QUANTITATIVE ANALYSES OF FACTORS AFFECTING PRODUCTIVITY IN CANADIAN CONSTRUCTION PROJECTS

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by

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A thesis submitted to the School of Graduate Studies in partial fulfillment of the requirements for the degree of Master of Engineering

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March, 1993
St. John's Newfoundland

ISBN 0-315-82639-8

Abstract

The decline in construction productivity across the North America since the mid 1970's has been reported by many researchers. Potential exists to affect major cost savings if the factors underlying this decline can be identified and quantified and solutions found. The issue is complex. However, it is generally acknowledged that productivity improvement is a management responsibility and that problems are within the control of management to solve.

This work uses a survey to study the perception of Canadian construction professionals toward factors affecting construction productivity. Findings for different regions of the country are presented and contrasted. Factors analyzed are clustered into the following groupings: a) contract environment, b) planning, c) site management, d) working conditions, e) working hours and f) motivation. Major factors affecting productivity are identified.

In addition, a weather-related factor model is developed to predict productivity as a function of weather and other site factors. Significant findings are that a high percentage of the variation in productivity is accounted for by height of worksite above grade and by average temperature, wind and rain. A method is suggested to allow the calculation of time-location modifiers that would account for local weather conditions and seasonal effects. They will be of use in more accurate project planning and costing.

Acknowledgements

The author wishes to thank the Faculty of Engineering and Applied Science for affording him the opportunity of conducting this work. Particularly, the supervision of Dr. Awad Hanna and his suggestion of an exciting research topic is greatly appreciated. The support and encouragement of Dr. T. R. Chari, former Associate Dean of the Faculty is also acknowledged.

The author wishes to thank Dr. Linda Inkpen, President of the Cabot Institute of Applied Arts and Technology and its Board of Governors for providing a year of educational leave and financial support so that the present work could be initiated.

The author is grateful to the Faculty of Engineering for financial support in the form of teaching assistantships during his year of residence at Memorial University.

Finally, the patience and understanding of the author's wife and family during the research period is greatly appreciated.

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Chapter 1

Introduction

Construction productivity is of critical importance to the profitability of most construction projects. Lessened productivity, for whatever reasons has the effect of increasing the time required to complete scheduled activities with subsequent cost over runs.

Interest in construction productivity improvement dates to the time of the ancient Egyptians. Legend says that Hamid, a construction superintendent working on the Great Pyramid complained so vehemently regarding the inefficiency and lack of safety on the project that an aggressive constructability improvement project was undertaken. Modern estimates indicate that as a result, ensuing pyramids were constructed 13.5% faster and at an overall cost savings of 23.8%.

In 1983, the Business Roundtable's Construction Industry Cost Effectiveness Project (CICE) completed a four-year study to promote quality, efficiency, productivity and cost effectiveness in the construction industry. Its twenty-four reports are results of studies begun in 1979 that involved 250 volunteer participants from some of the worlds largest companies. The Canadian perspective was well represented via membership in the study groups. The reports presented 223 recommendations for improvement directed toward owners, contractors, organized labor, government agencies, the design community and academics. Although primarily related to the North American construction industry, much of the material also concerns construction world wide.

Since that time, the Construction Industry Institute (CII) at the University of Texas was created as a focal point of research into new management methods and techniques to improve the construction industry.

Productivity is widely acknowledged to be a management function. The Business Roundtable studies and the subsequent work of the Construction Industry Cost Effectiveness project (Business Roundtable Report A-6, 1982) fault management for poor use of modern planning methods and are critical of owners for not acknowledging the economic payoff from planning. These latter studies have had the effect of heightening awareness of these issues and have lead to a growth of graduate programs in Construction Management in American and Canadian universities.

Unwillingness or laziness on the part of the work force is rarely a cause of poor worker efficiency. The Craftsman Questionnaire (Chang & Borcherding, 1985b) investigated causes of problems that effect craftsman productivity and motivation. Factors include rework, materials problems, tools, heavy equipment availability, crew interferences, overcrowded work areas, instruction, quality control inspection and management interventions. Many of these problems may be ameliorated by proper management and by the skill of experienced foremen (Maloney & McFillen, 1987a).

Many of the strategies that lead to improved productivity also lead to higher quality. Conversely the recent resurgence of interest in Total Quality Management (**TQM**) in North America has had the effect of improving productivity as well. The commonly held belief that high productivity can only be achieved at the expense of lowered quality is debunked by followers of TQM. An extract from the 1992 award criteria of the prestigious **Baldrige National Quality Award** stresses the concept of continuous improvement:

> Achieving the highest levels of quality and competitiveness requires a well-defined and well-executed approach to continuous improvement. Such improvement needs to be part of all operations and of all work unit activities

> of a company. Improvements may be of several types: (1) enhancing value to the customer through new and improved products and services; (2) reducing errors, defects, and waste; (3) improving responsiveness and cycle type performance; and (4) improving productivity and effectiveness in the use of all resources. Thus, improvement is driven not only by the objective to provide better quality, but also by the need to be responsive and efficient— both conferring additional marketplace advantages. To meet all of these objectives, the process of continuous improvement must contain regular cycles of planning, execution, and evaluation. This requires a basis — preferably a quantitative basis — for assessing progress, and for deriving information for future cycles of improvement.

The effectiveness of total quality control as practiced in Japan, has been discussed (Rounds & Chi, 1985) and the establishment of quality control circles (Gilly *et al.*, 1987a) has been recommended. The experiences of Brown and Root Inc. and other large organizations has been positive. Formal quality and productivity improvement programs have been implemented (Laufer, 1985) (Arditi, 1985) and are well known in the industry.

Formal techniques for productivity measurement and improvement, such as work sampling, lead to the selection of work crews that are balanced to produce optimum efficiency. Construction estimating handbooks offer accurate estimates of crew productivity based on a variety of management conditions and are widely used in the construction industry for planning and scheduling.

1.1 Productivity Measurement Methods

There are a number of measures of productivity that have application in economics and in construction. In economics, where the objective is to develop measures of use in policy planning, total factor productivity (TFP) is defined as follows:

$$\begin{aligned} \text{TFP} &= \frac{Total\ Output}{Total\ Input} \\ &= \frac{Total\ Output}{Labor + Materials + Equipment + Energy + Capital} \end{aligned} \tag{1.1}$$

In construction, it is usual to measure productivity with reference to project or task performance. Commonly productivity is defined as output per labour cost or output per labour hour. Alternatively the inverse can be used, so that labor productivity can be defined as:

$$\text{Labor Productivity} = \frac{\text{Labor costs or workhours}}{\text{Output}} \tag{1.2}$$

Productivity in a bricklaying activity, for example, may then be measured as person-hours per m^2. This method of representing productivity is used in this report. High values of productivity represent poor performance.

Productivity measurement techniques have been surveyed (Thomas *et al.*, 1990) and can broadly be classified as those based on work study models and those based on productivity models. Work study models use tools borrowed from industrial engineering. Productivity models are more suited to construction. Work sampling has been investigated (Thomas, 1991) and the relationship between direct work and productivity has been studied. In contrast to a number of previous studies, it was determined that productivity does not correlate with the amount of direct work. The conclusion is "that work sampling studies show how busy the crafts are but the results cannot be used to predict labor productivity or to quantify inefficient work hours."(ibid)

1.1.1 Work Study Models

A work study method is sometimes called a time-motion study. The study is done in two phases. The preferred method of doing the work is first determined (the motion study) and then a time study is done to determine the standard time to perform the task. Common data collection techniques used are time lapse photography, video photography, stopwatch timing and work sampling. Results are commonly presented using gang and crew balance charts, process charts and material flowcharts.

Work sampling is a technique in which a large number of observations are made over a period of time of a construction activity. The craftspeople, machines and processes are studied and the percentage of time spent in a number of work states is noted. The American Institute of Industrial Engineers' definition of work sampling is:

> "the application of statistical sampling theory and technique to the study of work systems in order to estimate universe parameters from sample data. It is commonly used in the work measurement and methods engineering area to produce statistically sound estimates of the percentages of time that a work system is in any of a variety of states of work activity. With appropriate procedures, work sampling can produce information from which time standards can be determined"

The selection of classifications for work requires great care. In construction four "work states" are commonly used and are described below:

Direct Work: This classification of work deals with activities that directly contribute to construction of the project. Examples include craftsmen using tools, a welder welding or employees operating a concrete vibrator.

Indirect Work: This classification of work is necessary work in support of but not an integral part of direct work. Examples include a craftsman cleaning up, an employee transporting material, workers studying drawings or a craftsman giving instruction to employees.

Idle: Idle classification covers activity or lack thereof that is unrelated to the project and unexplained. Examples include an employee standing idle while a second one cleans up, a craftsman walking empty handed, employees chatting while getting a glass of water.

Delay: This classification refers to inactivity that is related to unavailability of tools or queueing. Examples include craftsmen waiting in line at the tool shed, employees waiting for materials to be picked up by a crane or employees waiting for direction.

Often, in evaluation of the type of activity, a judgement call is necessary. For example employees on fire watch during a welding operation are considered to be doing direct work since their activity is an extension of the welding activity.

More classifications than the four discussed above are possible and are commonly used. Among these are a) personal breaks, b) direct work, c) giving or receiving instructions or assignments, d) late or early quitting, e) material or equipment handling f) transporting or materials, tools or equipment, g) travel empty handed and h) delays.

Scarfuto(1985) presents an example of construction work sampling and categorizes time spent as direct work, indirect work, idle time and delay time. Liou and Borcherding(1986) studied the correlation between the results of work sampling measurements and actual productivity. Results showed a close relationship between the two. In addition, the usefulness of work sampling information as a predictor in the productivity projection model was demonstrated. Thomas(1991) offered an opposing opinion. The hypothesis that direct work percentages from work sampling studies can be used to predict labor productivity was examined. Data and observations from a number of articles and databases were analyzed. The overwhelming conclusion of the investigation was that direct work cannot be used to predict labor productivity.

1.1.2 Craftsman Questionnaire

The Craftsman Questionnaire (CQ) is one of the techniques for measuring management performance. The main function of the CQ is to determine the cause of problems that adversely affect craftsmen's productivity and motivation. It requires craftsmen to estimate the loss of time that corresponds to problems and rank the severity of the problems. John D. Borcherding attempted to formulate a procedure for a Craftsman Questionnaire in a study of twelve large energy projects (Tucker *et al.*, 1983). Problems investigated included material availability, tool availability, rework, crew scheduling, overcrowded work areas, instruction, inspection delays, craft turnover, craft absenteeism, availability of labor, overtime, supervisory turnover and supervisory capacity.

The Craftsman Questionnaire has received considerable acceptance in construction since it involves the people closest to the workplace and provides a method of focusing on solutions to problems. The validity of the questionnaire has been the subject of some study. Chang and Borcherding(1985a) found that the percentage of lost hours as reported via the Craftsman Questionnaire agreed well with those obtained using parallel work sampling methods.

1.1.3 Camcorders

Eldin and Egger(1990) discuss the use of camcorders as a management to improve construction productivity. Their use produced measurable benefits to the project including improving communications between management and labor, identifying the reasons for productivity problems and providing irrefutable records of construction activities. Three construction activities were studied, a) tilt-up panels, b) precast units and c) metal studs and drywalls. In all cases, study of the camcorder films determined ways that operations could be made more efficient. In particular the following productivity improvement concepts were addressed:

- providing clear communications
- obtaining fast feedback
- more effective use of management time
- establishing a project team attitude
- improving site operations and erection procedures.

1.1.4 Rules of Credit

It is recognized that certain work may be only part completed at the end of a work day. A naive measurement, for example, of the number of pieces of structural steel placed in a given day may be optimistic if additional work (such as fastening and plumbing) is yet to be done. It is common practice in the measurement of work output to assign rules of credit to the components of an activity. Thomas and Yiakoumis (1987) give sample rules of credit for a number of activities. Some of these are shown in Table 1. Rules of credit for masonry block work are relatively simple. The

Table 1: Sample Rules of Credit

Task of commodity	Units of measure	Rules of credit	Description
Electrical cable (power and control)	Each or foot	50% pulled	Pulled and secured in raceway
		30% terminated	Terminations completed on both ends and accepted by QC.
		20% accepted	Tested and accepted by QC
Modular wall formwork	Square metre	45% outside form	Erect outside wall form
		10% plumb	Outside wall form braced and plumbed
		35% inside form	Erect inside form and secure
		10% strip clean	Strip, clean and oil

activity is seventy (70) percent completed on layout/placement of block and horizontal reinforcement. Twenty (20) percent of the activity involves grouting cavities and placing vertical reinforcement and the final ten (10) percent is spent in parging the outside wall.

1.2 Problem Statement

Oglesby, Parker and Howell (Oglesby *et al.*, 1989) define productivity as follows:

> The effectiveness with which management skills, workers, materials, equipment, tools and working space are employed at or in support of work-face activities to produce a finished building, plant, structure, or other fixed facility at the lowest feasible cost.

The Business Roundtable reports have concluded that construction productivity has been declining in the last two decades. Late completion of projects, resulting from this decline, delays the benefit of the project and brings inconvenience to the project owners. Construction managers have two problems regarding productivity:

1. To identify those factors responsible for lack of efficiency in construction sites
2. To quantify the effect of these factors in terms of dollars, time and percent of productivity reduction.

1.3 Methodology

This present work uses two approaches to study factors affecting construction productivity. A questionnaire has been designed to determine the opinion of construction management and foremen regarding factors that are known to have a positive or negative effect on productivity. In addition a construction site study was undertaken to test quantitatively the effect of a limited number of measurable factors on a blockwork project. Factors studied included weather conditions and constructability, measured as the number of interruptions for doors and windows in the day's work. A mathematical model (multiple linear regression) was developed that could be used to predict construction productivity.

The following are specific tasks that were undertaken to complete the project:

1. A review of the literature and compilation of factors relating to construction productivity

2. Development of a questionnaire,

3. Collection, compilation and ranking of responses - computer program

4. Analysis of responses and and study of variances,

5. Monitoring of blocklaying activity on a daily basis,

6. Study of the effect of selected factors on the blocklaying activity,

7. Development of a statistical model to quantify the effect of those selected factors

1.4 Objectives

This study has three objectives. The first is to collect, compile and rank those factors that contribute to lower productivity in Canadian Construction sites. The second is to quantify some of these factors via actual productivity measurements. The third objective is to develop a model of construction productivity that will allow the prediction of productivity with knowledge of weather conditions. As a consequence of this last objective a suggestion for the development of time-location modifiers for construction productivity will be presented.

1.5 Expected Results

The following are expected results of the research:

1. the identification of problem areas regarding productivity

2. the determination of the effect of various factors on productivity,

3. the quantifying of the effect of a select number of weather related factors on a specific construction activity.

4. the prediction of the increase or decrease in productivity by the use of a statistical model

1.6 Organization of the Research

Chapter 1 defines the research objectives and describes methodology. Chapter 2 reviews the current literature relating to construction productivity and formulates a survey questionnaire. Chapter 3 presents an analysis of the results of the survey. Chapter 4 describes the data collection technique used to measure the productivity data at the test site and presents an analysis of that data. Chapter 5 presents conclusions and recommendations.

Chapter 2

Productivity in Construction

Factors that affect construction productivity can be complex and interrelated. Some factors have a direct effect such as those that are worksite related. Clearly, if the worker is not supplied with appropriate tools and materials, productivity will suffer. Similarly, the effect of good supervision and clear instructions are direct effects. Weather is a third example of a factor having a direct effect on productivity. In contrast to these factors which have a direct impact on productivity, there are a number of factors whose impact is just as significant but for more indirect reasons. Among these are issues relating to the nature of the construction contract, the use of overtime and other non-standard work schedules and project management.

2.1 Factors Affecting Productivity

For the purpose of this study, factors have been classified into six groups: a) contract environment, b) planning, c) site management, d) working conditions, e) working hours and f) motivation. The survey questionnaire addressed factors clustered within these groups. Factors included in the questionnaire were drawn from a study of the literature, from brainstorming with colleagues and from informal discussions with local contractors.

2.1.1 Contract Environment

The contract environment determines the "rules of the game" for a construction project (Business Roundtable Report A-7, 1982). Four factors relate to contract environment. The first is the contractual relationship. The contract relationship is a legal understanding between the contractor and the owner or the owner's agent. The second factor is constructability. Good constructability arises from good planning where contractor expertise is brought to bear at all stages of the design process. Constructability becomes an integral part of the project's plans and specifications. The third rule of the game is the union/non-union factor. The form of collective agreement can have an effect on management's ability to undertake an aggressive productivity improvement program. The fourth factor is the inspection regime imposed both by the project management organization (or architect) and by government regulatory bodies.

Contractual relationship Many and vari· forms of contract relationships can be used to execute a construction project. Among them are turnkey, design/build, cost plus a fixed fee, guaranteed maximum price, lump sum, unit price, multiple contract and single prime contract. The selection of the type of contract will affect the way the owner applies a constructability program and the extent to which productivity improvements can be achieved (Ardery, 1991). In addition, the financial beneficiary of the improvement in productivity depends on the contracting strategy. For example, in a lump sum contract the benefits come to the contractor while in a cost plus contract the savings go to the owner. In either case, both direct cost savings and indirect savings arising from productivity improvements are significant.

McGeorge (1988), in discussing design productivity, suggests that reform may be necessary in the construction industry in the ways that consultants, designers and contractors are selected and paid. Present strategies militate against efforts at the design stage to improve productivity since the extra effort is often rewarded by a smaller professional fee.

Constructability Constructability is the capability of being constructed. Ardery (1991) in a survey of constructability issues for the Construction Management Committee of the ASCE defines a constructability program as:

> "the application of a disciplined, systematic optimization of the construction related aspects of a project during the planning, design, procurement, construction, test and start up phases by knowledgeable, experienced construction personnel who are part of the project team."

The importance of constructability issues and their effect on construction productivity has been recognized by the Business Roundtable reports (1982). The following comments are relevant:

- The constructability effort must start at the earliest phases of a project.
- Experienced construction personnel must be members of the project team.
- Constructability is not simply the review of plans and specifications after they are completed. This is usually too late. Constructability issues should form an integral part of the design
- Projects need an overall implementation plan, part of which is the constructability plan.
- It is necessary to convince the upper management of a company that it is cost beneficial to implement a constructability program.
- Constructability will pay off 10–20 times the cost of the program.

Because of the impacts on construction and engineering resources, the cost benefits of constructability programs can be analyzed (O'Connor, 1985). Data collection techniques include voluntary surveys, questionnaires and interviews with designers and constructors and pre-construction meetings (O'Connor *et al.*, 1986).

Union workforce Union issues were a major part of the Business Roundtable studies. Some restrictive provisions in union agreements (Business Roundtable Report C-4, 1982) were determined to be costly and widespread across North America. Further, owners and contractors do not seem to realize the impact of these costs. They seriously detract from the union contractor's ability to meet open shop competition. The phenomena of supervisors and foremen being members of unions (Business Roundtable Report C-3, 1982) was seen to compromise productivity, particularly where a division of the foreman's loyalty between the project and the union leads to less than vigorous action toward wasteful work practices. The report suggested that management should attempt to recover management rights bargained away over the years.

Local union politics can impact productivity (Business Roundtable Report C-7, 1982) if contractors are not sensitive to the effects of on-site politicking. On balance, the Business Roundtable concludes (Business Roundtable Report D-1, 1982) that to remain vigorous, the construction industry cannot afford the demise of the union sector of the industry which offers experienced and capable contractors and skilled management pool.

Inspection Administration and enforcement of building codes and regulations is critical if projects are to be executed in a compliant and safe fashion. The Business Roundtable (Business Roundtable Report E-1, 1982) found that for the most part, inspectors and code-enforcement personnel were held in high regard by contractors. However, some jurisdictions are understaffed , a condition that can cause inspection delays. A report recommendation was that inspectors be encouraged to seek further training.

2.1.2 Planning

The construction industry has been criticised, to a large extent justifiably, for its slow acceptance and use of modern management methods in the planning and execution of projects (Business Roundtable Report A-6, 1982). Planning and scheduling techniques exist in support of efficient planning of projects. Critical path and PERT methods have grown in sophistication over the years. During the decade since the release of the Roundtable reports, a revolution has occurred in computer hardware and software development. Micro and mini computers, sized and selected appropriately to the contractors needs have become readily available and cost effective, particularly if amortized over a number of projects. Systems are available to assist with, and monitor the project plan and schedule. Cost estimating, budgeting and control accounting allow dynamic access to up-to-date information about project costs. Modern project management software packages offer a varied selection of tools including scheduling and control, maintenance of resource availability datasets and resource leveling across projects. High end software products such are Artemis and Primavera are, in themselves, fourth generation database programs that allow full integration of project data with other financial and business applications.

Quality control and quality assurance plans allow the contractor to monitor and control the quality of sub-contractor work. It is common practice now, as part of a bid pre-qualifying process, to be required to demonstrate that a quality plan is in place.

Effective planning and adherence to a program of project updating and monitoring has the potential to provide significant productivity improvements.

2.1.3 Site Management

Site management issues relate to factors that impact productivity at the workplace. These factors directly influence the ability of the worker to do the assigned task in an effective way. They are largely within management's ability to control.

Change orders In construction, changes are frequently made during the course of the work. Further, owners and contractors rarely agree on the incremental impact of these change orders on final cost of the project. Experienced contractors and others familiar with construction claims report that the cost of change orders increases with time into the project (Tardif, 1990). Further, the effect of changes are particularly apparent when projects are fast tracked i.e. where design and construction are overlapped. It has been shown that change orders have a negative effect on the productivity of the contractors work force. An extensive study (Moselhi *et al.*, 1991) of over 50 construction projects used a linear regression model to show that there was a positive correlation between decrease in worker productivity and frequency of change orders during the projects. The effects of other factors, that were present in addition to the change orders, were studied as well and were found to have a cumulative effect on the decrease in worker productivity. The linear regression model proposed provides a method of estimating the effect of change orders.

Availability of working drawings In order for construction supervisors and crews to understand what is expected of them and to appreciate the scope of the project and their part in it, working drawings must be maintained on site. Without plans and specifications, foremen are unable to properly complete work assignments in a timely fashion. Further, they form the basis of the communication system between the site and head office and between the contractor and owner.

Site layout Effective site layout minimizes indirect work, wait time and idle time and hence contributes to project productivity. Often the site layout is affected by the availability and required mobility of equipment (cranes), the materials delivery schedule, site congestion, on site storage, and the access requirements of sub- contractors.

Task sequencing The project plan, if carefully designed, will give consideration to appropriate task sequencing. The logic of the plan which determines task precedences should make the flow of work on the job site efficient. The use of project float indiscriminately by the sub-contractors can have an adverse effect on site congestion. The amount of site congestion caused by the the late finish of activities is a function of task sequencing.

Materials Handling Recent Construction Industry Institute research has indicated that formal material management programs have the potential to yield sufficient construction cost savings yet small and medium sized commercial contractors may not feel that an integrated material management program is cost effective. Thomas et al.(1989) measured the effects of materials handling issues on construction productivity and determined the potential benefits of applying effective materials management practices on commercial construction projects.

The effects of known material handling difficulties were removed from the dataset so that an estimate of cost in the absence of material handling problems could be obtained. In addition, the results were compared with a similar project that did use a materials handling plan. An estimate of the cost of poor handling was a work-hour overrun of 18%.

Temporary facilities The availability of temporary facilities can allow work to proceed at an optimum level when weather and other disturbances would otherwise interrupt work. Examples of temporary facilities include a) weather enclosures, b) air, gas, water and electrical supply, c) crane support or rails and d) temporary road surfaces.

2.2 Working Conditions

Working conditions are factors relating to the environment in which the work is to be done. All but weather conditions are within management's ability to control. Management can, however, lessen the adverse effect of all of them.

Absenteeism Absenteeism was the focus of as Business Roundtable report (Business Roundtable Report C-6, 1982). The major causes of absenteeism are such job site de-motivators as excessive rework, poor supervision, and unsafe working conditions. Worker turnover is a serious problem as well, and has been identified as a symptom of poor management. Hinze et al.(1985) studied worker absenteeism on several construction projects. The research focus was on voluntary absenteeism i.e. being away from work without reasonable cause. The results of the research show that voluntary absenteeism is related to such factors as crew cohesion, job security, styles of supervision and travel distances to work. An important finding was that teamwork reduces absenteeism.

Accidents/safety Work-related injuries and illnesses, including fatalities, in construction occur at a rate 54% higher than that for all combined industries(Business Roundtable Report A-3, 1982). The direct and indirect (social and project) costs of such accidents is enormous. Contractors have, apart from their accepted moral responsibility, a financial incentive to provide a safe working environment. Further, an unsafe worksite is a major worker de-motivator affecting costly worker turnover.

Weather conditions Observation and experience indicate that construction productivity declines during periods of extreme weather conditions. Work performed is plagued by errors in judgement, carelessness, complaints, general lethargy, irritability and poor mental attitude, decreasing quality of workmanship, general slowdown of work pace and unscheduled stoppages of work. In regions where adverse weather is common, it is practice to introduce lost time due to weather as a contingency in the project plan. Attempts have been made to quantify the effects of weather on productivity. Koehn and Brown (1985) studied the effect of temperature and humidity on productivity and found, through a multiple linear regression analysis, that productivity declines at extremes of temperatures and also at high humidity values.

Thomas and Yiakoumis(1987) studied the effect of temperature and humidity on productivity by combining datasets from three tasks. Rules of credit were used to estimate the amount of work actually performed. After removing the effects of temperature and humidity, the data reasonably approximated the theoretical learning curve.

Construction equipment Efficient use of construction equipment is a major contributor to construction productivity. In road construction, for example, it is critical that equipment be properly selected and matched so that equipment wait time is minimized. In high-rise construction, it is important that the use of the crane and its operator be scheduled daily for optimum productivity. In many cases equipment can be used more efficiently than manual labor, and it is wise to consider this fact when requisitioning project resources.

Equipment breakdown must be anticipated and a contingency plan developed so that the project experiences minimum disruption.

2.2.1 Working Hours

The Business Roundtable reported(Business Roundtable Report C-2, 1980) that while occasional overtime may solve some immediate problems, the practice of long term scheduled overtime was counterproductive. The study reported that a nine hour day is on average 20% less productive than an 8 hour day. Thomas (1992) reviewed the literature and found results to be sparse and generally inconsistent. The belief that productivity suffers with increased workday or workweek has not been sustained. One source quoted, Daniel International (The Four-Ten 1979) concluded that a schedule based on four 10-hour workdays was more efficient than a normal schedule of five 8-hour days.

2.3 Motivation

The Business Roundtable, in its Construction Industry Cost Effectiveness project estimated that the annual volume of work in the construction industry in the United States is approximately $300,000,000,000. Of this amount 1/3 represents direct labor costs. The Roundtable(1982) estimates that implementation of a program to reduce absenteeism and turnover alone could result in a reduction of about 9% of direct labor costs. Applied to the Canadian scene, such a program would cause direct labor savings of close to $1,000,000,000 annually.

Roundtable studies contain two startling conclusions. First, construction productivity has either increased at a lower rate than other industries or has actually declined during the 1970's and early 80's. Second, worker absenteeism and voluntary turnover are relatively higher in the construction industry than in other industries. Maloney et al. (1986b) studied the nature of construction work as it relates to motivational issues and made the following observations:

1. Construction workers have growth needs that are similar in strength to other

blue collar trade workers

2. Contractors need to improve worker satisfaction with job content

3. The skill and knowledge of the workers, as evidenced by their levels of training and experience, appear to be adequate for the great majority of construction jobs.

Tucker(1986) attributes the decline in labour productivity to four factors. The first of these is the influence of labor costs on total project expenditure. Since the construction industry is a labor intensive sector, this effect of increased labor cost is expected to continue. The breakdown of communications as projects grow in size is a second cause of productivity decline. There is a need for effective project planning and control and comprehensive and efficient data and information flow within the contractor's organization. Related to the preceeding factor is the increase in the amount of project paperwork. Again the efficient use of computerized project management tools with emphasis on exception reporting and offering decision support capability will help in reducing the burden of paperwork. The fourth factor discussed is the lack of productivity training in university engineering programs.

Mendel(1991) suggests that the trend toward declining productivity in construction may have reversed so that during the period 1983–1991 there has been a net increase in productivity.

A model of worker motivation, performance and satisfaction has been developed and verified (Maloney & McFillen, 1987b) . In this model, called the expectancy model, motivation is defined as a function of both a worker's **expectancy**, i.e., his belief that he can convert his effort into a specified level of performance and a worker's **instrumentality** i.e., his belief that a specified level of performance will result in his receiving a specific outcome. The expectancy model has been found to provide a workable conceptual base for understanding the motivation of construction workers.

A survey of unionized construction workers from a large mid-western U.S. city (Maloney & McFillen, 1986a) found that the industry needs to devote particular attention to performance definition (the what, how and why of performance) and performance encouragement (providing workers with incentives). Regarding the latter, encouraging performance requires attention to five elements:

1. the value of the reward to be administered,
2. the amount of the award,
3. the timing of the administration of the award,
4. the likelihood in the worker's eyes that performance will be rewarded,
5. the equity of the rewards from the worker's perspective.

Studies have shown that several factors relating to interactions among people can have an impact on productivity. Among these factors are the attitude of the contractor, the makeup of the work crew, the attitude of the foreman, and the interaction among workers.

Contractor Attitude

The attitude of the contractor in the eyes of the worker was found to have an effect on worker motivation (Maloney & McFillen, 1987d). Actions that the contractor can take to improve motivation include (a) stressing the rewarding of good performance rather than the punishment of poor performance, (b) enhancing efforts to facilitate work and (c) encouraging greater participation of workers in decision making.

Construction Crew

An exploratory study (Maloney & McFillen, 1987c) of construction crews supports the basic contention that issues relating to crew interactions may have a significant influence on worker motivation, performance and satisfaction. A number of issues are addressed and are summarized below:

1. **Stability of employment.** An unstable employment pattern can cause difficulties affecting productivity. New workers have to undergo a period of job acclimatization (the learning curve). As well there is a process of socialization as the new member is exposed to the norms and goals of the group.

2. **Work crew staffing.** It is desirable to assemble work crews whose members are compatible and who can get along during periods of stress.

3. **Team building.** The building of a team identity can be important. Programs aimed at improving interpersonal communications, group decision making, and other group processes have been shown to improve the functioning of highly interdependent work teams.

4. **Goal setting.** Clear, difficult but attainable goals have repeatedly been shown to improve worker performance, but only if these goals have been accepted by the workers. Workers should have some part in their formulation, so that some degree of worker ownership is manifest.

5. **Incentives.** Proper individual and group incentives are necessary. Rewards that are valued by the workers must be based upon the workers' performance.

Foreman Attitude

The foreman is generally considered to have a critical role in worker motivation. Lemna et al. (1986) have investigated factors that differentiate successful (productive) foremen from those that are less productive. Three significant areas were identified. Firstly, it was found that highly productive foremen plan their work farther in advance than do less productive foremen. For the most part planning seems to take place in the foreman's head rather than on paper. Secondly, it appears that highly productive foremen generally order materials, tools, equipment and scaffold sooner than less productive foremen. Finally, more productive foremen generally are more honest in communicating the status of the project with the workers. Maloney and McFillen (1987b) surveyed unionized construction workers to gather their perceptions of the behavior of their foreman. Their conclusions with regard to the importance of supervision and the implications that they have for the selection and training of foremen are clear:

1. Foremen do have a strong impact on worker motivation, performance and satisfaction.

2. The job of foreman is truly multidimensional, requiring extensive knowledge of all contributing trades.

3. Actions must be taken to improve the support, facilitation and participation provided by foremen.

4. Actions should be taken to improve planning and scheduling, goal setting and communications.

Worker Interactions

Interactions and cooperation among workers has been recognized in Japan as a major contributor to increased productivity and quality improvement. Productivity and quality are not seen as factors that must be balanced or traded off against one another but rather as joint and compatible goals. Worker participation through the use of quality circles has been a means of motivating people to have 'ownership' of the product they produce.

The use of quality circles in construction have been successful in Japan (Gilly *et al.*, 1987b) and attempts have been made to introduce them in North America.

Characteristics of the construction industry that seem to be obstacles to introducing quality control in construction include (a) uniqueness of every project, (b) variable workforce, (c) project duration, (d) subcontractors, (e) owner influences and (f) hierarchical organization. Nonetheless, the success stories of some very large construction companies in the United States suggests that if implemented carefully, Quality programs can improve motivation, productivity and work quality.

2.4 Previous Work

Koehn and Caplan(1987) surveyed small to medium sized contractors to determine their views concerning construction productivity. Areas of high potential for improvement include supervision, labor contracts, labor training, planning, scheduling and communications. Agreement was found between the small and medium sized firms on planning, scheduling, site supervision and labor agreement functions. It is interesting to note that these are generally considered to be management related functions.

2.5 Survey Instrument

The survey of construction professionals, designed for this study, focused on the factors identified in this chapter. The actual survey form is shown in appendix A. The survey was tested on a small sample of local contractors and an iterative process of refinement was undertaken.

Respondents were asked specific questions regarding their perception of the factors affecting construction productivity. In addition, they were asked to rate factors as to importance and to offer comments. For the most part, comments were freely offered. The synthesis of these remarks form the basis of the discussion of chapter 3.

Chapter 3

Construction Productivity Survey

A survey of construction personnel was undertaken during the month of June 1992. The object of the survey was to gauge the opinion of personnel in the field of construction as to their perception of what factors most affect construction productivity. A second objective was to determine if there was any differentiation between Newfoundland and the rest of Canada in the perceptions of factors affecting productivity. The participants for the survey were selected from the *Directory of Corporate Member Firms and Member Associations of the Canadian Construction Association*. Two hundred fifty (250) survey forms were distributed. In order to get as broad an opinion as possible two forms were provided in each envelope and the addressee was asked that both a field and office person be asked to complete the survey. Altogether 58 or 23% were completed, a response typical of this type of survey. The results of the questionnaire were adequate to get a good feeling for factors that effect productivity.

The survey was constructed to elicit opinion on six groupings of factors. These groupings, and elements contained within them, were selected based on a review of the literature. The major groupings are a) contract environment, b) planning, c) site management, d) working conditions, e) working hours and f) motivation. In some cases, question were asked and opinions were sought (contract environment, planning and working hours) while in other cases, the respondent was asked to rate factors affecting productivity (site management, working conditions and motivation).

Comments were requested throughout the questionnaire. Space was provided for the respondent to provide factors that they considered important and which had not been included in the survey form. General comments were solicited as well.

3.1 Respondent Demographics

A number of questions were asked to determine the nature of the respondents, their companies and their construction specialties. The responses are discussed in the subsections that follow.

3.1.1 Regional

The breakdown of respondents by province is shown in Table 2. Responses were received from all provinces except Alberta and Prince Edward Island. In subsequent analysis, all provinces other than Newfoundland are grouped into traditional regions: the maritimes (Nova Scotia and New Brunswick), central (Ontario and Quebec) and West (Manitoba, Sasketchewan, and British Columbia). These three regions as well as Newfoundland represent a more reasonable classification of the respondents.

Table 2: Respondents by Province

Province	Number
Newfoundland	15
Nova Scotia	13
New Brunswick	8
Prince Edward Island	0
Quebec	1
Ontario	14
Manitoba	3
Saskatchewan	2
Alberta	0
British Columbia	2
Other	0
Total	58

3.1.2 Respondent Occupation and Construction Activity

Respondents varied in occupation from workface personnel to owners of relatively large companies. Table 3 lists the major occupations.

Table 3: Respondents by Occupation

Occupation	Number
Foreman	5
Field (project) engineer	1
Project manager	21
Other	31
Total	58

The type of construction activity performed by the respondent companies was varied as well. As evidenced by Table 4 , major areas of activity include commercial building and industrial construction. Several companies indicated activity in more than one major area.

Table 4: Respondents by Activity

Type of Construction	Number
Residential construction	11
Building construction - Commercial	36
Marine construction	13
Road/bridge construction	18
Industrial construction	31
Other construction	10
Total	119

3.1.3 Union Participation

Respondents represented companies that were union shops, non-unionized and a combination of both. Table 5 indicates the number of respondents of each type.

Table 5: Respondent by Union Participation

Union Affiliation	Number
Union operation	25
Non-Union operation	16
Union/Non-Union mixture	15
No response	2
Total	58

3.1.4 Company Size

A variety of sizes of companies participated in the survey. Tables 6 and 7 indicate that the respondents are split about 50–50, with half having 50 or more job-site employees and half having less than 50. For the purposes of the analysis, these will be identified as large and small respectively. The tables are consistent since the number of projects and the number of employees suggest the same division.

3.1.5 Productivity Study

Of the 57 respondents who answered this question, 18 indicated that they had undertaken a productivity study. Seventeen found the study useful. One did not find the study useful. Of the Newfoundland companies 6 had undertaken a productivity study, with 6 finding the exercise useful. A number of respondents indicated that they carefully monitored performance and compared against expected performance.

Table 6: Numbers of Projects

Number of Projects	Number of responses
1 to 5	8
6 to 10	10
11 to 15	9
More than 15	31
No response	2
Total	58

Table 7: Employee Strength

Number of Employees	Number of responses
Less than 5	1
5 to 9	7
10 to 19	6
20 to 49	18
50 or more	26
Total	58

3.2 Analysis of Questionnaire

In the subsections which follow, the results of the questionnaire are presented for each of the six groupings of productivity issues. Attempts have been made to contrast the Newfoundland responses with those from the rest of Canada as well as to determine if there are differences in perception arising from company size. Where possible an interpretation is proffered in the light of the Newfoundland economy and construction practices.

3.2.1 Contract Environment

Three issues relating to contract environment were studied: a) effect of contract type, b) constructability and c) inspection regime.

Contract Type

93.3% of the Newfoundland respondents felt that the form of the contract relationship has an effect on productivity. This contrasts and differs significantly (95% confidence) with the Canadian average of 78.6% and the non-Newfoundland results of 73.2%. Most respondents felt that the fixed price contracts tend to be most productive. It was generally felt that cost plus contracts were less productive. Lowest bid was seen to reduce overall project quality while cost plus produced a quality project but at greater cost.

The high response from the Newfoundland companies may have arisen from the proportionately large amount of government construction work done in relation to the private sector. For the most part government contracts are lowest bid. Cost plus contracts are relatively rare in Newfoundland.

72.0% of larger companies felt that the form of the contract affected productivity, compared with 83.9% for smaller companies. This is likely because a larger company is better able to absorb irregularities in contract execution that would severely effect the profitability of smaller companies.

Constructability

Constructability as a design issue is becoming more prominent. Much work is being reported in the literature as to how constructability affects project time and cost expenditure, and hence profitability. Several respondents indicated that the involvement of construction managers and general contractors in the design phase of a project can lead to significant savings. Designers, in general, lack construction skills and often focus on originality of design rather than constructability issues. Table 8 shows the importance attributed to constructability as a influence on productivity by region and company size. The data (number of responses) represents the opinion of the respondents as to whether they considered constructability to have an insignificant, moderate or great effect on productivity.

Table 8: Constructability Effect on Productivity

	Big Companies			Small Companies		
	Insignificant	Moderate	Great	Insignificant	Moderate	Great
Newfoundland	0	0	5	0	3	7
Maritimes	0	1	6	1	2	10
Quebec/Ontario	0	3	5	0	1	6
West	0	0	6	0	1	0

For the most part, constructability is regarded as a high contributor to productivity across the country. Both large and small companies report the same experiences — that productivity is higher and quality is better when an aggressive constructability program is implemented. A slight discrepancy is indicated in central Canada where some larger companies indicated a more moderate relationship between constructability and productivity. This may be because Ontario is more likely to have specialist prefabrication shops and is therefore already attuned to the issue of constructability. Generally, constructability is identified with good design and with good project documents (plans and specifications).

Inspection

Inspection issues caused the most respondent comment. Feelings toward the process were ambivalent but there was substantial agreement that the effect of the inspection regime was great. Table 9 shows the number of respondents, by company, who felt that inspection had an insignificant, moderate, great or negative effect on productivity.

Table 9: Attitude toward inspections

	Big Companies				Small Companies			
	Insig.	Moderate	Great	Negative	Insig.	Moderate	Great	Negative
Newfoundland	0	4	1	0	0	6	1	3
Maritimes	1	1	4	1	0	3	11	0
Quebec/Ontario	1	5	1	1	2	4	1	0
West	2	2	2	0	0	1	0	0

Many felt that inspectors were not knowledgeable of the plans and codes, and were not qualified and competent. On the other hand, it was acknowledged that an experienced inspector can reduce remedial costs and improve project quality. Inspections were seen by many as a source of delays if they are not timely and well planned and if the results are delayed. If performed correctly, inspections show flaws in construction design and give the opportunity to correct deficient designs. Good inspection identifies good contractors.

3.2.2 Planning

The vast majority of companies in the survey use some sort of project planning or Critical Path tools. See Table 10 . The reason for this proliferation is that the use of (computerized) project management methods is a requirement of most contracts. Many indicated that sub-contractors are difficult to schedule into the total project plan since they are beyond the day to day control of the prime contractor. The importance of proper monitoring of the project and its effect on the reduction of cost overruns was stressed.

Table 10: Use of Planning Tools

	Big Companies		Small Companies	
	Use CPM	No CPM	Use CPM	No CPM
Newfoundland	5	0	7	3
Maritimes	5	2	11	3
Quebec/Ontario	8	0	6	1
West	6	0	1	0

The attitude toward project planning and the effect on productivity was generally positive both in Newfoundland and elsewhere. Both users and non-users agreed that there was a moderate to great effect. Tables 11 and 12 show this trend.

Table 11: Attitude toward Planning - Newfoundland

	Productivity Increase			Productivity Decrease		
	Negligible	Moderate	Great	Negligible	Moderate	Great
Users of CPM	0	8	4	0	0	0
Non Users of CPM	0	1	0	0	0	0

Scheduling is one of the most important tools of construction when used properly. It puts pressure on supervisory personnel and workers alike to set goals. Proper use

Table 12: Attitude toward planning - Rest of Canada

	Productivity Increase			Productivity Decrease		
	Negligible	Moderate	Great	Negligible	Moderate	Great
Users of CPM	1	20	12	0	1	0
Non Users of CPM	0	4	0	0	0	0

implies a) determining correct task sequence (logic), b) establishing durations that reflect productivity and resources available, c) monitoring of progress on a continual basis and d) updating the network to reflect changed conditions. When this is done critical path scheduling has a great effect on construction productivity and whether or not the project makes a profit.

Planning forces the project team to build the job on paper, learn and understand the design documents and take a pro-active approach to problem resolution.

3.2.3 Site Management

A number of factors relating to site management were identified and the opinion of the survey participants was sought as to the degree that the factors affected productivity. The factors examined are shown in Table 13 along with the average responses from the regions. Factors were rated from a low of 1 (insignificant effect) to 5 (great effect). Results greater than four may be considered major factors. These major factors appear to be prevalent across the country. A significant anomaly appears in the central region (largely Ontario) in the attitude of respondents toward site layout. A possible explanation is that these companies have grown accustomed to working in congested urban settings and have developed experience in dealing with site layout problems.

The availability of clear working drawings appears to be the unanimous choice as the factor having the greatest effect on construction productivity. There appears to

Table 13: Factors relating to site management

Factor	Nfld.	Maritimes	Central	West	Canada
Change orders	3.8	4.0	4.2	4.6	4.2
Availability of working drawings	4.8	4.6	4.5	4.6	4.5
Site layout	4.0	4.3	3.1	4.7	4.0
Task sequencing	4.1	4.1	3.9	4.7	4.1
Materials management	3.9	4.5	3.7	4.3	4.2
On-site storage	3.1	3.3	3.1	3.2	3.2
Govt. and regulatory inspections	3.1	3.5	2.5	2.7	3.0
Weather enclosures	3.5	3.4	3.6	3.6	3.5
Air/gas/water/electrical supply	3.5	3.8	3.3	3.4	3.5
Temporary road surfaces	3.0	2.8	3.4	2.6	3.0

1 = insignificant effect —- 5 = great effect

be general agreement across the nation. Respondents were also asked to identify the two factors that had the greatest effect. Table 14 shows the results.

Newfoundland respondents were more adamant regarding the availability of working drawings. Four out of five named this factor as a prime contributor to productivity. In addition to the working drawing factors, major importance from all regions was given to task sequencing, material management and change orders. Task sequencing as a component of planning and materials management were considered to be within the power of effective project management efforts to control. On the other hand, change orders were considered to be less easily controlled and were associated with poor design and the unavailability of detailed drawings. Where change orders affect tasks on the critical path, the effect can be considerable both from the point of view of the project schedule and the total cost. In reducing the time and cost implications, good communications between owner and contractor is critical.

Table 14: Site management factors

Newfoundland	
Factor	Percent
Availability of working drawings	80.0%
Task sequencing	26.7%
Materials management	26.7%
Change orders	20.0%
Site layout	13.3%
Air/gas/water/electrical supply	13.3%
Weather enclosures	6.7%
Govt. and regulatory inspections	6.7%
Temporary road surfaces	6.7%
On-site storage	0.0%

Rest of Canada	
Factor	Percent
Availability of working drawings	53.7%
Task sequencing	48.8%
Change orders	34.1%
Materials management	22.0%
Site layout	12.2%
Govt. and regulatory inspections	9.8%
Weather enclosures	9.8%
Air/gas/water/electrical supply	7.3%
Temporary road surfaces	2.4%
On-site storage	0.0%

3.2.4 Working Conditions

Factors affecting working conditions are shown in Table 15 . There appears to be general agreement across the country on major factors. In comparing Newfoundland with the rest of Canada, there appears to be less concern in Newfoundland for safety and worker fatigue as factors affecting productivity. This could be interpreted positively as meaning that there is a vigorous program of safety and accident prevention in place and that therefore accidents do not have a major impact on construction productivity.

Tables 16 and 17 contrast responses from Newfoundland and elsewhere that were rated as most important. The data represents the percentage of respondents who rated the particular factor among the top two most important as to their effect on productivity. It is clear, across the country, that factors relating to construction equipment are of primary importance. It is agreed in Newfoundland and the rest of Canada that breakdown and non-availability are major factors. In Newfoundland the third factor identified related to the inappropriate use of manpower or manual tools

Table 15: Factors relating to working conditions

Factor	Nfld.	Maritimes	Central	West	Canada
Absenteeism	3.7	3.5	3.2	3.1	3.3
Worker turnover	3.6	3.4	3.5	3.9	3.5
Accidents/safety	3.0	3.4	3.9	3.7	3.7
Hot weather	2.3	3.2	3.1	3.0	3.1
Cold weather	3.5	3.8	3.4	4.0	3.7
Hight of worksite above ground	3.2	3.3	3.0	3.3	3.2
Site irritants - pollution, noise	2.4	2.7	2.2	3.3	2.6
Worker fatigue	2.9	3.6	3.2	3.4	3.4
Non-availability of tools	3.7	4.2	3.9	5.0	4.2
Equipment breakdown	4.2	4.5	4.1	5.0	4.4
Non-availability of constr. equipment	3.7	4.1	4.2	4.9	4.3
Inappropriate uses of tools/equipment	3.7	4.1	3.9	4.6	4.1

1 = insignificant effect — 5 = great effect

where construction equipment would be more appropriate. This factor was of considerable less importance outside Newfoundland. A possible explanation is the general scarcity of specialized construction equipment for rent and hire in Newfoundland.

Interesting additional comments from respondents, comments relating to working conditions, include:

- Height above ground can have an indirect positive effect on productivity if one presumes that the higher you go the greater is the repetition. On the other hand, working at height presents challenges for improved safety awareness and materials handling.
- Non-availability of tools is a demotivator.
- Tower cranes and other very specialized equipment can determine the entire productive cycle in high-rise construction.

Table 16: Working condition factors – Newfoundland

Factor	Percent
Equipment breakdown	35.7%
Non-availability of constr. equipment	35.7%
Inappropriate uses of tools/equipment	35.7%
Cold weather	28.6%
Worker turnover	21.4%
Non-availability of tools	14.3%
Height of worksite above ground	14.3%
Absenteeism	7.1%
Accidents/safety	7.1%
Site irritants - pollution, noise	0.0%
Worker fatigue	0.0%
Hot weather	0.0%

Table 17: Working condition factors – rest of Canada

Factor	Percent
Equipment breakdown	46.9%
Non-availability of constr. equipment	44.4%
Non-availability of tools	24.7%
Cold weather	19.8%
Absenteeism	17.3%
Accidents/safety	17.3%
Worker turnover	12.3%
Inappropriate uses of tools/equipment	9.9%
Height of worksite above ground	2.5%
Worker fatigue	2.5%
Hot weather	2.5%
Site irritants - pollution, noise	0.0%

- Drug or alcohol problems brought to the jobsite can have a great effect on productivity.

- It is rare for a job crew to perform poorly if they are properly equipped and supervised.

3.2.5 Working Hours

Factors relating to variable working hours were investigated in the survey. The effect on productivity of occasional overtime, scheduled overtime and shiftwork were studied.

Occasional Overtime

Table 18 shows the results of the survey relating to occasional overtime. For the most part, replies from across the country are consistent in saying, on a three to one basis, that occasional overtime has a moderate effect in increasing productivity. The key appears to be the sensible application of overtime, and judicious use only to expedite tasks on the critical path. Valid uses include a) working late or on weekends to get over a tight deadline, b) completing a task that could not safely be left overnight and c) completing a concrete pour on Friday so that the weekend would be available for curing. It was generally felt that more than occasional use of overtime has a serious negative impact on productivity.

Table 18: Attitude toward occasional overtime

	Increase in productivity			Decrease in Productivity		
	Negligible	Moderate	Great	Negligible	Moderate	Great
Newfoundland	0	9	1	0	3	1
Rest of Canada	4	24	3	3	7	0

Scheduled overtime

The attitude toward schedule overtime was generally negative, in contrast to that toward occasional overtime. Table 19 shows the results of the survey. Occasional overtime was seen as an emergency measure to address an immediate problem or opportunity. On the other hand, scheduled overtime was considered poor planning of inefficient use of manpower and material resources. Consequences of scheduled overtime include a) workers prolonging work in anticipation of overtime, b) worker fatigue and c) increased costs.

Table 19: Attitude toward scheduled overtime

	Increase in productivity			Decrease in Productivity		
	Negligible	Moderate	Great	Negligible	Moderate	Great
Newfoundland	0	2	1	0	5	6
Rest of Canada	1	6	1	1	15	16

Shiftwork

Shiftwork was placed by many in the same category as scheduled overtime and was generally regarded as having a negative effect on productivity. See Table 20 . Some respondents felt that construction work is not suitable for night work because of the necessary additional lighting and other services required. Several comments were made regarding alternate workweek plans. The use of 10 hr/day, 4 day/week scheduling has advantages in the summer when the days are long and the weather is fine. The total time spent on breaks is less that in the traditional 5 day week. The advantage disappears during the winter or during cold weather when the 8 hr/day, 5 day/week schedule is preferred.

Table 20: Attitude toward shiftwork

	Increase in productivity			Decrease in Productivity		
	Negligible	Moderate	Great	Negligible	Moderate	Great
Newfoundland	0	2	3	2	3	3
Rest of Canada	1	8	4	6	16	2

3.2.6 Motivation

Factors relating to motivation were examined and the opinion of the survey participants as to their effect on construction productivity was solicited. The results of the ratings are shown in Table 21

Table 21: Attitudes toward Motivation Factors

Factor	Nfld.	Maritimes	Central	West	Canada
End of project effect	4.3	3.5	3.6	3.3	3.5
Employee motivation	4.3	4.2	4.4	4.7	4.3
Rewards (money, recognition etc)	3.8	3.7	3.6	4.3	3.7
Foreman supervision	4.2	4.8	4.6	4.8	4.8
Team work, crew size and makeup	4.1	4.3	4.5	4.8	4.5
Communication	4.3	4.6	4.4	4.7	4.5
Incentive caused by UI benefits	4.4	3.1	2.5	1.8	2.7
Job reworking	3.7	3.6	3.4	3.8	3.6

1 = insignificant effect — 5 = great effect

Most noticeable in the results is the very surprising responses from the Newfoundland respondents relating both to the incentive caused by Unemployment Insurance benefits and the end of project effect. The Newfoundland results are significantly greater than other regions of Canada. In the case of UI benefits there appears to be a decreasing trend from east to west across the country. In the relatively bad economic times that Canada has faced in the past few years, unemployment has soared in

Newfoundland. Jobs in the construction industry have been declining. Many skilled Newfoundlanders have come to survive through judicious and opportune use of UI benefits. In some regions, as few as ten weeks employment will entitle a recipient to almost a year's benefit. Further, the more an employee is paid during the period of employment, the higher is the benefit. This provides a two-fold effect: a) there is little incentive to continue work past the ten week qualifying period and b) there is a disincentive to accept short term (less than a week) employment since it has a negative effect on the UI entitlement. This phenomenon reflects itself further in the "end of project" effect since those workers who are deficient in the required number of weeks employment are inclined to prolong the work to achieve their goal of UI entitlement.

The results contrasting the Newfoundland ratings with the rest of Canada are shown in Tables 22 and 23 . The data represents the percentage of respondents who rated the particular factor as among the top two most important as to their effect on productivity. Again the effect is dramatic. More than half the respondents from Newfoundland indicated that the UI effect was one of two prime factors affecting productivity. This contrasts with 10% for respondents from the rest of Canada. Apart from that anomaly, there is general agreement on other factors.

3.2.7 Other Factors

Respondents commented freely on factors that they considered to be of great importance to construction productivity. Most of the issues had been covered in the design of the questionnaire. Additional points that were raised are summarized below:

Quality of labor skill. Skilled workers were considered a positive contributor to productivity. There was some concern expressed that because of the terms and conditions of union agreements it was not always within the control of the contractor to select the most skilled workers.

Table 22: Attitude toward motivation – Newfoundland

Factor	Percent
Incentive caused by UI benefits	5[illegible].9%
Foreman supervision	37.0%
Teamwork, crew size and makeup	37.0%
Employee motivation	37.0%
End of project effect	22.2%
Communication	14.8%
Rewards (money, recognition etc)	0.0%
Job reworking	0.0%

Table 23: Attitude toward motivation – Rest of Canada

Factor	Percent
Foreman supervision	66.7%
Employee motivation	35.9%
Teamwork, crew size and makeup	33.3%
End of project effect	20.5%
Communication	20.5%
Incentive caused by UI benefits	10.3%
Job reworking	7.7%
Rewards (money, recognition etc)	5.1%

Project communication. The importance of a clear definition of priorities and the setting of goals was stressed. It is critical that all stakeholders from worker to owner 'buy into' the project and that channels of communication be open.

Timeliness. A pervasive feeling of the timeliness of actions was apparent. Issues raised include timely inspections, timely action on change orders, timely decisions by management and engineering staff on important matters, timely delivery of materials and timely expedition of monthly billings.

Equipping of crews. The importance of providing essential tools to work crews was stressed. The opinion was expressed that with proper tools and supervision, a crew would be productive.

Timely decisions are critical. There are a multitude of decisions to be made every day to keep things on track. The senior team members, regardless of discipline - owner, consultant, general contractor or subcontractor, must be able to priorize and act. Procrastination and lack or communication are generally the root cause of major problems (also litigations) and can kill a project's momentum, no matter how well equipped.

3.3 Summary

The analysis of the national survey has shown a reasonable distribution of respondents across the country. However, the preponderance of responses from the Atlantic and Ontario regions suggests that care be taken in extrapolating the results to Quebec and western Canada. For the most part, there was consensus regarding the factors that were considered to be major contributors toward productivity. Comments from the participants gave the researchers reason to believe that there were strong feelings regarding some issues. Highlights include:

1. About 30% of the respondents had conducted a productivity study and found the results useful.

2. Respondents felt that fixed price contracts were more productive and that lowest bid had an adverse effect on productivity. The Newfoundland participants were more convinced that the contract type had an effect on productivity.

3. Many respondents felt that inspectors were not knowledgeable of codes, did not thoroughly study plans and specifications and were not timely in the submission of their findings.

4. Planning and scheduling were considered of critical importance to project productivity and profitability.

5. Among site management factors, availability of working drawings was considered to have the greatest effect on productivity.

6. Of the factors relating to working conditions, those relating to construction equipment were most significant. In particular, non-availability of equipment, equipment breakdown and inappropriate use of labor where equipment would be more efficient were cited.

7. Regarding working hours there was national consensus that occasional overtime affected productivity positively while scheduled overtime and shiftwork caused a decrease in productivity. The exception was the wide spread belief that 10 hr/day, 4 day/week was more productive than the usual 8 hr/day, 5 day/week schedule for summer work.

8. The area of motivation showed a noticeable discrepancy between Newfoundland and the rest of Canada. The major source of decline in productivity was the disincentive to work caused by Unemployment Insurance benefits. This cause

was very low in the rest of Canada. Apart from this effect, there was general agreement that foreman supervision, teamwork, and employee motivation were major contributors to productivity.

Chapter 4

Productivity Statistical Model

A survey of the literature relating to the effect of weather on construction productivity suggests that for the most part, investigations have been limited to the effects of temperature and humidity. Other weather factors such as wind speed and direction, hours of sun and amount of precipitation appear not to be extensively studied.

Literature shows that dramatic weather conditions such as hurricanes, severe lightening and heavy rains usually cause cessation of work with resultant slippage of the project schedule. The effect of sudden and short term changes in weather such as a summer cloudburst is minor; workers quickly acclimatize to these changes since they are generally of short duration. What is not quite as apparent is the effect of day-to-day changes in weather or periods of prolonged adverse (at least to the construction activity) weather. Investigations have been hampered by the following factors:

1. Activities are not of sufficient duration to allow a sufficiently large sample of productivity data. Some researchers (Thomas *et al.*, 1987) have combined activities and projects to broaden the database, with varied success.

2. During the prime construction season in the north, the weather is not sufficiently variable to allow a clear articulation of the weather factors affecting productivity.

3. Other factors, perhaps unknown to the researcher/observer, are having a much

greater effect on productivity than attributable to weather

Newfoundland weather is well known for its variability. Typically a rainy, cloudy day remains so all day long. Similarly, a windy, clear day usually persists through the day. However, variability arises because it is not uncommon for fine days and adverse days to be mixed randomly. It is the author's experience that the mean time between these weather changes is smaller in Newfoundland than elsewhere in Canada. It would be interesting to verify this through a study of Atmospheric and Environmental Services (AES) data at major cities across Canada. In Newfoundland one would expect, therefore, that the effects of weather changes on construction productivity, would be more noticeable. The survey of construction personnel discussed in chapter 3 indicated that this is indeed the case. Cold weather, for example, is clearly regarded by Newfoundland respondents as having a more significant effect on productivity than is the experience in the rest of Canada.

4.1 Scope of Investigation

For the present investigation a masonry project was selected. Masonry construction is a preferred activity for study since rules of credit (See section 1.1.4) for determining work in place are straightforward and because the work is easily observed.

The project was a three story steel-framed building on a rural site. Its relatively simple plan allowed the study to focus on weather conditions rather than on issues of constructability. Workers on the site were unionized and for the most part, relations were stable. Most management conditions at the site were good and supervision was adequate. The focus of the data collection was on task level labour productivity, specifically the measurement of the work accomplished by a single crew in the placing of masonry blocks and the documentation of the factors that may affect the crew's work. Data collected included:

1. Total area of block installed,
2. Number and size of openings in the block façade
3. Anomalies at the site that caused short term interruptions
4. Factors that caused significant interruptions

In addition to the site observations, informal discussions were held with foremen and workers and notes made. Total manhours of work was provided daily by the contractor. Weather data was collected from the nearest station of the Atmospheric and Environment Services of Canada.

4.2 Site Observations

This study is based on observations made over a one month period at the site. A summary of data observed for the period from June 12, 1992 to July 16, 1992 is shown in Table 24 .

The sequential day number is the work day counted from the first day of the project. Number of windows represents the total count of all windows formed on the day indicated. The number of tiers completed is a count of the number of horizontal rows of block placed. Total block area placed in square metres on a particular day was calculated. From the number of man-hours provided by the contractor and the total area of blocks placed, the average daily productivity in units of man-hours per square metre was computed. This system of units for representing productivity is in common use. High values of productivity indicate lower worker performance. Days when no work was done because of rain (days 3 and 14) are excluded from further analysis.

In addition to 'work placed' measurements, conditions were noted that, in the opinion of the observer, could adversely affect productivity. These remarks are sum-

Table 24: Masonry (Block) Site Data

Date (1992)	Sequential Workday Number	Number of Windows	Number of Doors	Tiers Completed	Area of Work m^2	Man hours mh	Prod. mh/m^2
Jun 12	1	0	0	1	10.80	32	2.96
Jun 15	2	11	1	18	54.72	56	1.02
Jun 16	3		Severe rain – workers went home				
Jun 17	4	13	0	14	43.38	56	1.29
Jun 18	5	8	1	11	37.08	42	1.13
Jun 19	6	8	0	5	25.20	56	2.22
Jun 22	7	0	0	2	23.40	56	2.39
Jun 23	8	0	0	8	18.00	56	3.11
Jun 24	9	1	1	11	45.17	56	1.24
Jun 25	10	8	2	17	42.60	56	1.31
Jun 26	11	10	2	22	54.87	56	1.02
Jun 29	12	9	1	20	28.80	56	1.94
Jun 30	13	4	0	17	57.71	56	0.97
Jul 1	14		Severe rain – workers went home				
Jul 2	15	8	0	10	8.88	28	3.15
Jul 3	16	0	0	26	25.20	56	2.22
Jul 6	17	2	0	9	6.48	14	2.16
Jul 7	18	0	0	2	5.40	14	2.59
Jul 8	19	2	1	36	64.35	56	0.87
Jul 9	20	0	1	19	51.98	56	1.08
Jul 10	21	8	0	28	41.25	45	1.09
Jul 13	22	4	1	45	51.89	72	1.39
Jul 14	23	5	1	49	53.61	88	1.64
Jul 15	24	0	1	60	69.08	88	1.27
Jul 16	25	0	0	36	46.35	88	1.90

marized in Table 25. Days on which there were no observable adverse working conditions are omitted from the table.

From Table 25 a number of general qualitative observations can be made.

1. Rain has a number of effects. Firstly, it can cause suspension of work with resultant slippage of the project schedule. Secondly, it can slow the pace of the work when materials are wet. Thirdly, the approach of rain can slow the workers' pace as they wait in anticipation of its start. These last two effects can have an influence on productivity.

2. On days when the work includes a door, worker productivity appears to be higher. The presence of windows, however, does not have an effect on the net productivity.

3. During the course of the block laying activity, a number of adverse management and site conditions occurred from time to time. These include a) supervision, b) inefficient use of equipment, c) materials handling, d) site congestion, e) inspection delays and f) weather. No attempt was made to quantify the first five of these.

4. After the three days of heavy rain, it was observed that the workers were fast in achieving maximum effort. This is attributed to pressure exerted by the main contractor on the masonry sub-contractor.

5. Near the activity end, an 'end of project effect' was observed. Workers seemed to be involved in a lower proportion of direct work.

A plot of productivity (mh/m^2) versus time (days of active work completed) is shown in Figure 1 . An average productivity, over the project duration, of 1.75 mh/m^2 is shown.

Table 25: Site Conditions

Date	Note
Jun 15	Foreman not on site
Jun 16	Severe thunder and lightening storm before dawn - 40 mm rain accumulation. Further rain until 11:00 am. Block workers went home. No work accomplished.
Jun 18	Heavy rain - block work stopped around 2:00 pm
Jun 22	Steel support was attached to blocks requiring additional cutting of block
Jun 23	Top tier is half block which requires additional cutting
Jun 24	More block cutting. Block storage and cutting site is distant from the worksite.
Jun 25	Supervisor not on site
Jun 29	Inefficient block storage
Jun 30	Row of 1/2 blocks placed in window openings. Some vapour barrier installed
Jul 1	Heavy rain - no work done
Jul 2	Rain - block work suspended at noon
Jul 6	Heavy rain - no work done
Jul 7	Heavy rain - no work done
Jul 10	Masonry sub-contractor is being pressured by prime to make up lost time. Foreman is exerting great influence
Jul 14	Site getting congested with sub-trades
Jul 16	Workers are inefficient, frequently moving from wall to wall, packing and unpacking tools, indecisiveness - end of project effect.

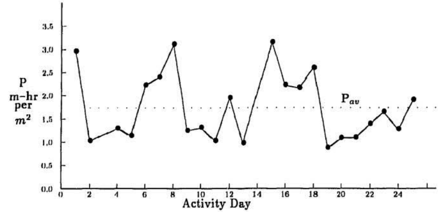

Figure 1: Graph of Productivity vs Day - Blockwork

It is interesting to note that for the ten(10) days that the calculated productivity exceeded the average, only one door was formed. Of the thirteen(13) days that the calculated productivity was less than the average, 12 doors were formed. In other words, if doors are formed during the process of laying blocks, worker productivity improves (smaller P). It should be emphasized that the areas of the doors are not included in calculating productivity.

This is a remarkable finding. A direct relationship is not apparent. However, a likely indirect cause is that work around a door is done at ground level. This simplifies the block placing process because scaffolding is not necessary and the movement of materials is much simpler. If this is a correct interpretation, then it is clear that elevation potentially has as great an effect on productivity as the weather conditions studied.

Further examination of Figure 1 and calculation of the average productivities with and without doors indicates that worker productivity is greater by a factor of two(2) when the work is performed at ground level, ie when doors are formed during the day's work. Also apparent from Figure 1 is an 'end of project effect'. From day 19 to activity completion on day 25 there is a clear decline in worker performance. This finding was documented during site visits where it was clear that the pace of activity was noticeably slowing during that period.

4.3 Weather Data

The Atmospheric and Environmental Services of Canada (**AES**) provides daily climatic data for the St. John's area. It is not possible to experimentally control the weather. Therefore, it is important to select the 'correct' weather variables to produce optimal experimental design. It is assumed that **AES** accurately measures the variables to be used and that for the most part it may be assumed that this is done without error.

Table 26 shows sample AES data for the period 12-Jun-1992 to 16-Jul-1992. The day-to-day variability of the weather is obvious. Table 27 shows average values of climatic factors computed from the AES data. TRMEAN trims the smallest 5% and largest 5% of the observations and averages the rest. STDEV is the standard deviation of the dataset and SEMEAN is the standard error of the mean. Table 28 shows a correlation analysis of the same data.

The selection of appropriate factors is based on an analysis of Table 28 and the heuristics of the problem.

Average Temperature. It is felt that average daily work-hour temperature would be a more reliable predictor of productivity than either maximum or minimum temperatures. Average temperatures are calculated from hourly temperatures, provided by the weather office, averaged over the working hours.

Average Humidity. AES data shows a maximum humidity near 100% for most of the days in the study. This is likely because St. John's is a coastal community and subjected to a lot of evening and night fog, as well as high-moisture-content prevailing on-shore winds. Minimum humidity is somewhat more variable. Average humidity was chosen as a candidate variable for the preliminary regression analyses.

Table 26: AES Weather Data – St. John's, NF – Jun 12 - Jul 16

Date	Day Num	Max Temp deg C	Min Temp deg C	Max Humidity %	Min Humidity %	Prec. mm	Wind Speed *km/h*	Hours of Sun	Average Temp deg C
Jun 12	1	11.8	0.8	99.0	66.0	3.2	9.9	6.3	7.6
Jun 15	2	23.5	9.4	96.0	53.0	3.0	16.5	10.5	20.0
Jun 16	3	18.3	8.8	97.0	80.0	48.2	14.8	1.3	15.3
Jun 17	4	11.5	1.5	97.0	60.0	0.2	24.5	5.7	9.9
Jun 18	5	7.9	1.9	99.0	75.0	16.4	27.3	1.7	4.2
Jun 19	6	7.4	4.5	99.0	96.0	1.0	14.9	0.0	6.1
Jun 22	7	10.2	4.7	100 0	95.0	1.0	7.8	0.0	7.6
Jun 23	8	11.6	6.5	100.0	95.0	1.2	6.5	0.0	9.8
Jun 24	9	16.4	7.0	100.0	82.0	0.4	4.2	4.8	13.0
Jun 25	10	18.5	6.9	97.0	71.0	0.0	10.6	8.9	15.0
Jun 26	11	11.1	6.9	99.0	78.0	5.2	17.0	0.0	7.8
Jun 29	12	12.8	5.4	98.0	78.0	1.8	17.1	1.0	8.9
Jun 30	13	13.6	5.3	95.0	60.0	0.0	28.1	6.4	9.3
Jul 1	14	14.8	5.5	97.0	78.0	14.2	9.4	1.7	10.6
Jul 2	15	6.6	4.3	99.0	96.0	21.6	12.9	0.0	6.1
Jul 3	16	7.4	4.3	98.0	89.0	1.0	20.3	0.0	6.4
Jul 6	17	12.4	6.5	98.0	79.0	8.4	16.1	0.0	8.7
Jul 7	18	16.7	10.9	97.0	93.0	30.0	13.8	0.0	13.7
Jul 8	19	20.0	10.5	97.0	80.0	2.8	18.5	3.5	17.7
Jul 9	20	19.7	10.4	95.0	61.0	0.0	21.9	10.2	16.0
Jul 10	21	14.5	9.3	97.0	85.0	19.0	14.3	0.0	11.6
Jul 13	22	11.6	6.3	96.0	72.0	0.0	11.5	2.8	9.2
Jul 14	23	11.9	6.3	96.0	61.0	0.0	13.1	11.6	9.8
Jul 15	24	20.3	9.8	95.0	65.0	0.0	26.3	12.8	17.1
Jul 16	25	17.1	7.5	94.0	60.0	1.6	28.8	8.4	13.8

Table 27: Average Climatic Conditions – St. John's, NF – Jun 12 - Jul 16

	N	MEAN	MEDIAN	TRMEAN	STDEV	SEMEAN
Maximum Temp.	25	13.904	12.800	13.304	4.535	0.907
Minimum Temp.	25	6.448	6.500	6.500	2.767	0.553
Maximum Humidity	25	97.400	97.000	97.435	1.708	0.342
Minimum Humidity	25	76.32	78.00	76.48	13.16	2.63
Rain	25	7.21	1.60	5.74	11.83	2.37
Wind	25	16.24	14.90	16.22	6.87	1.37
Hours of Sun	25	3.904	1.700	3.687	4.312	0.862
Average Temp.	25	11.008	9.800	10.913	4.138	0.828

Table 28: Correlation Coefficients – St. John's Climatic Conditions

	Maximum Temp.	Minimum Temp.	Maximum Humidity	Minimum Humidity	Rain	Wind	Hours Sun	Average Temp.
Maximum Temp.	1.000							
Minimum Temp.	0.758	1.000						
Maximum Humidity	-0.580	-0.462	1.000					
Minimum Humidity	-0.501	-0.042	0.710	1.000				
Rain	0.046	0.210	0.070	0.337	1.000			
Wind	0.101	0.008	-0.602	-0.508	-0.091	1.000		
Hours Sun	0.597	0.221	-0.659	-0.834	-0.416	0.329	1.000	
Average Temp	0.976	0.795	-0.569	-0.426	0.052	0.080	0.581	1.000

Precipitation. Precipitation in St. John's is erratic. During the project very heavy rain caused cessation of work. On days following heavy rainfall, worker efficiency was reduced because of delays caused while materials dried.

Wind. Wind is expected to have an effect on outside work particularly those activities requiring the use of a crane or scaffolding.

Hours Sun. Hours of sunshine naturally displays a high negative correlation with rain. This would suggest that it would contribute less to the regression than would average temperature which is not as highly correlated with rain. It is felt, then, that average temperature would be selected over hours of sun as a predictor variable.

Examination of Table 28 provides further assistance in the selection of 'independent' variables for the analyses. Intuitively, one would postulate that average temperature, wind and rain would be major contributors to construction productivity. It is interesting that there is very little correlation among these three. This is important since they therefore qualify as truly independent variables. Further, this lack of multicollinearity among the independent variables is critical if the results of the multiple linear regression model are to be interpreted. Multicollinearity has the effect of compromising the interpretation of the coefficients of the model. In other words, while the predictive value of the model could be good, it would not be possible to quantify the individual effect of each factor, other than to say it has a significant effect on productivity.

Including hours of sun in the analysis may not be expected to contribute significantly to the regression since it correlate with average temperature. Further, its presence would compromise the interpretation of the results. On the basis of this first stage analysis, four independent weather variables are suggested: a) average temperature, b) rain, c) humidity and d) wind.

4.4 Model Development

The development of a model that combines both predictive and descriptive capabilities has in the past been tedious. Modern computer packages have simplified this process. None-the-less, at preliminary stages of the model development, all available factors should be considered a potential candidates for the model. From the available AES data and from site measurements, seven independent variables are suggested. These are: number of doors in the block façade, number of windows, number of tiers of blocks, rain, wind speed, average temperature and average humidity. The sections following describe the results of preliminary analysis and the selection of a model.

4.4.1 Preliminary analysis

Extensive exploratory multiple linear regression analyses were performed and the effects of all seven factors noted above were studied. This preliminary work suggested three findings. Firstly, number of tiers placed was found not to be a good candidate for the model since it rarely entered the regression via the stepwise procedures used. Secondly, one data item was consistently identified as an outlier. This day, July 10 immediately followed four days of heavy rain and was a day of improved worker performance. This effect was documented as arising from pressure exerted by the prime contractor on the masonry sub-contractor because the project was falling behind schedule. This data item was removed from further analysis. The third finding was, that among the possible interaction terms, the one containing wind speed and temperature was the only one that contributed significantly to the model.

On the basis of these preliminary investigations, seven factors were identified as candidates for a detailed analysis leading toward model selection. Two of these were site factors - number of doors and number of windows. Four were weather factors - rain, wind speed, average temperature and average humidity. The seventh factor was a wind - temperature interaction term. These factors and the resultant productivity values are shown in Table 29 .

4.4.2 Identification of factors

In the development of the model two approaches were used. The first used an all-possible-regressions method with three criteria for evaluation. The second approach used three stepwise procedures.

All regressions selection procedure

The all-possible-regressions selection procedure calls for an examination of all possible regression models involving the potential independent variables (X-variables) and identifying subsets according to some criterion. For the present study, this would involve performing $2^7 - 1 = 127$ regression analyses and then selecting the 'best' model. The summary results of the regressions are shown in Appendix B. For each of the 127 models evaluated, the following data is shown:

$$
\begin{aligned}
p &= \text{number of parameters in the model} - \text{one} \\
  & \text{more than the number of variables} \\
df &= \text{number of degrees of freedom in the model} \\
SSE_p &= \text{error sum of squares for the model with p parameters} \\
R_p^2 &= \text{coefficient of multiple determination for the model} \\
MSE_p &= \text{mean square error} \\
C_p &= \text{Mallows' estimator}
\end{aligned}
$$

This data and three different selection criteria - R_p^2, MSE_p and C_p - will be used.

R_p^2 criterion The R_p^2 criterion calls for an examination of the coefficient of multiple determination R_p^2, defined as follows:

Table 29: Site and Weather Factors

Date	Day Num	Doors	Windows	Precip. mm	Wind Speed km/h	Average Temp. deg C	Average Humidity %	Prod. mh/m^2	Wind x Temp.
Jun 12	1	0	0	3.2	9.9	7.60	83.5	2.96	75.24
Jun 15	2	1	11	3.0	16.5	20.00	74.5	1.02	330.00
Jun 17	4	0	13	0.2	24.5	9.90	78.5	1.29	242.55
Jun 18	5	1	8	16.4	27.3	4.20	87.0	1.13	114.66
Jun 19	6	0	8	1.0	14.9	6.10	97.5	2.22	90.89
Jun 22	7	0	0	1.0	7.8	7.60	97.5	2.39	59.28
Jun 23	8	0	0	1.2	6.5	9.80	97.5	3.11	63.70
Jun 24	9	1	1	0.4	4.2	13.00	91.0	1.24	54.60
Jun 25	10	2	8	0.0	10.6	15.00	84.0	1.31	159.00
Jun 26	11	2	10	5.2	17.0	7.80	88.5	1.02	132.60
Jun 29	12	1	9	1.8	17.1	8.90	88.0	1.94	152.19
Jun 30	13	0	4	0.0	28.1	9.30	77.5	0.97	261.33
Jul 2	15	0	8	21.6	12.9	6.10	97.5	3.15	78.69
Jul 3	16	0	0	1.0	20.3	6.40	93.5	2.22	129.92
Jul 6	17	0	2	8.4	16.1	8.70	88.5	2.16	140.07
Jul 7	18	0	0	30.0	13.8	13.70	95.0	2.59	189.06
Jul 8	19	1	2	2.8	18.5	17.70	88.5	0.87	327.45
Jul 9	20	1	0	0.0	21.9	16.00	78.0	1.08	350.40
Jul 10	21	0	8	19.0	14.3	11.60	91.0	1.09	165.88
Jul 13	22	1	4	0.0	11.5	9.20	84.0	1.39	105.80
Jul 14	23	1	5	0.0	13.1	9.80	78.5	1.64	128.38
Jul 15	24	1	0	0.0	26.3	17.10	80.0	1.27	449.73
Jul 16	25	0	0	1.6	28.8	13.80	77.9	1.90	397.44

$$R_p^2 = \frac{SSR_p}{SSTO} = 1 - \frac{SSE_p}{SSTO} \quad (4.1)$$

where SSR_p = regression sum of squares

SSE_p = error sum of squares

$SSTO$ = total sum of squares

Since SSTO is the same for all models, the value of R_p^2 will increase with increasing p. This is because SSE_p decreases as variables are added. The intent of the R_p^2 criterion is to find the point where adding more independent variables is not worthwhile because it leads to a very small increase in R_p^2. A plot of R_p^2 versus p-1 (number of X variables) is shown in Figure 2. The value of R_p^2 plotted is the maximum for each p value.

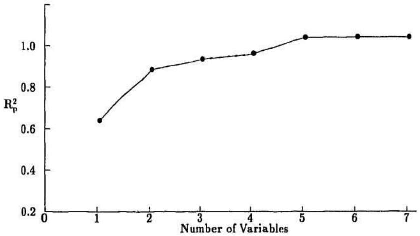

Figure 2: Graph of R_p^2 vs Number of Variables

The graph suggests a model having five predictor variables, W_Speed, Rain, Doors, Tav and the W_Speed×Tav interaction term. The addition of a sixth variable does not improve (increase) the value of R_p^2.

The MSE_p criterion The mean square error (MSE_p) criterion takes the number of parameters in the model into account through the degrees of freedom of the model. It is equivalent to an R_a^2 criterion where R_a^2 is the adjusted coefficient of determination. Using this criterion, a model is selected that minimizes the value of MSE_p or which is so close to the minimum that it is not worthwhile to include more variables.

A plot of MSE_p versus (p-1) is shown in Figure 3.

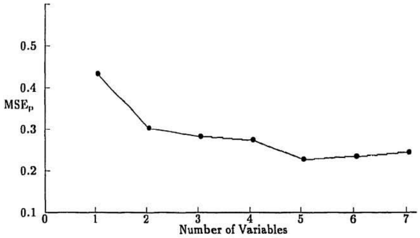

Figure 3: Graph of MSE_p vs Number of Variables

The graph suggests a model having the same five predictor variables as identified using the R_p^2 criterion. This number of variables (5) minimizes the value of MSE_p

The C_p criterion This criterion is concerned with the total mean squared error of the n fitted values for each of the various subset regression models. The C_p estimator is given as follows:

$$C_p = \frac{SSE_p}{MSE(X_1, \ldots, X_4)} - (n - 2p) \qquad (4.2)$$

where SSE_p = error sum of squares for the model with p parameters

MSE = mean square error for the model with all variables

n number of observations

p number of parameters in the model

C_p is an estimate of the bias in including an incorrect variable in the model. In using the C_p criterion, one seeks to identify a subset of X variables for which a) the value of C_p is small and b) the C_p value is less than or equal to p. Models for which C_p is larger than p exhibit bias and are therefore less desirable. An examination of C_p from Appendix B suggests the models shown in Table 30.

Table 30: Results of C_p Model Selection Criterion

Model	p	C_p
Rain, W_Speed, Tav, Doors, TavWsp	6	4.105
Rain, W_Speed, Tav, Doors, TavWsp, Windows	7	6.035
Rain, W_Speed, Tav, Doors, TavWsp, Hav	7	6.017

The preferred model is the one having the smallest C_p value relative to the value of p and is the same model identified by the R_p^2 and MSE_p criteria.

Stepwise procedures

Stepwise procedures are search procedures that are favoured when the number of candidate factors for the model make the all-regressions selection procedure computationally prohibitative. Three stepwise algorithms are used to develop the productivity model a) standard stepwise regression, b) forward selection method and c) backward elimination method.

The standard stepwise procedure starts by fitting a simple regression model for each of the p-1 variables. For each simple one-variable regression model the F^* statistic is calculated. The model having the largest F^* value is chosen as the first candidate model. A second step involves constructing a model having the X previously selected and a second X candidate. Again the model is selected that has the largest F^* value and for which this F^* value exceeds a certain minimum. When a third X variable has entered the regression, the procedure now checks to see if any of the previously entered values can be dropped. The procedure continues until no new variables can be entered or deleted.

The forward selection procedure is similar to the above, except that the test to remove variables is not performed. The backward elimination procedure is the opposite of forward selection. This process starts with all variables in the model and then systematically attempts to remove variables.

The results of the stepwise and forward selection methods were the same and are shown in Table 31.

These procedures suggest that a model containing just Doors and W_Speed as predictor variables would account for 67.2% of the variation in productivity. The other five candidate variables did not enter the model since their individual effects, on their own merit were not significant enough to warrant their inclusion in the model.

The backward elimination procedure, shown in Table 32 shows five variables in the model.

The five variables in the model are Rain, Doors, Wind speed, Average temperature and an interaction term between Wind speed and average temperature. It is significant to note that the five model coefficients do not change significantly as unwanted

Table 31: Results of stepwise regressions and forward selection

Stepwise Regression of Productivity on 7 Predictors, with n = 22			Forward Selection of Productivity on 7 Predictors, with n = 22		
Step	1	2	Step	1	2
Constant	2.194	3.063	Constant	2.194	3.063
Doors	-0.72	-0.75	Doors	-0.72	-0.75
t-ratio	-3.86	-5.18	t-ratio	-3.86	-5.18
W_Speed		-0.051	W_Speed		-0.051
t-ratio		-3.76	t-ratio		-3.76
s	0.571	0.443	s	0.571	0.443
R^2	42.73	67.20	R^2	42.73	67.20

variables are removed. This is further evidence that justifies their removal.

According to this model, productivity is a function of the product of wind speed and temperature. While all three of wind speed, temperature and their product were not able to enter the regression on their own strength, the combination of all three make a significant contribution.

4.4.3 Proposed model

The analyses of the previous section are consistent in suggesting a five factor model that has the following form:

$$\begin{aligned} \text{Productivity} &= a_0 + a_1 \times \text{Doors} + a_2 \times \text{Rain} + \\ & a_3 \times \text{W\_Speed} + a_4 \times \text{Tav} + \\ & a_5 \times \text{W\_Speed} \times \text{Tav} \end{aligned} \qquad (4.3)$$

Where	Doors =	Number of doors formed
	Rain =	Amount of precipitation (rain) in mm
	W_Speed =	Wind speed in km/h
	Tav =	Average temperature in degrees Celsius

and where productivity is measured as man-hour per square metre of block layed.

Table 32: Backward elimination procedure

Backward elimination of

Productivity on 7 predictors,

with n = 22

STEP	1	2	3
CONSTANT	4.648	4.998	4.963
Rain	0.027	0.028	0.028
t-ratio	2.26	2.67	2.74
W_Speed	-0.151	-0.154	-0.149
t-ratio	-3.34	-3.65	-3.96
Tav	-0.213	-0.217	-0.213
t-ratio	-2.79	-3.00	-3.10
Hav	0.003		
t-ratio	0.20		
Doors	-0.49	-0.49	-0.48
t-ratio	-3.21	-3.36	-3.53
TavWSp	0.0098	0.0099	0.0095
t-ratio	2.54	2.65	2.79
Windows	0.006	0.006	
t-ratio	0.27	0.27	
s	0.370	0.358	0.347
R-SQ	83.17	83.13	83.04

4.5 Statistical Analysis

A multiple linear regression analysis was undertaken to determine the functional relationship between productivity and the five weather and site factors.

4.5.1 Multiple Regression Model

The regression analysis produced the following equation:

$$\begin{aligned}\text{Productivity} &= 4.96 - 0.479\ \text{Doors} + 0.0281\ \text{Rain} - 0.149\ \text{W\_Speed} \\ &\quad -0.213\text{Tav} + 0.00954\text{W\_Speed} \times \text{Tav}\end{aligned} \tag{4.4}$$

Table 33 shows the results of the analyses. The constant term and model coefficients

Table 33: Results of Multiple Linear Regression

Predictor	Coef	Stdev	t-ratio	p
Constant	4.9632	0.6965	7.13	0.000
Doors	-0.4791	0.1357	-3.53	0.003
Rain	0.02813	0.01027	2.74	0.015
W_Speed	-0.14910	0.03763	-3.96	0.001
Tav	-0.21257	0.06851	-3.10	0.007
W_Speed × Tav	0.009538	0.003415	2.79	0.013

$s = 0.3472$ $R^2 = 83.0\%$ $R^2_{adj} = 77.7\%$

are significant at levels greater than 95%. The model is capable of explaining 83% of the variation in productivity. This result is a significant improvement over models that restrict the analysis to weather variables. The analysis of variance shown in Table 34 indicates an F-value of 15.67 which means that the model is significant as a whole, again at levels greater than 99%. Also, the sum of squares variation (SS) for the regression is significantly greater than for the error terms. Further, the

Durbin-Watson statistic at 2.81 indicates that autocorrelation is not a consideration.

Table 34: Analysis of variance

SOURCE	df	SS	MS	F	p
Regression	5	9.4423	1.8885	15.67	0.000
Error	16	1.9282	0.1205		
Total	21	11.3705			

4.5.2 Interpretation of results

The results shown in Equation 4.4 relates productivity, measured in man-hours per square metre of block placed, to a number of site and weather variables. That the equation adequately represents the observed data is clear from Figure 4 which shows observed and fitted data.

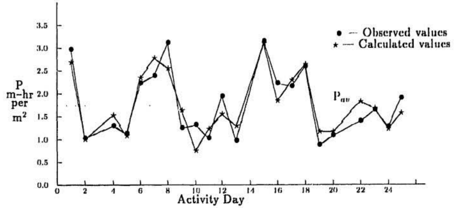

Figure 4: Graph of Observed and Predicted Values

It must be stressed, however, that the model has predictive value only if the same management and site conditions prevail, the observations span the same range of the independent variables and only if a crew of similar work capacity and motivation is used. This is the assumption made by labour estimating manuals which assume constant and average conditions. This present method, when further articulated by more study at different locations and times, has the potential to refine the process of cost estimating to include the affect of temperature, wind and rain on worker performance.

It is in the interpretation of the functional form of the model that new light can be shed upon the effect of weather and site conditions on task level productivity. Interpretation of the coefficients of the model is possible if there is not a great deal of multicollinearity among the 'independent' variables. However, it is clear that wind speed and temperature are each correlated with the interaction term. This means that an interpretation of the coefficients of these three terms independently is not useful. To solve this problem a weather interaction term that combines the effect of wind and temperature is proposed as follows:

$$\text{Chill} = (\text{W\_Speed} - 22.2)(\text{Tav} - 15.6) \tag{4.5}$$

where Chill is in km-degree Celsius/h and is a measure of the combined effect of wind speed, W_Speed and average temperature, Tav. Then Equation 4.4 becomes

$$\begin{aligned} \text{Productivity} &= 4.96 - 0.479\ \text{Doors} + 0.0281\ \text{Rain} \\ &\quad -0.149\ \text{W\_Speed} + 0.0954\ \text{Chill} \end{aligned} \tag{4.6}$$

A correlation analysis was conducted and is shown in Table 35 . The multicollinearity among the new 'independent' variables is low which means that it is legitimate to interpret their individual effects on productivity.

Constant term. This represents the productivity expected when there is no rain, no doors framed and the wind and temperature near 22.3 km/h and 15.6 degrees Celsius respectively. This value is also the minimum value of productivity with respect to W_Speed and Tav and therefore represents maximum worker output.

Table 35: Productivity model correlation coefficients

	Productivity	Doors	Rain	Chill
Productivity	1.000			
Doors	-0.654	1.000		
Rain	0.374	-0.212	1.000	
Chill	0.710	-0.255	-0.035	1.000

Rain. The model indicates that for every mm of rainfall on the sample day, the calculated value of productivity increases by 0.0281 m-h/m^2. This means a decline in worker performance, as might be expected. This interpretation is limited to days when work proceeded in spite of rain. Days of heavy rainfall when no work was done are not part of the model.

Doors. The number of doors framed during the sample day was observed to be a strong contributor to worker performance. In fact, each door framed produced a bonus in productivity of 0.479. Man-hours were reduced thereby indicating improved worker performance. A possible explanation of this phenomenon is the positive effect of introducing variety in the blocklaying task as a result of the forming of a door. The work is vertically oriented rather than horizontal and a different type of cutting and fitting is required. The author feels that the effect is more likely that doors are formed at ground level and that what is being observed is the effect of elevation. Blockwork at height is clearly more complicated because of materials handling and safety considerations. This belief is sustained by the observation that the number of windows formed seemed to have no effect on productivity. Further study is required to confirm and quantify the effect of elevation.

Chill. This factor suggests that the physiological effect of wind speed and temperature on workers is complex. In this discussion it is assumed that the observed effects on productivity arise from the effects of temperature and wind on the workers directly and not on the site and building materials. This is valid since observed values of wind and temperature were not so extreme as to affect building materials (block, mortar, drying etc.).

A positive value of chill increases man-hours per square metre and hence is a measure of reduced worker performance. The model suggests that while high temperatures or high winds can be tolerated (or cause an increase in worker performance) the combination of extremes of both wind and temperature together has an adverse effect on productivity.

The pivotal values of wind and temperature (22.3,15.6) are a function of the crew's response to weather conditions as opposed to average wind speed and temperature which are characteristics of the St. John's climate.

4.5.3 Residuals

The remaining variation in worker productivity is unexplained by the model. Possible contributors include a) foreman supervision, b) start-up effect, c) end of project effect and d) effect of rain on construction materials.

4.6 Summary

An analysis of weather and site factors affecting construction productivity indicates that the number of doors formed is the primary predictor. Among the factors related to weather, average temperature, precipitation, wind and a combination of wind and temperature have the greatest effect. These five factors are capable of explaining over 80% of the variation in productivity.

The effect of wind and temperature is a combined effect. High temperature or high wind do not adversely affect productivity. However the combination of the two does seem to diminish worker performance. As might be expected, rain has an adverse effect on productivity.

The high coefficient of determination for this study is significant and much larger than found in previous studies. However, other work has not considered elevation either explicitly or indirectly as a factor and therefore results are predictively lower.

Chapter 5

Conclusions

The analysis of the national survey has shown a reasonable distribution of respondents across the country. There was consensus regarding the factors that were considered to be major contributors toward productivity. Comments from the participants gave the author reason to believe that there were strong feelings regarding some issues.

The results of the questionnaire relating to a number of weather factors were sustained by data collected on a masonry block project. A multiple linear regression model was used to develop a predictor equation for productivity. Major factors contributing to the model included number of doors framed by the block work activity, average temperature, precipitation, wind and a combination of wind and temperature.

5.1 Survey Results

About 30% of the respondents had conducted a productivity study and found the results useful.

Factors quoted by respondents as having a positive effect on productivity include:

1. fixed price contracts
2. planning and scheduling
3. availability of working drawings

4. effective use of occasional overtime

5. foreman supervision, teamwork and worker motivation

Factors regarded as having a negative impact include:

1. lowest bid contracts

2. ineffective and inefficient inspection regime

3. non-availability of construction equipment, equipment breakdown and inappropriate use of labor where equipment would be more efficient

4. scheduled overtime and shiftwork

5. in Newfoundland, the disincentive to work caused by Unemployment Insurance benefits.

The last of these items was most significant. Among motivational issues, the disincentive caused by Unemployment Insurance benefits was highest on the list of adverse factors quoted by Newfoundland respondents and appeared to be of little importance elsewhere in Canada.

5.2 Multiple Linear Regression Model

An analysis of weather and site factors affecting construction productivity indicates that the number of doors framed is the primary predictor. Among the factors related to weather, average temperature, precipitation, wind and a combination of wind and temperature have the greatest effect. An interaction term called chill has been proposed that is not correlated with rainfall or number of doors and which allows interpretation of the regression results. The model is capable of explaining over 80% of the variation in productivity.

Factors favorably affecting worker performance include number of doors and moderate temperature and wind. Rainfall and extremes of temperature and winds occurring together have an adverse effect on productivity.

5.3 Major Contribution of the Work

The articulation of factors affecting productivity has demonstrated some significant differences between the perceptions of Newfoundland respondents and those from the rest of Canada. Most important among these is the perceived effect of the disincentive to work caused by unemployment insurance benefits. This effect is well known in Newfoundland. What is surprising is that the effect is not prevalent elsewhere.

The high coefficient of determination for the multiple linear regression factor model of productivity described in this study is significant and much larger than found in previous studies. The results of the analysis are intuitively correct. The effect of multicollinearity in compromising the interpretative power of the regression is minimal. The outcome of the study has application to predicting the weather-related contribution to construction productivity. Using historical weekly average data from AES, it is possible to predict average worker productivity for this activity. The present analysis has shown this value to be 1.78 man-hours/m^2 for the period of the study. Tables can be constructed that provide this value for any time (date) and location. These time-location modifiers would be useful in project planning and costing. The number of doors is a project specific item and would not be accounted for in the tables.

5.4 Recommendations for Further Research

A number of directions for future work present themselves. It would be interesting to revisit some of the published work and to attempt to include elevation (story) as a factor. A preliminary analysis of the work of Thomas(1987) suggests that elevation plays a significant role in the determination of productivity. Thomas used a model based on LOG(temperature) and EXP(humidity) for combined steel, formwork and masonry work on a seven story building. The regression equation explained 24% of the variation. If, in the spirit of the present work, a model is proposed that productivity is a function of temperature and a Boolean variable ground (1 if at ground level, 0 otherwise) the coefficient of determination for the masonry component of Thomas's data becomes 72.7% The assumption is made that one-seventh of the time is spent at ground level. The author believes that the significance of other studies would improve as well.

The analysis indicates that it is possible to calculate time-location modifiers that can be used to correct labour productivity for time of year and for location. These modifiers are a function of historical weather data. They would have the effect of characterizing the local impacts of weather on productivity. It would be very interesting to observe whether or not any patterns arise that would show similarities among outside activities and among locations. Such a study would produce a valuable tool for refining project schedules and costs.

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Appendix A

Survey Questionnaire

Memorial University of Newfoundland

and

Cabot College of Applied Arts, Technology and Continuing Education

Construction Productivity Study

Thank you for agreeing to participate in this survey. We estimate that to complete the questions will take five minutes.

Please indicate your preferred response by placing a check mark in the appropriate brackets (   ) or in the space provided in the table.

Your comments are important to the success of the study and they are welcomed. Should you need more space, please write your additional (labeled) comments on the back of the questionnaire.

Should you need any clarification, please contact one of the following.

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We would be pleased to send you a summary of our report. If you so wish, please include your name and address or a business card.

A. Background

A1. Please indicate your occupation in the construction industry.

( ) Foreman ( ) Field (project) Engineer

( ) Project Manager ( ) ______________________

A2. Please indicate the types of construction most commonly undertaken by your company. (Check as many as are appropriate)

( ) Residential construction

( ) Building construction - Commercial

( ) Marine construction

( ) Road/bridge construction

( ) Industrial construction

( ) ______________________

A3. Is the company work force union ( ) or non-union ( ) or a ( ) mixture of both?

A4. How many projects are undertaken in a typical year ?

( ) 1 to 5 ( ) 6 to 10

( ) 11 to 15 ( ) more than 15

A5. What is the average dollar value of work performed annually?

( ) less than $100,000

( ) $100,000 to $500,000

( ) $500,000 to $1,000,000

( ) more than $1,000,000

A6. How many construction workers (on average) are employed in your company?

( ) less that 5 ( ) 5 to 9

( ) 10 to 19 ( ) 20 to 49

( ) 50 or more

A7. a) Has your company ever undertaken a productivity study?

( ) Yes ( ) No

b) If so, was it useful?

( ) Yes ( ) No

B. Contract Environment

B1. Do you think the form of the construction contract relationship (lowest bid, cost plus etc) has an effect on construction productivity?

( ) Yes ( ) No

Comment: ____.

B2. The term constructability relates to design efforts that lead to ease of construction of a project. In your opinion, how important are these efforts in improving construction productivity?

( ) insignificant
( ) moderate effect
( ) great effect

Comment: ____.

B3. How important is the inspection process in improving construction productivity?

( ) insignificant
( ) moderate effect
( ) great effect
( ) has a negative effect

Comment: ____.

C. Planning

C1. Does your company use, or has it used, project planning and critical path scheduling (CPM) in project execution?

( ) Yes ( ) No

Comment: ____.

C2. In your opinion, do project planning and critical path scheduling techniques cause an overall ( ) increase or ( ) decrease in construction productivity? Do you consider this effect to be ( ) great, ( ) moderate or ( ) negligible?

Comment: ____.

D. Site Management

Please rate the factors below as to their effect on construction productivity by placing a check in the appropriate column. 1 means that the effect is insignificant and 5 means that the effect is large.

#	Factor	1 (Insignificant)	2	3	4	5 (Large)
1.	Change orders					
2.	Availability/clarity of working drawings.					
3.	Site layout					
4.	Task sequencing					
5.	Materials management					
6.	On-site storage					
7.	Govt. and regulatory inspections					
8.	Temporary facilities such as					
	a) weather enclosures					
	b) air/gas/water/electr. supply					
	c) temporary road surfaces					
9.	Other (Specify):					

Please indicate by factor # (from table above) the two factors that you consider to have the greatest effect.

Greatest effect ( ) Next greatest effect ( )

Comment: ____________________

E. Working Conditions

Please rate the factors below as to their effect on construction productivity by placing a check in the appropriate column. 1 means that the effect is insignificant and 5 means that the effect is large.

#	Factor	1 (Insignificant)	2	3	4	5 (Large)
1.	Absenteeism					
2.	Worker turnover					
3.	Accidents/safety					
4.	Hot weather and hot weather acclimatization					
5.	Cold weather acclimatization					
6.	Height of worksite above ground					
7.	Site irritants-pollution, noise					
8.	Worker fatigue					
9.	Non-availability of tools					
10.	Equipment breakdown					
11.	Non-availability or inappropriateness of construction equipment (cranes,hoists, loaders, trucks etc)					
12.	Inappropriate use of tools or use of labor where equipment more appropriate.					
13.	Other (Specify):					

Please indicate by factor # (from table above) the two factors that you consider to have the greatest effect.

Greatest effect (   )   Next greatest effect (   )

Comment: ______________________________

F. Working Houras

F1. Does shorterm or occasional overtime cause an overall ( ) increase or ( ) decrease in construc tion productivity? Do you consider this effect to be ( ) great, ( ) moderate or ( ) negligible?

Comment: ____.

F2. Does longterm or scheduled overtime cause an overall ( ) increase or ( ) decrease in construction productivity? Do you consider this effect to be ( ) great, ( ) moderate or ( ) negligible?

Comment: ____.

F3. Do alternate work hours (other than 8 h/d, 5 d/w) and shiftwork cause an overall ( ) increase or ( ) decrease in productivity? Do you consider this effect to be ( ) great, ( ) moderate or ( ) negligible?

Comment: ____.

G. Motivation

Please rate the factors below as to their effect on construction productivity by placing a check in the appropriate column. 1 means that the effect is insignificant and 5 means that the effect is large.

#	Factor	1 (Insignificant)	2	3	4	5 (Large)
1.	End of project effect					
2.	Employee motivation					
3.	Rewards (money, recognition etc)					
4.	Foreman supervision					
5.	Teamwork, crew size & makeup					
6.	Communication					
7.	Incentive caused by Unemployment Insurance benefits					
8.	Job reworking					
9.	Other (Specify):					

Please indicate by factor # (from table above) the two factors that you consider to have the greatest effect.

Greatest effect (   )　　　　Next greatest effect (   )

Comment: ____

H. Other

Please take a moment to list/discuss any other factors that you feel contribute to construction productivity.

____

____

____

____

____

Appendix B

All-possible-regressions Data

Model	p-1	SSE	df	MSE	R^2	C_p
Rain	1	9.778	20	0.489	0.140	53.526
W_Speed	1	8.994	20	0.450	0.209	47.792
Tav	1	9.040	20	0.452	0.205	48.132
Hav	1	7.007	20	0.350	0.384	33.259
Doors	1	6.512	20	0.326	0.427	29.635
Tavwsp	1	8.351	20	0.418	0.266	43.089
Windows	1	10.581	20	0.529	0.069	59.403
Rain, W_Speed	2	7.464	19	0.393	0.344	38.601
Rain, Tav	2	8.039	19	0.423	0.293	42.804
Rain, Hav	2	6.787	19	0.357	0.403	33.650
Rain, Doors	2	5.851	19	0.308	0.485	26.799
Rain, Tavwsp	2	7.410	19	0.390	0.348	38.206
Rain, Windows	2	9.010	19	0.474	0.208	49.909
W_Speed, Tav	2	7.070	19	0.372	0.378	35.717
W_Speed, Hav	2	6.763	19	0.356	0.405	33.473
W_Speed, Doors	2	3.729	19	0.196	0.672	11.282
W_Speed, Tavwsp	2	8.156	19	0.429	0.283	43.666
W_Speed, Windows	2	8.621	19	0.454	0.242	47.062
Tav, Hav	2	6.668	19	0.351	0.414	32.778
Tav, Doors	2	5.857	19	0.308	0.485	26.848
Tav, Tavwsp	2	8.220	19	0.433	0.277	44.135
Tav, Windows	2	7.380	19	0.388	0.351	37.990
Hav, Doors	2	4.212	19	0.222	0.630	14.809
Hav, Tavwsp	2	6.794	19	0.358	0.402	33.701
Hav, Windows	2	6.530	19	0.344	0.426	31.772

Model	p-1	SSE	df	MSE	R^2	C_p
Doors, Tavwsp	2	4.360	19	0.229	0.617	15.891
Doors, Windows	2	6.418	19	0.338	0.436	30.952
Tavwsp, Windows	2	7.109	19	0.374	0.375	36.004
Rain, W_Speed, Tav	3	6.066	18	0.337	0.467	30.373
Rain, W_Speed, Hav	3	6.383	18	0.355	0.439	32.694
Rain, W_Speed, Doors	3	3.144	18	0.175	0.723	9.001
Rain, W_Speed, Tavwsp	3	7.050	18	0.392	0.380	37.571
Rain, W_Speed, Windows	3	7.101	18	0.395	0.376	37.944
Rain, Tav, Hav	3	6.440	18	0.358	0.434	33.108
Rain, Tav, Doors	3	5.335	18	0.296	0.531	25.028
Rain, Tav, Tavwsp	3	7.328	18	0.407	0.356	39.604
Rain, Tav, Windows	3	6.514	18	0.362	0.427	33.652
Rain, Hav, Doors	3	4.130	18	0.229	0.637	16.210
Rain, Hav, Tavwsp	3	6.509	18	0.362	0.428	33.618
Rain, Hav, Windows	3	6.289	18	0.349	0.447	32.009
Rain, Doors, Tavwsp	3	4.007	18	0.223	0.648	15.312
Rain, Doors, Windows	3	5.730	18	0.318	0.496	27.918
Rain, Tavwsp, Windows	3	6.236	18	0.346	0.452	31.619
W_Speed, Tav, Hav	3	6.253	18	0.347	0.450	31.741
W_Speed, Tav, Doors	3	3.357	18	0.187	0.705	10.557
W_Speed, Tav, Tavwsp	3	5.167	18	0.287	0.546	23.796
W_Speed, Tav, Windows	3	6.053	18	0.336	0.468	30.281
W_Speed, Hav, Doors	3	3.276	18	0.182	0.712	9.966
W_Speed, Hav, Tavwsp	3	6.712	18	0.373	0.410	35.102
W_Speed, Hav, Windows	3	6.380	18	0.354	0.439	32.671
W_Speed, Doors, Tavwsp	3	3.586	18	0.199	0.685	12.230
W_Speed, Doors, Windows	3	3.727	18	0.207	0.672	13.266
W_Speed, Tavwsp, Windows	3	7.109	18	0.395	0.375	38.004

Model	p-1	SSE	df	MSE	R^2	C_p
Tav, Hav, Doors	3	4.182	18	0.232	0.632	16.591
Tav, Hav, Tavwsp	3	6.654	18	0.370	0.415	34.674
Tav, Hav, Windows	3	5.798	18	0.322	0.490	28.414
Tav, Doors, Tavwsp	3	4.175	18	0.232	0.633	16.544
Tav, Doors, Windows	3	5.437	18	0.302	0.522	25.774
Tav, Tavwsp, Windows	3	6.727	18	0.374	0.408	35.208
Hav, Doors, Tavwsp	3	3.833	18	0.213	0.663	14.038
Hav, Doors, Windows	3	4.136	18	0.230	0.636	16.255
Hav, Tavwsp, Windows	3	6.095	18	0.339	0.464	30.588
Doors, Tavwsp, Windows	3	4.047	18	0.225	0.644	15.608
Rain, W_Speed, Tav, Hav	4	5.798	17	0.341	0.490	30.416
Rain, W_Speed, Tav, Doors	4	2.868	17	0.169	0.748	8.981
Rain, W_Speed, Tav, Tavwsp	4	3.430	17	0.202	0.698	13.089
Rain, W_Speed, Tav, Windows	4	5.158	17	0.303	0.546	25.734
Rain, W_Speed, Hav, Doors	4	2.995	17	0.176	0.737	9.907
Rain, W_Speed, Hav, Tavwsp	4	6.337	17	0.373	0.443	34.354
Rain, W_Speed, Hav, Windows	4	6.008	17	0.353	0.472	31.950
Rain, W_Speed, Doors, Tavwsp	4	3.089	17	0.182	0.728	10.593
Rain, W_Speed, Doors, Windows	4	3.144	17	0.185	0.723	11.001
Rain, W_Speed, Tavwsp, Windows	4	6.204	17	0.365	0.454	33.387

Model	p-1	SSE	df	MSE	R^2	C_p
Rain, Tav, Hav, Doors	4	4.095	17	0.241	0.640	17.959
Rain, Tav, Hav, Tavwsp	4	6.401	17	0.377	0.437	34.827
Rain, Tav, Hav, Windows	4	5.534	17	0.326	0.513	28.481
Rain, Tav, Doors, Tavwsp	4	3.821	17	0.225	0.664	15.950
Rain, Tav, Doors, Windows	4	4.908	17	0.289	0.568	23.901
Rain, Tav, Tavwsp, Windows	4	5.945	17	0.350	0.477	31.492
Rain, Hav, Doors, Tavwsp	4	3.701	17	0.218	0.675	15.072
Rain, Hav, Doors, Windows	4	4.044	17	0.238	0.644	17.579
Rain, Hav, Tavwsp, Windows	4	5.746	17	0.338	0.495	30.030
Rain, Doors, Tavwsp, Windows	4	3.678	17	0.216	0.677	14.903
W_Speed, Tav, Hav, Doors	4	3.156	17	0.186	0.722	11.087
W_Speed, Tav, Hav, Tavwsp	4	4.500	17	0.265	0.604	20.916
W_Speed, Tav, Hav, Windows	4	5.485	17	0.323	0.518	28.127
W_Speed, Tav, Doors, Tavwsp	4	2.833	17	0.167	0.751	8.726
W_Speed, Tav, Doors, Windows	4	3.309	17	0.195	0.709	12.203
W_Speed, Tav, Tavwsp, Windows	4	4.949	17	0.291	0.565	24.203
W_Speed, Hav, DOors, Tavwsp	4	3.267	17	0.192	0.713	11.898
W_Speed, Hav, DOors, Windows	4	3.275	17	0.193	0.712	11.954
W_Speed, Hav, Tavwsp, Windows	4	6.094	17	0.359	0.464	32.582
W_Speed, Doors, Tavwsp, Windows	4	3.563	17	0.210	0.687	14.064

Model	p-1	SSE	df	MSE	R^2	C_p
Tav, Hav, Doors, Tavwsp	4	3.719	17	0.219	0.673	15.203
Tav, Hav, Doors, Windows	4	4.036	17	0.237	0.645	17.525
Tav, Hav, Tavwsp, Windows	4	5.766	17	0.339	0.493	30.178
Tav, Doors, Tavwsp, Windows	4	3.990	17	0.235	0.649	17.189
Hav, Doors, Tavwsp, Windows	4	3.642	17	0.214	0.680	14.644
Rain, W_Speed, Tav, Hav, Doors	5	2.838	16	0.177	0.750	10.762
Rain, W_Speed, Tav, Hav, Tavwsp	5	3.375	16	0.211	0.703	14.690
Rain, W_Speed, Tav, Hav, Windows	5	5.014	16	0.313	0.559	26.680
Rain, W_Speed, Tav, Doors, Tavwsp	5	1.928	16	0.121	0.830	4.105
Rain, W_Speed, Tav, Doors, Windows	5	2.816	16	0.176	0.752	10.599
Rain, W_Speed, Tav, Tavwsp, Windows	5	3.365	16	0.210	0.704	14.618
Rain, W_Speed, Hav, Doors, Tavwsp	5	2.987	16	0.187	0.737	11.848
Rain, W_Speed, Hav, Doors, Windows	5	2.993	16	0.187	0.737	11.894
Rain, W_Speed, Hav, Tavwsp, Windows	5	5.736	16	0.359	0.496	31.960
Rain, W_Speed, Doors, Tavwsp, Windows	5	3.073	16	0.192	0.730	12.481
Rain, Tav, Hav, Doors, Tavwsp	5	3.573	16	0.223	0.686	16.135
Rain, Tav, Hav, DOors, Windows	5	3.928	16	0.246	0.655	18.733

Model	p-1	SSE	df	MSE	R^2	C_p
Rain, Tav, Hav, Tavwsp, Windows	5	5.464	16	0.342	0.519	29.969
Rain, Tav, Doors, Tavwsp, Windows	5	3.622	16	0.226	0.681	16.496
Rain, Hav, Doors, Tavwsp, Windows	5	3.477	16	0.217	0.694	15.434
W_Speed, Tav, Hav, Doors, Tavwsp	5	2.614	16	0.163	0.770	9.120
W_Speed, Tav, Hav, Doors, Windows	5	3.119	16	0.195	0.726	12.818
W_Speed, Tav, Hav, Tavwsp, Windows	5	4.376	16	0.274	0.615	22.010
W_Speed, Tav, Doors, Tavwsp, Windows	5	2.833	16	0.177	0.751	10.724
W_Speed, Hav, Doors, Tavwsp, Windows	5	3.258	16	0.204	0.714	13.830
Tav, Hav, Doors, Tavwsp, Windows	5	3.604	16	0.225	0.683	16.364
W_Speed, Tav, Hav, Doors, Tavwsp, Windows	6	2.611	15	0.174	0.770	11.102
Rain, Tav, Hav, Doors, Tavwsp, Windows	6	3.435	15	0.229	0.698	17.129
Rain, W_Speed, Hav, Doors, Tavwsp, Windows	6	2.977	15	0.199	0.738	13.781
Rain, W_Speed, Tav, Doors, Tavwsp, Windows	6	1.919	15	0.128	0.831	6.035
Rain, W_Speed, Tav, Hav, Tavwsp, Windows	6	3.319	15	0.221	0.708	16.282
Rain, W_Speed, Tav, Hav, Doors, Windows	6	2.792	15	0.186	0.754	12.421
Rain, W_Speed, Tav, Hav, Doors, Tavwsp	6	1.924	15	0.128	0.831	6.071
Rain, W_Speed, Tav, Hav, Doors, Tavwsp, Windows	7	1.913	14	0.137	0.832	7.996