1-1-2006

Human physiological limitations during prolonged multi-tasks: An aiding tool.

Ali I. Mohamed
University of Windsor

HUMAN PHYSIOLOGICAL LIMITATIONS DURING PROLONGED MUTI-TASKS: **An Aiding Tool**

By
Ali I. Mohamed

A Dissertation to the Faculty of Graduate Studies and Research
through Industrial and Manufacturing Systems Engineering
in partial fulfillment of the Requirements for
the Degree of Doctor of Philosophy at the
University of Windsor

Windsor, Ontario, Canada

2006

Your file Votre référence
ISBN: 978-0-494-35984-6
Our file Notre référence
ISBN: 978-0-494-35984-6

ABSTRACT

Physical work capacity refers to the maximum capabilities of the physiological system to produce energy for muscular work. Physical work capacity plays a central role in the process of carrying out ergonomic stress analysis in industry where a balance between job stress requirements and physical work capacity is maintained. If physical work capacity is exceeded, the worker is at risk of overexertion and may be producing lower quality work. If the job stress requirements are less than Physical work capacity, the worker may be underutilized and this could be an opportunity for productivity gains.

Over the last four decades, ergonomics researchers and practitioners have devoted considerable resources to solving the problems associated with handling materials manually. Researchers have also agreed that since manual lifting is physically the most stressful material handling activity, it is best to contain the manual lifting injury hazard. Results of such efforts are reflected in terms of various guidelines and weight limit recommendations for manual lifting activities (e.g. NIOSH and the revised NIOSH). However, the cost, number, and severity of injuries had either continued to rise or remain unchanged because of the way the problem has been historically approached. Most industrial manual material handling tasks involve more than one type of activity (lifting, turning, carrying, etc.). And yet, most efforts have been directed at only one activity, little attention has been paid to designing/analyzing tasks that include multiple and diverse manual handling activities. By relating the energy expended in a job to the aerobic power of the individuals for endurance effort, an objective assessment can be made of the work capacity of the worker performing these activities without undue fatigue. Based on the assumption that a job can be divided into sub-tasks, and the average metabolic energy expenditure rate of the job can be predicted by knowing the energy expenditure of the simple tasks and the time duration of the job), the energy requirement to perform a certain task can be determined by summing the time weighted energy cost of all task elements over the time duration that task is being performed.

This research utilizes most suitable model(s) that could be used in determining human capabilities of performing multiple jobs. It also utilizes the physiological approach in determining human capacity for multiple jobs, and examines the combinations of lifting, carrying, and lowering activities, to develop an evaluation and a decision making tool that help designers, engineers, and managers overcome human limitations in all stages of design of product and process. Another contribution of this study is the development of general models that could be used in determining the maximum energy expenditure of individuals of certain age, height, weight, and gender within a targeted percentile.

As a contribution to the area of physiological assessment of work, this study provides designers and practitioners, especially in the field of cellular manufacturing environment where high volume is dealt with, with a simple tool that could be used during both early stages of the design and during production stages to evaluate the physiological requirements of work and the capacity of people needed to perform them. The tool helps in labor assignment, determining work/rest periods needed to overcome peoples' fatigue besides the usual breaks assigned during the work shift. Despite its great advantages, there are some limitations that could be addressed in depth to further enhance the tool for better performance.

DEDICATION

To my family

ACKNOWLEDGEMENT

I would like to express my sincere appreciation to my supervisor Dr. L. Oriet for his guidance, advice and assistance during the course of this study. I am also grateful to the members of my committee, Dr. F. Moro, Dr. J. Zhang, Dr. M. Wang and the external examiner Dr. O. Basir for their suggestions and cooperation.

Sincere thanks to Mrs. Mummery and Mr. Barakat for his efforts and help. Finally, my thanks are due to my family for their patience and moral support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1 General Overview:

Ergonomics (also known as human factors) is the branch of science that is concerned with the achievement of optimal relationships between workers and their work environment. It deals with the assessment of the human's capabilities and limitations, work and environmental stresses, static and dynamic forces on the human body structure, fatigue, design simulation and training, and design of workstations and tools. The two conflicting factors in this optimization process are workers' productivity and their health and physical well being. That is, while workers should perform their job in the most efficient manner possible, they must also be protected against undue physical, biological, and psychological strain that may occur as a result of performing the required tasks (Tayyari and Smith, 1997).

1.2 The Role of Human Factors

Human factors professionals are well positioned to play a significant role in the workforce renewal process and in the identification of product features that make products more effective and satisfying to use and process features that optimize human-machine system to produce superior products. According to Plonka (1997) ergonomists and human factors professionals can assist to:

1. Identify work force attributes that are important for successful performance in the manufacturing environment.
2. Address the correct mixture of experience, theory, and practice to support a continuous development and training process.
3. Help workers to redefine workplace and to gain competitive advantage.
4. Play a significant role in problem solving and the transfer of lessons learned into practice by reducing their experiences to principles that machine designers can use to enhance machine and equipment performance.

5. Besides mitigating the effects of system complexity, human factors professionals classify work from the perspective of cognitive, skill, and knowledge demands for workers rather than the traditional approaches used by labor unions using seniority and historical precedence.

Humans build the products that are consumed, and this reality that will be studied and supported with this research.

1.3 Workplace stress factors

Every workplace represent its own, distinctive physical and mental workload stress factors such as: complexity and number of tools used in the workplace; and unnatural environmental conditions (thermal, noise, vibration).

The stress from these factors placed on the worker are significant, and the above mentioned ergonomic principles can be applied to the design of the workplace so that the strain placed on the worker is reduced in balance of productivity goals and objectives..

1.4 Ergonomics Applications

Ergonomics principles can be used in the following industrial applications:

1. design, modification, replacement and maintenance of equipment for enhanced productivity, work-life and product quality;
2. design and modification of work spaces and workplace layout for ease and speed of operation, service and maintenance;
3. design and modification of work methods, including automation and task allocation between human operators and machines;
4. Controlling physical factors in the workplace for the best productivity and safety of employees.

1.5 Ergonomics Results

Application of these principles to the workplace is expected to result in the following:

1. Understanding the effects of a particular type of work on workers' bodies and their job performance;

2. Predicting the potential long-term (or cumulative) effects of work on workers;
3. Assessment of the worker interface with process and tools;
4. Improvement of productivity and well-being of workers by "fitting the task to the person", rather than "fitting the person to the task". The result is to achieve the best matching between worker capabilities and job requirements;
5. Establishment of a knowledge base support for designers, engineers, and medical personnel for improving the productivity and well-being of individuals.

1.6 Physical work capacity

Physical work capacity (PWC) refers to the maximum capabilities of the physiological system to produce energy for muscular work. PWC plays a central role in the process of carrying out ergonomic stress analysis in industry. The objective of applying ergonomic principles in the workplace is to maintain a balance between job stress requirements and PWC. If PWC is exceeded, the worker is at risk of overexertion and producing lower quality work. If the job stress requirements are less than PWC, the worker is underutilized and there is a productivity loss. Tichauer pointed out that ergonomic stress can be classified into two main categories:

1. traumatogenic (high dose over short duration) and
2. Cumulative (low dose over long duration.

The maximal oxygen uptake or the maximal aerobic power is defined as the highest oxygen uptake the individual can attain during exercise (2-6 min depending on type of exercise) engaging large muscle groups while breathing air at sea level (Astrand and Rodahl, 1986).

In a normal healthy person, the PWC is directly related to the capability of the cardiovascular system to provide oxygen to the working muscles and to remove waste products of metabolism. PWC can be defined in terms of specific muscle group activities (e.g. lifting tasks) or for whole-body activities (walking) (Tayyari and Smith 1997). Aerobic capacity is denoted by Vo_2 max and usually expressed in liters per minute or milliliters of oxygen per kilogram body weight per minute for a given gender and age group. Its synonyms are PWC, maximal oxygen uptake, and Vo_2 max. In many types of exercise, it has been proven that the oxygen uptake increases roughly linearly with an increase in the rate of exercise. If a given task demands an oxygen uptake of 2.0 liter/min, the person with a maximal O_2 uptake of 4.0 liter/min has a satisfactory safety margin, but the 2.5 liter individual must exercise close to his/her maximum, and consequently his/her internal equilibrium becomes much more disturbed. It is obvious that the individual's maximal aerobic power play a decisive role in his/her physical performance It has been found that for each liter of O_2 consumed, about 5kcal; range of 4.7 to 5.05; of energy will be delivered; hence the higher the oxygen uptake, the higher energy aerobic output) (Astrand and Rodahl, 1986). During the simulated automobile assembly tasks, Chung et al. (2001) evaluated heart rate; oxygen consumption and subjective discomfort rating were evaluated. Although no statistically significant increase was observed in heart rate for the poor leg posture, all three physiological measures, heart rate, oxygen consumption and subjective discomfort rating, showed a significant increase for the heavy load and for the laterally bent and twisted trunk posture. From the results it was confirmed that heavy load and lateral bending and twisting postures are very harmful to workers from a physiological as well as a biomechanical perspective.

1.7 Manual Material handling and Human Limitations

In tasks like assembly, maintenance, packaging, and construction, despite the increasing degree in mechanization and automation, manual material handling (MMH) carried out by humans continues to be an important and essential requirement of many industrial service occupations.

As described by Shephard (1991), the human body can be recognized as a very good mechanical design. However, it is not indestructible and there are some limitations of the human body because of the material and the mechanical structure, the level of mechanical stress cannot exceed some physical bounds at some given time at some given tasks within the musculoskeletal system.

In order to reduce injuries, improve productivity, and improve quality, the job demands should match the capacities of the individuals. This can be done by adjusting the task characteristics to fit the workers. MMH is affected by three factors:

1. Workers related factors; age, gender, anthropometry, strength

2. Task related factors; workplace geometry, posture range of movement, container size shape, handles frequency and load stability.
3. Workplace environment factors; temp, lighting, and vibration.

Transporting materials is always costly in terms of machinery, space, and energy. In many existing facilities, reduction and simplification of material movement can lower the expense of material transport which amounts to 30 to 75 percent of total operating cost, Karl and Kroemer (1997). From a human point of view, redesigning, improving, or eliminating manual carrying transport lines would increase the possibility of reducing the risks of overexertion and injury to workers.

Cumulative trauma disorder (CTD), known also as Repetitive Strain Injury (RSI) occurs when an activity is repeated so often that it overloads the body parts involved. In order to avoid such injuries, there exist some conditions that need to be avoided when designing the workplace. Among these conditions are;

1. Work that requires prolonged or repetitive exertion of more than about one third of the operator's static muscular strength available for that activity.
2. Putting body segments in extreme positions.
3. work that makes the person maintain the same body posture for long periods of time

There are also some recommendations and guidelines provided by the National Institute for Occupational Safety and Health (NIOSH) that need to be followed and considered during the design stage of a manufacturing facility. These recommendations are published in the Work Practice Guide (WPG) for manual lifting.

1.8 Cellular manufacturing

Cellular manufacturing is a lean manufacturing approach that helps companies build a variety of products for their customers using lean manufacturing techniques. In cellular manufacturing, equipment and workstations are arranged in a sequence that supports a smooth flow of materials and components through the process, with minimal transport or delay. Cellular manufacturing is a major building block of lean manufacturing.

A manufacturing cell consists of the people and the machines or workstations required for performing the steps in a process, with the machines arranged in the processing sequence. Arranging people and equipment into cells helps companies achieve one-piece flow and high-variety production. One-piece flow is the state that exists when products move through a manufacturing process one piece at a time, at a rate determined by the needs of the customer. Operating so that products flow one piece at a time allows the company to deliver products to customers quicker, reduces storage and transport requirements, lowers the risk of damage, and exposes other products to address.

Cellular manufacturing offers companies the flexibility to give customers the variety they want, it allows variety by grouping similar products into families that can be processed on the same equipment. It also encourages companies to shorten changeover time so product type can be changed more frequently. Converting a factory to cellular manufacturing means eliminating waste from processes as well as from operations. Fig 1.1 lists all eight aspects of waste recognized in manufacturing as stated by Ott (1999). A process is a continuous flow in which raw materials are converted to finished goods in a series of operations. The focus of a process is the path of the materials as they are transformed into something to sell. An operation is any action performed by workers or machines on the raw materials, work-in-process, or finished products.

Cellular manufacturing can help make companies more competitive by cutting out costly transport and delay, shortening the production lead time, saving factory space that can be used for other value-adding purposes, and promoting continuous block low-inventory production. It also helps employees by strengthening the company competitiveness, which helps support job security. It also makes daily production work go smoother by removing the clutter of access WIP inventory, reducing transport and handling, reducing the walking required, and addressing causes of defects and machine problems, Ott (1999).

Waste Type	Example
Defects	Scrap , rework, replacement production, inspection
Waiting	Stock-outs, lot processing delays, equipment downtime, capacity bottlenecks
Processing	Unnecessary or incorrect processing
Overproduction	Manufacturing items for which there are no orders
Movements	Human motions that are unnecessary or straining
Inventory	Excess raw material, WIP, or finished goods
Transport	Carrying WIP long distances, inefficient transport
Unused employee creativity	Lost time, ideas, skills, improvements

Fig 1.1 Wastes in Manufacturing

1.9 Motivation for the Study

It is well established that occupational injuries and illness accounts for a significant portion of lost workdays in industry. When an employee is injured or becomes ill, the cost of that injury or illness is not easily calculated due to a variety of factors. Aside from medical, indemnity and risk management costs associated with an injury or illness, there are also ancillary or indirect costs such as lost productivity; overtime associated with compensating for injured; work-site modification and/or supervision of injured workers, recruitment and retraining of replacement workers, human resource department costs for managing injured and legal fees. These factors combined represent a significant opportunity for cost reduction since occupational injuries are manageable and in many instances preventable. Many studies call workplace disruption and lost productivity indirect costs because they are not costs of treating the injury. Nevertheless, these costs affect an employer's profitability directly whenever an employee misses work, works at less than usual capacity, or are diverted to less demanding tasks. Uninjured co-workers may also lose productivity by assuming additional work-load during the absence of their colleague absence. As a result, an employer may have to pay overtime. In other cases, work may be rescheduled awaiting the injured person return. Replacement of an employee may cause further productivity loss because the replacement is less skilled, need to be trained, has a start-up period, or so skilled that they can not be replaced.

Employers lose more productivity when coworkers divert their attention from their work to help their injured coworker out of curiosity or sympathy or they may at least chat about the accident rather than producing. Supervisors and executives lose productivity when they are diverted to injury investigation to secure evidence against liability actions or point the way to future prevention. Insurers and claims processors may also investigate, passing the cost to the employer as claims administration expenses. Supervisors lose time assisting injured employee, reschedule production, hiring temporary or permanent replacement, or providing training. Further reduction in profitability may result from interference with production, failure to meet orders in time, loss of bonuses, or payments of forfeits. Injured employees and their family have to cope with the accident for some time. They alone bear the tears, despair, and reduced quality of life that injury can bring. Consequently, employers have to pay higher wages to induce people to take risky jobs. These wage premiums can be viewed as prospective insurance premiums. They compensate in advance for their possible future losses (T. Miller, 1997).

Musculoskeletal disorders (MSD) due to cumulative trauma represent a major health and financial burden to the employees and to the industry. In the US in 1989 alone, the total compensable cost for the upper-extremity work-related MSDs was estimated to be $563 million. In recent years; many companies have implemented office ergonomic training programs to reduce and prevent MSDs among VDT users (Lewis et al, 2002).

Workplace injuries cost the US an estimated $140 billion annually. This estimate includes $17 billions in medical and emergency services, $60 billions in lost productivity, $5 billion in insurance costs, and $62 billion in lost quality of life.

As been mentioned by Guidotti (1995), the Canadian province of Alberta's expenditures on workers' compensation claim costs increased to 470million dollars in 1997, $62 million overbudget and representing a 3% growth over 1996 costs. In 1998, cost increased to $555 million, $90 million overbudget and 15% growth over 1997costs. In 1999, $821 million, 45% overbudget, and 75% over the total claim cost in 1997. In light of these staggering costs, the need for occupational injury and illness control research and ensuing remedial action has never been more apparent. Mital et al (1993) reported that manual material handling injuries have continued to be a major injuries problem. MMH tasks pose physical stresses to the operator that is shown as strains on the musculoskeletal and cardiovascular system. When this strain exceeds the human body capacity, it results in discomfort, fatigue, and injuries.

The literature review indicates that several techniques and models are developed to help in designing production cells. Many of these models consider several functions such as material handling, machine investments, setup, tooling and processing times, and unutilized capacity. The studies tackled mainly the cost aspect of each evaluation criteria. However, all these models failed to address the importance of including human limitations in the design of cells. There is also a lack of comprehensive data base of human related data, especially in terms of manual material handling. Hence, there exists the need to develop a model(s) which will include the effect of human interaction with such systems.

1.10 Scope and Objective of the Study

Over the last four decades, ergonomics researchers and practitioners have devoted considerable resources to solving the problems associated with handling materials manually. Researchers have also agreed that since manual lifting is physically the most stressful material handling activity it is best to contain the manual lifting injury hazard. Results of such efforts are reflected in terms of various guidelines and weight limit recommendations for manual lifting activities (e.g. NIOSH and the revised NIOSH). However, despite these efforts to contain the hazards of MMH, the cost, number, and severity of injuries has either continued to rise or remains unchanged because of the way the problem has been historically approached. Most industrial manual material handling tasks involve more than one type of activity (lifting, turning, carrying, etc.). And yet, most efforts have been directed at only one activity – manual lifting (for instance, the user's manual associated with the revised NIOSH lifting guide); little attention has been paid to designing/analyzing tasks that include multiple and diverse manual handling activities.

To date, limited efforts have been directed at designing and analyzing handling tasks involving multiple and diverse activities. One such effort was initiated by Mital 1983. The procedure that was developed was revised (Jiang et al, 1986), after the publication of Manual Material Handling Guide by Mital et al., 1993).

The primary scope and objectives of this research will be focused on three main aspects: Firstly, to develop regression models which will be used in determining maximum human physiological capabilities; Secondly, to utilize available physiological models in determining job physiological demand and; Finally, to use the above mentioned two objectives in developing a decision aiding tool that help designers, engineers, and managers overcome human limitations in all stages of design and during production.

Despite the useful use of this decision aiding tool in all areas where manual handling of materials is being performed, an ideal application of such tool would be in the area of cellular manufacturing. Such systems are characterized by high volume, high variety, routinely performed material handling, and human wasted movements. Become of such characteristics of this system, the proposed aiding tool of this study would enable addressing the ergonomic issues of such system such as human maximum reach, frequency of movements, maximum walk, and maximum load capacity.

1.11 Thesis Organization

The remainder of this report will be organized as follows:

Chapter 2 includes literature review of previous studies conducted regarding the area of physiological work, manual material handling, available tools and standards governing such activities with their applications and limitations, and finally selected work done in the area of cellular manufacturing systems. Chapter 3 represents maximum energy expenditure regression models developed and how they are used besides the existing available models to develop the decision aiding tool. Chapters 4 and 5 describe and explain how the aiding tool is developed and used. Finally, Chapter 6 represents some conclusions regarding this study, its limitations, and suggestions for future work that would enhance the advantages of using such tool and overcomes some of its limitations.

CHAPTER 2
LITERATURE REVIEW

2.1 Ergonomics Impact

Ergonomics, as a tool, is not only limited to predicting and eliminating workplace injuries, but can also be used to enhance productivity, reduce production costs, increase productivity, quality and profit. The following literature represents the impact of applying ergonomics principles within some industries and services;

Miller (1997) concluded that occupational injury and illness control and prevention represents an avenue of substantial revenue recovery if this problem can be attenuated. Ergonomics has been shown to be an effective method of addressing the problem of occupational injury and illness by the general accounting office in the US.

Resnick and Zanotti (1997) suggested that the optimal workplace design must consider both ergonomics and productivity as main objectives despite the fact that they present conflicting recommendation for workstation design. In this way, a workplace can be designed to improve long term performance and maximize the contribution of the job to the profitability of the organization.

Martin and Burri (1995) in their study of IBM manufacturing plant emphasized the importance of ergonomics as a tool for improving work environments for people and its overall contribution to productivity. Within this study, four manufacturing facilities were evaluated and redesigned. These ergonomics improvements resulted in $7,375,000 savings. The authors estimated the savings from such programs to reach $130 millions for the past ten years.

Stanton and Baber (2003) in their article regarding cost-effectiveness of ergonomics posed the question of whether organizations can afford not to have ergonomics after its obvious impact on organizations. After checking literatures on the significance of ergonomics, the author concluded that all papers reviewed suggest that the cost of ergonomic involvement and intervention are likely to be a small fraction of the total budget. These figures range from 1% to 12% with payback periods of less than one year.

Although the cost of interventions used by Yeow and Sen (2003) was less than $1100, this cost resulted in average savings in yearly rejection cost of $574,560. When the authors conducted a study to improve workstations for electrical tests in a printed circuit assembly, they concluded a reduction in rejection rate, increase in monthly revenue, improvements in productivity, quality, and operators working conditions and occupational health and safety and enhancement in customer satisfaction.

2.2 Manual Material Handling

Despite the recommendation for using mechanical means in handling materials in any production environment, manual material handling (MMH) continues and will continue to be a part of many occupations (Burt et al, 1999). Such activities are considered as main reason behind lower back and other related injuries. In the pursuit of reducing the effect of such activities on humans, researchers developed indices such as the job severity index and the lifting index. These indices were developed with the assumption that the severity of a job in terms of its injury potential is a function of job demands and job capacity. i.e. if the requirements of the job are well above that of a person's capacity to perform that particular job, a fair assumption is that the job can be dangerous for that person.

Techniques for analyzing manual handling tasks take a variety of forms, i.e., biomechanical (Anderson et al., 1985; Schultz et al., 1982; Freivalds et al., 1984; Hsiang and Ayoub, 1994), psychophysical (Snook and Ciriello, 1991), physiological (Garg et al., 1978) and epidemiological (Winkel and Mathiassen, 1994). Some techniques use postural analyses to develop ergonomic interventions (Derksen et al., 1994; Kant et al., 1990; Burdorf et al., 1991; Burdorf et al., 1992; Mattila et al., 1993; Kivi and Mattila, 1991; Genaidy et al., 1994; Kuorinka, 1994). Other techniques look at specific tasks in the field and make recommendations based on physiological or subjective results (Kemper et al., 1990; Torner et al., 1988; Vink, 1992, Ljungberg et al., 1989; Damlund et al., 1986; lhammar et al., 1986). Some investigators have combined techniques of task analysis so that comparisons can be made between the multiple assessment approaches (Rohmert, 1985).

Yeung et al. (2002) explored whether professional expertise can be relied on, through the use of a systematic procedure, to quantify the effects of lifting task parameters on perceived effort and risk of injury outcome measures. Three international experts participated in the research reported herein and evaluated the interactive effects of 6 lifting variables: (a) weight of load, (b) horizontal distance, (c) frequency of handling, (d) work duration, (e) twisting angle, and (f) height of lift. They predicted the lifting effort and the injury risk of a large number of lifting configurations. A linguistic approach was used to describe the lifting activities. Logistic regression analyses were employed to model effort as a function of various lifting task variables. The results showed that all 3 experts rated the weight of load as the most dominant variable and the height of lift as the least important variable. Furthermore, they differed slightly in ranking the relative importance of other variables. In general, the effect of weight of load on physical effort was, at a minimum, 2 times more important than other lifting task variables. The horizontal distance, work duration, frequency, and twisting angle variables were considered to be more important than the height of lift by 25% to 33%. Collectively, these findings indicate that the experts agreed on the most and least important variables.
Snook and Ciriello, (1991) noted that It is also important to note that some of the weights and forces in Snook's tables will exceed recommended physiological criteria when performed continuously for 8 h or more.

The recommended 8 h criteria are approximately 1000 ml/min of oxygen consumption for males; 700 ml/min for females (NIOSH 1981). Tables give maximum acceptable weights and forces for individual manual handling tasks or components. (e.g. lifting). Frequently, however, industrial tasks involve combinations with more than one component (e.g. lifting, carrying, and lowering). Previous results indicate that, in a multiple component task, the weight or force of the component with the lowest percent of population is the best estimate of the maximum acceptable weight or force for the entire task. Therefore, each component of a combined task should be analyzed separately using the frequency of the combined task. The weight or the force of the combined task with the lowest per cent of the population represents the maximum acceptable weight or force for the combined task. However, since the physiological cost of the combined task will be greater than the cost for individual components, it should be recognized that some of the combined tasks may exceed recommended physiological criteria for extended period of time.

2.2.1 MMH Cost and Impact

It has been documented in the literature that a worker's risk factor of incurring a low back pain has been directly related to occupational activities such as manual material handling due to inappropriate handling techniques used (Bigos et al. 1986; Marras et al. 1993; Snook 1989). Four specific occupational risk factors associated with low back pain have been identified as: lifting, work posture, frequent bending and twisting and repetition (Genaidy et al. 1994; Andersson 1985). MMH tasks pose physical stresses to the operator shown as strains on the musculoskeletal and cardiovascular system. Discomfort, fatigue, or injury will result when the strain imposed on one of these systems exceeds the capacity of the system.

MMH-related injuries are responsible for about 41% of the cost of workers' compensation keeping 20% of workers out of the workplace for an average of 3 weeks to 6 months. Treatment and disability expenses resulting from MMH is approaching $14-18 Billion (Haldeman, 1990). In the province of Ontario, Canada, it has been reported by Worker Compensation Board (WCB), that the average number of days lost per claim due to back injuries is 83 days and the average cost per claim is $10,949 (WCB report, 1997). Lifting, defined as moving object by hands from lower position to a higher one (Kroemer, 1992), is associated with up to one-half of lower back injuries (Nelson, 1987). Lavender et al., (2003) Lifting and material handling have been associated with the onset of low backpain in several epidemiological studies (Andersson, 1991, 1999; NIOSH, 1997). In particular, lifting which requires severe trunk flexion has been shown to increase the likelihood of low-back disorders (LBDs) (Marras et al., 1993; Punnett et al., 1991). Both static and dynamic linked segment biomechanical models have been used to describe the forces and moments acting on the spine as lifts are performed in the laboratory and in industry; Freivalds et al., 1984; Lavender et al., 1999; Potvin et al., 1992. The studies above showed how effective ergonomics tools are when applied to a workplace design in terms of their impact on the total production costs. These studies and applications are in fact all have a reactive nature dealing with present existing situations. Applying such tools in such manner would constitute an extra cost factor, which is cost of change. This cost could be augmented or eliminated if these principles are applied proactively. That is, during early stages of the design process.

2.3 The NIOSH Original Lifting Model

In 1981, NIOSH published the work practice guide for manual lifting (WPG). WPG was based on the thought that "an overexertion injury is the result of job demands that exceed a worker's capacity" (Waters et al, 1997).

The WPG was developed with the input of many experts. It involved epidemiological, biomechanical, physiological, and psychophysical studies of the capabilities and limitations of people while performing MMH activities. In establishing the scope and limit of the recommendations of the WPG, the following assumptions were presented:

1. smooth lifting;
2. two-handed, symmetric lifting in the sagittal plane;
3. moderate width;
4. unrestricted lifting posture;
5. good coupling;
6. favorable ambient environments. (Tayyari and Smith, 1997)

2.3.1 NIOSH Guidelines

Mital and, Ramakrishnan (1999) demonstrated that manual lifting activity does not limit a person's ability to perform manual materials handling activities. Using a complex manual materials handling task from the railroad industry, it is demonstrated that the capability to perform multiple activity materials handling jobs is limited by different materials handling activities for different people. The complex manual materials handling task, which involved lifting, turning, carrying, and pushing activities, was analyzed using both the old and revised NIOSH lifting guidelines. It is concluded that both old and revised NIOSH guidelines are of little use in analyzing multiple jobs. It is suggested that the failure to study realistic manual handling activities, and the resulting lack of guidelines to design such jobs, is a dominant reason why the hazards of manual materials handling have not been contained. The study leads to the conclusion that in a multiple activity task, lifting is not always the limiting activity for everyone. This further demonstrates the limitation of the revised NIOSH guide, particularly when it comes to designing and/or analyzing realistic industrial jobs. The study recommended weights also demonstrates the need to develop population capability data for multiple activity tasks.

Mital and Ramakrishnan (1999) mentioned that the efforts to develop population capability data for multiple activity materials handling tasks, at least in the initial stages, owing to a vast number of possible combinations, will have to be limited to pervasive and industry-specific activities. However, unless such efforts are undertaken, containing the manual materials handling hazard cannot be assured.

Most studies in manual material handling (MMH) have paid attention to single MMH activities such as lifting, lowering, carrying, holding, pushing or pulling and have ignored combined activities. Also, most studies have involved two-handed (symmetric) MMH activities rather than one-handed MMH activities. Very few studies have reported information on workers' capacities for combinations of one-handed MMH activities (e.g. lifting a box, then carrying the box, and lowering the box). These kinds of combined activities are common in industry and in our daily lives. Very few studies have examined the capacities of combinations of two or more activities such as lifting a box, then carrying the box and lowering the box with two hands (Jiang, 1984; Morissey and Liou, 1988). Jiang (1984) used the psychophysical methodology to find the maximum acceptable weight of two-handed combined manual material handling activities

2.3.2 NIOSH Limitations

The original NIOSH equation was criticized by practitioners because it was difficult to use and many of its underlying assumptions were inflexible (DeClercq and Lund, 1993).

In using the NIOSH WPG in real-world situation, the following considerations should be taken into account:

1. Other MMH (holding, carrying, pushing, and pulling) are assumed to be minimal.
2. When lifting activities are not performed, the individual is assumed to be at rest.
3. The work force is physically fit and accustomed to physical labor.
4. Safety factors commonly used by engineers to account for the unexpected conditions are not included.

The Work Practices Guide for Manual Lifting provided by the National Institute for Occupational Safety and Health of USA (NIOSH, 1981) or the Revised NIOSH Lifting Equation (Putz- Anderson and Waters, 1991; Waters et al., 1993, 1994), respectively, is accepted as a valuable tool for the design and evaluation of manual lifting in ergonomics and occupational health. Many industries have found the Work Practices Guide to be very useful in identifying problems and reducing injuries. Moreover, the NIOSH method has gained considerable recognition in the drafting of European and international standards (CEN, 1996; ISO, 1995).

Jager and Luttmann (1999) claim that although several critical issues were considered in this survey, the Work Practices Guide for Manual Lifting provided by NIOSH (1981) remains, nevertheless, a valuable compendium for ergonomists and practitioners, demonstrating the wide scope of stress-and-strain influences and consequences for persons performing manual materials handling tasks during a working life. A revised lifting equation has been developed by (Waters et al., 1994) to account for the quality of the couplings and twisting action during lifting. However, the revised lifting equation has not been accepted and its future implementation is in question

The NIOSH models attempt to determine the amount of weight that could be lifted such that the compressive forces on the spine would not exceed 3430N in most individuals performing a lift during a specified set of lifting conditions. The 1981 lifting guide required the following lift specifications: the initial vertical location of the load, the vertical displacement of the load, the maximum horizontal distance between the load and a point midway between the ankles, and the frequency of lifting (NIOSH, 1981). The revised model also includes the asymmetry of the lift (angular deviation from the mid-sagittal plane) and the quality of the hand to object coupling (Waters et al., 1993). Unfortunately, the role of dynamics has not been incorporated. In fact, the model still assumes that the lifts are performed slowly over a 2–4 s period.

Snook, (1978); Snook and Ciriello, (1991) investigated the relationship between lifting and lowering demands (as expressed by the revised NIOSH lifting equation (Waters et al., 1994)) and reporting of workers' compensation claims and concluded a fairly high percentage of lifting, lowering, and carrying tasks do not accommodate a sufficient proportion of the female population, whereas a higher percentage of pushing and pulling tasks were acceptable according to the psychological data. The NIOSH equation was formulated according to the empirical model suggested by Drury and Pfeil (1975). Particularly, its development required two inputs: (a) data generated in the published literature, and (b) expertise of committee members convened under the auspices of NIOSH. No formal approach was deployed to use human expertise to establish manual lifting guidelines

2.4 Physical Work Capacity

PWC refers to the maximum capabilities of the physiological system to produce energy for muscular work. The maximal oxygen uptake or the maximal aerobic power is defined as the highest oxygen uptake the individual can attain during exercise (2-6 min depending on type of exercise) engaging large muscle groups while breathing air at sea level. (Astrand and Rodahl, 1986). In a normal healthy person, the PWC is directly related to the capability of the cardiovascular system to provide oxygen to the working muscles and to remove waste products of metabolism. PWC can be defined in terms of specific muscle group activities (e. g lifting tasks) or for whole-body activities (walking) (Tayyari and Smith 1997).

Aerobic capacity is denoted by Vo_2 max and usually expressed in liters per minute or milliliters of oxygen per kilogram body weight per minute. Its synonyms are PWC, maximal oxygen uptake, and Vo_2 max. In many types of exercise, it has been proven that the oxygen uptake increases roughly linearly with an increase in the rate of exercise. If a given task demands an oxygen uptake of 2.0 liter/min, the person with a maximal O_2 uptake of 4.0 liter/min has a satisfactory safety margin, but the 2.5 liter individual must exercise close to his/her maximum, and consequently his/her internal equilibrium becomes much more disturbed. It is obvious that the individual's maximal aerobic power play a decisive role in his/her physical performance. It has been found that for each liter of O_2 consumed, about 5kcal; range of 4.7 to 5.05; of energy will be delivered; hence the higher the oxygen uptake, the higher energy aerobic output) (Astrand and Rodahl, 1986)

During the simulated automobile assembly tasks, Chung et al. (2001) evaluated heart rate, oxygen consumption, and subjective discomfort rating. Although no statistically significant increase was observed in heart rate for the poor leg posture, all three physiological measures, heart rate, oxygen consumption and subjective discomfort rating, showed a significant increase for the heavy load and for the laterally bent and twisted trunk posture. From the results it was confirmed that heavy load and lateral bending and twisting postures are very harmful to workers from a physiological as well as a biomechanical perspective.

2.4.1 Maximum Aerobic Capacity

Individuals have a maximum aerobic capacity they could produce during certain physical exercise. When designing jobs for these individuals, the energy requirement for these jobs should not reach this maximum value since individuals will perform these jobs for prolonged time. The issue of how much value of this maximum capacity should be used as an acceptable limit has been the topic of discussion of the people concerned with this field.

Christensen proposed that work could be performed at 50 percent of maximum aerobic power for eight-hour work day. Astrand expressed serious doubts that this was too high an expectation. Research by Brauha supports the theory that a work capacity limit based on 50 percent of the maximum aerobic capacity of an individual was a fatigue-generating energy expenditure rate.

Studies by Lehmann recommended 33 percent of the maximum aerobic power of a normal healthy person as the maximum energy expenditure rate that should be expended for an eight-hour work day. Generally, 16 kcal/min is taken as the maximum aerobic power of a normal healthy young male for a highly dynamic job (walking, bicycling...).

For an eight-hour continuous work period, a physical work capacity limit of 5.2 Kcal/min is recommended by Chaffin. This is based on 33 percent of 16Kcal/min taken as the maximum aerobic power for a healthy male. As stated by Moores, the aforementioned 5.2 Kcal/min was also deemed an average acceptable level by Lahmann from studies undertaken throughout German industry. Indeed, older workers and female workers will require a much smaller physical work capacity limit. (Louhevaara, 1999) quantified physical work load of blue-collar workers and compared the work load factors between ageing (45 years) and young workers.

Energy expenditure, HR and the proportions of poor work postures were similar when the ageing and young subjects were compared in their occupational groups. i.e., physical work load of blue-collar workers seems not to be affected by age. The study recommended that physical work load should be reduced with age. Ergonomic and organizational measures, exercise and health promotion and the continuous improvement of occupational skills are needed for promoting work ability, health and well being of all, and, particularly, ageing blue-collar workers. As stated by Pollock (1973) Maximal oxygen consumption rate (Vo_2max) is often considered to be the most representative measure of cardiorespiratory fitness. However, Vo_2max is a measure of the maximal capabilities of the oxidative systems and may not be the most appropriate measure for determining work capacity at sub-maximal workloads. For example, it has been noted that Vo_2 does not reflect accurately either the environmental demands of a task or the subjective estimates of fatigue (Christensen 1953). In addition, a Loree et al. (1957) claim that measurement of Vo_2max requires subjects to exercise to volitional exhaustion, which may not be appropriate in many subjects, and requires expensive laboratory equipment and trained technicians. Other techniques for determining work capacity that involve measurement of parameters other than Vo_2 have been proposed in the literature.

Alternatively, Muller (1953) has suggested that the heart rate (HR) response at a submaximal power output and the physical working capacity (PWC) at a submaximal HR should be considered as important as Vo_2max in determining the effectiveness of exercise training programs Muller defined the endurance limit (EL) in absolute terms as approximately 2000 kcal in an 8-h work shift. However, factors other than the workload, such as heat, isometric contractions, and the movement of body weight, influence EL. Therefore, Muller (1953) states that, ``we tried to end a test which would indicate, in all types of muscular activity, whether a given intensity of work can be endured for hours without symptoms of fatigue." Thus, he used HR as an indicator of the adequate blood supply to the working muscles that are necessary in order to avoid

Levushkin, (2001) estimated the physical work capacity of young men (17–21 years old). A comparative analysis of the physical work capacity in subjects with different levels of motor activity showed that the indices of physical development, physical fitness, and aerobic capacity in 17-year-old athletes exceeded the same indices in the untrained age-matched group. Physical work capacity was significantly higher in athletes than in the untrained subjects during the whole juvenile period. In athletes the age-related physical fitness and aerobic capacity increased to a greater extent but physical development increased to a lesser extent than the same in the untrained subjects.

Physical development of male subjects significantly increases at the age of 17–18 years, and at the age of 18–21 years it stabilizes around the level achieved by 18 years. Physical fitness during early adulthood changes insignificantly: general and back muscle strength slightly increases, spine flexibility decreases, and speed is virtually unchanged. The aerobic capacity in subjects increases at the age of 17–18. However, at the age of 18–21 years the changes in aerobic capacity are insignificant. Weibel (1999) attributed the limitation of oxygen supply to muscles to two main conditions: (1) in heavy exercise where endurance work becomes limited when Vo_2max is reached; and (2) at high altitude. The study suggested that it has been demonstrated that oxygen supply to the muscle cells becomes limited by the diffusing capacity of the lung when individuals work hard under hypoxic conditions such as at high altitude.

2.5 Factors Affecting Aerobic Capacity

Personal, task, and environmental parameters are important factors affecting the physical work capacity. Some of the most important personal factors are age, gender, body weight, and fitness level. As it has been mentioned in the literature, Individual's age is one of the main factors affecting the value of the maximal oxygen uptake. The maximal oxygen uptake increases with age up to between sixteen to seventeen years in females, and eighteen to twenty years in males. Beyond these ages there is a gradual decline so that the sixty years old individual attains about 70% of the Vo_2 max from what it was at the his/her age of twenty five. Vo_2 max of a female is about 25-30% lower of that of males (Tayyari and Smith 1997). It is well established that environmental factors affects the worker's physical work capacity. For example, it was found that lifting capacity decreased by about 12% when individuals are handling loads at 32 degrees temperature compared to lifting loads at moderate ambient temperature of < 27 degrees. Fig 2.2 was adapted from Kroemer et al (2001) to represent all these factors.

The maximal oxygen uptake increases with age up to between sixteen to seventeen years in females, and eighteen to twenty years in males. Beyond these ages there is a gradual decline so that the sixty years old individual attains about 70% of the Vo2 max from what it was at the his/her age of twenty five. In the post-40-year category physical "fitness begins to decrease and may impair work capacity and performance particularly in physically demanding blue-collar jobs. Physical work load should be adjusted according to the work capacity of each individual worker for preventing overstrains, fatigue, disorders and injuries. In principle, physical work load should be decreased with increasing age due to the natural and evident decline of physical work capacity (Ilmarinen, 1992).

According to health and safety representatives the most negative factors affecting physical work load are excessive physical job demands, time pressure, cold, heat, humidity, and noise (Heikkinen et al., 1994; Miettinen and Louhevaara, 1994; Louhevaara et al., 1998).

The greater requirements of work output, and the effects of ageing, may considerably increase physical strain and work-related disorders in blue-collar jobs.

The decline in muscle capacity with age is mainly related to changes in muscle composition, decreased muscle mass due to reduced physical activity and less efficient neurogenic motor control [Aoyagi and Shephard, 1992; Bemben et al., 1991; Frontera et al., 1991]. There are still doubts about whether a primary age-dependent process within the muscle fibers also contributes to the observed reduction in muscle strength with age [McCarter, 1990]. Astrand et al. [1973] report that the decline in aerobic power with age is mainly related to reduced maximal heart rate and consequently reduced maximal cardiac output. Nygard et al., (1987, 1988b) and Era, (1992) reported that despite the positive effect of activity on physical capacity, a negative relationship between capacity and physical activities at work has been observed in recent studies among middle-aged and elderly worker's. Since the relationship between physical capacity and physical work load among young workers is positive, these findings support the hypothesis that long-term physically demanding activities might have a deleterious effect on physical capacity possibly in combination with aging.

Physical performance is greatly influenced, directly or indirectly by factors in the external environment. Air pollution affects physical performance directly by increasing airway resistance and indirectly causing ill health. The same applies for tobacco use and alcohol. Noise damages hearing and elevates heart rate and affects other performance parameters that reduce physical performance. Cold can reduce physical performance due to numbness of the hands or lower body temperature. Heat, if intense, can greatly reduce endurance because more of the circulating blood volume must be devoted to transporting heat rather than oxygen and because sweating results in dehydration. Astrand et al, (2003).

Physical activities performed in hot, humid conditions may cause fatigue and exhaustion sooner than in more moderate conditions. Cold significantly affects physical work due to the reduction in limb and whole body temperature. This reduction in temperature affects the limbs muscular control, and reduced muscular strength and endurance because of the reduction in the metabolic rate. People perception of comfort is influenced by three factors: air temperature with a comfort zone of 20-25 C; relative humidity of comfort zone 30-70%; and air velocity with a comfort zone of 0.1-0.3 m/s.

Wooson et al, (1992) assigned a lower and an upper heat threshold. Between these two values lies the comfort zone that should be used for work design. Winter comfort zone of 65-70F and summer comfort zone of 69-75F, both with relative humidity of 30-70%.

Below 65F, heavy clothing will be needed which will affect the individual comfort when performing heavy work. However, above 75F clothed subjects experience physical fatigue, become sleepy, and feel warm.

Noise has mixed results as a factor affecting performance. While some studies showed performance decrements, others showed no effect or even an improvement in performance. (Atwood et al, 2004 and Oborne, 1995)

OSHA had set a standard of 90dBA as maximum level noise for an 8 hr shift duration above which at least half of the people in any given group will judge the environment as being too noisy, even though they expected a noisy environment. Although temporary hearing loss occurs between 300-1200 Hz, skill errors and mental decrement will be frequent, Wooson et al, 1992).

In addition, Van der Beek et al., (1993) reported that evaluating physical demands based on job titles may cause substantial misclassification of individuals. However, a negative influence of physically heavy loads on physical capacity and health has also been found when comparing workers performing the same kind of jobs at different work places and of groups doing similar work but with different ergonomic conditions at the same work place. Torge et al., (1999) concluded that physically heavy work seems to have a varying impact on different parts of the musculoskeletal system, an effect that is also different between men and women and indicated a possible maintaining and/or training effect of the upper extremities.

Training is another factor that affects Vo_2 max. Schibye et al., (2001) investigated the effect of waste collection on the physical capacity of the workers. The aerobic power was lower among the elderly workers compared with the young workers of both groups and found no differences between waste collectors and control groups.

No training effect is found for the aerobic power, and a discrepancy between work demand and individual aerobic capacity may occur among elderly workers resulting in a negative health effect unless the work task is evaluated according to age dependent criteria. Nygard et al., (1994) concluded that aerobic power and muscle strength normally decrease with age. However, training of the specific capacities is known to counteract this decrease. On the other hand, it has been found that performing physically heavy work may have a deteriorating effect on aerobic power and muscle force. The practical consequences thus indicate that if the job demand is not reduced corresponding to the decrease in aerobic power, the relative workload among elderly workers will be higher than among younger workers. A discrepancy between work-demand and individual aerobic capacity may occur among elderly workers resulting in a negative health effect. In order to follow the recommendation of keeping the relative workload at the same level for different age groups and thereby avoiding overstrain, a work task should be evaluated according to age-dependent criteria.

Karlqvist et al., (2003) investigated the prevalence of the excess of metabolic level (metabolic demands in work exceeding one-third of the individual's aerobic capacity) of working men and women today and to describe the population whose metabolic level is exceeded. A second aim was to explore how externally assessed metabolic demands match with the physical function and capacity of working men and women in jobs with the lowest and the highest demands.

The study indicated that metabolic demands in working life today remain high. Work exposures are strongly related to the excess of metabolic level, particularly for women. There seem to be large gender differences with regard to the characteristics of women and men with excess of metabolic level.

Goran and Poehlman (2005) determined the effects of short-term endurance training in 11 elderly volunteers (56-78 years) on changes total energy expenditure (TEE), Endurance training increased maximum oxygen consumption (VO_2max) by 9%· There was no significant change in TEE before and during the last 10 days of endurance training. The study concluded that in healthy elderly persons, endurance training enhances cardiovascular fitness, but does not increase TEE because of a compensatory decline in physical activity during the remainder of the day

2.6 Thermal Comfort

2.6.1 Temperature and Humidity

To have "thermal comfort" means that a person wearing a normal amount of clothing feels neither too cold nor too warm. Thermal comfort is important both for one's well-being and for productivity. It can be achieved only when the air temperature, humidity, and air movement are within the specified range often referred to as the "comfort zone". Where air movement is virtually absent and when relative humidity can be kept at about 50%, the ambient temperature becomes the most critical factor for maintaining thermal comfort. Unfortunately, however, temperature preferences vary greatly among individuals and there is no one temperature that can satisfy everyone. Nevertheless, it is fair to say that a work place which is too warm makes its occupants feel tired; on the other hand, one that is too cold causes the occupants' attention to drift, making them restless and easily distracted. Workers begin worrying about how to get warm again. Maintaining constant thermal conditions in the offices is important. Even minor deviation from comfort may be stressful and affect performance and safety. Workers already under stress are less tolerant of uncomfortable conditions.

A general recommendation is that the temperature be held constant in the range of 21-23°C (69-73°F). In summertime when outdoor temperatures are higher it is advisable to keep air-conditioned workplaces slightly warmer to minimize the temperature discrepancy between indoors and outdoors. When relative humidity is kept at about 50%, workers have fewer respiratory problems (specifically in the winter) and generally feel better. Higher humidity makes the workplace feel "stuffy". More important, it can contribute to the development of bacterial and fungal growth (especially in sealed buildings).

Humidity lower then 50% causes discomfort by drying out the mucous membranes, contributing to skin rashes. Dry conditions cause electrostatic charge on both workplace equipment and their users. Air velocity below 0.25 meters/second (or about 50 feet/minute) does not create any significant distraction even in tasks requiring sustained attention.

2.6.2 Standards on workplace temperatures

Table 2.1 presents the values from the CSA International's Standard CAN/CSA Z412-00 - "Office Ergonomics" which gives temperature and relative humidity requirements for workplaces in Canada. These values are based on the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Standard 55 - 2004 "Thermal Environmental Conditions for Human Occupancy". These values are designed to meet the needs of 80% of individuals which means a few people will feel uncomfortable even if these values are met. Additional measures may be required. ASHRAE Standard 55 recommends a range of temperature and humidity values for thermal comfort in workplace. (National Research Council Canada, 2005)

Temperature and Humidity of an Office Environment CSA Z412-00		
	Temperature	**% Relative Humidity**
Heating Season	20-23.5C° 68-75F°	50%
Cooling Season	23-26C° 73-79F°	50%

Table 2.1 Acceptable temperatures for people with typical winter and summer clothing doing secretary work at 50% relative humidity and mean air speed less than 0.15 meters/second (30 feet/minute).

ASHRAE recommends that relative humidity be maintained below 60%. There is no recommended lower level of humidity for achieving thermal comfort, but very low humidity can lead to increased static electricity and health problems, such as skin irritation. The relative humidity should be greater than 30%.

Examples of acceptable operative temperature ranges based on comfort zone diagrams in ASHRAE Standard-55-2004		
Conditions	**Acceptable operative temperatures**	
	°C	°F
Summer		
Relative humidity 30%	24.5 - 28	76 - 82
Relative humidity 60%	23 - 25.5	74 - 78
Winter		
Relative humidity 30%	20.5 - 25.5	69 - 78
Relative humidity 60%	20 - 24	68 - 75

Table2.2 shows ASHRAE's acceptable ranges of operative temperature (a combination of air and radiant temperatures) for relative humidity levels of 30% and 60%.

Temperature		Response
°F	°C	
78	25	Optimal for bathing, showering. Sleep is disturbed
75	24	People feel warm, lethargic and sleepy. Optimal for unclothed people.
72	22	Most comfortable year-round indoor temperature for sedentary people.
70	21	Optimum for performance of mental work.
64	18	Physically inactive people begin to shiver. Active people are comfortable.

Table 2.3 summarizes some typical responses to various temperatures, Canadian Centre for Occupational Health & Safety (2005).

2.6.3 What is Humidex

Humidex is a measure of how hot we feel. It is an equivalent temperature intended for the general public to express the combined effects of warm temperatures and humidity. It provides a number that describes how hot people feel, much in the same way the equivalent chill temperature, or "wind chill factor," describes how cold people feel. Humidex is used as a measure of perceived heat that results from the combined effect of excessive humidity and high temperature.

Humidex Range	Degree of Comfort
20-29°C	comfortable
30-39°C	some discomfort
40-45°C	great discomfort; avoid exertion
above 45°C	dangerous
above 54°C	heat stroke imminent

Table 2.4 Humidix and comfort ranges

The body attempts to maintain a constant temperature of 37°C at all times. In hot weather, the body produces sweat, which cools the body as it evaporates. As the humidity or the moisture content in the air increases, sweat does not evaporate as readily. Sweat evaporation stops entirely when the relative humidity reaches about 90 percent. Under these circumstances, the body temperature rises and may cause illness.

The relation between humidex and comfort is subjective. It varies widely between individuals. Environment Canada provides the following guide as a measure of discomfort according to humidex:

- Where humidex levels are less than 29°C, most people are comfortable.
- Where humidex levels range from 30°C to 39°C, people experience some discomfort.
- Where humidex levels range from 40°C to 45°C, people are uncomfortable.
- Where humidex levels are over 45°C, dangerous conditions exist and many types of labor must be restricted.
- Where humidex exceeds 54°C, heat stroke is imminent.

The following are some examples of guidelines used by various agencies for office work:

- The Public Works Canada guideline, "Environmental standards for office accommodation," recommends a minimum temperature of 20°C when heating and a maximum temperature of 26°C when cooling.
- The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Standard "Thermal environmental conditions for human occupancy" recommends temperature ranges of 20°C to 26°C at 50% relative humidity as comfortable for sedentary work. An air temperature of 26°C at 50% relative humidity corresponds to a humidex of 29°C.

Air-conditioning in factories is usually prohibitively expensive. Therefore, it is often difficult to provide an ideal working environment, and it maybe too cool in the winter and too warm in the summer. Nonetheless, relatively inexpensive but effective measures can be taken to improve factory workers' comfort.

A fundamental requirement is to remove or control all unnecessary sources of heat such as radiation, steam, water vapor and hot air produced by plant and processes. In some regions evaporative cooling, especially if ducted to workstations, can provide cost effective improvement in work conditions.

The most common causes of summer discomfort in factories are poor ventilation and inadequate air movement. In winter comfort can to some extent be obtained by wearing more clothing but some heating may be required.

In some industries there is a need to move between hot and cold conditions, for example in the food industry. These circumstances are not a health hazard and comfort can be achieved by wearing suitable changes of clothing.

2.7 Heat Stress Management

For humans, an increase in body temperature of 1°C encroaches on the brain's ability to function.(2,3) Considering how closely body temperature is normally regulated to an upper level of survivability, it is little wonder that heat stress is so disabling and endangering for humans. We must all constantly struggle under the loads of thermal stress to adjust our heat gain and loss rates with considerable agility and precision so that our body heat content and, more critically, our deep body temperature remains in a narrow range around 37°C (98.6°F). Cold stress and heat stress present their own problems, but both attempt to push humans off the balance point for keeping a constant temperature, Houdas, and Ring (1982) and Schmidt-Nielsen,(1983).

2.7.1 Heat Stress

Heat stress is the net heat load to which a worker may be exposed from the combined contributions of metabolic cost of work, environmental factors, (i.e., air temperature, humidity, air movement, and radiant heat exchange) and clothing requirements. A mild or moderate heat stress may cause discomfort and may adversely affect performance and safety, but it is not harmful to health. As the heat stress approaches human tolerance limits, the risk of heat-related disorders increases. Understanding the dynamics of body temperature regulation and the role it must play requires distinguishing between the concept of heat stress and that of heat strain. They are related, but they are not the same. Heat stress is described in terms of external demands and limits placed on a person. For example, air temperature, relative humidity, air flow velocity, the intensity of infrared thermal radiation, the type of clothing worn, and how much heat is produced with physical activity are all factors defining potential heat stress, which are assessed with varying degrees of precision and accuracy. Such measures provide valuable and useful information about the thermal load to which humans must adjust. These measurements, however, provide no information about the safety of the exposure or the extent to which humans are compromised in their abilities to adjust to it, Table 2.5. Measurements of thermal stress, no matter how accurately they are assessed, only quantify the internal and external thermal demands that challenge thermoregulation. They are unreliable predictors of how safe someone will be when working in that environment. Accurate measurements of heat stress provide the basis for an assessment of how hot an environment is. Measuring just air temperature, for instance, seldom provides much useful insight. Additional data about ambient humidity, air velocity, infrared radiant intensities, and emissivities of clothing and nearby objects provide a much more complete picture for the level of heat stress. Havenith, and Middendorp (1990) and Havenith et al (1995).

	Acclimatized				Unacclimatized			
Work Demands	Light	Moderate	Heavy	Very Heavy	Light	Moderate	Heavy	Very Heavy
100% Work	29.5	27.5	26		27.5	25	22.5	
75% Work; 25% Rest	30.5	28.5	27.5		29	26.5	24.5	
50% Work; 50% Rest	31.5	29.5	28.5	27.5	30	28	26.5	25
25% Work; 75% Rest	32.5	31	30	29.5	31	29	28	26.5

Table 2.5 Screening Criteria for Heat Stress Exposure (WBGT values in °C)

2.7.2 Heat Strain

Heat strain is the overall physiological response resulting from heat stress. The physiological adjustments are dedicated to dissipating excess heat from the body. Acclimatization is a gradual physiological adaptation that improves an individual's ability to tolerate heat stress.

The risk and severity of excessive heat strain will vary widely among people, even under identical heat stress conditions. The normal physiological responses to heat stress provide an opportunity to monitor heat strain among workers and to use this information to assess the level of heat strain present in the workforce, to control exposures, and to assess the effectiveness of implemented controls.

Heat strain reflects the extent to which the individual has to marshal defenses to keep total body heat content and deep body temperature in a workable and livable range. It is a characteristic that is unique to each person and will, in fact, change even for the same person from time to time.(4,5) Heat strain is the cost of adjusting to heat stress. It is not a measure of how successfully the adjustment is made. Gross measures of heat strain include body core temperature, heart rate, and sweat loss. Other important responses are allocations of the fluid volumes in the body, electrolyte concentrations in the intra- and extra-cellular spaces, levels of hormones, and blood pressure. Heat strain is not reliably predicted from heat stress. This means that environmental measurements cannot safely or accurately predict heat strain, the amount of discomfort, or the degree of danger being faced by an individual at any time. The predictive gap is largely explained by personal risk factors. These are each person's unique strengths and weaknesses for distributing heat in the body and for dissipating it to the surrounding environment. Havenith, and Middendorp (1990) and Havenith et al (1995).

2.7.3 Personal Factors

The likelihood and severity of heat strain experienced by an individual for a given level of heat stress depends on the physiological capacity of that individual to respond to the stress. Personal risk factors are those elements that may reduce an individual's tolerance for heat stress. Personal factors may include age, obesity, state of hydration, use of medications and drugs, gender, and acclimatization state. Acclimatization is a set of physiological adaptations. Full-heat acclimatization requires up to 3 weeks of continued physical activity under heat-stress conditions similar to those anticipated for the work

2.7.4 ACGIH Guidelines for Limiting Heat Strain

Monitoring signs and symptoms of heat-stressed workers is sound industrial hygiene practice, especially when clothing may significantly reduce heat loss. For surveillance purposes, a pattern of workers exceeding the limits is indicative of a need to control the exposures. On an individual basis, the limits represent a time to cease an exposure until recovery is complete.

One or more of the following measures may mark excessive heat strain, and an individual's exposure to heat stress should be discontinued when any of the following occur:

- Sustained (several minutes) heart rate is in excess of 180 bpm (beats per minute) minus the individual's age in years (180–age), for individuals with assessed normal cardiac performance; or
- Body core temperature is greater than 38.5°C (101.3°F) for medically selected and acclimatized personnel; or greater than 38°C (100.4°F) in unselected, unacclimatized workers; or
- Recovery heart rate at one minute after a peak work effort is greater than 110 bpm; or
- There are symptoms of sudden and severe fatigue, nausea, dizziness, or lightheadedness.

An individual may be at greater risk if:

- Profuse sweating is sustained over hours; or
- Weight loss over a shift is greater than 1.5% of body weight; or
- 24-hour urinary sodium excretion is less than 50 mmoles

2.7.5 ACGIH Guidelines for Heat Stress Management

ACGIH 2001 provides the following guidelines for heat stress management;

General Controls

- Provide accurate verbal and written instructions, frequent training programs, and other information about heat stress and strain
- Encourage drinking small volumes (approximately 1 cup) of cool, palatable water (or other acceptable fluid replacement drink) about every 20 minutes
- Permit self-limitation of exposures and encourage co-worker observation to detect signs and symptoms of heat strain in others
- Counsel and monitor those who take medications that may compromise normal cardiovascular, blood pressure, body temperature regulation, renal, or sweat gland functions; and those who abuse or are recovering from the abuse of alcohol or other intoxicants
- Encourage healthy life-styles, ideal body weight and electrolyte balance
- Adjust expectations of those returning to work after absence from hot exposure situations and encourage consumption of salty foods (with approval of physician if on a salt-restricted diet)
- Consider pre-placement medical screening to identify those susceptible to systemic heat injury

Job-Specific Controls

- Consider engineering controls that reduce the metabolic rate provide general air movement; reduce process heat and water-vapor release, and shield radiant heat sources, among others
- Consider administrative controls that set acceptable exposure times, allow sufficient recovery, and limit physiological strain
- Consider personal protection that is demonstrated effective for the specific work practices and conditions at the location

2.8 MMH Design Approaches

There are some approaches used in designing manual material handling. Among these approaches, the biomechanical approach that deals with forces loaded on the muscuskeletal system as predictors of tissue tolerance and muscle strains and sprains (Garg and Herrin, 1979); The physiological approach that involves the measurement of an individual's physiological responses during MMH activities; The psychophysical approach which deals with the relationship between human sensations and their physical stimuli (Mital, 1983)

2.8.1 The Biomechanical Approach

The biomechanical design approach deals with force loading on the musculoskeletal system as predictor of tissue tolerance and muscle strains and sprains (Garg and Hernein, 1979). The objective of this method is to reduce work related injuries of the musculoskeletal system. While lifting, the forces exerted with the hands must be transmitted through the whole body to the floor via wrists, elbows, shoulder, and other body musculoskeletal parts where the weakest link in the system determines the capability of the body to perform the work.

Biomechanical approach computes the compression force and shear force on the spinal column in the area of L5/S1 joint. This location is widely accepted as the primary means of stress on the spine during manual material handling activities (Garg 1989). In order to determine if a task is acceptable, either a static or dynamic biomechanical model is used to provide estimates of the variable of interest.

Biomechanical approach application to only infrequent lifting rather than repetitive tasks, makes this the only restriction known to this approach so far.

2.8.2 The Physiological Approach

The physiological approach that involves the measurement of an individual's physiological responses during MMH activities, the physiological measures often used in the literature as indices of heaviness of work performed are oxygen consumption (Vo_2), heart rate (HR), or pulmonary ventilation volume. (Aquilano, 1986) concluded that from the standpoint of practical instrumentation and reliability as indicators, HR and Vo_2 are the most useful measures. In repetitive manual handling a worker's endurance is primarily limited by the capacity of oxygen transportation and utilization systems and not by his/her muscular strength (Chaffin 1982).

The goal of the physiological approach is to develop limits using oxygen consumption, and/or heart rate criteria and then determine the lifting capacity based on the chosen criterion. It is generally accepted in industry that an eight-hour average metabolic rate should not exceed approximately 5 kcal/min and that mean heart rate should not exceed 110-115 beats/min (Mital, 1984). The Vo_2 max is, under standardized conditions, a highly reproducible measure of the individual's aerobic fitness and it provides an accurate measure of the aerobic power, and it is highly related to the cardiac output. It is however subject to some variations.

The main factor behind such variation is the proportional change in the stroke volume. It can be determined directly on young well-trained subjects or indirectly, which much less stressful, on industrial populations. The advantage of the direct methods is its accuracy. However, the risk associated with stressing the physiological system to the limits of their capacity is considered a disadvantage. The indirect method does not consider the variation in maximum heart rate among individuals.

2.8.3 The Psychophysical Approach

The psychophysical approach has been widely utilized to determine the manual materials handling (MMH) capability. This approach estimates an individual's handling capability by quantifying his or her subjective tolerance to the stresses of MMH activities (Ayoub, 1987). The most popular way of quantifying an individual's handling capability is by determining the maximum acceptable weight of lift (MAWL). Arguments in favor of the psychophysical methodology are as follows: (1) it is simple to use, (2) only an individual worker can sense the various strains associated with manual handling operations, and only he or she can integrate the various sensory inputs into a meaningful response, (3) a greater frequency of low back injuries has been reported for those jobs which workers believed to be harder (Garg and Saxena, 1982; Magora, 1970; Dehlin et al., 1976).

Lee (2003) determined the minimal acceptable handling time interval (MAHTI) for 4 h of endurance manual materials handling tasks using a psychophysical approach. The results showed that the heavier load produced a larger MAHTI, and the overall descending sequence of MAHTI values for the six ranges was FS, KS, SF, FK, KF, and SK. The MAHTI for each lifting tasks was significantly higher than that of its corresponding lowering task: All MAHTI data were further verified by tests run on an additional nine subjects; this showed that the psychophysically determined MAHTIs were appropriate with no apparent underestimation. Gallagher et al. (1988) showed decreases of psychophysical lifting capacity as well as increases of the metabolic stress and internal load on the spine in the kneeling posture compared to the stooped posture, which are frequently taken during underground mining tasks. Many of the manual tasks in the manufacturing industry, which is a major part of modern industries in developing countries, still require workers to carry out their jobs in improper postures and even involve manual handling of heavy loads.

2.9 Methods for Estimating Energy

The measurement of oxygen consumption rate is used by researchers to estimate the metabolic energy expenditure for various manual activities. However, on the job measurement of oxygen utilization, although measurement of oxygen utilization is the most straightforward, is sometimes difficult due to interference of measuring equipments with the normal work methods. Also, in manual material handling jobs the methods, work operations, weight, and size of working material and the particular work are changing constantly. Therefore, oxygen uptake measurements made today may not be valid sometime late in the future. Moreover, a single oxygen uptake measurement does not reflect how personal task factors influence metabolic work load.

The macro-studies, on the other hand, have a common objective of determining the metabolic rate expended by average people who are performing complex manual activities under different working conditions (such as unloading coal cars, handling boxes, stapling, etc.).

Table values provide only a very rough approximation of the metabolic load of any given job. Errors can easily be made due to the overly simplistic descriptions of jobs. For example, lifting 4.5 kg of load from the floor to a 0.91 m high table is more than twice as expensive in net metabolic cost as lifting the same load from 0.91 m high table to 1.68 m high table. There for a single lifting value will be in serious error. Metabolic energy expenditure estimates are very specific to particular work situations employed at the time of measurements and do not reflect the effect of important personal and task parameters such as frequency, weight, height, etc.

A second group of studies designated as micro-studies, relates the magnitude of the metabolic energy expended by a person to the magnitude of the various common physical measures of manual activity. This approach, primarily through regression and analysis of variance models, provides functional relationships between the metabolic rate and one or more of the physical parameter of the job. A general conclusion is that relatively minor changes in the physical parameters that are commonly used to describe a person's manual activity result in significant changes in the metabolic energy expenditure rate. In short, any physiological fatigue criteria (whether 5.2 Kcal/min or some other) can not be used by the work analyst unless he/she can convert it into useful design parameters such as frequencies, weights, distances, etc. Ciriello el al, 1990 investigated maximum acceptable weight and forces when performing manual handling tasks continuously for four hours at frequencies of 4.3 per minute or slower. In this experiment, it was concluded that heart rate for combined tasks was higher than those of individual ones. Jiang et al (1986) observed the same results when studied combined activities.

Morrissey and Liou (1988) also studied maximum acceptable weights of combination tasks consisting of lifting, carrying, and lowering. Their study indicates that combination tasks are affected by frequency, distance, and container size, in the same way that individual components are affected. All of these studies indicate that combination tasks are to be estimated by using the limiting component in the task as the acceptable weight. However, concerns for increased calorie expenditure in a fast combination task should not be overlooked. In the post-40-year category physical "fitness begins to decrease and may impair work capacity and performance particularly in physically demanding blue-collar jobs. Physical work load should be adjusted according to the work capacity of each individual worker for preventing overstrains, fatigue, disorders and injuries. In principle, physical work load should be decreased with increasing age due to the natural and evident decline of physical work capacity (Ilmarinen, 1992).

2.10 Prediction Models

As might be suspected, few researchers have tried to develop prediction models for energy cost of manual materials handling tasks. Frwederick (1959) developed a simple linear model to estimate Vo_2 max for lifting activities. Garg (1976) used regression analysis to estimate metabolic energy expenditure rate for lifting and other activities. This model was further modified by Garg et al (1978). Garg's model was based on the assumption that a job can be divided into simple tasks, and that the average metabolic energy expenditure rate of the job can be predicted by adding the energy expenditures of the simple tasks. Even though the models developed by Garg et al (1978), Asfour (1980), and Karwowski and Ayoub (1984) work very well with each of their respective data sets, Garg's model tends to overestimate and Asfour's model tends to underestimate the metabolic energy requirement for other data sets. The model by karwowski and Ayoub appears to provide more accurate estimation of oxygen consumption. However, its use is limited to analyze lifting from floor to knuckle. These models should reflect some additional variables such as container size, body twist, and task duration. Recently, Genaidy and Asfour (1989), and Genaidy et al (1990) established endurance time curve for lifting tasks for up to 8 hr. Genaidy outlined a procedure for the use of PWC within the context of the physical ergonomics job design cycle centered upon the ergonomic index EI as stress requirements divided by physical work capacity.

2.10.1 Maximum Aerobic Capacity

Oxygen consumption or metabolic energy expenditure has been adopted as the criterion for repetitive lifting where the load is presumed to be within the physical strength of the individual. Bink (1964) concluded that a safe criterion for physiological work capacity for 8 hr should be 33% of the maximum oxygen uptake. Although basic laboratory evidence obtained from work on treadmill bicycles and hand cranks has fundamental importance, its application to manual material handling activities must be approached with caution. Petrofsky and lind (1987) concluded that lifting a weight had substantially higher oxygen and vetilatory cost than similar levels of work on the bicycle ergometer. The reason for these differences appears to lie in the energy cost of moving parts of the body. If the current physiological criterion of 5 Kcal/min for 8 hr was based on the Vo_2 max from the bicycle ergometer, the physiological criterion for lifting tasks might be 4 Kcal/min, according to Ptrofsky and Lind's finding. Therefore, if a physiological limiting criterion is selected, it should be based on the Vo_2 max attainable for the particular lifting task under investigation, rather than for standard tasks such as bicycling or treadmill walking. The recent studies by Khalil et al (1985), Fernandez (1986), and Kim (1990) confirm this contention.

Levushkin, (2001) estimated the physical work capacity of young men (17–21 years old). A comparative analysis of the physical work capacity in subjects with different levels of motor activity showed that the indices of physical development, physical fitness, and aerobic capacity in 17-year-old athletes exceeded the same indices in the untrained age-matched group. Physical work capacity was significantly higher in athletes than in the untrained subjects during the whole juvenile period. In athletes the age-related physical fitness and aerobic capacity increased to a greater extent but physical development increased to a lesser extent than the same in the untrained subjects. Physical development of male subjects significantly increases at the age of 17–18 years, and at the age of 18–21 years it stabilizes around the level achieved by 18 years. Physical fitness during early adulthood changes insignificantly: general and back muscle strength slightly increases, spine flexibility decreases, and speed is virtually unchanged.

It is generally accepted in industry that an eight-hour average metabolic rate should not exceed approximately 5 kcal/min and that mean heart rate should not exceed 110-115 beats/min (Mital, 1984).

The Vo_2 max is, under standardized conditions, a highly reproducible measure of the individual's aerobic fitness and it provides an accurate measure of the aerobic power, and it is highly related to the cardiac output. It is however subject to some variations. The main factor behind such variation is the proportional change in the stroke volume. It can be determined directly on young well-trained subjects or indirectly, which much less stressful, on industrial populations.

The advantage of the direct methods is its accuracy. However, the risk associated with stressing the physiological system to the limits of their capacity is considered a disadvantage.

2.10.2 Physiological Fatigue Limit

Researchers had different opinions on the maximum amount of Vo_2 that should be considered safe for individuals when performing an 8-hour work compared to their Vo_2 max. Christensen (1955) proposed that work could be performed at 50 percent of maximum aerobic power for eight-hour work day. Astrand (1960) expressed serious doubts that this was too high an expectation. Research by Brauha (1960) supports the theory that a work capacity limit based on 50 percent of the maximum aerobic capacity of an individual was a fatigue-generating energy expenditure rate. Studies by Lehmann (1953) recommended 33 percent of the maximum aerobic power of a normal healthy person as the maximum energy expenditure rate that should be expended for an eight-hour work day. Generally, 16 kcal/min is taken as the maximum aerobic power of a normal healthy young male for a highly dynamic job (walking, bicycling,..). For an eight-hour continuous work period, a physical work capacity limit of 5.2 Kcal/min is recommended by Chaffin (1972). This is based on 33 percent of 16Kcal/min taken as the maximum aerobic power for a healthy male. As stated by Moores (1971), the aforementioned 5.2 Kcal/min was also deemed an average acceptable level by Lahmann from studies undertaken throughout German industry. Indeed, older workers and female workers will require a much smaller physical work capacity limit. Muller (1962) defined the endurance limit (EL) in absolute terms as approximately 2000 kcal in an 8-h work shift.

In a comprehensive study that included different loads and frequencies, Genaidy (1990) used frequency and weight of load as independent factors to determine human physiological capabilities for prolonged lifting tasks performed from floor to table height. In the study, an eight-hour work duration can be maintained at 23% of Vo_2 max. This value is much lower than values obtained by other studies. Michael et al (1961) reported that eight-hour work duration could be completed without undue fatigue whenever the metabolic energy costs did not exceed 35% of the $V\ o_2$ max as determined by running uphill on the treadmill. Based on Genaidy's study, it was found that each subject could not work at an average oxygen consumption of 1.8 l/min for more than 1.67 hrs. It was also found that only a 4 times/min – 10 kg lifting task can be endured for about seven hours at the oxygen value of 1.0 l/min.

NIOISH developed an upper and a lower limit of energy expenditure for an eight-hour lifting duration of 5 and 3.5 kcal/min, respectively. It was apparent from these values that they rely on single value and do not take into account the interaction of lifting task parameters. The study suggests that the load of 20kg lifted at frequency of 10 times/min should not be exceeded for lifting tasks from floor to table height.

In another study where lifting height was from table height to shoulder height, Asfour et al (1991) concluded that an 8 hr work day can be maintained at oxygen consumption of 17% of maximum oxygen uptake Fig 2.1.

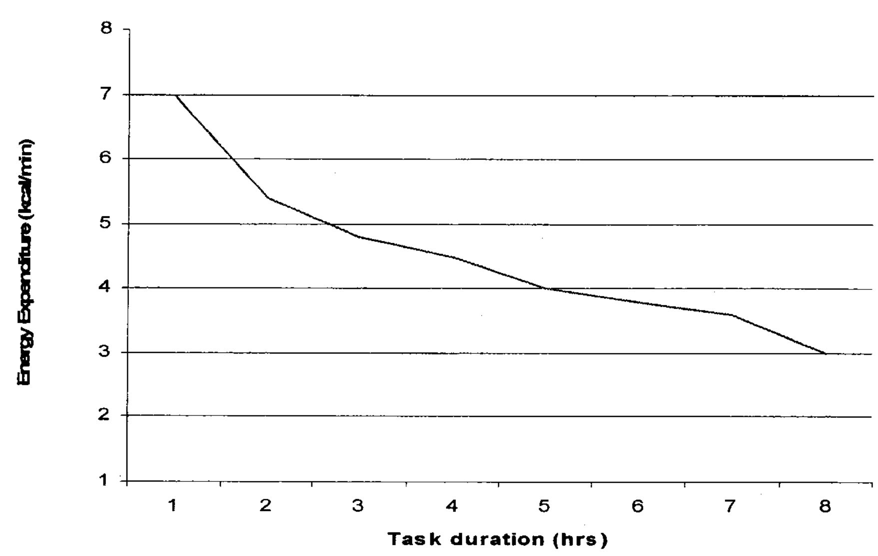

Fig 2.1 Energy expenditure as a function of task duration for continuous

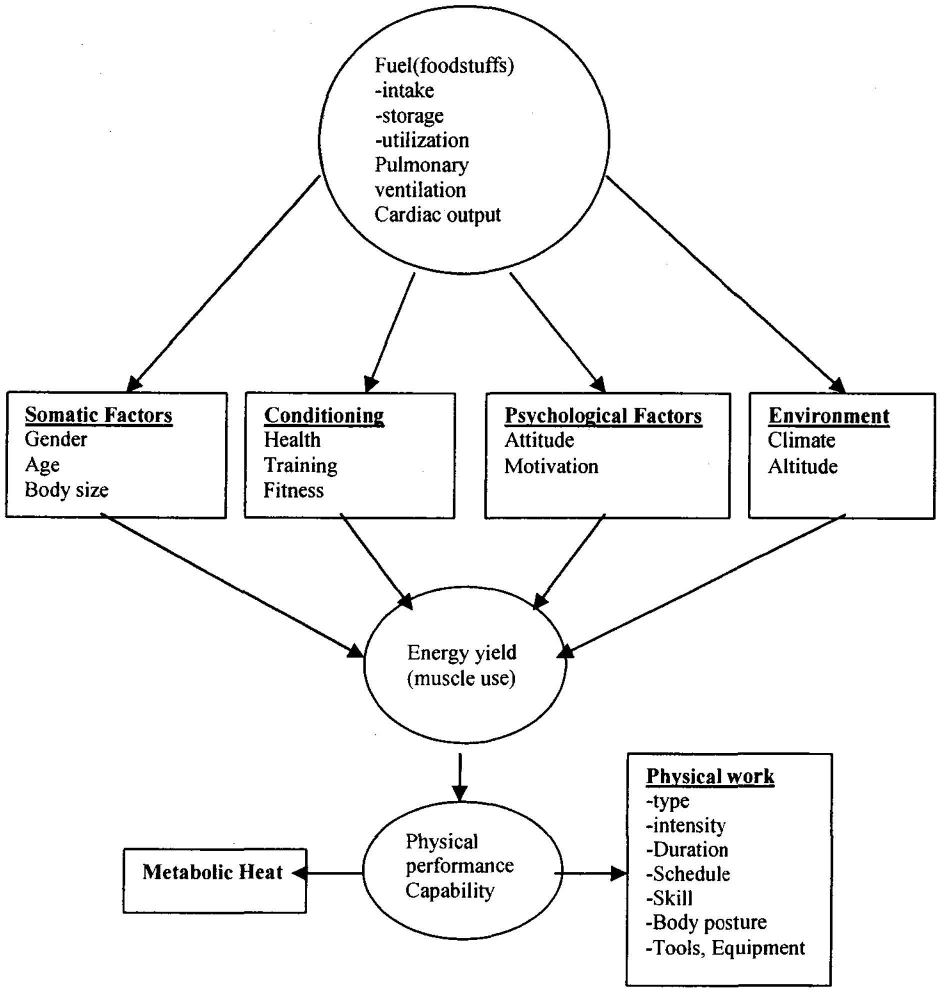

Fig 2.2 Determiners of individual physical work capacity
(Kroemer et al (2001)

Above model factors will be used as guidelines through this study. Quantifiable determinants such as age, gender, body weight, temperature, humidity, and noise level will be used with their values and ranges suggested in the studies mentioned at the beginning of this chapter. However, other factors will be assumed as controlled factors that could be maintained within the normal working environment by the work controller. Physical work energy requirement will be based on Garg's models discussed at later chapters.

2.10.3 Work-Rest Periods

When average energy expenditure during a typical work cycle based on all job tasks performed is estimated, the amount of work and rest required can be determined to establish a fair-day workload. According to the international labour office, a generally accepted standard workload is equivalent to the workload generated by an average physique man walking without carrying a load in a straight line on level ground at a speed of 4 mph (6.4 km/hr), Tayyari and Smith, (1997).

Edholm (1967) developed a model to estimate the rest work periods however, these models calculate only the total time during the work shift that should be taken as rest. The models do not determine the optimal arrangement of work-rest cycles.

Fig 2.3 below is adopted from Woodson et al (1992) for determining rest periods needed based on energy expenditure consumed during certain period of time.

Rest values are based on approximation due to individual differences in energy considered as an acceptable standard. The chart will be used by this study to determine rest period whenever energy expenditure required surpasses the allowed for the individual.

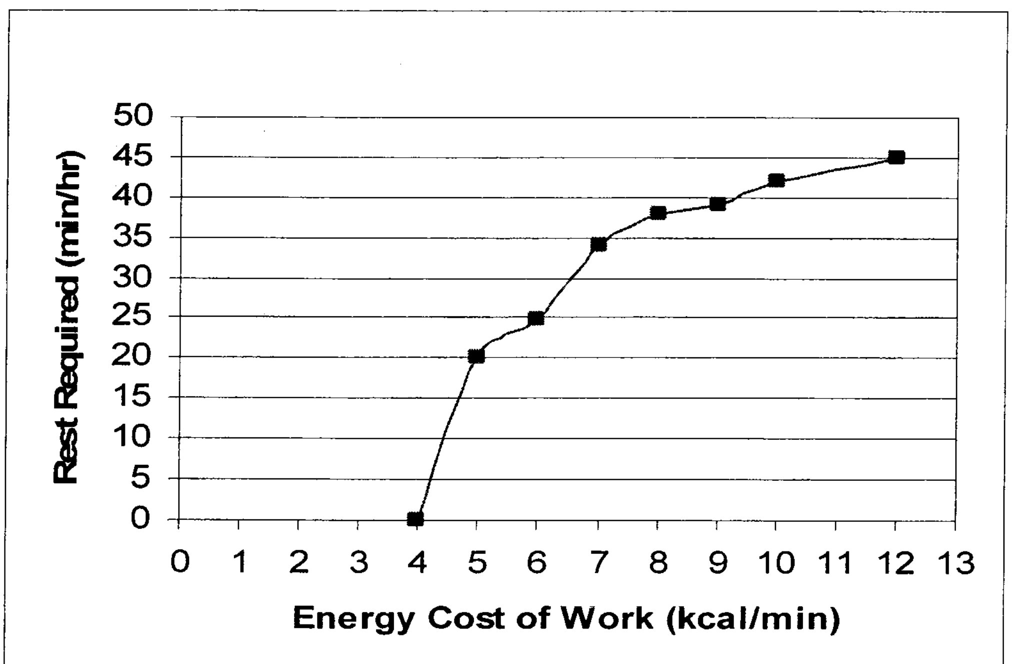

Fig 2.3 Rest Requirements after Work

2.11 Manufacturing Systems

The introduction of cellular manufacturing was a result of efforts to overcome limitations of conventional manufacturing represented by job shop manufacturing systems which deal with high part variety and low volume, mass production systems which are appropriate for high volume and low part variety, and in between these two systems lies the batch system which is suitable when producing medium volume and medium variety of products. Part movements within these systems resulted in an increase in total material handling cost, decrease system productivity, and loss of production time due to the increase in set up time and large in-process inventories. The introduction of cell manufacturing systems had resulted in advantages and compensated for the shortcomings of the conventional manufacturing systems. Among these advantages as mentioned by Burbidge and Halsall (1993) are increased output and profit, increased rate of return on investment, improved quality, decreased overdue orders, decreased setup time and work in-process inventories, reduced material handling cost and space requirements, and simplified scheduling. Manufacturing cells are also known with their high intensity of labor physical work that requires high metabolic energy of people.

As described by Ott and Jones (1999), cellular manufacturing environment deals with high variety and volume and considered human motions that are unnecessary or straining resulting from carrying WIP long distances.

2.11.1 Manufacturing Systems Models and Techniques

When designing manufacturing cells, researchers devoted most of their research towards optimizing cost function and techniques used in designing these cells. The main emphasis was on reducing material handling cost, set up cost, subcontracting and other costs related to production. The following literature review represents some of these studies:

2.11.2 Cost Criteria

Researchers tackled some cost aspects related to manufacturing processes design. Among these aspects capital investment, part subcontractor, and material handling by Taboun *et al.* (1998) and Rajamani et al. (1996), machine duplication cost and inter-cell movement cost by Boctor (1996) and Ho and Moodie (1996), and cell and inter-cell load unbalance costs, and machine investment cost by Su and Hsu (1998).

Askin and Chiu (1990) incorporated Machine depreciation, inventory, material handling, and setup costs into a mathematical model to solve the cell formation problem. The cost model is then divided into two sub-problems to facilitate the solution. The first sub-problem determines the assignment of parts to machines, while the second determines the assignment of machines to cells.

Taboun *et al.* (1998) developed an integer-programming model aims at minimizing the various system costs including capital investment, part subcontractor, and material handling. Later in the study they presented a heuristic algorithm is also presented to solve large-scale problems.

Among other researchers, Beaulieu *et al.* (1997) presented a two-phase heuristic method to form manufacturing cells considering machine and intra-cell costs. It also considers alternative process plans. In the second phase they consider the introduction of inter-cell movement to improve machine utilization.

Ho and Moodie (1996) included machine duplication cost, operating cost, and inter-cell movement cost in their model objective function to determine the unification of these three criteria. They assumed a flexible routing for parts and used a heuristic to form part families in the first stage of their approach based on the similarities of the parts operation sequences.

Taboun *et al.* (1998) developed an integer-programming model, which simultaneously forms part families and machine groups. The model aims at minimizing the various system costs including capital investment, part subcontractor, and material handling. A heuristic algorithm is also presented to solve large-scale problems. Different problems are used to test the developed models, and the results show that the proposed models are able to find an optimum solution and handle large-size problems.

Shafer et al (1992) considered three cost factors in presenting a mathematical programming model for dealing with exceptional elements. These factors are inter-cell transfer cost, machine duplication cost, and part subcontracting cost. The authors developed an initial solution using a cell formation procedure and then they eliminated the exceptional elements by changing the design or the process plan of the part and by using part subcontracting or machine duplication through an optimization model.

Sankaran and Kasilingam (1993) studied set of costs in developing an integer programming model to determine cell membership, cell size and capacity selection. They studied processing cost, inter-cell and intra-cell movements cost, spatial cost, and annual amortization cost.

Liang and Taboun (1995) developed a bi-criterion nonlinear integer programming model to maximize system efficiency and system flexibility. Their objectives were to maximize system flexibility and efficiency. They then proposed a two phase heuristic to generate the approximate efficient solutions.

Boctor (1996) unified inter-cell movements and machine duplications criteria to achieve a multi-objective model in order to optimize the design of a manufacturing cell. The model objective consists of two costs; machine duplication cost and inter-cell movement cost. A weighting approach with equal weights assigned to each criterion is used to tackle the conflicting nature of the two criteria.

Ho and Moodie (1996) included machine duplication cost, operating cost, and inter-cell movement cost in their model objective function to determine the unification of these three criteria. They assumed a flexible routing for parts and used a heuristic to form part families in the first stage of their approach based on the similarities of the parts operation sequences.

Rajamani et al. (1996) utilized the idea of using the column generation scheme and branch and bound technique to develop a mixed integer programming model that minimizes process and material handling costs and the sum of investment costs. In developing their model, they assumed flexible process plans for parts.

Su and Hsu (1998) considered intra-cell and inter-cell load unbalance costs, and machine investment cost in their model in order to unify these factors using a simulated annealing approach. Their model objective was to minimize the total cost of inter-cell transportation and machine investment; minimize intra-cell machine load unbalances; and minimize inter-cell machine load unbalance. The authors then made use of the crossover and mutation functions of the genetic algorithm to deal with the high execution time drawback.

2.11.3 Cell Formation Techniques

There are several cell formation techniques and methods used by the field researchers. These methods have been classified into five main groups; classification and coding groups, algorithmic, graph partitioning, artificial intelligence, and mathematical programming approaches. The following shows how some of these techniques are used by some researchers:

Waghodekar and Sahu (1984) developed a method known as machine-component cell formation in which three similarity measures have been used. They used the similarity coefficient proposed by Carrie (1973) to determine machine groups, a similarity coefficient based on total number of parts is used to determine the inter-cell movement and manufacturing cells, a similarity coefficient based on total flow of common parts processed by a particular machine type. This method resulted in a minimum number of exceptional elements when illustrated using a practical problem. It proved to be computationally straight and easy to understand.

Han and Ham (1986) used a classification and coding system to develop a mathematical programming to minimize the distance function between any two parts. The model forms mutually exclusive cells where each part can belong to only one cell. Because only part families problems could be solved using this model, another model was needed to tackle the whole situation.

Yasua and Yin (2001), represented the average voids value (AVV) measure, which represents the dissimilarity of a pair of machine groups and indicates the number of newly produced voids when a pair of machine groups are combined was proposed. Sarker and Saiful Islam (1999), also evaluated the performance of a number of the most commonly used similarity and dissimilarity coefficients used to measure the groupability of clusters in group technology. The study showed that there exist a large number of similarity and dissimilarity coefficients which may not be suitable to tackle a certain problem.

Salum (2000), proposed a two-phase method to tackle the problem of cell design based on total manufacturing lead time reduction. The study used the waiting times of parts and the volume of parts-flow between machines obtained from simulation during the first phase to find the similarity measures between the machines. Based on these similarities, the mean similarity of machine pairs is then found. Machine pairs were sorted in an ascending order with respect to the mean similarities in the second phase using a computer program. The study suggested using a better way in assigning the mean similarities and increasing the number of each machine type to be increased in order to allow for using more than one machine type.

Sankaran (1990) and Kusiak and Cho (1992) considered similarity method to tackle the CM design problem. The former used similarity of parts according to their need for machines and tools, availability of machining capacity, number of total movement of parts, capital investment on machines, and optimal operating cost as multiple goals in order to establish a cell formation procedure. While the latter considered alternative processing requirements to solve the cell formation problem.

Wang and Roze (1997) developed a non-linear integer-programming model to form part families or machine groups. When used for forming part families, the model maximizes the similarity of parts subjected to a limitation on the maximum number of parts in each cell. It maximizes the machine similarity to form machine groups subjected to a limitation on the maximum number of machines per cell.

Escoto *et al.* (1998) presented a three-phase algorithm to form part families and machine groups. The first phase minimizes the dissimilarity of the part families. The second phase minimizes the number of operations needed to finish each part outside the part family. The third phase determines the load for each machine and assigns each machine to a machine group. An industrial application is presented to test the proposed algorithm.

Shafer and Rogers (1993) presented a new similarity measure for solving the cell formation problem using the similarity between two machines. The similarity between two parts is computed as the maximum of two ratios. The first ratio is computed as the total number of machines required by both parts over the number of machines required by the first part. The second ratio is computed as the number of machines that the two parts have in common over the number of machines required by the first one.

Seifoddini (1989) investigated the economic trade-off between machine duplication and inter-cell movement in the cell formation problem. This procedure was based on the decomposition of the machine-part matrix. While Veeramani and Main (1996) proposed a two stage algorithm in order to minimize the total number of exceptional elements.

Akturk and Balkose (1996) considered six criteria in their model for a manufacturing cell design. Their model included dissimilarity of parts based on their manufacturing and design attributes and based on their operation sequences, machine investment cost, number of machines a part skips in each operation sequence, workload variability within cells, and sum of cell workload variability sum of cell workload variability.

Gunasingh and Lashkari (1989) presented a sequential approach to solve the cell formation problem using 0-1 integer programming. In this model, they used machine capability to process a part in grouping parts and machines into cells. The approach starts by considering the machine groups based on their similarity in part processing followed by the allocation of parts to machine groups based on the processing requirements follows.

Min and Shin (1993) utilized part similarity, machine processing time, machine capabilities/ operator skills matching, and operators wage differences in forming machine cells and human cells simultaneously using mixed integer goal programming model.

Logendram (1993) developed an integer-programming model for solving the machine-part grouping problem. The objective function of the model focuses on maximizing a measure of effectiveness evaluated as the sum of the total number of moves and in-cell utilization. The model assumes that the desired number of manufacturing cells can be computed in advance by management personnel.

Taboun et al (2000), Wei and Gaither (1990), Moon and Kim (1999), Lee and Garcia-Diaz (1996), Dahel and Smith (1993), Suresh et al. (1995), and Amira and Choobineh (1996) presented a 0-1 programming models to solve the cell formation problem based on different criterion.

Rajamani *et al.* (1990) developed three integer-programming models based on the availability of alternative process plans. In this model each part has alternative process plans and each operation can be performed on alternative machines. The first model provides information to formulate a part-machine process matrix that can be solved using existing cell formation techniques. The second model assumes part families are known to form the cells, while the third model identifies both part families and machine cells simultaneously.

Okogba *et al.* (1992) developed an algorithm to solve the part-machine cell formation problem in three stages. In the first stage, machine groups are formed. In the second stage, machines are reallocated to minimize the number of inter-cell movements. Parts are assigned to associated machine groups that perform the maximum number of their operations in stage three. The developed algorithm is evaluated using a simulation model to investigate the performance of machine utilization and flow time.

Venugopal and Narendran (1992), Chen and Srivastava (1994), Adil et al. (1996), Bazargan-Lari and Harraf (2000), and Taboun et al (2000) all presented a simulated annealing algorithm to solve the machine-part grouping problem. The developed algorithms are tested using a numerical example selected from the literature, and the results show the capability of these algorithms to solve large-size problems. They also proved to be easy to understand and implement.

Genetic algorithm method proved to be very efficient and flexible when used in part-machine formation. Venugopal and Narendran (1992) utilized it and proposed a bi-criteria mathematical model to minimize inter-cell movements and total within-cell load variation.

Hwang and Sun (1996) incorporated relevant production requirements such as production volume, processing time, and cell size in their model. While Joines *et al.* (1996) developed a genetic algorithm that allows the designer to remove the constraints on the number of allowable cells. Su and Hsu (1998) made use of the crossover and mutation functions of the genetic algorithm to deal with the high execution time drawback.

Zhao and Wu (2000) employed generic algorithm as a methodology to minimize intercell/intracell part movements, total exceptional elements, and total within cell workload variation. Balakrishnan and Cheng (2000) developed and tested an improved genetic algorithm to tackle a dynamic layout problem. The model used mutation and generational replacement approach to increase population diversity. It also employed a different crossover operator to increase the search space.

Lee-Post (2000), proposed a new part family identification technique to explore the nature of part similarities and to capture the identification power of humans in solving the part family identification problem. The study addressed also the issue of establishing a broad basis for similarity exploitation in forming part families in order to meet the needs of different users.

Dimopoulos and Mort (2001) combined genetic programming with a classic hierarchical clustering procedure to present a framework for the solution of binary cell-formation. While Onwubolu and Mutingi (2001), used genetic algorithm approach in the minimization of inter-cellular movements, minimization of cell load variation, and a combination of both aforementioned objectives. The inclusion of such options in the GA allows the decision maker to specify the maximum cell size or number of machines in each cell and the number of cells to arrive at an optimal machine allocation to cells based on the design criteria.

Lin *et al.* (1996) proposed a two-stage integer-programming model for forming part-machine cells. The first stage determines an initial form of the machine-part incidence matrix into production cells. The second stage searches for improvements in the design of production cells. When the proposed algorithm is compared with three other algorithms from the literature, it showed a highly efficient computational performance.

Hwang and Ree (1996) developed a mathematical model to solve the route selection problem based on only one process plan for the part. In the second stage, part families are formed based on the results obtained from the first stage using the p-median formulation. This model aims to maximize the similarity coefficient of parts in the same family by forming the machines based on the minimum number of exceptional elements. A numerical example is presented to illustrate the solution procedure and the results are compared with those obtained from applying the p-median model. The grouping solution obtained by applying the proposed model is better than those obtained by applying p-median; however, it takes more computational time to determine the optimum solution.

Lee and Chen (1997) combined workload balances for duplicated machines, number of machine cells and part families in a two stages solution model to be used in optimizing the quality of the formation results in a third stage using an estimation procedure and a heuristic approach.

Bazargan-Lari (1999) presented a multi-objective model to generate the layout designs for machines and cells in cellular manufacturing environment in order to provide the decision maker with qualitative and quantitative aspects of the layout. The model addresses closeness relationships, location restriction/preferences, and machine/cell orientation as issues related to the practical implementation of cellular manufacturing structure.

Akturk and Turkcan (2000) proposed an integrated algorithm to solve cell formation problems while considering the within cell layout. The model used a holonistic approach to maximize the system profit assuming that each cell is maintaining a level of profit self-sufficiency. One advantage of using this approach is the accurate portrayal of the cell manufacturing systems operations using production volume, processing times, operations sequences, and alternative routes to assess the impact of capacity constraints. A local search algorithm was proposed and used in this study to help find a feasible solution in less computational time.

Islam and Sarker (2000), developed a similarity coefficient that follows the properties necessary for evaluating an incident matrix. The model is used in solving the machine-parts grouping problems in cellular manufacturing systems. The relative matching coefficient developed in this study was able to reflect the extent of true similarity of pairs of machines or parts in an incident matrix. When this model was applied to some well-known problems, it reduced the number of variables and constraints. It also yielded better and sometimes equal grouping efficiencies when compared with other models. The heuristic approach used in this model indicated satisfactory performance for reasonably large instances and reduced the computer times significantly.

Shafer and Rogers (1991) used Goal programming when considering set-up times, inter-cell movements, investing in new equipments, and machine utilization. The authors utilized the combination of p-median and the traveling salesman problem for identifying part families using the former and to determine the optimal sequence of parts using the latter.

2.11.4 Ergonomics implications

The above-mentioned studies whether related to models developed or techniques used by the researchers, have covered large aspects of costs associated with production and manufacturing in different sectors of industries and services. Despite the importance of human factors and ergonomics and despite their impact on production, none of these models or techniques tackled this impact on the total production. The effect of ergonomics could have been assumed implicitly within the total production. However, it had neither been addressed specifically as a main factor or component nor as a productivity issue.

CHAPTER 3

DEVELOPMENT OF REGRESSION MODELS

3.1 Introduction

One of the objectives of this study was to develop prediction models for determining the maximum energy expenditure for both male and female individuals. For building such models, the data was tested, number of independent variables was reduced using stepwise regression, model was validated, and then tested with the provided data.

The intention was to develop a simple model that could describe the data well, predict well results, and easier to implement and used in industry. To do so, predictor variables should be able to represent individual's characteristics, and highly correlated to the dependent variables.

For the models development, some statistical criteria were used. Measuring of the strength of the regression to determine how well the regression line fits the data is performed using the value of R^2. Confidence interval statistics was used to determine the reliability of the models. Lastly, t-test was performed to test for any significance difference between predicted and observed variables of the models.

Some independent variables were chosen for such purpose. These variables are person's height, weight, gender, and age. To establish the relationship of between these independent variables and the dependent variable, a stepwise regression was performed to economize the computational efforts by eliminating all non-affecting variable.

3.2 Data Source

The Canadian standardized test of fitness (CSTF) was developed following the recommendation of the national conference of fitness and health held in Ottawa in 1972. This test was developed in order to establish a simple field test of fitness which would include a standardized cardiovascular performance test.

The CSTF is a set of procedures used to evaluate specific fitness components. These include standardized measurements of antropometry, aerobic fitness, muscular endurance and flexibility and are accompanied by norms and percentiles for Canadians 15 to 59 years-of-age. The fundamental objective of the CSTF is to provide fitness appraisal with a simple safe and practical field procedure to evaluate the major components of fitness in apparently healthy individuals in order to motivate them to enhance their participation in physical activity.

The survey sample consists of 11,884 households which had been identified by Statistics Canada and which were located in the urban and rural areas of each province. Of these chosen households, 15,519 persons between the ages of seven and sixty nine years inclusive undertook this test. The CSTF was the largest and most comprehensive study of physical activity and fitness ever undertaken.

Due to its reliability, CSTF is adopted in the National Physical Fitness Appraisal Certification and Accreditation (FACA) to form the basis for registration as a Registered Fitness Appraiser (RFA). In terms of its use, the test was criticized for its safety and precision. Shephard et al (1991) stated that more regulations have been added to prevent any safety concerns and to obtain more accurate results. However, the broad range of data collected makes it statistically accepted by all parties.

Among the data produced by this study were subjects' Vo_2max, Height, body weight, and heart rate. Subjects' values for such data are represented in Table 3.1-Table 3.3 below:

AGE (yr)	15-19		20-29		30-39		40-49		50-59		60-69	
Gender	M	F	M	F	M	F	M	F	M	F	M	F
Percentile												
95	62	45	59	43	51	39	44	36	40	31	32	26
90	61	43	58	41	50	38	43	35	39	30	31	26
85	60	43	57	40	48	37	42	35	38	30	30	25
80	59	42	56	39	47	37	42	34	38	29	30	25
75	59	41	55	39	47	36	41	33	37	28	29	24
70	58	40	54	38	46	35	40	33	36	28	29	24
65	58	40	52	37	46	34	40	32	36	27	29	24
60	57	39	48	37	45	33	39	31	35	27	28	23
55	57	38	44	36	44	32	38	30	35	26	28	23
50	56	38	43	35	43	32	38	28	34	26	28	22
45	54	37	43	35	42	31	37	26	34	25	27	22
40	52	37	42	34	41	31	37	25	33	25	27	22
35	47	36	42	34	40	30	36	25	33	24	27	21
30	46	35	41	33	39	30	35	24	32	23	27	21
25	44	35	40	32	38	29	34	24	31	22	26	20
20	43	34	40	31	37	29	32	23	28	21	26	19
15	42	34	39	31	36	28	31	22	26	20	25	19
10	41	33	38	30	34	28	30	22	25	19	24	18
5	40	32	37	29	33	27	29	21	24	19	23	17

Table 3.1 Subjects Predicted Vo_2max values in ml/kg.min

Age (yrs)	15-19		20-29		30-39		40-49		50-59		60-69	
Gender	M	F	M	F	M	F	M	F	M	F	M	F
percentile												
95	86	74	96	74	100	82	101	86	97	87	101	85
90	81	70	89	69	94	76	95	78	93	79	94	78
85	78	66	86	66	89	71	92	75	89	75	90	75
80	75	64	83	63	87	69	88	71	87	72	87	72
75	73	62	80	62	85	67	86	70	85	71	85	70
70	71	60	79	61	83	64	85	68	84	69	83	69
65	70	59	77	59	81	63	83	66	82	68	81	67
60	69	58	76	58	79	61	81	65	81	67	79	65
55	67	57	74	57	78	60	79	63	79	65	78	63
50	66	56	73	56	76	59	78	62	78	64	77	62
45	65	55	71	55	75	58	76	60	76	63	76	61
40	64	54	70	54	73	57	75	59	75	62	74	60
35	62	53	69	53	72	56	73	58	73	61	73	59
30	61	52	67	52	70	55	72	57	72	59	72	58
25	60	51	66	51	68	54	70	55	70	58	70	56
20	58	49	65	80	67	53	68	54	68	56	68	55
15	56	48	63	49	65	51	66	53	66	54	66	54
10	54	46	61	47	62	50	64	51	64	53	65	53
5	52	44	57	45	58	47	60	49	60	50	62	50

Table 3.2 Percentile by age groups and gender for body weight (kg)

Age (yrs)	15-19		20-29		30-39		40-49		50-59		60-69	
Gender	M	F	M	F	M	F	M	F	M	F	M	F
percentile												
95	191	175	191	175	190	175	190	175	190	174	188	174
90	189	174	189	174	188	174	188	174	187	173	184	172
85	187	173	188	173	186	172	186	172	185	171	180	169
80	185	171	186	171	184	171	183	171	183	170	176	167
75	183	170	184	170	183	169	181	169	180	168	175	165
70	181	169	182	169	181	168	179	168	178	166	174	163
65	179	167	181	167	179	167	177	167	176	165	173	160
60	177	166	179	166	177	165	175	165	175	163	172	159
55	175	165	177	165	175	164	174	164	173	161	171	158
50	174	163	176	163	174	162	172	162	172	160	170	156
45	172	162	174	162	172	161	171	161	171	158	169	155
40	171	161	173	161	171	159	170	159	169	157	168	154
35	169	159	171	159	169	157	169	158	168	155	166	152
30	168	157	169	157	168	156	167	156	167	153	165	151
25	167	155	168	155	167	154	166	154	166	152	164	150
20	165	153	166	153	165	152	165	152	164	150	163	148
15	164	150	165	150	164	150	163	150	163	149	162	147
10	162	148	163	148	162	148	162	148	162	147	161	146
5	161	146	161	146	161	146	161	146	161	145	160	145

Table 3.3 Percentile by age groups and gender for STANDING HEIGHT(CM)

3.3 Data Analysis

The data is statistically verified in terms of normality, and dependency. Since the data is presented in terms of group percentiles, independency of the data can not be assumed due to the lack of raw data. However, this does not prevent us from using it. As for the normality test, the large number of samples taken (15519 subjects) proves that the data distribution is automatically normal since the sample size is greater than 35.

Age, body weight, height, gender, and heart rate were assumed to be factors that affect the value of Vo_2max. To test this effect, a stepwise regression is performed. Age group intervals mid-points were used since only group intervals are provided. Amount of Vo_2max is used as the response variable while the other factors were used as independent variables. Fig 3.1 below represents the effect of age on the value of Vo_2max for an average male and female person.

The figure represents also the difference in Vo_2max value between males (presented as continuous line) and females individuals (presented with dotted lines) as an indication of how gender plays a significant role in determining the Vo_2max value. For the rest of other percentiles, refer to appendix A.

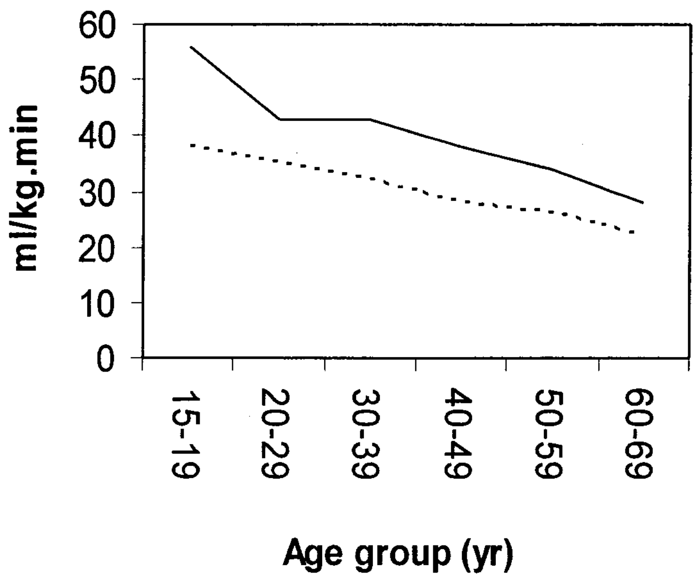

Fig 3.1 Difference in Vo_2 max for 50% male/female subjects

3.4 Male Individuals Vo_2max Prediction Regression Models

Data values are first arranged to represent all factors and values used to determine Vo_2max. Stepwise regression is performed (using Minitab 12 statistical software) on the data to eliminate all non significant independent factors, (in this case, Height, Age, Weight, Heart Rate (HR), and Gender) that have no effect on determining the dependent factor (Vo_2max). Age values are taken as the mid-point for each group range. The following section will discuss in more details the regression models for the 5th, 10th, 75th, and 95th percentiles due to the popular use of these percentiles in industry and design. The 75th percentile is added to the other percentiles due its recent popular use in other ergonomic standards such as Mitel and Snook's Tables. The MOL Ergonomics Inspectors generally require that at least 75% of the population (25^{th} percentile) be accommodated in manufacturing at any second stage work refusals.

3.4.1 Stepwise Regression for the 95^{th} Percentile Population

For the 95^{th} percentile population, the stepwise regression eliminated both weight and height and included age as per Table 3.4 below with the response variable as Vo_2max. Based on the results of the stepwise regression, the following regression equation was obtained:

$$\mathbf{Vo_2\ max = 73.1 - 0.630\ age}$$

Predictor	Coef	StDev	T	P	R-sq	C.I.	
Constant	73.105	1.22	59.91	0	99.20%	-0.7	-0.6
Age	-0.63	0.028	-22.29	0			

Table 3.4 Regression analysis table for the 95^{th} %

To test the goodness of fit for the model, a two tailed confidence interval test was constructed based on 95% confidence interval value. The interval range did not include the value zero. This indicates that the true value of the independent variable is not zero. The high value of R^2 of 99.2 indicates that a very good fit is present between the line and the data. This is also proved by the small of P presented in the table.

3.4.2 Stepwise Regression for the 75^{th} Percentile Population

The regression for this percentile equation is

$$\mathbf{Vo_2\ max = 69.3 - 0.618\ age}$$

Table 3.6 represents the regression analysis performed on the model for the 75^{th} percentile model. The table did not show any strange value that need to be scrutinized for more details as regarding the R^2 , the confidence interval or the P value.

Predictor	Coef	StDev	T	P	R-sq	C.I.	
Constant	69.27	1.115	62.14	0.0	99.30%	-0.7	-0.6
Age	-0.62	0.025	-23.91	0.0			

Table 3.5 Regression analysis table for the 75th %

3.4.3 Stepwise Regression for the 50th Percentile Population

For this part of the population, Height and Age were the only variables affecting the value of Vo_2max. Weight seems to have no or little effect in determining Vo_2max since the value of R-seq is 97.4%. The regression equation is

$$\mathbf{Vo_2\ max = 499 - 0.753\ Age - 2.48\ Height}$$

Predictor	Coef	StDev	T	P	R-sq	C.I	
Constant	499	158.1	3.15	0.051	97.40%	-1	-0.5
Age	-0.753	0.103	-7.31	0.005			
Height	-2.476	0.893	-2.77	0.069			

Table 3.6 Regression analysis table for the 50^{h} %

With the indicated statistics above in Table 3.7, a conclusion could be drawn that this model has no statistics whether P value R^2 or the confidence interval is an outliner that need to be discussed further or studied.

3.4.4 Stepwise Regression for the 5th Percentile Population

For the 5th percentile of the population, Height, and Age were the only variables affecting the value of Vo_2max. Weight seems to have no or little effect in determining Vo_2max since the value of R^2 is 99.8%. The regression equation is

$$\mathbf{Vo_2max = 490 - 0.417\ age - 2.75\ ht}$$

The equation shows that only age and height has an effect on Vo_2max for female subjects.

Predictor	Coef	StDev	T	P	R-sq	C.I.	
Constant	489.98	94.41	5.19	0.014	99.80%	-0.45	-0.387
Age	-0.417	0.013	-31.78	0.0			
Ht	-2.75	0.585	-4.7	0.018			

Table 3.7 Regression analysis table for the 5th %

The confidence interval did not include the zero value in it, R^2 has a high value of 99.8%, and P has very small values for both independent variables.

3.4.5 Prediction Models for Other Male Percentiles

The following models in Table 3.9 represent the rest of the population percentiles that will also be used in addition to the above mentioned models despite their non popularity in design choices which emphasizes the use of average, range, minimum, or maximum.

95%	**Vo_2max = 73.1 - 0.63 Age**
90%	**Vo_2max = 72.1 - 0.63 Age**
85%	**Vo_2max = 70.81 - 0.627 Age**
80%	**Vo_2max = 69.25 - 0.6 Age**
75%	**Vo_2max = 69.27 - 0.618 Age**
70%	**Vo_2max = 67.85 – 0.603 Age**
65%	**Vo_2max = 66.77 - 0.584 Age**
60%	**Vo_2max = 64.17 - 0.556 Age**
55%	**Vo_2max = 507.61 – 0.766 Age – 2.5 Height**
50%	**Vo_2max = 498.63 - 0.753 Age – 2.48 Height**
45%	**Vo_2max = 58.92 - 0.488 Age**
40%	**Vo_2max = 552.6 – 0.775 Age – 2.99 Height + 0.36 Weight**
35%	**Vo_2max = 52.82 - 0.385 Age**
30%	**Vo_2max = 51.4 - 0.37 Age**
25%	**Vo_2max = 49.67 - 0.356 Age**
20%	**Vo_2max = 49.09 - 0.371 Age**
15%	**Vo_2max = 48.28 - 0.379 Age**
10%	**Vo_2max = 46.99 - 0.376 Age**
5%	**Vo_2max = 489.98 - 0.417 Age - 2.75 Height**

Table 3.8 Vo_2max models for male subjects

3.5 Female Individuals Vo_2max Prediction Regression Models

Tables 3.9 to 3.12 represent the statistics for models developed for the 5th, 50th, 75th, and 95th percentiles for female individuals. By looking at the p-values, R^2 (98.6-99.5) and the 95% confidence interval values, for these models, a conclusion is drawn that these model are reliable and present a good model for predicting the values of the dependent variable.

Predictor	Coef	StDev	T	P	R-sq	C.I.	
Constant	52.41	0.944	55.55	0.0	98.80%	-0.45	-0.345
Age	-0.395	0.022	-18.07	0.0			

Table 3.9 Regression analysis table for the 95th % female individuals

Predictor	Coef	StDev	T	P	R-sq	C.I.	
Constant	47.71	0.912	52.3	0.0	98.60%	-0.41	-0.308
Age	-0.37	0.021	-16.88	0.0			

Table 3.10 Regression analysis table for the 75th % female individuals

Predictor	Coef	StDev	T	P	R-sq	C.I.	
Constant	43.161	0.503	85.85	0.0	99.50%	-0.35	-0.299
Age	-0.33	0.012	-28	0.0			

Table 3.11 Regression analysis table for the 50th % female individuals

Predictor	Coef	StDev	T	P	R-sq	C.I	
Constant	37.16	1.174	31.64	0.0	97.30%	-0.39	-0.263
Age	-0.33	0.027	-11.99	0.0			

Table 3.12 Regression analysis table for the 5th % female individuals

Table 3.13 represents all the percentiles.

95%	**Vo_2max = 52.41 - 0.395 Age**
90%	**Vo_2max = -234.66 - 0.294 Age + 1.62 Height**
85%	**Vo_2max = -101.19 - 0.385 Age + 0.365 Weight + 0.73 Height**
80%	**Vo_2max = 21.73 - 0.437 Age + 0.44 Weight**
75%	**Vo_2max = 47.71 - 0.357 Age**
70%	**Vo_2max = -93.49 – 0.236 Age + 0.81 Height**
65%	**Vo_2max = 45.46 - 0.329 Age**
60%	**Vo_2max = - 15.1 - 0.284 Age + 0.35 Height**
55%	**Vo_2max = 43.38 - 0.315 Age**
50%	**Vo_2max = 43.16 - 0.326 Age**
45%	**Vo_2max = 148.17 - 0.413 Age – 0.64 Height**
40%	**Vo_2max = 41.62 – 0.317 Age**
35%	**Vo_2max = 144.09 - 0.41 Age – 0.63 Height**
30%	**Vo_2max = 195.46 - 0.433 Age – 0.97 Height**
25%	**Vo_2max = 39.87 - 0.323 Age**
20%	**Vo_2max = 204.9 - 0.434 Age – 1.07 Height**
15%	**Vo_2max = 148.7 – 2.39 Weight**
10%	**Vo_2max = 38.35 - 0.335 Age**
5%	**Vo_2max = 37.16 - 0.326 Age**

Table 3.13 Vo_2max models for female subjects

3.6 Models Validation

Model developed for both genders were tested using the available data as presented in Tables 3.14 – 3.21. These tables present the error values between the observed and predicted values of Vo_2 max. By looking at these values we notice that the difference error between the observed and the predicted values is marginal and represents minimal error. However, the results were tested statistically using the t-test. A paired t-test with α =0.025 and 5 degrees of freedom. When the calculated t-test values for all models were compared to table t-test value of 2.571, they all resulted in a value less than the table value Table 3.22. These values ranged between 0.2 and 0.98. This indicates that there is no significant difference between the predicted and the observed value for the models.

Characteristic	predicted	observed	Error	Absolute (error %)
17	62.39	62	0.39	0.629032
24.5	57.665	59	-1.335	2.26271
34.5	51.365	51	0.365	0.715686
44.5	45.065	44	1.065	2.420455
55.5	38.135	40	-1.865	4.6625
65.5	31.835	32	-0.165	0.51563

Table 3.14 Comparison of predicted and observed values (95% male individuals)

Characteristic	predicted	observed	Error	Absolute (error %)
17	58.794	59	-0.206	0.34915
24.5	54.159	55	-0.841	1.52909
34.5	47.979	47	0.979	2.082979
44.5	41.799	41	0.799	1.94878
55.5	35.001	37	-1.999	5.4027
65.5	28.821	29	-0.179	0.61724

Table 3.15 Comparison of predicted and observed values (75% male individuals)

Characteristic	predicted	observed	Error	Absolute (error %)
17	54.679	56	-1.321	2.35893
24.5	44.0715	43	1.0715	2.49186
34.5	41.5015	43	-1.4985	3.48488
44.5	38.9315	38	0.9315	2.451316
55.5	30.6485	34	-3.3515	9.85735
65.5	28.0785	28	0.0785	0.280357

Table 3.16 Comparison of predicted and observed values (50% male individuals)

Characteristic	predicted	observed	Error	Absolute (error %)
17	55.19219	40	15.19219	37.98047
24.5	36.99697	37	-0.00303	0.0082
34.5	32.94354	33	-0.05646	0.1711
44.5	28.67606	29	-0.32394	1.11703
55.5	23.95274	24	-0.04726	0.19691
65.5	22.57269	23	-0.42731	1.85789

Table 3.17 Comparison of predicted and observed values (5% male individuals)

Characteristic	predicted	observed	Error	Absolute (error %)
17	45.685	45	0.685	1.522222
24.5	42.7225	43	-0.2775	0.64535
34.5	38.7725	39	-0.2275	0.58333
44.5	34.8225	36	-1.1775	3.27083
55.5	30.4775	31	-0.5225	1.68548
65.5	26.5275	26	0.5275	2.028846

Table 3.18 Comparison of predicted and observed values (95% female individuals)

Characteristic	predicted	observed	Error	Absolute (error %)
17	41.631	41	0.631	1.539024
24.5	38.9535	39	-0.0465	0.11923
34.5	35.3835	36	-0.6165	1.7125
44.5	31.8135	33	-1.1865	3.59545
55.5	27.8865	28	-0.1135	0.40536
65.5	24.3165	24	0.3165	1.31875

Table 3.19 Comparison of predicted and observed values (75% female individuals)

Characteristic	predicted	observed	Error	Absolute (error %)
17	37.658	38	-0.342	0.9
24.5	35.213	35	0.213	0.608571
34.5	31.953	32	-0.047	0.14687
44.5	28.693	28	0.693	2.475
55.5	25.107	26	-0.893	3.43462
65.5	21.847	22	-0.153	0.69545

Table 3.20 Comparison of predicted and observed values (50% female individuals)

Characteristic	predicted	observed	Error	Absolute (error %)
17	31.658	32	-0.342	1.06875
24.5	29.213	29	0.213	0.734483
34.5	25.953	27	-1.047	3.87778
44.5	22.693	21	1.693	8.061905
55.5	19.107	18	1.107	6.15
65.5	15.847	17	-1.153	6.78235

Table 3.21 Comparison of predicted and observed values (5% female individuals)

%	T-value
95 Male	0.56149
95 Male	0.538117
95 Male	0.981815
95 Male	0.89747
95 Female	0.58833
95 Female	0.63528
95 Female	0.40539
95 Female	0.1668241

- Error = (predicted value – observed value)
- Absolute error = | predicted value – observed value| /observed value * 100

Table 3.22 Calculated T-test values

3.7 Work Capacity Prediction Models

As it was discussed in earlier chapters, despite the appendance of work done to predict metabolic rate, most of these studies relied on either a single factor affecting the aerobic capacity or on a limited time of experimentation without taking into account longer periods of work.

In their work, Garg et al (1978) produced prediction models to estimate the metabolic rate for different material handling jobs. These models covered jobs that include manual material handling tasks such as lifting, lowering, carrying, and walking and the like. Among these models, models dealing with manual material handling jobs will be considered and used through this study. Such models are as follows:

1. Sitting

$$\mathbf{E = 0.023\ BW}$$

2. Standing

$$\mathbf{E = 0.024\ BW}$$

3. Stoop lifts (Kcal/lift)

$$\mathbf{E = 10^{-2}[\ 0.325\ BW\ (0.81 - h_1) + (1.41L + 0.76S \times L)\ (h_2 - h_1)]\ for\ h_1 < h_2 < 0.81}$$

5. Squat lift (Kcal/lift)

$$\mathbf{E = 10^{-2}[\ 0.514\ BW\ (0.81 - h_1) + (2.19L + 0.62S \times L)\ (h_2 - h_1)]\ for\ h_1 < h_2 < 0.81}$$

6. Stoop lower (Kcal/lift)

$$\mathbf{E = 10^{-2}[\ 0.268\ BW\ (0.81 - h_1) + (0.675L)\ (h_2 - h_1)] + 5.22\ S\ (0.81 - h_1)]}$$

for $h_1 < h_2 < 0.81$

7. Squat lower (Kcal/lift)

$$\mathbf{E = 10^{-2}[\ 0.511\ BW\ (0.81 - h_1) + (0.701L)\ (h_2 - h_1)]\ for\ h_1 < h_2 < 0.81}$$

8. Walking

$$\mathbf{E = 10^{-2}[\ 51 + 2.54\ BW\ (V2) + 0.379\ BW\ (G)(V)]T}$$

9. Arm lift (Kcal/lift)

$$\mathbf{E = 10^{-2}[\ 0.062\ BW\ (h_2 - 0.81) + (3.19L - 0.52\ S \times L)\ (h_2 - h_1)]}\ \text{for } 0.81 < h_1 < h_2$$

10. Arm lower (Kcal/lower)

$$\mathbf{E = 10^{-2}[\ 0.093\ BW\ (h_2 - 0.81) + (1.02L + 0.37\ S \times L)\ (h_2 - h_1)]}\ \text{for } 0.81 < h_1 < h_2$$

11. Pushing/Pulling at bench height (0.8 meter) kcal/push

$$\mathbf{E = 10^{-2}[\,0.112\,BW\ +1.15F + 0.505\,SxF]}$$

12. Pushing/Pulling above bench height (1.5 meter) kcal/push

$$\mathbf{E = X\,[\,0.086 + 0.036\,F]}$$

13. One hand lift (Kcal/lift)

$$\mathbf{E = 10^{-2}[\,0.352\,BW\,(0.81 - h_1) + (3.03L)\,(h_2 - h_1)]} \text{ for } < h_1 < h_2 < 0.81$$

Where,

E = metabolic rate (kcal/performance)

BW = Body weight (Kg)

h_1 = vertical height from floor (m) starting pint for lift and ending point for lower.

h_2 = vertical height from floor (m) end pint for lift and starting point for lower

L = weight of the load (kg)

S = gender, 1 for male and 0 for female

V = Speed of walking (m/s)

T = time (minutes)

G = grade of walking surface (%)

F = pushing/pulling force (kg)

X = horizontal movement of work piece (m)

These models are widely used and considered as most suitable models related to manual material handling. As it has been mentioned by the authors, the above models were validated and showed a strong correlation coefficient compared to measured metabolic rate.

3.8 Work Methodology

This study is based on two main sources of data for determining individuals' capability and work capacity. The data collected from 15,519 subjects by the Canadian standardized fit of fitness and the data predicted by Garg's models.

The theme of this study is to establish a way of matching individual work capacity that is suitable for performing a certain task or some tasks together. Individuals' capacity is determined by the models produced by this study based on the data collected by CSTF. Garg's model will be used to determine the work required capacity. Factors affecting either the individual or work capacity will be included in the matching based on their values or standards set by other parties such as NIOSH, OSHRAE, OSHA, and standards references. These values will be detailed more in the next chapter. Models developed and Garrg's models will be the basis for developing the decision aiding tool presented in the next chapter. Based on the individual characteristics, the tool will determine which of the models is suitable for calculating the value of Vo_2 max for that specified individual. Energy required to perform a job will be based on the job characteristics. The tool will evaluate the environmental condition at which the job is being performed. In case any of these factors has any effect of the tool assumptions, the tool provides its user with recommendations about how to modify that factor. Fig 3.2 presents how these models are used to develop the suggested aiding tool. Chapter 4 provides more details about the tool.

Working environment will be based on OSRAE recommendations discussed in Chapter2. Maximum allowable lifting/lowering tool and their frequencies are based on NIOSH guidelines discussed also in the mentioned chapter. When the user of the tool is recommended to perform the heat stress management, it is meant to refer to Chapter 2 to follow the steps required for such a program.

To ensure the correct use of the developed models, half of the source data is used to generate the models, while the other half is used to validate them.

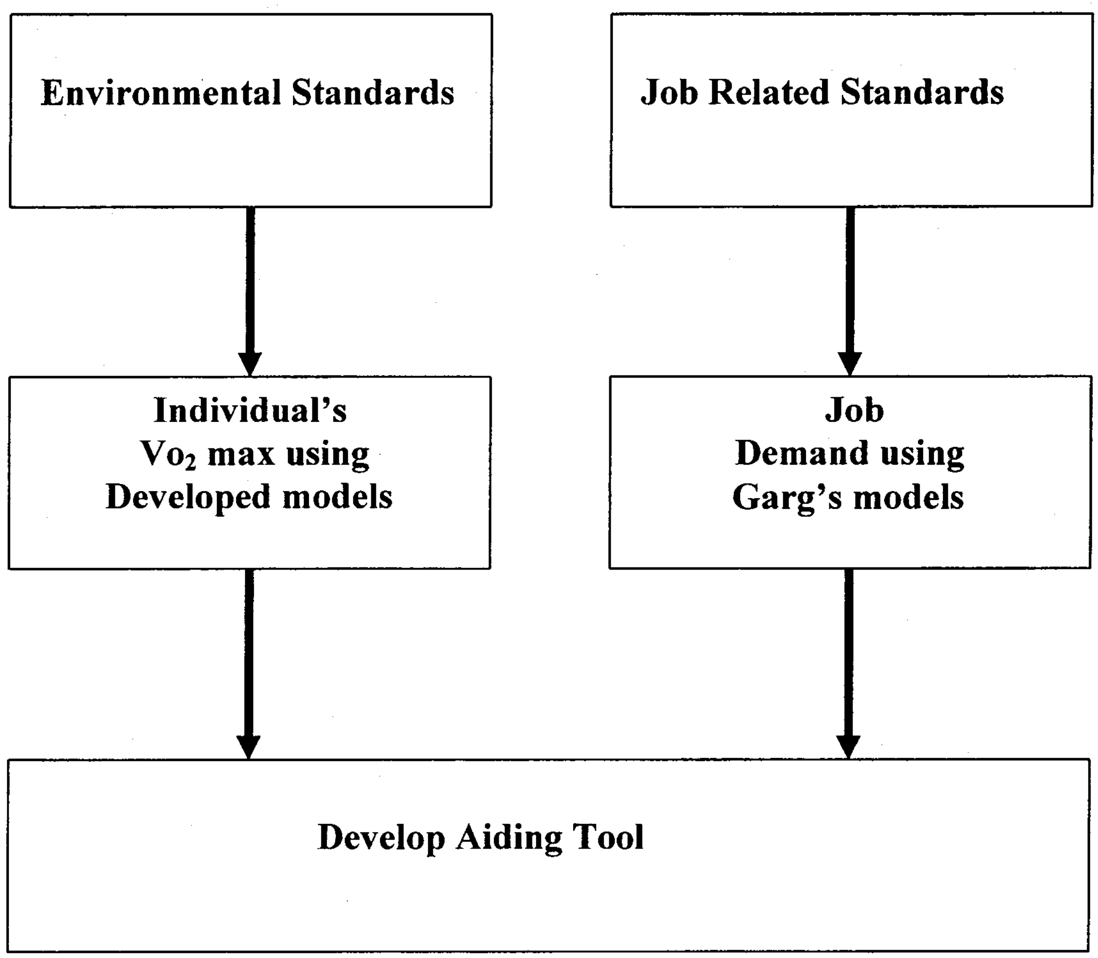

Fig 3.2 Methodology for developing the aiding tool

CHAPTER 4
TOOL DESCRIPTION

4.1 Introduction

The aid tool presented in this study consists of three main parts;

1. Individual's characteristics used to calculate the person's maximum energy expenditure
2. Task characteristics used to determine the total job physical demand
3. Environmental factor which affect the determination of both above characteristics.

These three parts will be discussed in the following sections.

4.2 Individual's Characteristics

Regression models developed in Chapter 3 are used to calculate the individual's Vo_2max. These models require the input of the individual's characteristics pertaining to the model requirements. Such inputs cover individual height, age, weight, targeted percentile, heart rate, and gender. To be consistent with the models assumptions, all these factors will be kept within the values used to develop the models based on the data generated by CSTF. Minimum values are based on the 5th percentile while the maximum values are based on the 95th percentile related to their age group.

4.2.1 Person's Height values

All persons heights used for this tool are between 160 and 191 cm for male persons and 145 and 175 cm for female subjects.

4.2.2 Person's Weight values

Persons body mass values are 52 to 101 kg for males and 44 to 85 kg for females.

4.2.3 Age values

The age grouping used to cluster the population will control the minimum and maximum age value for both genders. These two values are 15 to 69 years of age.

4.2.4 Targeted Percentile values

User targeted percentile value when entered will determine the suitable and corresponding regression model to be used for determining the maximum energy expenditure for the specified person. This value will range between the 5^{th} and 95^{th} percentile including other percentiles between these two values in an increasing order by a value of five.

Figure 4.1 below represents how he input of these values affects the use of the developed aiding tool. When all these values are entered, the tool will assess, verify, and validate each of these values to ensure its compliance with the model assumptions. In case any of these values represent an outlier, the system will stop to allow the user to modify and re-enter the value. Rectangular boxes on Fig 4.1 used to enter data are user specific and they represent the boundary between the user and the system.

Once all of these entries are entered and verified, the tool will calculate the corresponding person's maximum energy expenditure.

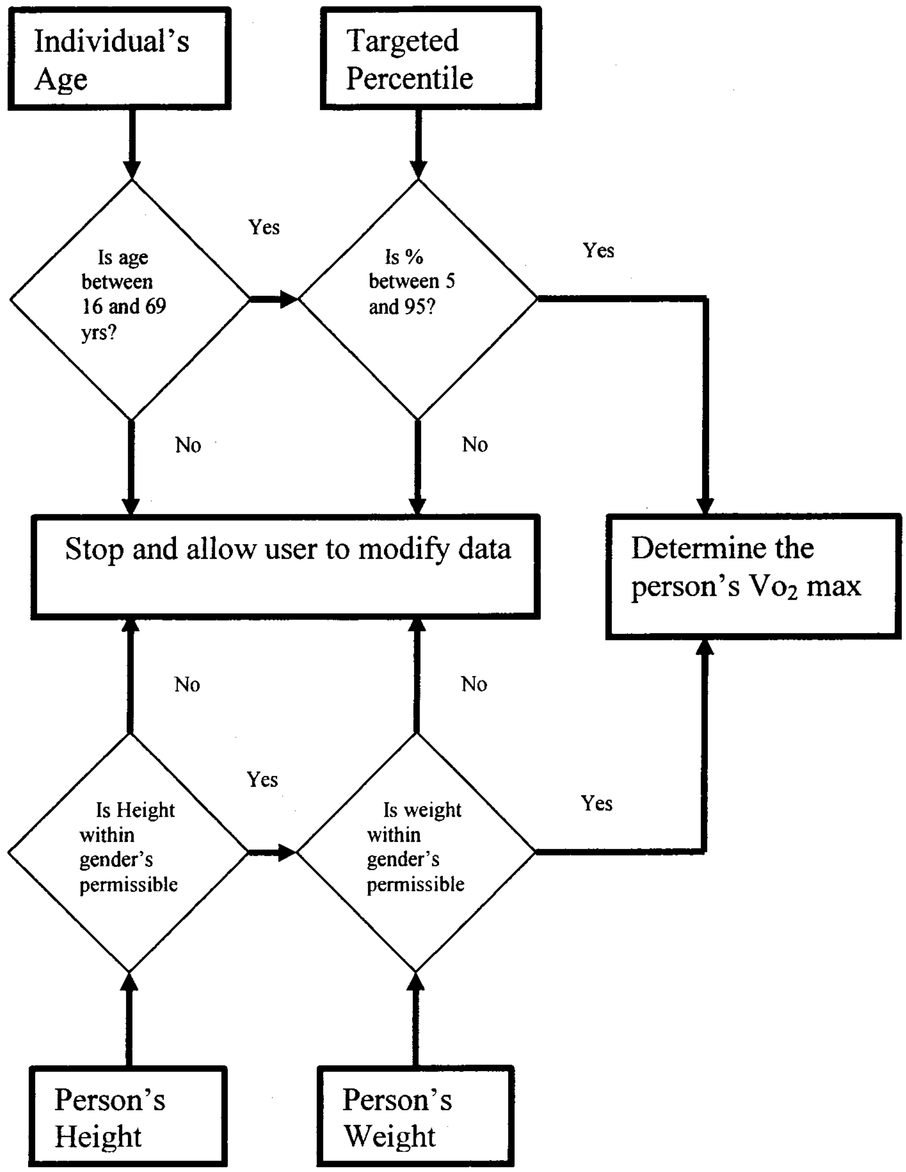

Fig 4.1 Verifying Individual's Data

4.3 Job Characteristics

The proposed aiding tool is designed to determine the physical demand of jobs consisting of one or more tasks. Fig 4.2 represents these tasks and their characteristics.

The user will input the data concerning the tasks to be performed. The time associated with performing each task will be used to calculate the total energy requirement to perform those tasks.

The parameters of each task will be entered after that. For walking tasks, speed of walking, grade of the walking surface, and the time required to perform any of these tasks will all be entered into the system.

Lifting and lowering jobs will require the lifting range. This range is specified by the models in Chapter 3 to be between 0 and 81 cm to comply with Garg'd model assumptions. Frequency of lifting and lowering presenting the amount of lifts and lowers performed within the specified shift. Amount of load being lifted or lowered which are set to be less than 23 kg based on NIOSH lifting standard. Pushing/pulling activities will require the user to determine and provide the pulling/pushing horizontal force and the horizontal movement of the work piece.

Maintenance of body posture within the task cycle constitutes some amount of energy expenditure. This amount has to be determined and added to the total task energy requirements.

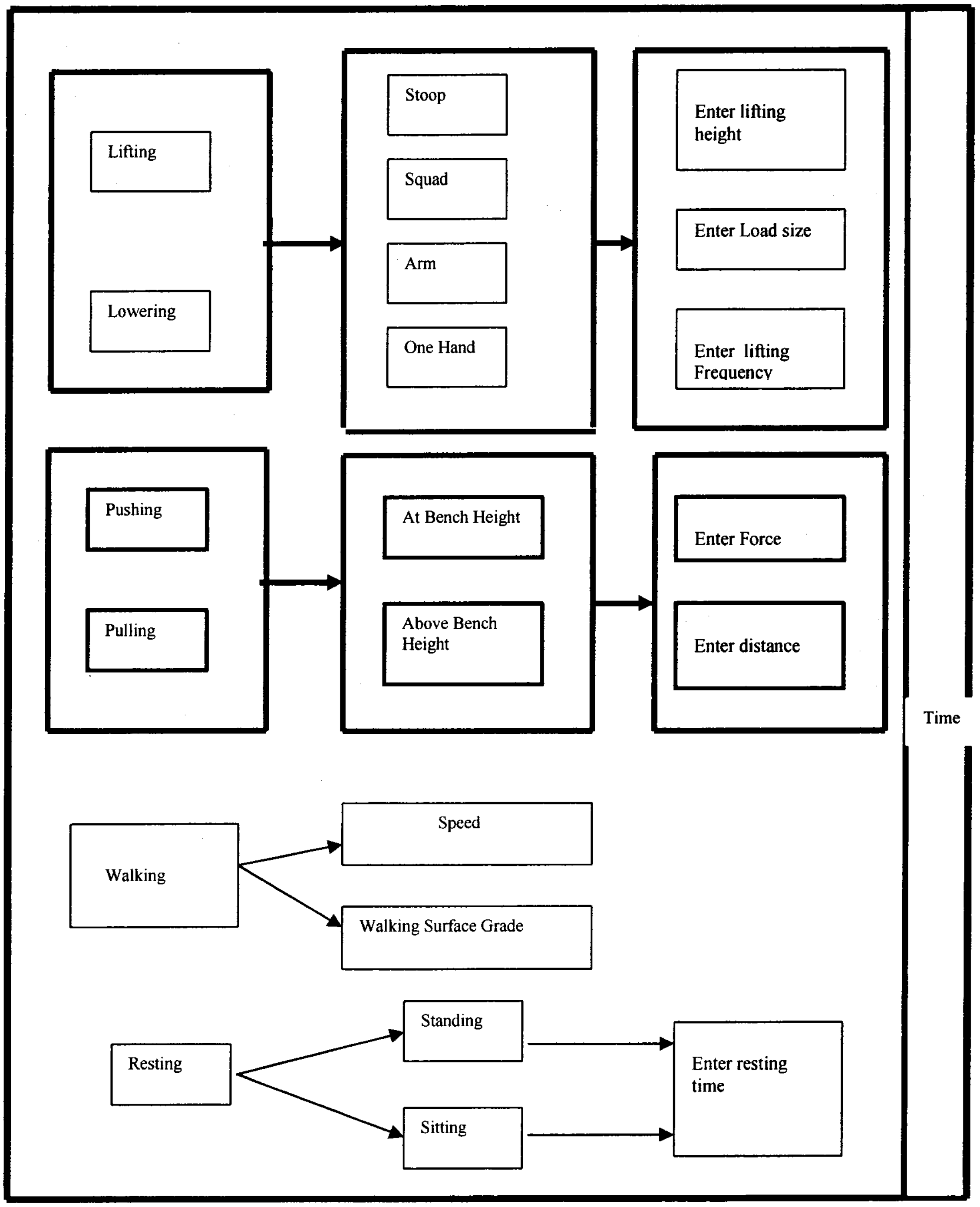

Fig 4.2 Job Characteristics

4.4 Task Control Factors

The ambient temperature is the main environmental factors affecting the individual's performance. As it is mentioned in the literature in a previous chapter, individual performance is reduced by 12% whenever the temperature exceeds 32 degrees Celsius.

OSHRAE recommends a comfortable zone of 18 to 35 degrees Celsius. Since on indication of how much increase in energy expenditure will result from working in an environment that has a temperature between 32 and 35, the 35 degrees will be assumed as the maximum temperature the user is allowed to use.

Other factors such as humidity and noise are assumed to be controlled by the person supervising the work being performed.

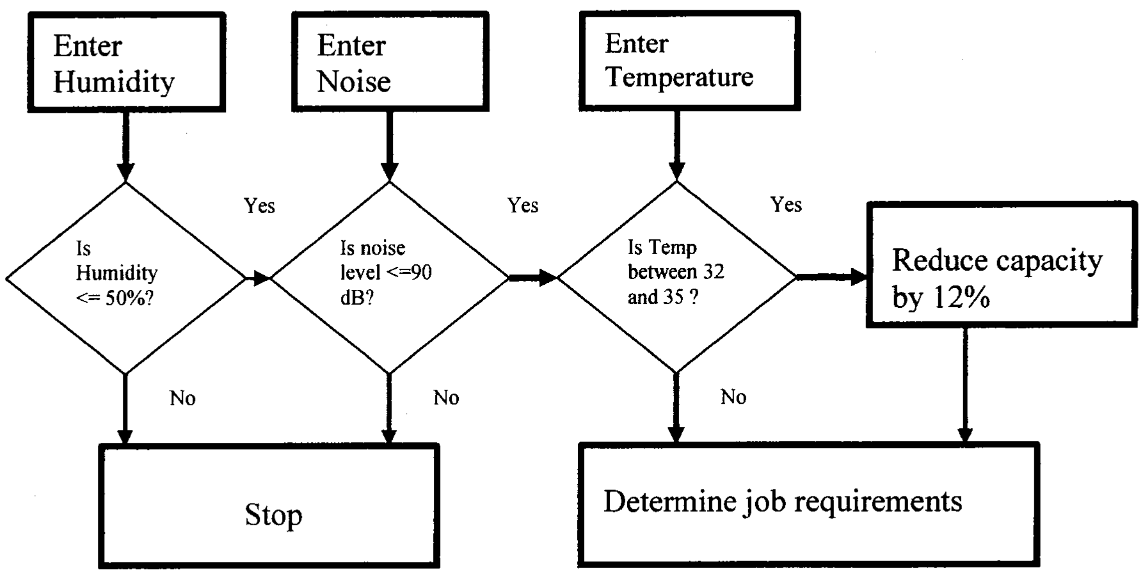

Fig 4.3 Environmental data verification

4.5 System Process

Based on the user selection, the system matches the input with the appropriate regression model that exactly fits the individual characteristics and calculates that persons maximum energy expenditure in Kcal/min. For the job being performed by that individual, the system calculates the total energy expenditure of that job by summing all of the energy expenditures values of all the sub-tasks included within that job. This is based on the assumption that the energy requirement to perform a certain task can be determined by summing the time weighted energy cost of all task elements over the work day Garg (1978). The system calculates the total time required to perform that job and the total resting time to determine the actual time spent performing the job. Because the human energy expenditure is measured in Kcal/min, the job demand has to be calculated in such way that it can be compared to the individual's capacity. Therefore, the job requirement is divided by the total time for that job to match it with the individual's level.

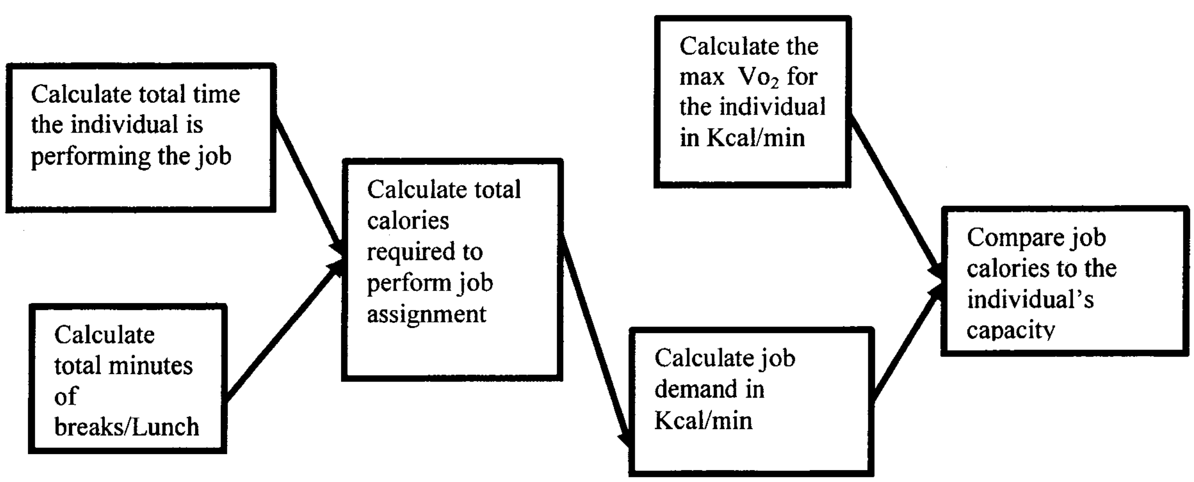

Fig 4.4 System's main processes

4.6 System Output

The system presents the user with the individual maximum energy expenditure value and the recommended 33% of that value that is used for an 8 hr work period Fig 4.4. The user is also presented with the amount of energy required to perform the tasks. These two values are used to determine the operator's threshold. Based on the comparison result, the system will determine whether this individual will be able to perform that job or not. Other factors related to the job are also presented to allow the user to relate and attribute the final score and results to any of these factors and regulate it for better job environment.

The system will decide also whether the assigned rest periods are enough to provide the operator with the required recovery period.

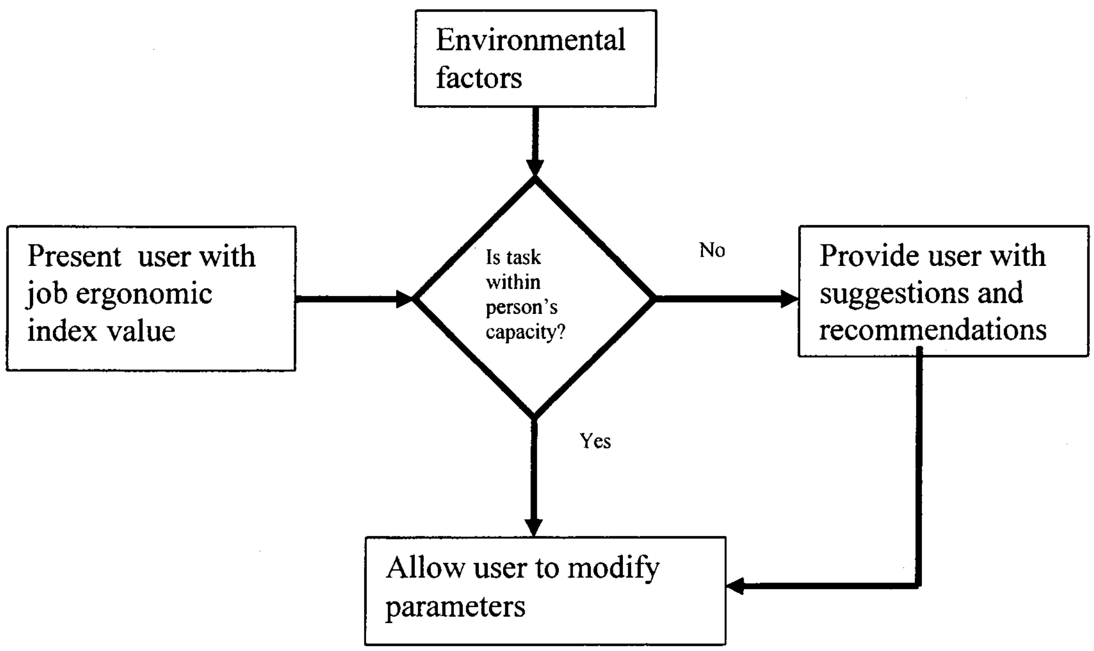

Fig 4.5 System Output

4.7 Job redesign

Another feature of the system is its flexibility. Instead of presenting the user with a yes/No style answer, the system will allow the user to modify the individual and the job design (characteristics) and reiterate until a satisfied result is obtained. This could be achieved by altering the individual characteristics or the task properties. The system will also provide some suggestions to help the user modify the design.

CHAPTER 5
TOOL DESIGN

5.1 Software

Borland C++ Builder 3 is used to write the code of the program. This builder is based on the latest programming technology used in object programming. It enables its users to write easy and quick interfaces to a program using drag-and-drop techniques for true rapid application development.

The user interface developed here consists of three main screens; the individual data screen, the job characteristics screen, and the report screen.

5.2 Individual Data Screen

This is the first screen the user is presented with when the program is run (Fig.5.1 represents this screen). It presents the user with all data pertaining to the person performing the tasks. The user is required to select the age of the individual, gender, and to what percentage of the population the individual belongs to. The user is also required to enter the height, and body mass of the individual and then press OK to be transferred to the second screen. The data entered is used mainly to determine the maximum metabolic rate of the individual based on the developed regression models presented in chapter 3. Except for the body mass, height, and exact individual age fields where the user has to enter a value for it, all other fields are designed to be clicked for only a single value since they pertain to one person.

Age group field combined with targeted percentile will determine what model to be used. However, exact age of the individual will be used by the model to calculate the exact value of Vo_2 max.

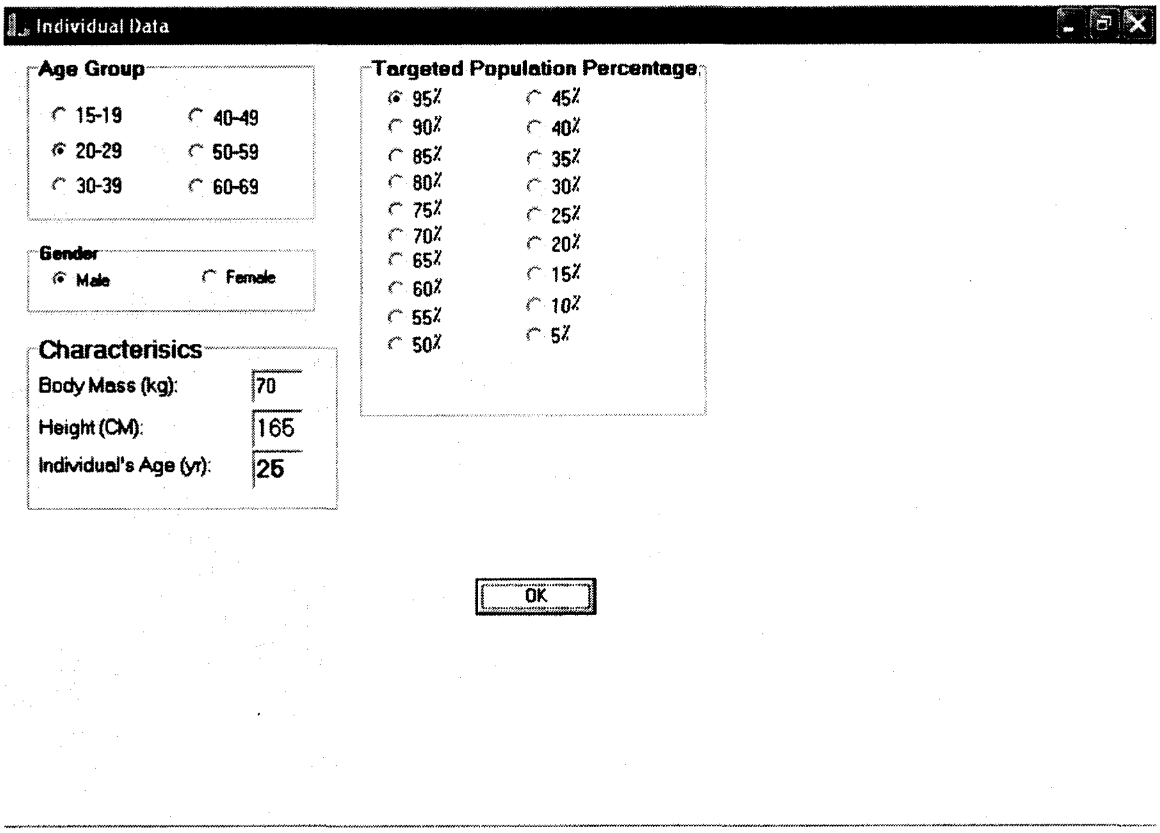

Fig 5.1 Individual Data Screen

5.3 Job Characteristics Screen

Once the user finishes entering and selecting parameters for the first screen, the software then displays the job characteristics (Fig. 5.2 represents this screen). On this screen all tasks expected to be performed by the person and their related aspects are presented. For lifting and lowering tasks, the user is asked to select the tasks and then enter their parameter such as the lifting and/or lowering height in cm, load size in kg, frequency of lifting or lowering as lifts/lowers per minute, and the duration for which that task is being done in min.

For pushing and pulling tasks, the user is asked to enter the pushing/pulling force in kg, Pulling/pushing distance in m, and duration in min. When the person is resting in either standing or sitting postures, only the resting time in min is required to be entered. Walking tasks require the user to specify the walking speed in m/min, walking time in min, and walking surface grade as percentage. The last field the user is asked to deal with is the environmental factors during which the tasks are being performed. The temperature field is required with any task selected since it determines the effect of the environment on the amount of metabolic rate when the temperature exceeds 32 degrees. However, based on ASHRAE recommendation, a value between 18 and 35 degrees Celsius will be used as a comfortable range to perform the work. Humidity should also be kept below 60% and noise level of less than 90dB according to the same standard. When the user entered any value that exceeds these values, the program will present the user with recommendations to modify the values since the lack of any standard that exist to determine the effect of these factors beyond these values.

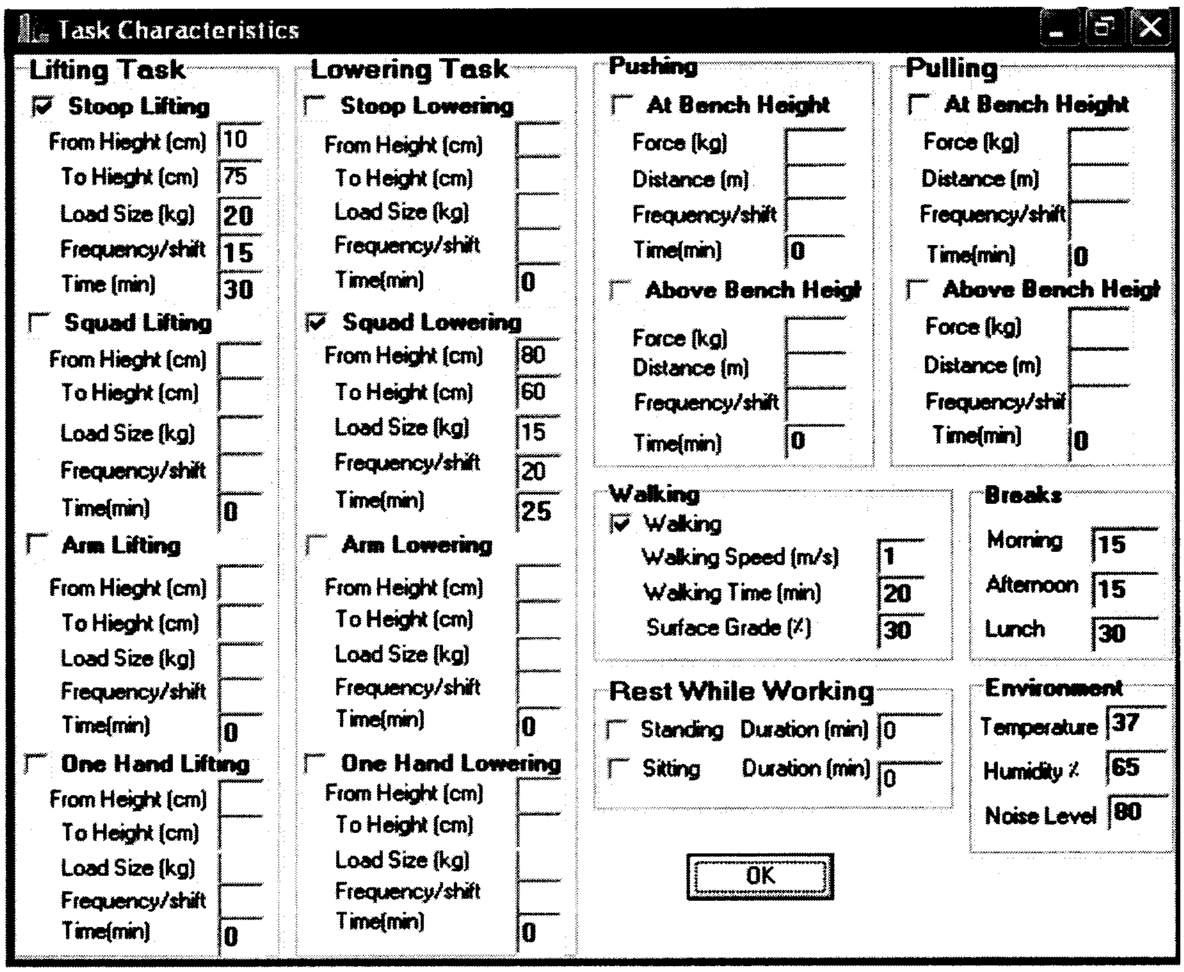

Fig. 5.2 Job Characteristics Screen

5.4 Report Screen

The third screen as presented in Fig 5.3 is the report screen. On this screen the result of the program is displayed. The user is presented with the value of the job required Vo_2 and the values of the individual's Vo_2max. Only 33% of the total person's Vo_2max will be used based on the NIOSH 1981 recommendation for 8 hrs maximum work duration. The ratio of the job value and the individual value will also be presented to determine how close to the threshold the person will be based on the formula presented by Genaidy et al (1990). In this study, the authors outlined a procedure for the use of PWC within the context of the physical ergonomics job design cycle centered upon the ergonomic index.

EI = Stress requirements/Physical work capacity

This index is divided into three main categories representing the level of job severity. Job is considered safe for the operator when the index is less than 50%. If the index is more than 50% and below 80%, the job is considered hard for the operator. When the ergonomic index surpasses the 80% value, it is considered dangerous for the operator and therefore the job had to be investigated for better assignment.

The screen will also present the user with some recommendations regarding the parameters the user entered about the job and the individual. Among these recommendations is whether the value of the any of the environmental factors needs to be reconsidered for recommended comfort zone. Extra break periods are also recommended if the job requires more than the assigned breaks. This extra break is assigned to the worker based on the severity of the work to the operator and on the amount of job requirements as presented in Fig 2.2 in Chapter 2. Based on these results, the user will then have the choice to terminate the program or to return to the previous screen to modify either individual's or task's parameters.

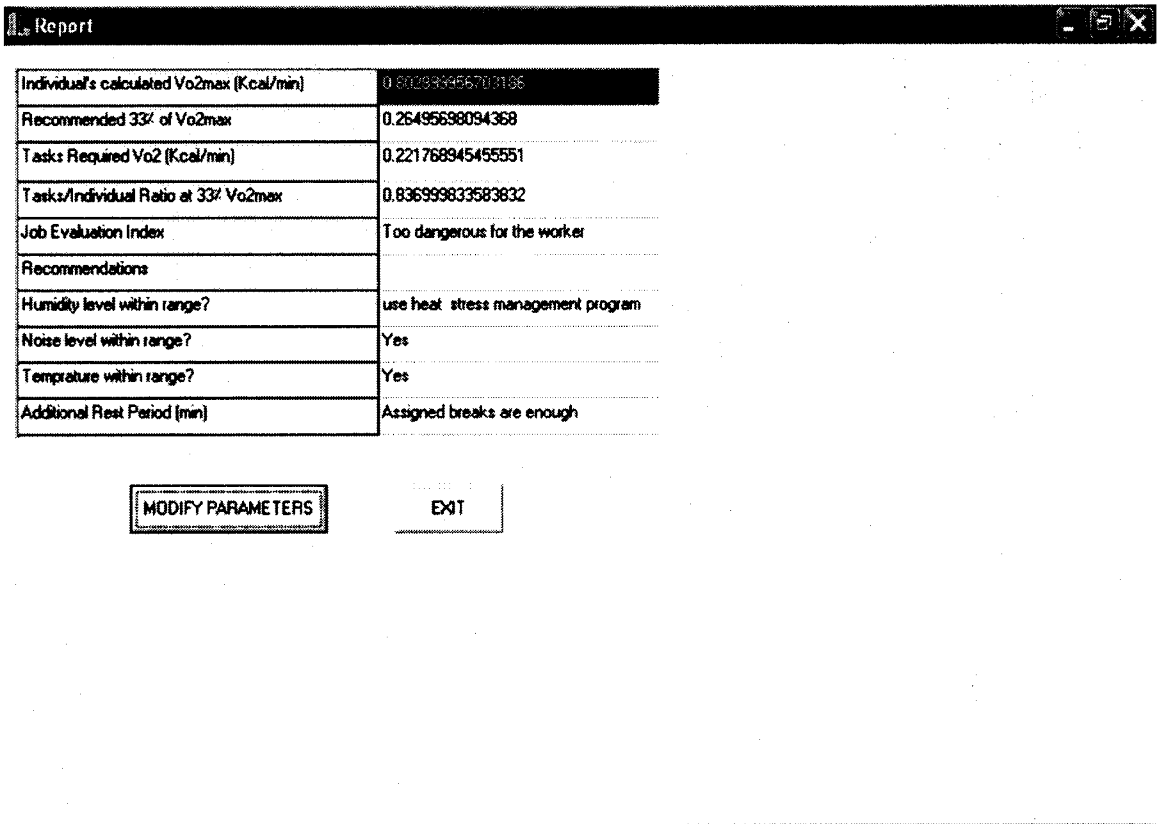

Fig. 5.3 Report Screen

5.4 Data Validation

Data used in this program, whether entered by the user or used within the program itself, is verified and validated to ensure that right values and ranges are used. To eliminate the chance of making any error, user is prompted, whenever possible, with selections only rather than fields that need to be filled with the user. This feature of the program software can be noticed on the first screen where the program does not allow the user to have more than one selection. When the user is asked to enter a value for any field as in the task characteristics screen, this field is subjected to some tests to ensure that value is permissible. User is not allowed to leave the field empty or enter a data type that is not suitable for calculation or comparison for any task selected.

For instance, average body mass assumed in this program is used as recommended by Statistics Canada values. It is recommended that the minimum value for body weight is 55 and 65 kg for females and males respectively. However the maximum values are 85 and 100 kg for females and males respectively. When the user enters any value that is out of this range, the program rejects this value and prompts the user to change it. All other parameters have a certain value or range of values based on the assumptions stated earlier are validated based on these assumptions; see also the discussion on next chapter for more details.

5.5 Program Development and Testing

This program was developed in three stages based on number of screens it consists of. When each screen is created, a grid screen that displays the values of all parameter is created. This screen allows the developer to double check each value entered or retrieved to ensure that the program is working correctly. Invalid values are also used to test the validation feature of the program. Numerical values were used to test that all calculation performed by the program produce the correct values. These values are checked against other results obtained manually to determine their validity.

The above shown screens represent a situation where a male operator is performing three main tasks within a cell on an assembly line. This operator belongs to the 95th % of the population, of an age of 25 years, and weighs 70 kg, of height of 165. Within that cell, the operator picks up a 20 kg part from the stock located at 10 cm height, moves to a different location with a speed of one meter per second and surface grade of 30% inclination for a total of 20 min. The operator then lowers another part of 15kg from an elevation of 80 cm. to 60 cm elevation. The operator performs part lifting for 15 times and part lowering for 20 times for a total of one hour and twenty five minutes.

The program results showed that this person has a maximum energy expenditure of 0.8 Kcal/min. The three tasks energy requirement 0.22 kcal/min. When the task requirement is compared to the 33% of the operator maximum energy expenditure, it resulted in an index of 84%. If the operator continues to perform this work for that rate, it would be considered physically dangerous for that operator according to the index adopted in this study. However, the assigned breaks when compared to the job requirements, it turned out to be enough to compensate for the operator lost energy. The humidity at which this operator is working is considered out of the comfort zone. This may affect the total job requirement and it is recommended by the program the users uses a heat stress management program to deal with the situation.

CHAPTER 6
DISCUSSIONS AND CONCLUSIONS

6.1 General Discussion

Studies of energy expenditure in humans have been going on since early last decade. Despite the tremendous work been done so far, this work has not yet covered all aspect and applications of this field. Among these aspects is the energy expenditure in prolonged multiple tasks performed by humans within their work area. Research has been performed so far on single activities in specific situations such as lifting, skiing, swimming. General standards are set to be used by some researchers that determine the maximum threshold for people performing works in general. However, these rules have some limitations and based on subjective evaluation rather than practical or experimental conclusions. To determine the ability of an individual to perform any work along certain period of time, one would require to determine two main factors; first, the maximum energy this individual can attain during this period and secondly, the energy required to perform the work. Because of the factors affecting the maximum physical work capacity of individuals, it is not possible to produce a general prediction model or formula to calculate this value. However, it becomes more realistic to calculate such values for a group of people under almost the same working and physical conditions.

6.2 Regression Models

This study had contributed to the field of determining the maximum aerobic capacity of an individual based on gender and physical characteristics by introducing some regression models. These models are based on pre-gathered data that has covered a large number of the population. Among the factors determining Vo_2 max for an individual, age, gender, height, and weight were the main factors affecting the value of Vo_2 max.

The main advantage of the models presented here is that they provide designer with separate model for any targeted percentile for either gender.

6.3 The Decision aiding Tool

In this research, a decision aiding tool that could be used to evaluate the human capacity in performing multiple prolonged activities is suggested to be used by designers and managers. This tool determines the maximum physical capacity of the individual based on gender, age, height, the population targeted percentile, and body mass. This maximum value is extracted using the regression model developed based on the data provided by Statistics Canada for the Canadian standardized test of fitness. This data was subjected to some tests to determine its validity and conformance with the assumptions of the maximum physical capacity values stated by the field researchers. Despite the on going debate of how much of the maximum individual's energy expenditure value should be considered safe for individuals to work with, the tool user is provided with the 33% based on NIOSH standard values of the maximum individual capacity. The tool determines also the energy required to perform the tasks.

Some material handling related tasks were selected to be used such as lifting, lowering, and walking. These tasks were selected for two main reasons. First, to represent the common activities done in any industrial environment and secondly, because of the availability of models specific to the nature of these tasks developed by Garg et al (1978) despite the availability of other general models which are not task specific, Tayyari and Smith (1997). Garg models are the base models for most of other developed software available in the market (Appendix C).

After determining the maximum Vo_2 for the individual and the Vo_2 for the tasks, the tool determines the individual's capability of doing the work based on the Ergonomic Index developed by Genaidy et al (1990). This formula determines how close the individual is stretching his/her capacity in terms to his/her maximum ability. The tool provides the designer with a choice to modify some of the individual or task parameter to determine who is most suitable in performing what task. This feature is suitable for What-If scenarios practiced during design stages of any project.

The tool's main advantage is that it saves time of determining the individual's capacity of performing tasks which was traditionally determined empirically. Subjects' presence is eliminated since data available is enough to compensate for that. The tool is also straight forward and simple to use. It also eliminates the need for laboratories equipment needed to determine the task requirements and individual's capacity that is when used either interferes with production if used on site or simulates non-realistic working environment when used at the laboratory.

Based on the amount of energy expenditure produced by the individual, the tool recommends the amount of hourly rest time needed for recovery.

6.4 Tool Limitations

Despite of the aforementioned advantages, the tool has some limitations in terms of coding and design. Data validation during the program run is not given enough attention in terms of programming practices. Although the user is advised that an error exists when entering the data, the program continues to run with some wrong fields. This requires the user to rerun the program back to the previous part in order to correct it.

The program total result is based on time weighted average of all tasks performed. This may give an indication that the maximum is reached at some pint of time. However, each individual task's result is determined alone on the second screen to determine which of the tasks causes the person to exceeds his/her limit Frequency of performing any task indicates how many times the task is being done during certain period of time within the work shift rather than within unit of time.

Ergonomists usually divide lifting and lowering heights to several levels, from floor to table height, to shoulder height, above shoulder height, etc. This tool is limited to the most general type of lifting; floor to table height. i.e 0 to 0.81m. It also assumes the standard way of lifting or lowering.

Although the tool deals with exact heights, it does not take into consideration any unusual posture during these activities. Maximum loads used in the tool are based on the maximum allowable determined by NIOSH. Individuals' minimum and maximum values for ages and minimum and maximum values for individuals' body mass are limited to the values used within the study performed to evaluate the Vo_2 max for the individuals.

The tool assumes that all environmental factors are within recommended values for normal work place environment. It only takes into consideration the effect of temperature within certain range after the normal one due to the presence of a study that had determined that effect. Because of the lack of any study that determines the amount of effect of humidity and noise on energy expenditure, the program is designed to present the user with recommendation that they are either within the recommended range or not. This leaves the user with the conclusion that the program capability does not cover such environmental situations.

6.5 Conclusions

This research is a contribution work to the area of physiological assessment of work. Besides the general models for determining maximum aerobic capacity for an individual, the study provides designers and practitioners with a simple decision aiding tool that could be used during both early stages of the design and during production stages to evaluate the physiological requirements of work and the capacity of people needed to perform them. Besides labor assignment, this tool can be used also to determine work/rest periods needed to overcome people fatigue besides the usual breaks assigned during the work shift. This tool is based on some assumptions and on general models widely used within the industry. Despite its great advantages, there are some limitations that need to be addressed in depth in order to improve the tool for better performance. These limitations are addressed in the next section of this chapter as recommendation for further work to be performed in the future.

6.6 Recommendations for Future Work

This study provided some data and guidelines for some work that could be pursued in the future in order to contribute to the field of physiological work in general and in order to overcome the limitations of the tool developed within this study. Some of these suggested works are:

1. Expanding the lifting models to include lifting jobs in asymmetric postures and heights levels other than the ones being used in the study.
2. Energy expenditure is not only related to the tasks listed on the tool. All other activity done by the person need to be included as well. Such activities will be eating, drinking, using tools, climbing stairs, ...etc.
3. The tool could also include other general activities that their energy requirements had been determined empirically. Of those would be sports activities and the like.

4. Amount of effect that can be imposed by the environmental factor when they exceed or fall below their normal values should be determined and added to the tool features including a heat stress management program.
5. Since this tool does not replace existing tool rather it enhance their use and application, it would be useful to integrate the tool with other existing tols. For instance NIOSH, Snook's tables, and the like.
6. The tool can be modified to allow for multi-job assignment that allows for the full utilization of the operator when an extra energy is available.

REFERENCES

Adil, G. K., Rajamani, D. and Strong D., "Cell Formation Considering Alternative Routings". International Journal of Production Research. 1996, Vol. 34, No. 5, 1361-1381.

Aghazadeh, F. Advances in Industrial Ergonomics and Safety VI. Taylor and Francis, London, pp. 81-88.**Allen, D.M.**,." Mean square error of prediction as a criterion for selection variables". Technometrics 16, 125-127, 1971

Akturk, M.S. and Balkose, H.O.," Part-machine grouping using a multi-objective cluster analysis". International Journal of Production Research, 1996, No. 34, 2299-2315.

Akturk, S., and Turkcan, A. "Cellular manufacturing system design using a holonistic approach", International Journal of production research, 2000, Vol. 38, No 10, 2327-2347.

Amell, T., Kumar, S., and Rosser, B., "Ergonomics, Loss management, and Occupational injury and Illness Surveilance. Part 2: Injury and Illness Incident Profile. Sample Data", International Journal of Industrial ergonomics, Vol 29, pp 199-210, 2002.

Amira, F., and Choobineh F., "Identifying the Composition of Cellular Manufacturing Systems". International Journal of Production Research. 1996, Vol. 34, No. 9, 2471-2488.

Anderson, C.K., Cha¦n, D.B., Herrin, G.D., Mathews, L.S., 1985. A biomechanical model of the lumbosacral joint during lifting activities. Journal of Biomechanics 18, 571-584.

Anderson, F. and Pandy, M., "Dynamic Optimization of Human Walking" Journal of Biomechanical Engineering OCTOBER 2001, Vol. 123 pp 381-390

Andersson, G., Posture and compressive spine loading: Intra-discal pressure, trunk myoelectrical activities, intra-abdominal pressures and biomechanical analysis, Ergonomics, 1985, 28, 91-93.

Aoyagi Y, Shephard R. "Ageing and muscle function". Sports Med 14:376-396. 1992.

Aquilano, N. A physiological evaluation of time standard for strenuous work. Industrial engineering, 1986, 37, 425-432.

Askin, R. G., and Chiu, K. S., "A Graph Partitioning Procedure for Machine Assignment and Cell Formation in Group Technology". International Journal of Operational Research. 1990, Vol. 28, N0, 8, 1555-1572.

Astrand, A. E. ,Hallbaeck P.O., Kilbom A E. "Reduction in maximal oxygen uptake with age". Journal of Applied Physiology, 35: 649-654, 1937

Astrand, P., Rodahl, K., Dahl, H., Stromme, S., Textbook of Work Physiology: Physioloical bases of exercise, Fourth edition, Trnscontinental, Canada, 2003

Astrand, I., Ryhming, I., "A nomogram for calculation of aerobic capacity (physical fitness) from pulse rate during submaximal work". Journal of Applied Physiology. 7, 1954, 218–221.

Astrand, I., 1960. "Aerobic work capacity in men and women with special reference to age". Acta Physiol. Scand. 49 (Suppl. 169), 45–60.

Attwood, D., deeb, J., Danz-reece, M., Ergonomic Solutions for the Process Industries, Elsevier, Burlington, MA, USA, 2004

Ayoub, M.M., 1987. The problem of manual material handling. In: Asfour, S.S. (Ed.), Trends in Ergonomics/Human Factors IV. North-Holland, New York.

Ayoub, M.M., McDaniel, J.W., 1974. Effects of operator stance on pushing and pulling tasks . Transactions of the American Institute of Industrial Engineers 6, 185-195

Balakrishnan, J., and Cheng, C. H., "Genetic Search and the Dynamic Layout Problem", Computer and Operations Research, 2000, No 27, 587-593.

Baril-Gingras, G., Lortie, M., 1995. The handling of objects other than boxes: Univariate analysis of handling techniques in a large transport company. Ergonomics 38 (5), 905-925.

Barsky I .and Dutta, S.P., (Cost assessment for ergonomic risk (KAFER)), International Journal of Industrial ergonomics, Vol 20, pp 307-315, 1997.**Bigos, S.J.,**

Bazargan-Lori, M. Keabernick, H, and Harraf, A.," Cell Formation and Layout Design in a Cellular Manufacturing Environment-a case study", International Journal of production research, 2000, Vol 38, No 7, 1689-1709.

Bazargan-Lori, M., " Layout design in cellular manufacturing", European journal of operational research 112 (1999) 258-272.

Beaulieu, A., Gharbi, A., and Ait-Kadi, "An Algorithm for the Cell Formation and the Machine Selection Problems in the Design of Cellular Manufacturing Systems". International Journal of Production Research. 1997, Vol. 35, No.7, 1857- 1874.
Beaulieu, A., Gharbi, A., and Ait-Kadi, "An Algorithm for the Cell Formation and the Machine Selection Problems in the Design of Cellular Manufacturing Systems". International Journal of Production Research. 1997, Vol. 35, No.7, 1857- 1874.
Bigos, S., Spengler, D., Martin, N., Back injuries in industry, A retrospective study. Spine, 1986, 11, 252-256.

Bobick, T. ,Belard, J. Hsiao, H. Wassell, T. "Physiological effects of back belt wearing during asymmetric lifting", Applied Ergonomics 32 (2001) 541–547

Boctor, F. I., "Minimum-Cost Machine -Part Cell Formulation Problem". International Journal of Production Research. 1996, Vol. 34, 1045-1063.
Journal of Production Research. 1996, Vol. 34, 1045-1063.
Borg, G. (1982). Psychophysical bases of perceived exertion. Medicine and Science in Sports and Exercise, 14, 377–381.

Brogmus, G.E., Sorock, G.S., Webster, B.S., 1996. Recent trends in work-related cumulative trauma disorders of the upper extremities in the United States: an evaluation of possible reasons. Journal of Occupational and Environmental Medicine 38 (4), 401-411.

Burbidge, J. L., and Halsall, J., "Group Technology and Growth at Shalibane". Production Planning & Control. 1994, Vol. 5, No. 2, 213-218.

Burdorf, A., Derksen, J., Naaktgeboren, B., van Riel, M., 1992. Measurement of trunk bending during work by direct observation and continuous measurement. Applied Ergonomics 23 (4), 263-267.

Burdorf, A., Govaert, G., Elders, L., 1991. Postural load and back pain of workers in the manufacturing of prefabricated concrete elements. Ergonomics 34 (7), 909-918

Burt, C., Henningsen, N. and Consedine, N., Promoting correct lifting posure using signs. Applied ergonomics, 1999, 30, 353-359

Canadian Centre for Occupational Health & Safety 1997-2005

Chaffin, D. Some effects of physical exertion. Industrial Ergonomics, 1982, 14, 24-29.

Chen, W., and Srivastava, B., "Simulated Annealing Procedures for Forming Machine Cells in Group Technology". European Journal of Operational Research. 1994, Vol. 75, No. 3, 100-111.

Choobineh, F. A., "Framework for the Design of Cellular Manufacturing Systems". International Journal of Operation Research. 1988, Vol. 26, N0. 7, 1161-1172.

Christensen, E.H.,: Physical working capacity of old workers and physiological background for work test and work evaluations.

Chung, M., Kee, D." Evaluation of lifting tasks frequently performed during "re brick manufacturing processes using NIOSH lifting equations" International Journal of Industrial Ergonomics 25 (2000) 423}433

Chung, M., Lee, I. , and Yeo, S. "Physiological workload evaluation of screw driving tasks in automobile assembly jobs" International Journal of Industrial Ergonomics 28 (2001) 181–188

Ciriello, V., Snook, S. "Survey of manual handling tasks "International Journal of Industrial Ergonomics 23 (1999) 149-156

Ciriello, V.M., Snook, S.H., 1983. A study of size, distance, height, and frequency effects on manual material handling tasks. Human Factors 25 (5), 473-483.

Ciriello, V.M., Snook, S.H., Hughes, G.J., 1993. Further studies of psychophysically determined maximum acceptable weights and forces. Human Factors 35 (1), 175-186.

Ciriello,V.M., Snook, S.H., Blick, A.C., and Wilkinson,P.L.,"The effect of task duration on psychophysically-determined maximum acceptable weights and forces", Ergonomics, 1990, Vol 33,no2, 187-200.

Dahl,N.E. and Smith, S.B., "Design flexibility into cellular manufacturing systems". International Journal of Production Research,1993, No. 31, 933-945.

Damlund, M., Goth, S., Hasle, P., Munk, K., 1986. Low back strain in Danish semi-skilled construction work. Applied Ergonomics 17 (1), 31-39.

De Zwart B, Frings-Dresen M, van Dijk F "Physical workload and the aging worker: a review of the literature". International Archive of Occupational and Environmental Health 68:1–12, 1995

Dehlin, O., Hedenrud, B., Horal, L., 1976. Backsymptoms in nursing aides in a geriatric hospital. Scandinavian. Journal of. Rehabilitating. Medecine. 8, 47–53.

Dempsey , P."A survey of lifting and lowering tasks" International Journal of Industrial Ergonomics 31 (2003) 11–16

Derksen, J.C.M., Van Riel, M.P.J.M., Van Wingerden, J.P., Snuders, C.J., 1994. A comparison of working postures of parcel sorters using three different working methods. Ergonomics 37 (2), 299*Ð*309.

Dimopoulos, C. and Mort, N., " A hierarchical clustering methodology based on genetic programming for the solution of simple cell-formation problem", International journal of production research, 2001, Vol 39,No 1, 1-19.

Drury, C., & Pfeil, R.E. (1975). A task-based model of manual lifting performance. International Journal of Production Research, 13, 137–148.

Drury, C.G., Law, C., Pawenski, C.S., 1982. A survey of industrial box handling. Human Factors 24 (5), 553-565.

Edholm, O.G., The Biology of Work, McGraw Hill , New York, 1967.

Era P. "Determinants of isometric muscle strength in men of different ages". Journal of Applied Physiology 64:84-91, 1992

Escoto, R. P., McDonnell, R. L., Salort, E. V., and Esteban F. C., "Development of an Algorithm for the Application of Group Technology in the Design of Manufacturing Systems". Production Planning & Control. 1998, Vol. 9, No.3, 267- 274.

Evans, E. ,MRacette, . S. B. , Peterson, L. R. , Villareal, D. T. , Greiwe, J. S. , and Holloszy, J. O., Aerobic power and insulin action improve in response to endurance exercise training in healthy 77-87 yr old. Journal of Applied Physiology, January 1, 2005; 98(1): 40 - 45.

Fernandez, J.E., Ayoub, M.M., Smith, J.L., 1991. Psychophysical lifting capacity over extended periods. Ergonomics 34, 23–32.

Ford E., Merritt R., Heath G., Powell K., Washburn R., Kriska A, Haile G. "Physical activity behaviors in lower and higher socioeconomic populations". American Journal of Epidemiology 133:1246-1256, 1991

Fothergill, D.M., Grieve, D.W., Pheasant, S.T., 1991. Human strength capabilities during one-handed maximum voluntary exertion in the fore and aft plane. Ergonomics 34,563-573.

Freivalds, A., Cha¦n, D.B., Garg, A., Lee, K.S., 1984. A dynamic biomechanical evaluation of lifting maximum acceptable loads. Journal of Biomechanics 17, 251-262.

Frontera , W., Hughes V., Lutz K., Evans W. "A cross-sectional study of muscle strength and mass in 45 to 78-yr-old men and women". Journal of Applied Physiology 71:644-650, 1991

Gamberale, F., Ljungberg, A.S., Annwall, G., Kilbom, A., 1987. An experimental evaluation of psychophysical criteria for repetitive lifting work. Applied. Ergonomics. 18, 311–321.

Garg, A., Methods for estimating physical fatigue, 1989, Proceedings **of** AIIE Conference, San Francisco, CA, USA, 68-75.

Garg, A., and Herrin, G., Stoop and Squat: a biomechanical and metabolic evaluation. AIIE transactions, 1979, 11, 293-302.

Garg, A., Chaffin, D.B., Herrin, G.D., 1978. Prediction of metabolic rates for manual handling jobs. American Industrial Hygiene Association Journal 39, 661-674.

Garg, A., Saxena, U., 1982. Maximum frequency acceptable to female workers for one-handed lifts in the horizontal plane. Ergonomics 25, 839–853.

Genaidy, A., Al-Shedi, A., and Karwowski, W., Postural stress analysis. Applied Ergonomics, 1994,25, 77-87

Gleerups, Lund. Cha¦n, D.B., 1974. Human strength capability and low-back pain. Journal of Occupational Medicine. 16, 248-254.

Government of Canada, "Canadian Standardized Test of Fitness (CSTF): Operations Manual", Third edition, 1987

Grandjean E "Fitting the task to the man". A textbook ofoccupational ergonomics, 4th edn. Taylor and Francis, London, pp 92–99, 1988

Guidotti, T., "Occupational Injuries in Alberta: responding to recent trends", Occupational Medicine, Vol 45, No 2, 81-88, 1995

Gunasingh, K. R., and Lashkari, R. S., "The Cell Formation Problem in Cellular Manufacturing System: a Sequential Modelling Approach". Computers in Engineering. 1989, Vol. 16, No. 4, 469-476.

Gupta,Y., Gupta, M., Kumar, A. and Sundaram, C.," A genetic algorithm-based approach to cell composition and layout design problems". International Journal of Production Research,1996, No. 34, 447-482.

Hagberg, M "Exposure variables in ergonomic epidemiology". American Journal of Industrial Medecine 21, 1992,:91–100

Haldeman, G., selected biomechanical assessment of lifting known and unknown loads.

Hallqvist J, Moller J, Ahlbom A, Diderichsen F, Reuterwall C, de Faire U."Does heavy physical exertion trigger myocardial infarction? A case-crossover analysis nested in a population based case-referent study" . American Journal of Epidemiology 151(5), 2000, 459–467

Han, G., and Ham. I., "Multiobjective Cluster Analysis for Part Family Formation". Journal of Manufacturing Systems. 1986, Vol. 5, No, 4, 223-230.

Havenith, G.; Van Middendorp, H.: The Relative Influence of Physical Fitness, Acclimatization State, Anthropometric Measures and Gender on Individual Reactions to Heat Stress. European Journal of Applied Physiology 61(5-6):419–427 (1990).

Havenith, G.V.; Luttikholt, G.; Vrijkotte, T.G.: The Relative Influence of Body Characteristics on Humid Heat Stress Response. European Journal of Applied Physiology. 70(3):270–279 (1995).

Heikkinen, A., Polari, J., Louhevaara, V., "Job demands, strain and work ability of elderly and young construction workers. In: Noy, I. et al. (Eds.)", Proceedings of the 12th Triennial Congress of the International Ergonomics Association, vol. 6: general Issues, University Press, Toronto, 1994, pp. 159-160.

Helander, M., and Burri, G., "Cost Effectiveness of Ergonomics and Quality Improvements in Electronics Manufacturing" International Journal of Industrial Ergonomics, 15, 137-155,1995

Heragu, S. S. and Gupta, Y. P., "A Heuristic for Design Cellular Manufacturing Facilities". International Journal of Production Research. 1994, Vol. 32, No. 1, 125-140.

Heragu, S. S., "Group Technology and Cellular Manufacturing". IEEE Transactions on Systems, Man, and Cybernetics. 1994, Vol. 24, No. 2, 203-215.

Hidalgo, J., Genaidy, A., Karwowski, W., Christensen, D., Huston, R., & Stambough, J. (1997). A comprehensive lifting model: Beyond the NIOSH lifting equation. Ergonomics, 40, 916–927.

Ho, Y.C. and Moodlie, C.L.," Solving cell formation problems in a manufacturing environment with flexible processing and routing capabilities. composition and layout design problems". International Journal of Production Research,1996, No. 34, 2901-2923.

Hoonyong Y., James L. S "Psychophysical and physiological study of one-handed and two-handed combined tasks "International Journal of Industrial Ergonomics 24 (1999) 49-60

Houdas, Y.; Ring, E.F.J.: Human Body Temperature, pp. 83. Plenum Press, New York (1982).

Hsiang, S.M., Ayoub, M.M., 1994. Development of methodology in biomechanical simulation of manual lifting. International Journal of Industrial Ergonomics 13, 271-288.

Hwang, H., and Ree P. "Routes Selection for the Cell Formation Problem with Alternative Part Process Plans". Computer and Industrial Engineering. 1996, Vol. 30, No. 3, 423-431.

Hwang, H., and Sun J., "A Genetic Algorithm-Based Heuristic for the GT Cell Formation Problem". Computer and Industrial Engineering. 1996, Vol. 30, No. 4, 941-955.

Ilmarinen J. "Job design for the aged with regard to decline in their maximal aerobic capacity: Part I. Guidelines for the practitioner". International Journal of Industrial Ergonomics 10:53–63, 1992

Ilmarinen, J. " Job design for the aged with regard to decline in their maximal aerobic capacity: Part 2. The scientific basis for the guide". International Journal of Industrial Ergonomics 10:65–77, 1992

Islam, K., and Sarker, B., "A Similarity Coefficient Measure and Machine-parts Grouping in Cellular Manufacturing Systems", International Journal of production research, 2000, Vol 38, No 3, 699-720.

Jager,M., Luttmann, A." Critical survey on the biomechanical criterion

Jiang, B.C, .Smith, J.L. and Ayoub, M.M.,"Psychophysical modeling for combined manual material handling activities, Ergonomics, 29,1179-1190, 1986,

Joines, A. J., Culbreth, T. C., and King E. R., "Manufacturing Cell Design: an Integer Programming Model Employing Genetic Algorithms". IIE Transactions. 1996, 28, 69-85.

Jorgensen K "Permissible loads based on energy expenditure measurements". Ergonomics 28:365–369, 1985

Josephson, M., Hagberg, M., & Hjelm, E.W. (1996). Self-reported physical exertion in geriatric care. A risk indicator for low back symptoms? Spine, 21, 2781–2785

Kant, I., Notermans, J.H.V., Borm, P.J.A., 1990. Observations of working postures in garages using the Ovako Working Posture Analyzing System (OWAS) and consequent workload reduction recommendations. Ergonomics 33 (2), 209-220.

Karl, H. and Kroemer, E. 1997, Ergonomic Design of Material Handling Systems, CRC Press, Boca Raton, NY.

Karl, H. and Kroemer, E. 1997, Ergonomic Design of Material Handling Systems, CRC Press, Boca Raton, NY.

Karlqvist ,L., Leijon ,O., and Ha renstam A. "Physical demands in working life and individual physical capacity" European Journal of Applied Physiology (2003) 89: 536–547

Karwowski, W., & Ayoub, M.M. (1984). Fuzzy modelling of stresses in manual lifting tasks. Ergonomics, 27, 641– 649.

Karwowski, W., Vilkki, M., 1993. Analysis of working postures in hammering tasks on building construction sites using the computerized OWAS method. Applied Ergonomics 24 (6), 405-412.

Karwowski,W., Mulholland, N.O.,Ward, T.L., Jaganathan, V., & Kirchner, Jr. (1986). LIFTAN: An experimental expert system for analysis of manual lifting tasks. Ergonomics, 29, 1213–1224.

Kemper, H.C.G., van Aalst, R., Leegwater, A., Maas, S., Knibbe, J.J., 1990. The physical and physiological workload of refuse collectors. Ergonomics 33 (2), 1471-1486.

Kivi, P., Mattila, M., 1991. Analysis and improvement of work postures in the building industry: Application of the computerized OWAS method. Applied Ergonomics 22 (1), 43-48.

Kroemer, K.H. Personal training for safer material handling. Ergonomics, 1990,35, 1119-1134.

Kuorinka, I., 1994. Manual handling in warehouses: The illusion of correct working postures. Ergonomics 37 (4), 655-661.

Kusiak, A. and Cho, M., "Similarity Coefficient Algorithms for Solving the Group Technology Problem". International Journal of Production Research. 1992, Vol. 30, No. 11, 2633-2646.

Lavender, S., Andersson, G., Schipplein, O. Fuentes , H."The effects of initial lifting height, load magnitude, and lifting speed on the peak dynamic L5/S1 moments" International Journal of Industrial Ergonomics 31 (2003) 51–59

Leamon, T., Murphy, P.L., 1995. Occupational slips and falls: more than a trivial problem. Ergonomics 38 (3), 487-498.

Lee, H., and Garcia-Diaz, A., "A Network Procedure for the Analysis of Cellular Manufacturing Systems". IIE Transactions. 1996, 28, 333-345.

Lee, S.D. and Chen, Y. L.,"A approach for cellular manufacturing design: minimizing inter-cell movements and balancing workload among duplicated machines". International Journal of Production Research,1997, No. 35, 1125-1146.

Lee-Post, A."Part Family Identification Using a Simple Genetic Algorithm", International Journal of production research, 2000, Vol 38, No 4, 793-810.

Leigh, J. P., Cone, J.E., and Harrison, R.H., "Costs of Occupational Injuries and Illnesses in California" Preventaive Medicine, Vol 32, pp 393-406, 2001.

Levushkin S.P.,"A Broad-Based Estimation of the Physical Work Capacity of Young Men' Human Physiology, Vol. 27, No. 5, 2001, pp. 568–575.

Lewis R., M. Krawiec, E. Confer, D. Agopsowicz, and E. Crandall, " Musculoskeletal disorder worker compensation costs and injuries before and after an office ergonomics program", International Journal of Industrial ergonomics, Vol 29, pp 95-99, 2002.

lhammar, H.R., Leskinen, T.P.J., Kuorinka, I.A.A., Gautreau, M.H.J., Troup, J.D.G., 1986. Postural, epidemiological and biomechanical analysis of luggage handling in an aircraft luggage compartment. Applied Ergonomics 17 (3), 177-183.

Liang, M. and Taboun. S. M.," Converting functional manufacturing systems into focused machine cells : a bi-criteria approach". International Journal of Production Research, 1995, No. 33, 2147-2161.

Liang, M., and Taboun S. M., "Converting Functional Manufacturing Systems Focused Machine Cells: a Bicriterion Approach". International Journal of Production Research. 1995, Vol. 33, No. 8, 2147-2161.

Lin, L. T., Dessouky, M. M., Kumam, R. K., and Ng M. S., "A Heuristic-Based Procedure for The Weighted Production-Cell Formation Problem". IIE Transactions. 1996, 28, 579-589.

Ljungberg, A., Kilbom, A_ ., Haag, G.M., 1989. Occupational lifting by nursing aides and warehouse workers. Ergonomics 32 (1), 59-78.

Logendran, R., A "Binary Integer Programming Approach for Simultaneous Machine-Part Grouping in Cellular Manufacturing Systems". Computers and Industrial Engineering. 1993, Vol. 24, No. 3, 329-336.

Lohmann, T.G., Roche, A.F., Martorell, R., 1991. Anthropometric Standardization Reference Manual, Abridged ed. Human Kinetics Books, Champaign, IL

Loree L. Weir J. Housh J. " Effect of an aerobic training program on physical working capacity at heart". European Journal Applied Physiology (1997) 75: 351-356.

Louhevaara, V., Heikkinen, A., Polari, J., Korhonen, O., 1998."Older versus younger construction workers: Physical work load, strain, "fitness and work ability. In: Ilmarinen, J., Louhevaara, V. (Eds.), Respect for the Ageing } Finn Age Programme 1991}1996: Summary, Finnish Institute of Occupational Health, Helsinki (in press).

Louhevaara,V.,"Is the physical work load equal for ageing and young blue-collar workers?" *International Journal of Industrial Ergonomics 24 (1999) 559}564*

Luczak, H., & Ge, S. (1989). Fuzzy modeling of relations between physical weight and perceived heaviness: The effect of size-weight illusion in industrial lifting tasks. Ergonomics, 32, 823–837.

Luopaj.arvi, T., Nygard, C.-H., Mattila, M., Kulha, K., H.anninen, E.,"From Experience to Innovation". IEA '97. proceedings of the 13th Triennial Congress of the International Ergonomics Association, Tampere, Finland 1997. Finnish Institute of Occupational Health, Helsinki, pp. 536–538

Lusa S, Louhevaara V, Kinnunen K. "Are the job demands on physical work capacity equal for young and aging fire fighters? Journal of Occupational Medecine 36:70-74, 1994

Magora, A., 1970. Investigation of the relationship between low back pain and occupation. Ind. Med. Surg. 39, 504–510.

Mansouri, S. A., Husseini, S. A., and Newman, S. T.,"A review of the modern approaches to multi-criteria cell design", International Journal of production research, 2000, No. 38, no 5, 1201-1218.

Marras, W., Karwowski, W., Sm8th, J., and Pacholski, L., The ergonomics of manual work, Taylor and Francis, Washington, D.C. USA. 1993

Martin, N.A., Zeh, J., Fisher, L., Nachemson, A., Wang, M.H., 1986. Back injuries in industry: a retrospective study: II. Injury factors. Spine 2, 246-251.

McCarter R. "Age-related changes in skeletal muscle function". Aging 27-38, 1990

Miettinen, M.and Louhevaara, V., "Job demands, physical fitness, work ability, and age of vehicle inspectors". International Journal of Industrial Ergonomics 13,194, 337-342.

Miller T. R. and Galbraith, M.,"Estimating the costs of occupational Injury in the United States", Accident analysis and Prevention, Vol 37, N0. 6, pp741-744, 1995.

Miller, T. "Estimating the Costs of Injury to U.S. Employers". Journal of Safety Research, Vol 28, No. 1, pp 1-13, 1997.

Min, H. and Shin, D.," Simultaneous formation of machine and human cell in grouptechnology: a multiple objective approach". International Journal of Production Research,1993, No. 31, 2307-2318.

Mital, A. , Ramakrishnan, A. "A comparison of literature-based design recommendations and experimental capability data for a complex manual materials handling activity" International Journal of Industrial Ergonomics 24 (1999) 73-80

Mital, A., Garg, A., Karwowski, W., Smith, J. , and Ayoub, M. , Status in Human Strength Research and Application. IIE Transactions, 1993, No 25, 57-69.
Mital, A., Garg, A., Karwowski, W., Smith, J. , and Ayoub, M. , Status in Human Strength Research and Application. IIE Transactions, 1993, No 25, 57-69.
Mital, A., Manivasagan, I., 1983. Subjective estimates of one-handed carrying tasks. Applied Ergonomics 14, 265-269.

Mital, A., Maximum weight of lift acceptable to male and female industrial workers for extended work shifts, Ergonomics, 1984,27, 1115-11126

Mital, A., Nicholson, A.S., Ayoub, M.M., 1997. A Guide to Manual Materials Handling. 2nd ed., Taylor & Francis, London, UK.

Mital, A., The psychological approach in manual lifting; a verification study. Human Factors, 1983, 25, 485-491

Moon, C., and Kim, J. "Genetic algorithm for maximizing the parts flow within cells in manufacturing cell design, Computers and Industrial Engineering", 1999, N. 36, 379-389.

Morrissey, S.J. and Liou, Y.H.,"Maximum acceptable weight in load carriage," Ergonomics, 31,217-226, 1988

Morrissey, S.J., Liou, Y.H., 1988. Maximum acceptable weights in load carriage. Ergonomics 31, 217-226.**Nicholson, L.M., Legg, S.J.**, 1986. A psychophysical study of the effects of load and frequency upon selection of workload in repetitive lifting. Ergonomics 29, 903–911.**Mattila,**

Murphy, P.L., Sorock, G.S., Courtney, T.K., Webster, B.S., Leamon, T.B., 1996. Injury and illness in the American workplace: a comparison of data sources. American Journal

National Research Council (Canada), Indoor Air Quality and Thermal Comfort in Open-Plan Offices, Construction Technology Update No. 64 , October 2005 http://irc.nrc-cnrc.gc.ca/pubs/ctus/64_e.html

Nelson, R, Prevention: a government perspective. Ergonomics, . 1987,30, 221-226

Nygard C-H, LuopajaErvi T, Cedercreutz G, Ilmarinen J. "Musculoskeletal capacity of employees aged 44-58 years in physical, mental and mixed types of work." Journal of Applied Physiology 56:555-561, 1987

Nygard, C-H., Kilbom, A., Hjelm, E.W., Winkel, J., "Life-time occupational exposure to heavy work and individual physical capacity". . International Journal of Industrial Ergonomics 14, 1994, 365–372.

Oborne, D., Ergonomics at Work: humanfators in design and development, 3rd edition,John Wiley & sons, Chichester, England, 1995

Okogba, G. O., Chen, M. T., Changchit, C. and Sell, R. L., "Manufacturing System Cell Formation and Evaluation Using a New Inter-cell Flow Reduction Heuristic". International Journal of Production Research. 1992, Vol. 30, 1101-1118.

Onwubolu, G. C. and Mutingi, M., " A genetic algorithm approach to cellular manufacturing systems", Computers and industrial Engineering, 39 (2001), 125-144.

Ott, S. and Jones, K. " Cellular Manufactring: One-piece Flw Workteams", Productivity Press, Portland, OR, 1999.

Ozdemir. A., "Simultaneous part family and machine Cell Formation in Cellular Manufacturing System: An Analytical and Algorithmic Approach", Masters Degree Thesis, 1995, 35-45.

Plonka, F., "Developing a lean and Agile Work Force", Human Factors and Ergonomics in manufacturing, Vol 7, No 1, 11-20, 1997

Punnett, L. , Finr, I., Keyserling, W., Herrin, G., Chaffin, D., Back disorders and non-neutral trunk postures of automobile assembly workers. Scandinavian Journal of Work Environment and Health, 1991, No17, 337-346.

Punnett, L. , Finr, I., Keyserling, W., Herrin, G., Chaffin, D., Back disorders and non-neutral trunk postures of automobile assembly workers. Scandinavian Journal of Work Environment and Health, 1991, No17, 337-346.

Rajamani, D., Singh, N., and Aneja, Y. P., "Integrated Design of Cellular Manufacturing Systems in the Presence of Alternative Process Plans". International Journal of Production Research. 1990, Vol. 28, No, 8, 1541-1554.

Rajamani, D., Singh, N., and Aneja, Y.P.," Design of cellular manufacturing systems". International Journal of Production Research,1996, No. 34, 1917-1928.

Rantanen T, Parkatti T, Heikkinen E. "Muscle strength according to level of physical exercise and educational background in middle-aged women in Finland". European Journal of Applied Physiology 65:507±512, 1992

Rantanen T, Parkatti T, Heikkinen E. "Muscle strength according to level of physical exercise and ducational backgroundin middle-aged women in Finland". European Journal of Applied Physiology 65:507–512, 1992

Rasanen, K., Notkola, V., & Husman, K. (1997). Perceived work conditions and work-related symptoms among employed Finns. Social Science & Medicine, 45(7), 1099–1110.

Resnick, M., and Zanotti, A., "Using Ergonomics to Target Productivity Improvements", Computers and Industrial Engineering, Vol 33, No 1-2, 185-188, 1997

Rohmert, W., 1985. AET-a new job-analysis method. Ergonomics 28 (1), 245-254

Salum, L., "The Cellular Manufacturing Layout Problem", International Journal of production research, 2000, Vol 38, No 5, 1053-1069.

Sankaran, S., and Kasilingam, R. G., "On Cell Size and Machine Requirments Planning in Group Technology Systems". European Journal of Operational Research. 1993, Vol. 69, 373-383.

Sankaran, S.," Multiple objective decision making approach to cell formation: a goal programming model". Mathematical and computer Modeling,1990, No. 13, 71-81.

Sarker, B. R., and Saiful Islam, K., "Relative Performance of Similarity and Dissimilarity Measures", Computers and Industrial Engineering, 2000, Vol 37, 769-807.

Schibye B, Hansen A., Søgaard K., Christensen H 'Aerobic power and muscle strength among young and elderly workers with and without demanding work tasks". Applied Ergonomics 32:425–431,2001**Shephard, R.**, 1991, Biological Anthropology, Cambridge University Press.

Schibye, B., Christensen, H., "The work load during waste collection and meat cutting among workers in different age groups". Arbete och H.alsa 29,1997, 272–278.

Schibye, B., van Lelieveld, D., " Cardiovascular load during waste collection in Denmark". PREMUS Book of abstracts, 1995, pp. 235–237.

Schmidt-Nielsen, K.: Animal Physiology: Adaptation and Environment, p.265. Cambridge University Press, London (1983).

Schult, A.B., Andersson, G.B.J., Haderspeck, K., Ortengren, R., Nordin, M., Bjork, R., 1982. Analysis and measurement of lumbar trunk loads in tasks involving bends and twists. Journal of Biomechanics 15, 669-675.

Seifoddini, H., "Duplication Process in Machine Cells Formation in Group Technology". IIE Transactions. 1989, 21, 382-388.

Shafer, S. M., and Rogers, D. F., "Similarity and Distance Measures for Cellular Manufacturing. Part II. An Extension and Comparison". International Journal of Production Research. 1993, Vol. 31, No. 6, 1315-1326.

Shafer, S.M. and Rogers, D.F.,"A goal programming approach to the cell formation problem". Journal of Operations Management,1991, No. 10, 28-43.

Shephard, R., 1991, Biological Anthropology, Cambridge University Press.

Snook, S. , " Manual Material handling: Understanding and preventing back trauma". American Industrial Hygiene Association, Arkon, Ohio, USA. 1989

Snook, S.H. and Ciriello, V.M. ," The design of manual material handling tasks: revised tables of maximum acceptable weights and forces", Ergonomics, vol 34, No. 9, 1197-1213. 1991.

Snook, S.H., 1978. The design of manual handling tasks. Ergonomics 21, 963–985.

Snook, S.H., Campanelli, R.A., Hart, J.W., 1978. A study of three preventive approaches to low back pain. Journal of Occupational Medicine 20 (7), 478-481.

Snook, S.H., Ciriello, V.M., 1991. The design of manual handling tasks: revised tables of maximum acceptable weights and forces. Ergonomics 34, 1197-1213.

Snook, S.H., Irvine, C.H., 1968. Maximum frequency of lift acceptable to male industrial workers. American. Industrial. Hygiene. Association. Journal. 29, 531–536.

Spengler, D.M., Bemben, G., Massey, B., Bemben ,A ., Misner, J., and Boileau, R.. "Isometric muscle force production as a function of age in healthy 20- to 74- yr-old men". Med Sci Sports Exerc 23:1302-1310, 1991

Steudel, H. J. and Ballakur, A., "A Dynamic Programming Based Heuristic for Machine Grouping in Manufacturing Cell Formation". Computers and Industrial Engineering. 1987, 12, 215-222.

Su, C.-T., and Hsu, C.-M., "Multi-Objective Machine-Part Cell Formation Through Parallel Simulated Annealing". International Journal of Production research. 1998, Vol. 36, No. 8, 2185-2207.

Suresh, N.C., Slomp, J., and Kaparathi, S.," The capacitated cell formation problem: a new hierarchical methodology". International Journal of Production Research, 1995, No. 33, 1761-1784.

Taboun S. M., Merchawi N. S., and Ulger, T., "Two-stage Model for Cost Effective Part Family and Machine Cell Formation". Computer and Industrial Engineering. 1998a, Vol. 34, No.4, 759-776.

Torgen M, Punnett L, Alfredsson L, Kilbom A. "Physical capacity in relation to present and past physical load at work: A study of 484 men and women aged 41 to 58 years". American Journal of Industrial Medecine 36:388–400,1999

Torner, M., Blide, G., Eriksson, H., Kadefors, R., Karksson, R., Petersen, I., 1988. Workload and ergonomics measures in Swedish professional pushing. Applied Ergonomics 19 (3), 202-212.

Tzu-Hsien Lee "Minimal acceptable handling time intervals for lifting and lowering tasks "Applied Ergonomics 34 (2003) 629–634

Valencia, ME., McNeill, G., Brockway, JM., Smith, JS., The effect of environmental temperature and humidity on 24 h energy expenditure in men, British Journal of Nutrition, 1987 Nov 58(3) 347-356

Van der Beek A, Frings-Dresen M, Van Dijk F, Kemper H, Meijman T. " Loading and unloading by lorry drivers and musculoskeletal complaints". International Journal of Industrial Ergonomics 12:13-23, 1993

Veeramani, D., and Mani K., "A Polynomial-Time Algorithm for Optimal Clustering in a Special Class of {0,1} Matrices". International Journal of Production Research. 1996, Vol. 34, No. 9, 2587-2611.

Venugpoal, V., and Narendran T. T., "A Genetic Algorithm Approach to the Machine-Component Grouping Problem with Multiple Objectives". Computers and Industrial Engineering. 1992a, Vol. 22, No, 4, 469-480.

Venugpoal, V., and Narendran T. T., "Cell Formation in Manufacturing Systems through Simulated Annealing: an Experimental Evaluation". European Journal of

Operational Research. 1992b, Vol. 63, 409-422.

Vink, P., 1992. Application problems of a biomechanical model in improving roof work. Applied Ergonomics 23 (3), 177-204.

Waghodeka, P. H., and Sahu, S., "Machine-Component Cell Formation in Group Technology: MACE". International Journal of Production Research. 1984, Vol. 22, No. 6, 937-948.

Wagner, R., 1985. Job analysis at ARBED. Ergonomics 28 (1), 255-273.

Waikar, A., Lee, K., Aghazadeh, F., Parks, C., 1991. Evaluating lifting tasks using subjective and biomechanical estimates of stress at the lower back. Ergonomics 34 (1), 33-47.

Wang, J., and Roze, C., "Formation of Machine Cells and Part Families: a Modified P-Median Model and a Comparative study". International Journal of Production Research. 1997, Vol. 35, No.5, 1259- 1286.

Wang, M.J., Garg, A., Chang, Y., Shih, Y., Yeh,W., and Lee C. (1998). The relationship between low back discomfort ratings and the NIOSH lifting index. Human Factors, 40(3), 509–515.

Warwick, D., Novak, G., Schultz, A., Berkson, M., 1980. Maximum voluntary strengths of male adults in some lifting, pushing, and pulling activities. Ergonomics 23, 49-54.

Waters, T.R., Putz-Anderson, V., Garg, A., Fine, L.J., 1993. Revised NIOSH equation for the design and evaluation of manual lifting tasks. Ergonomics 36 (7), 749-776.

WCB report, in ergonomics and Injury Prevention. Course notes, department of Kinesiology, university of windsor, 1997

Webster, B.S., Snook, S.H., 1994. The cost of 1989 Workers, O. Compensation low back pain claims. Spine 19 (10), 1111-1116.

Wei,J.C. and Gaither, N.,"A capacity constrained multi-objective cell formation method". Journal of Manufacturing Systems,1990, No. 9, 222-232.

Weibel, E.R., "Understanding the limitation of O2 supply through comparative physiology" Respiration Physiology 118 (1999) 85–93

Wigaeus, E, Winkel, J., Nygard C., Wiktorin C, Karlqvist L," Can cardiovascular load in ergonomic epidemiology be estimated by self-report?" Journal of Occupational and Environmental Medecine 10:1210–1217, 1995

Winkel, J., Mathiassen, S.E., 1994. Assessment of physical work load in epidemiologic studies: Concepts, issues and operational considerations. Ergonomics 37 (6), 979-988.

Woodson, W., Tillman, B., Tillman, P., Human Factors Design Handbook, 2nd edition, Mcgraw Hill, Inc, New York, USA,1992

Won, Y., "Two-phase approach to GT cell formation using efficient *p*-median formulations", International Journal of production research, 2000, Vol 38, No 38,1601-1613.

www.ccohs.ca/oshanswers/phys_agents/thermal_comfort.html

Yasuda, K. and Yin, Y., "A dissimilarity measure for solving the cell formation problem in cellular manufacturing", Computers and industrial engineering, 39 (2001) 1-17.

Yates, J.W., Kamon, E., Rodgers, S.H., Champney, P.C., 1980. Static lifting strength and maximal isometric voluntary contractions of back, arm and shoulder muscle. Ergonomics 23, 37-47.

Yeung , S. ,. Genaidy, A. and Karwowski, R "An Expert Cognitive Approach to Evaluate Physical Effort and Injury Risk in Manual Lifting—A Brief Report of a Pilot Study" Human Factors and Ergonomics in Manufacturing, Vol. 12 (2) 227–234 (2002)

Yew, P., and Sen, R., "Quality, Productivity, Occupational Health and Safety and Cost Effectiveness of Ergonomics Improvements in the Test Workstations of an Electronic factory", International Journal of Industrial Ergonomics, 32, 147-163, 2003

Zhao, C., and Wu, Z., "Ageneric Algorithm for Manufacturing cell formation with multiple routes and multiple objectives", International Journal of production research, 2000, No. 38, no 2, 385-395.

Appendix A

Data Tables

Stepwise Regression data table for the male 95th percentile

Vo_2max	Weight	Height	Age
62	86	191	16.5
59	96	191	24.5
51	100	190	34.5
44	101	190	44.5
40	97	190	54.5
32	101	188	64.5

Stepwise Regression data table for the female 95th percentile

Vo_2max	Weight	Height	Age
45	74	175	16.5
43	74	175	24.5
39	82	175	34.5
36	86	175	44.5
31	87	174	54.5
26	85	174	64.5

Stepwise Regression data table for the male 75th percentile

Vo_2	Weight	Height	Age
59	73	183	16.5
55	80	184	24.5
47	85	183	34.5
41	86	181	44.5
37	85	180	54.5
29	85	175	64.5

Stepwise Regression data table for the female 75th percentile

Vo2	Weight	Height	Age
41	62	170	16.5
39	62	170	24.5
36	67	169	34.5
33	70	169	44.5
28	71	168	54.5
24	70	165	64.5

Stepwise Regression data table for the male 50th percentile

Vo_2	Weight	Height	Age
56	66	174	16.5
43	73	176	24.5
43	76	174	34.5
38	78	172	44.5
34	78	172	54.5
28	77	170	64.5

Stepwise Regression data table for the female 50th percentile

Vo2	Weight	Height	Age
38	56	163	16.5
35	56	163	24.5
32	59	162	34.5
28	62	162	44.5
26	64	160	54.5
22	62	156	64.5

Stepwise Regression data table for the male 5th percentile

Vo_2	Weight	Height	Age
40	52	161	16.5
37	57	161	24.5
33	58	161	34.5
29	60	161	44.5
24	60	161	54.5
23	62	160	64.5

Stepwise Regression data table for the female 5th percentile

Vo2	Weight	Height	Age
32	44	146	16.5
29	45	146	24.5
27	47	146	34.5
21	49	146	44.5
19	50	145	54.5
17	50	145	64.5

Appendix C

List of Some Ergonomics Software

Software	Description
Vision 3000	Video-based system for upper and lower body posture analysis and biomechanical lifting assessments
OCS TOOLS	Video-based time and motion study system
3D	Static strength prediction program
Jack	Human factors design tool for use with CAD systems
LifTrak	Determines lumbar isometric compression forces during lifting, pushing, pulling, and sitting down activities and compares to NIOSH lifting standard
Micro Saint Animation simulation software	Manpower estimation and performance prediction
Dynalift	Calculates L5/S1 shear and compression forces at joint for lifting tasks
Manual material handling	Determines psychophysical and NIOSH calculated load limits for manual material tasks, as well predicting individual capacity
2D Static Strength Prediction Program	Predicts human static strength requirements of manual material handling tasks

VITA AUCTORIS

Name:	Ali I. Mohamed
Place of Birth:	Brack, Libya
Data of Birth:	November 11, 1957
Education:	University of Garyounis, Benghazi, Libya 1976-1982 B.Sc. – Industrial Engineering
	University of Waterloo, Waterloo, Ontario, Canada 1990-1993 M.A. Sc. – Management Science
	University of Windsor, Windsor, Ontario, Canada 1993-1996 M.A. Sc. – Industrial Engineering
	University of Windsor, Windsor, Ontario, Canada 2000-2006 Ph.D. – Industrial and Manufacturing Systems Engineering