UNIVERSITÀ DELLA CALABRIA
DIPARTIMENTO di MECCANICA

DOTTORATO DI RICERCA IN INGEGNERIA MECCANICA

CICLO XXIII (2007-2010)

(INDUSTRIAL AND MECHANICAL PLANT): ING-IND/17

Workplace Design Methodology based on Modeling & Simulation

A Dissertation submitted in partial fulfilment of the requirements for the
Doctoral Research degree in Mechanical Engineering

Doctoral Research Director
Prof. Sergio Rizzuti
Sergio Rizzuti

Supervisor
Dr. Francesco Longo
Francesco Longo

Candidate
Dr. Antonio Cimino
Antonio Cimino

Index

Introduction

This thesis presents the results of the activities carried out over the three years PhD course at the Mechanical Department of the University of Calabria (Italy), Industrial Engineering Section. The PhD course focuses on the Effective Design of Industrial Workplace by using advanced investigation approaches based on Modeling & Simulation. The first step of the PhD course was to correctly define the research area: after an initial pre-screening of the literature and according to the ongoing research activities at the Modeling & Simulation Center – Laboratory of Enterprise Solutions (MSC-LES, at Mechanical Department of University of Calabria) it was decided to focus on the development of a methodology for effectively designing industrial workplaces.

The PhD thesis focuses on the development of a multi-measure based methodology that can be used by industrial engineers for achieving the effective design of workplaces within industrial environments. The design methodology is based on multiple design parameters and multiple performance measures and aims at considering both the interaction of the operators with their working environment (ergonomic issues) and the work methods (time issues). Such methodology must take into account all the design parameters affecting the performance measures related to work measurement and ergonomics. However an industrial workplace is a quite complex system characterized by different design parameters (i.e. objects dimensions, tools position, operator work methods). As a consequence, the design methodology has to be supported by an approach capable of recreating the complexity of a real industrial workplaces. To this end, Modeling & Simulation (M&S) tools are used for recreating, with satisfactory accuracy, the evolution over the time of the real industrial workplaces. Moreover, simulation can be jointly used with virtual three-dimensional environments in which observe the system and detect ergonomic and work measurement problems that otherwise could be difficult to detect. The 3D simulation model of the industrial workplaces is used for investigating and comparing different workplaces configurations in terms of workplaces layout, tools disposition, and alternative operators' work methods. The generation of the alternative configurations comes out from the variation of multiple design parameters that affect multiple performance measures (ergonomic and time performance measures). The evaluation of the effects of the multiple design parameters on the multiple performance measures allows to choose the final configuration of the workplace.

The PhD course has been subdivided into three parts: review of the state of the art, training and research activities.

An accurate review of the state of the art was carried out in the area of Effective Workplace Design: all the academic books, international journals articles and conference proceedings articles reported in the bibliography (and cited within each chapter) have been read, deeply analyzed and discussed. Chapter 1 briefly summarizes the core of the research topics related to this PhD thesis. Herein the basic industrial engineering tools, methods, and procedures related to work measurement and time standards as well as manufacturing ergonomics and workplace design application areas are presented. Chapter 2 provides the reader with an accurate overview on methodologies and scientific approaches proposed (during the last decades) by researchers, scientists and practitioners working in the Effective Workplace Design area. Chapter 2 passes through the description of several research works, as they run through the literature, according to the methodology or scientific approach they propose. The initial search identifies a huge number of references (about 600 references) which were reduced to about 180 references based on contents and quality. The descriptive analysis of the literature reveals heterogeneity among the scientific approaches due to the different models, techniques and methods used for facing the effective workplace design problem within industrial environments. In particular, three main scientific approaches have been identified: the first and the second are based on the use of ergonomic and work measurement methodologies; while the third one deals with the integration of ergonomic and work measurement methodologies with the most widely used Modeling & Simulation (M&S) tools. The identification of several research shortages on this area concludes the chapter. This PhD thesis comes in help of such research shortages by proposing a design methodology for achieving the workplaces effective design.

The main goal of training activities was twofold: (i) to learn the main principles on the basis of the main ergonomic and work measurement methodologies and (ii) to gain knowledge and experience in using different simulation software tools to develop simulation models of industrial workplaces. Among the others, the following has to be concerned as the most widely used ergonomic methodologies: anthropometric data analysis, RULA method, NIOSH 81 and NIOSH 91 lifting equations, Burandt Schultetus analysis, University of Michigan's 2D, 3D analysis, Snook and Ciriello method, ErgoMOST, University of Michigan's Energy-Expenditure, Garg analysis, Ovako Working Posture Analyzing System (OWAS), Occupational Repetitive Action methods (OCRA). Among the work measurement tools, here a bunch of them is reported: Methods Time Measurement (MTM), Work Factor (WF) System, Basic Motion Time study (BMT), MODAPTS, General Sewing Data (GSD), MTM-MEK, ANDARD DATA (USD), Master Standard Data (MSD), MTM-2, MTM-3, Maynard Operation Sequence Technique (MOST). Moreover detailed studies have been made concerning simulation modeling principles, input data analysis, Verification, Validation and Accreditation (*V&VA*), simulation runs planning by using the Design of Experiments (*DOE*) and Genetic Algorithms (*GA*). The software tools adopted for the implementation of simulation models and simulation results analysis are: eM-Workplace™ by *Tecnomatix Technology* (simulation software), Pro-Engineer by PTC (CAD software), and Rhinoceros by McNeel (CAD software). Ergonomic and time methodologies are deeply described in Chapter 2, while Modeling & Simulation (M&S) tools, VV&A, DOE and GA are detailed presented across Chapter 2 and Chapter 3.

The main results of the research activity are presented in Chapters 3 and Chapter 4.

Chapter 3 introduces and presents the design methodology that can be used by industrial engineers for achieving the effective design of workplaces within industrial environments. The chapter brings clarity to the foundational understanding of the methodology placing specific emphasis on its principles and procedures. To this end, the methodology steps will be deeply discussed. The methodology main steps can be summarized as follows: STEP 1 Problem Formulation and Objectives Definition, STEP 2 Performance Measures and Design Parameters Definition, STEP 3 Data Collection, STEP 4 Simulation Model Development, STEP 5 Effective Workplace Design, STEP 6 Results Presentation and Implementation.

Chapter 4 presents a series of case studies related to the application of the design methodology deeply discussed in the previous Chapter. The methodology's entire development process as well as the quantitative and the qualitative results are explained. Practical examples are provided that allow the industrial engineer to understand the use of the methodology to affect and improve ergonomics and productivity within industrial workplaces. All the application examples regard either industrial workplaces where highly manual tasks are performed or industrial workplaces characterized by man machine operations. The first ones belong to an industrial plant producing leather goods such as leather bags, leather planner cases, leather handbags, leather pockets, etc., while the second ones belong to an industrial plant that manufactures high pressure hydraulic hoses. Moreover, the case studies are listed according to the design approaches, (*trial and error and design of experiment based approaches*), used for generating workplaces alternative configurations. Finally, in the last part of the chapter, the application of the design methodology to industrial workplaces still not in existence is presented. An assembly line for heaters production and an industrial plant that manufactures mechanical parts for agricultural machineries engines are considered.

Chapter 1

Fundamentals of Industrial Engineering: work measurement and manufacturing ergonomics

The historical events that led to the birth of industrial engineering provide significant insights into many of the principles that dominated its practice and development throughout the first half of the twentieth century. While these principles continue to impact the profession, many other conceptual and technological developments that currently shape and continue to mold the practice of the profession originated in the second half of the twentieth century. The objective of this chapter is twofold: (1) briefly summarize major events that have contributed to the birth and evolution of industrial engineering and assist in identifying common elements that continue to impact the purpose and objectives of the profession; (2) cover the basic industrial engineering tools, methods, and procedures and specify their appropriate application areas for improvement and problem solving. Among the others, work measurement and time standards as well as manufacturing ergonomics and workplace design application areas will be detailed description due to the fact they represent the core topics of the research activities related to this PhD thesis.

1.1 Industrial Engineering Definition

In 1955, the American Institute of Industrial Engineers (now the Institute of Industrial Engineers, IIE) adopted the following definition of industrial engineering:

Industrial engineering is concerned with the design, improvement, and installation of integrated systems of men, materials, and equipment. Industrial engineering draws upon specialized knowledge and skill in the mathematical, physical, and social sciences together with the principles and methods of engineering analysis and design, to specify, predict, and evaluate the results to be obtained from such systems

1.2 History

Born in the late nineteenth century, industrial engineering is a dynamic profession whose growth has been fueled by the challenges and demands of manufacturing, government, and service organizations throughout the twentieth century. It is also a profession whose future depends not only on the ability of its practitioners to react and to facilitate operational and organizational change but, more important, on their ability to anticipate, and therefore lead, the change process itself. The historical events that led to the birth of industrial engineering provide significant insights into many of the principles that dominated its practice and development throughout the first half of the twentieth century (Emerson and Naehring, 1988).

1.2.1 Early origins

The Industrial Revolution

Even though historians of science and technology continue to argue about when industrial engineering began, there is a general consensus that the empirical roots of the profession date back to the Industrial Revolution, which began in England during the mid-eighteenth century. The events of this era dramatically changed manufacturing practices and served as the genesis for many concepts that influenced the scientific birth of the field a century later. The driving forces behind these developments were the technological innovations that helped to mechanize many traditional manual operations in the textile industry. These include the flying shuttle developed by John Kay in 1733, the spinning jenny invented by James Hargreaves in 1765, and the water frame developed by Richard Arkwright in 1769. Perhaps the most important innovation, however, was the steam engine developed by James Watt in 1765. By facilitating the substitution of capital for labor, these innovations generated economies of scale that made mass production in centralized locations attractive for the first time. The concept of a production system, which lies at the core of modern industrial engineering practice and research, had its genesis in the factories created as result of these innovations.

Specialization of Labor

The concept presented by Adam Smith in his treatise *The Wealth of Nations* also lie at the foundation of what eventually became the theory and practice of industrial engineering. His writing on concepts such as the division of labor and the “invisible hand” of capitalism served to motivate many of the technological innovators of the Industrial Revolution to establish and implement factory systems. Examples of these developments include Arkwright’s implementation of management control systems to regulate production and the output of factory workers, and the well-organized factory that Watt, together with an associate, Matthew Boulton, built to produce steam engines. The efforts of Watt and Boulton and their sons led to the planning and establishment of the first integrated machine manufacturing facility in the world, including the implementation of concepts such as a cost control system designed to decrease waste and improve productivity and the institution of skills training for craftsmen. Many features of life in the twentieth century including widespread employment in the large scale factories, mass production of inexpensive goods, the rise of big business, and the existence of a professional manager class are a direct consequence of the contributions of Smith and Watt.

Another early contributor was Charles Babbage. The findings that he made as a result of visits to factories in England and the United States in the early 1800s were documented in his book entitled *On the Economy of Machinery and Manufacturers*. The book includes subjects such as the time required for learning a particular task, the effects of subdividing tasks into smaller and less detailed elements, the time and the cost savings associated with changing from one task to another, and the advantages to be gained by repetitive tasks. In his classic example on the manufacture of the straight pins, Babbage extends the work of Adam Smith on the division of labor by showing that money could be saved by assigning lesser-paid workers (in those day women and children) to lesser skilled operations and restricting the higher-skilled, higher paid workers to only those operations requiring higher skills levels. Babbage also discusses notions related to wage payments, issues related to present-day profit sharing plans, and even ideas associated with the organization of labor and labor relations. It is important to note, however, that even though much of Babbage’s work represented a departure from conventional wisdom in the early nineteenth century, he restricted his work to that of observing and did not try to improve the methods of making the product, to reduce the times required, or to set standards of what times should be.

Interchangeability of Parts

Another key development in the history of industrial engineering was the concept of interchangeable parts. The feasibility of the concept as a sound industrial practice was proven trough the efforts of Eli Whitney and Simeon North in the manufacture of muskets and pistols for the U.S. government. Prior to the innovation of interchangeable parts, the making of a product was carried out in its entirely by an artisan, who fabricated and fitted each required piece. Under Whitney’s system, the individual parts were mass-produced to tolerances tight enough to enable their use in any finished product. The division of labor called by Adam Smith could now be carried out to an extent never before achievable, with individual workers producing single parts rather than completed products. The result was a significant reduction in the need for specialized skills on the part of the workers – a result that eventually led to the industrial environment, which became the object of study of Frederick W. Taylor.

1.2.2 Pioneers of Industrial Engineering

Taylor and Scientific Management

While Frederick W. Taylor did not use the term industrial engineering in his work, his writings and talks are generally credited as being the beginning of the discipline. One cannot presume to be well versed in the origins on industrial engineering without reading Taylor's books: *Shop Management* and *The Principles of scientific Management*. The core of Taylor's system consisted of breaking down the production process into its components parts and improving the efficiency of each. Paying little attention to rules of thumb and standard practices, he honed manual tasks to maximum efficiency by examining each component separately and eliminating all false, slow, and useless movements. Mechanical work was accelerated trough the use of jigs, fixtures, and other devices (many invented by Taylor himself). In essence, Taylor was trying to do for work unit what Whitney had done for materials units: standardize them and make them interchangeable.

Improvement of work efficiency under the Taylor system was based on the analysis and improvements of work methods, reduction of the time to carry out the work and the development of work standards. Taylor's contribution to the development of the "Time Study" was his way of seeking the same level of predictability and precision for manual tasks that he had achieved with his formulas for metal cutting.

Taylor's interest in what today we classify as the area of work measurement was also motivated by the information that studies of this nature could supply for planning activities. In this sense, his work laid the foundation for a broader "science of planning": a science totally empirical in nature but one that he was able to demonstrate could significantly improve productivity. To Taylor, scientific management was a philosophy based not only on the scientific study of work but also on the scientific selection, education, and development of workers.

His classic experiment in shoveling coal, which he initiated at the Bethlehem Steel Corporation in 1898, not only resulted in development of standards and methods for carrying out this task, but also led to the creation of tools and storage rooms as service departments, the development of inventory and ordering systems, the creation of personnel departments for worker selection, the creation of training departments to instruct workers in the standard methods, recognition of the importance of the layout of manufacturing facilities to ensure minimum movement of people and materials, the creation of departments for organizing and planning production, and the development of incentive payment systems to reward those workers able to exceed standard outputs. Any doubt about Taylor's impact on the birth and development of industrial engineering should be erased by simply correlating the previously described functions with many of the fields of work and topics that continue to play a major role in the practice of the profession and its educational content at the university level.

Frank and Lillian Gilbreth

The other corner stone of the early days of industrial engineering was provided by the husband and wife team of Frank and Lillian Gilbreth. Consumed by a similar passion for efficiency, Frank Gilbreth's applications of the scientific method to the laying of bricks produced results that were as revolutionary as those of Taylor's shoveling experiment. He and Lillian extended the concepts of scientific management to the identification, analysis and measurement of fundamentals motions involved in the performing work. By applying the motion-picture to the task of analyzing motions they were able to categorize the elements of human motions into 18 basic elements or *therbligs*. This development marked a distinct step forward in the analysis of human work, for the first time permitting analysts to design jobs with knowledge of the time required to perform the job. In many respects, these developments also marked the beginning of the much broader field of human factor and ergonomics. While their work together stimulated much research and activity in the field of motion study, it was Lillian who provided significant insight and contributions to the human issues associated with their studies. Lillian's book, *They Psychology of Management,* advanced the premise that because of its emphasis on scientific selection and training, scientific management offered ample opportunity for individual development, while traditional management stifled such development by concentrating power in central figure. Lillian brought to the industrial engineering profession a concern for human welfare and human relations that was not present in the work of many pioneers of the scientific management movement.

Other Pioneers

In 1912, the originators and early pioneers, the first educators and consultants, and the managers and representatives of the first industries to adopt the concepts developed by Taylor and Gilbreth gathered at the annual meeting of the American Society of Mechanical Engineers (ASME) in New York City. The all-day session on Friday, December 6, 1912, began with a presentation titled *The Present State of the Art of Industrial Management*. This report and the subsequent discussions provide insight and understanding about the origin and relative contributions of the individuals involved in the birth of a unique new profession: industrial engineering.

In addition to Taylor and Gilbreth, other pioneers present at this meeting included Henry Towne and Henry Gantt. Towne used ASME as the professional society to which he presented his views on the need for a professional group with interest in the problems of manufacturing and management. This suggestion ultimately led to the creation of the Management Division of ASME, one of the groups active today in promoting and disseminating information about the art and science of management, including many of the topics and ideas industrial engineers are engaged in. Towne was also concerned with the economic aspects and responsibilities of the engineer's job including the development of wage payment plans and the remuneration of workers.

Gantt's ideas covered a wider range than some of his predecessors. He was interested not only in standards and costs but also in the proper selection and training of workers and in the development on incentive plans to reward them. He was also interested in scheduling problems and is best remembered for devising the Gantt chart: a systematic graphical procedure for planning and scheduling activities that is still widely used in project management.

In attendance were also the profession's first educators including Hugo Diemer, who started the first continuing curriculum in industrial engineering at the Pennsylvania State College in 1908; William Kent, who organized an industrial engineering curriculum at Syracuse University in the same year; Dexter Kimball, who presented an academic course in works administration at Cornell University in 1904; and C. Bertrand Thompson, an instructor in industrial organization at Harvard, where the teaching of Taylor's concepts had been implemented. Consultants and industrial managers at the meeting included Carl Barth, Taylor's mathematician and developer of special purpose slide rules for metal cutting; John Aldrich of the New England Butt Company, who presented the first public statement and films about micro-motion study; James Dodge, president of the Link-Belt Company; and Henry Kendall, who spoke of experiments in organizing personnel functions as part of scientific management in industry. Two editors present were Charles Going of the *Engineering Magazine* and Robert Kent, editor of the first magazine with the title *Industrial Engineering*.

Another early pioneer was Harrington Emerson. Emerson became a champion of efficiency independent of Taylor and summarized his approach in his book, the *Twelve Principles of Efficiency*. These principles, which somewhat paralleled Taylor's teachings, where derived primarily through his work in the railroad industry. Because he was the only efficiency engineer with firsthand experience in the rail road industry, his statements carried enormous weight and served to emblazon scientific management on the national consciousness.

1.2.3 The Post World War I Era

Method Engineering and Work Simplification

Gilbreths' efforts in methods analysis became the foundation for the resurgence of industrial engineering in the 1920s and 1930s. In 1927, H.B. Maynard, G.J. Stegmerten, and S.M. Lowry wrote *Time and Motion Study*, emphasizing the importance of motion study and good methods. This eventually led to the term *methods engineering* as the descriptor of a technique emphasizing the "the elimination of every unnecessary operation" prior to the determination of a time standard. In 1932, A.H. Mogenson published *Common Sense Applied to Time and Motion Study*, in which he stressed the concept of motion study through an approach he chose to call *work simplification*. His thesis was simply that the people who know any job best are the workers doing that job. Therefore, if the workers are trained in the steps necessary to analyze and challenge the work they are doing, then they are also the ones most likely to implement improvements. This concept of taking motion study training directly to the workers through the work simplification programs was a tremendous boon to the war production effort during World War II. The first Ph.D. granted in the United States in the field of industrial engineering was also the result of research done in the area of motion study. It was awarded Ralph M. Barnes by Cornell University in 1933 and was supervised by Dexter Kimball. Barne's thesis was written and published as *Motion and Time Study*: the first full-length book devoted to this subject. The book also attempted to bridge the growing chasm between advocates of time study versus motion study by emphasizing the inseparability of these concepts as a basic principle of industrial engineering.

Another result of the reaction was a closer look at the behavioral aspects associated with the workplace and the human element. Even though the approach taken by Taylor and his followers failed to appreciate the psychological issues associated with worker motivation, their work served to catalyze the behavioral approach to management by systematically raising questions on authority, motivation, and training. The earliest writers in the field of industrial psychology acknowledged their debt to scientific management and framed their discussion in terms consistent with this system.

The Hawthorne Experiment

A major episode in the quest to understand behavioral aspects was the series of study conducted at the Western Electric Hawthorne plant in Chicago between 1924 and 1932. These studies originally began with a simple question: How does workplace illumination affect worker productivity? Under sponsorship from the National Academy of Science, a team of researchers from the Massachusetts Institute of Technology (MIT) observed groups of coil-winding operators under different lighting levels. They observed that productivity relative to a control group went up as illumination increased, as had been expected. Then, in another experiment, the observed that productivity also increased when illumination decreased, even to the level of moonlight. Unable to explain the results, the original team abandoned the illumination studies and began other tests on the effect of rest periods, length of work week, incentive plans, free lunches, and supervisory styles on productivity. In most cases the trend was for higher than normal output by the groups under study.

Approaching the problem from the perspective of the "psychology of the total situation", experts brought in to study the problem came to the conclusion that the results were primarily due to "a remarkable change in the mental attitude in the group". Interpretations of the study were eventually reduced to the simple explanation that productivity increased as a result of the attention received by the workers under study. This was dubbed the Hawthorne effect. However, in subsequent writings this simple explanation was modified to include the argument that work is a group activity and that workers strive for a sense of belonging - not simple financial gain - in their jobs. By emphasizing the need for listening and counseling by managers to improve worker collaboration, the industrial psychology movement shifted the emphasis of management from technical efficiency - the focus of Taylorism - to a richer, more complex, human-relations orientation.

Other Contributions

Many other individuals and events should be recorded in any detailed history of the beginnings of industrial engineering. Other names that should be included in any library search, which lead to other contributors, include L.P. Alford, Arthur C. Anderson, W. Edwards Deming, Eugene L. Grant, Robert Hoxie, Joseph Juran, Marvin E. Mundel, George H. Shepard, and Walter Shewart. In particular, Shewart's book , *Economic Control of the Quality of Manufactured Product*, published in 1931, contains over 20 years of work on the theory of sampling as an effective approach for controlling quality in the production process. While many of his ideas were not applied until after World War II, his work marked the beginning of modern statistical quality control and the use of many of the tools that today are taught to everyone, including workers, as a means of empowering them to control the quality of their work.

Status at the End of the Era

In 1943, the Work Standardization Committee of the Management Division of ASME included under the term *industrial engineering* functions such as budgets and cost control, manufacturing engineering, systems and procedures management, organization analysis, and wage and salary administration. Most of the detailed activities were primarily related to the task of methods development and analysis and the development of time standards, although other activities such as plant layout and materials handling, and the production control activities of routing and scheduling, were also contained in this definition. From an educational perspective, many of the methodologies and techniques taught in the classrooms and laboratories were very practical and largely empirically derived. Sophisticated mathematical and computing methods had not yet been developed, and further refinement and application of the scientific approach to problems addressed by industrial engineers was extremely difficult. Like other professional areas, the start of industrial engineering was rough, empirical, qualitative, and, to a great extent, dependent on the commitment and charisma of the pioneers to eloquently carry the day. The net effect of all this was that industrial engineering, at the end of this era, was still a dispersed discipline with no centralized focus and no national organization to bring it together. This situation started to change shortly after World War II.

1.2.4 The Post World War II Era

The Emergence of Operations Research

During World War II and the balance of the 1940s, developments of crucial importance to the field occurred. The methods used by the industrial engineer, including statistical analysis, project management techniques, and various network-based and graphical means of analyzing very complex systems, were found to be very useful in planning military operations. Under the pressure of wartime, many highly trained scientists from a broad range of disciplines contributed to the development of new techniques and devices, which led to significant advances in the modeling, analysis, and general understanding of operational problems. Their approach to the complex problems they faced became known as operations research (Schultz, 1970). Similarities between military operational problems and the operational problems of producing and distributing goods led some of the operations researchers from wartime to extend their area of activity to include industrial problems. This resulted in considerable interaction between industrial engineers and members of other scientific disciplines and in an infusion of new ideas and approaches to problem solving that dramatically impacted the scope of industrial engineering education and practice.

The decade of the 1950s marked the transition of industrial engineering from its prewar empirical roots to an era of quantitative methods. The transition was most dramatic in the educational sector where research in industrial engineering began to be influenced by the mathematical underpinnings of operations research and the promise that these techniques provided for achieving the optimal strategy to follow for a production or marketing situation.

While the application of operations research concepts and techniques was also pursued by practicing industrial engineers and others, the gap between theoretical research in universities and actual applications in government and industry was still quite great during those years.

The practice of industrial engineering during the 1950s continued to draw heavily from the foundation concepts of work measurement, although the emergence of a greater scientific base for industrial engineering also influenced this area. A significant development that gained prominence during these years was predetermined motion time systems. While both Taylor and Gilbreth had essentially predicted this development, it was not until the development of *work factor* that the vision of these two pioneers was converted into industry-usable tools for what still the most basic of industrial engineering functions.

By the 1960s, however, methodologies such as linear programming, queuing theory, simulation, and other mathematically based decision analysis techniques had become part of the industrial engineering educational mainstream. Operations research now provided the industrial engineer with the capability to mathematically model and better understand the behavior of large problems and systems. However, it was the development of the digital computer and the high-speed calculation and storage capabilities provided by this device that provided the industrial engineer with the opportunity to model, design, analyze, and essentially experiment with large system. The ability to experiment with large systems also placed industrial engineers on a more equal footing with their engineering counterparts. Other engineers were generally not limited in their ability to experiment prior to the computer age because they could build small-scale system. However, prior to the development of the digital computer, it was practically impossible for the industrial engineer to experiment with large-scale manufacturing and production systems without literally obstructing the capabilities of the facilities under study.

These developments essentially changed industrial engineering from a field primarily concerned with the individual human task performed in a manufacturing setting to a field concerned with improving the performance of human organizations. They also ushered in an era where the scope of application of industrial engineering grew to include numerous service operations such as hospitals, airlines, financial institutions, educational institutions, and other civilian and non-governmental institutions.

Status at the End of This Era

The decades of the 1960s and 1970s are considered by many to constitute the second phase in the history of industrial engineering during the twentieth century. During these years the field became modeling-oriented, relying heavily on mathematics and computer analysis for its development. In many respects, industrial engineering was advancing along a very appropriate path, substituting many of the more subjective and qualitative aspects of its early years with more quantitative, science-based tools and techniques. This focus was also consistent with the prevalent mind-set of the times that emphasized acquisition of hard facts, precise measurements, and objective approaches for the modeling and analysis of human organizations and systems. While some inroads were made in the area of human and organizational behavior, particularly in the adoption of human factors or ergonomics concepts for the design and improvement of integrated work systems, industrial engineers during this era tended to focus primarily on the development of quantitative and computational tools almost to the exclusion of any other concerns.

Evolution of the IE Job Function

Figure 1.1 illustrates how the job functions of industrial engineers (IEs) changed in the 1960s and 1970s (Pritsker, 1990). Activities throughout the early part of the 1960s were still concerned primarily with work simplification and methods improvement, plant layout, and direct labor standards. In the next five years, work began on indirect labor standards and project engineering. During the 1970s, quantitative approaches and computer modeling caused a dramatic shift in job functions. By the end of the 1970s, over 70 percent of industrial engineering job functions were estimated to be in the areas of scientific inventory management, systematic design and analysis, and project engineering. The evolutionary trends illustrated in figure 1.1 reflected a future where the fraction of workers in direct labor positions would continue to decrease and the number of positions in the service industries would increase. These changes, along with increased information processing capabilities, pointed toward a future where industrial engineering functions and roles would provide input and impact the decision and planning processes of management at higher levels than ever before.

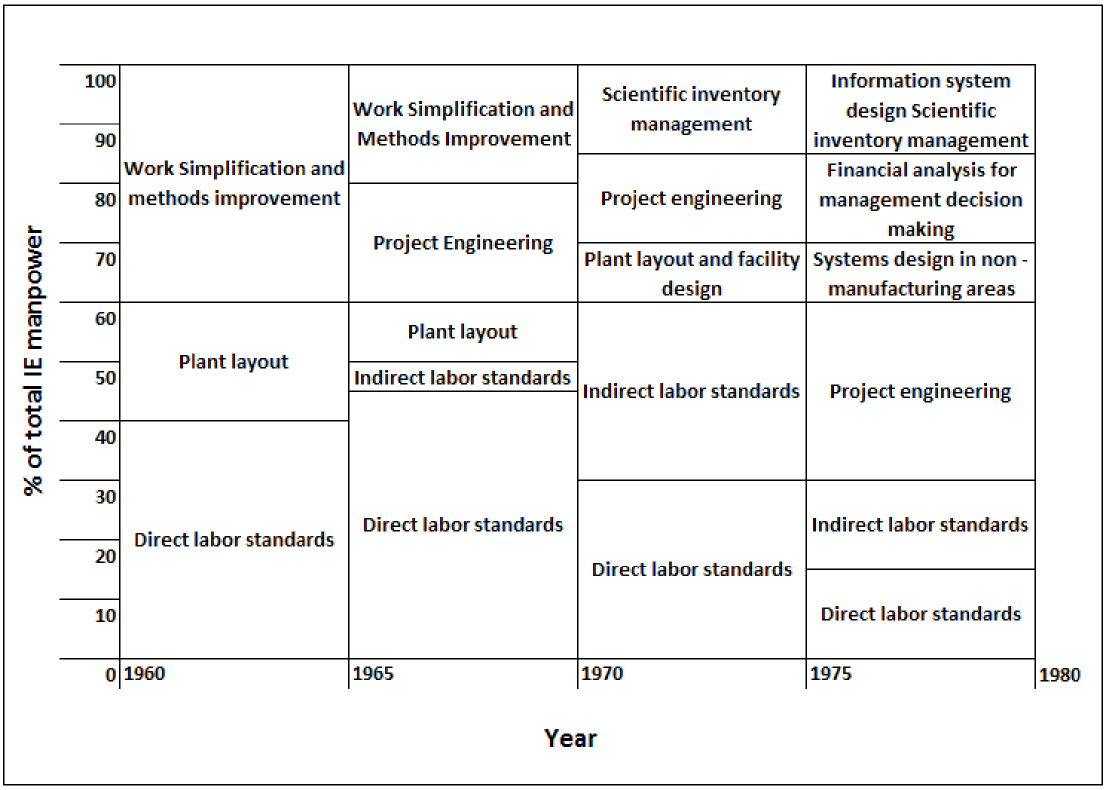


Figure 1.1 - Changes in the IE function between 1960 and 1980 (adapted from Pritsker, 1990)

1.2.5 The Era from 1980 to 2000

Organizational leadership responsibilities

During this decade the role of the industrial engineer expanded significantly beyond its traditional support functions to include organizational leadership responsibilities in both the design and integration of manufacturing and service systems. In the case of manufacturing, these functions oftentimes included the design and development of new hardware and software that enabled the automation of many production and support functions and the integration of these functions within operational environments.

With many manufacturing environments now consisting of complex arrays of computerized machines, the design and integration of information systems that could effectively control and handle data related to product designs, materials, parts inventories, work orders, production schedules, and engineering designs became a growing element in the role of the industrial engineer. The automatic generation of process plans, bills of materials, tools release orders, work schedules, and operator instructions, the growth in numerically controlled machine tool capability, and the use of robots in a variety of industrial settings are examples of applications in which industrial engineering played a major role during the 1980s. Many of these functions, which include tasks critical to the success of computer aided design (CAD), computer aided manufacturing (CAM), or computer-integrated manufacturing (CIM) efforts, reflected the broadening, systems-related role of the industrial engineer in many manufacturing organizations.

Sophisticated tools with which to analyze problems and design systems, which by now had become part of the industrial engineering toolkit, were also applied successfully in service activities such as airline reservation systems, telephone systems, financial systems, health systems, and many other non-manufacturing environments. Many of these developments were a natural outgrowth of the emphasis on quantitative and computational tools that had impacted the profession during prior decades. While a number of these applications also reflected a growing role in design and integrations functions, a major impact of the field on the service sector was the creation of a growing appreciation of the more generic nature of the term *production systems* to include the provision of services and the value of the role of industrial engineering in these environments. In addition to assuming increasingly higher-level managerial responsibilities in both manufacturing and service organizations, the roles of industrial engineers expanded to include functions such as software developer, consultant, and entrepreneur. The broad preparation of the industrial engineer, combined with the technological developments of this decade, had apparently resulted in a profession and a legion of professionals uniquely qualified to play the integrative, system-oriented role that was now required to enhance the effectiveness of organizations.

Evolution of the Role of the IE During this Era

In the 1980s, the problem of using excessive technologies without proper integration led to the creation of many "islands of automation", or situations where various parts of a factory automated by computers, robots, and flexible machines did not result in a productive environment because of a lack of integration among the components. A greater focus on systems integration has yielded more organizations whose functions are mutually rationalized and coordinated through appropriate levels of computers in conjunction with information and communication technologies. The role played by industrial engineers during the 1990s in these efforts includes not only the integration of shop floor activities and islands of automation, but also a greater emphasis on shortened development and manufacturing lead times, knowledge sharing, distributed decision making and coordination, integration of manufacturing decision processes, enterprise integration, and coordination of manufacturing activities with external environments. The impact of the industrial engineer in new manufacturing technologies can also be illustrated through the field's growing role in the development and application of concepts such as flexible, agile, and intelligent manufacturing systems and processes, design techniques and criteria for manufacturing, assembly, and concurrent engineering, rapid prototyping and tooling; and operational modeling including very significant contributions in factory simulation and integrated modeling capabilities (Shaw, 1994; White and Fowler, 1994).

Similar statements can be made for the impact of industrial engineering in government and service sectors where the catalyst has been a renewed focus on process modeling, analysis, and improvement, and the development and application of operational modeling and optimization-based approaches. Sectors where the industrial engineer is playing an increasingly active role include financial services, both in new product development and process improvement; distribution and logistics services, particularly through the development of new software and operational modeling, analysis, and design capabilities; government services; and many segments of the growing worldwide market for information services and technologies.

Figure 1.2 illustrates a projection for future IE roles as presented in Pritsker (1990). This projection was based on the premise that the conceptual framework for an industrial engineer parallels the framework for decision makers in general, thereby allowing future roles to be categorized as those associated with strategic planning, management control, or operational control. Strategic planning was defined as the process of deciding on the objectives of an organization, on changes in these objectives, on the resources used to obtain these objectives, and on the policies that are to govern the acquisition, use, and disposition of resources. Management control was defined as the process by which managers assure that the required resources are obtained and used effectively and efficiently in the accomplishment of the organization's objectives. Operational control refers to the process of assuring that specific tasks are carried out effectively and efficiently.

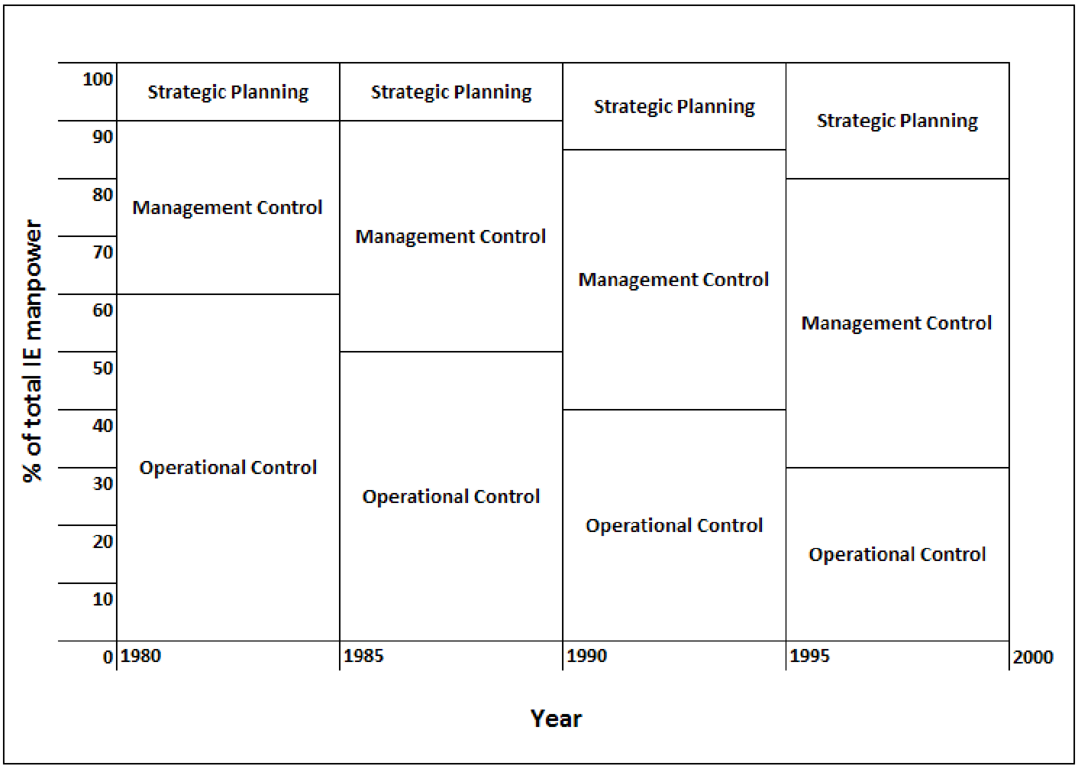


Figure 1.2 - Changes in the IE function between 1980 and 2000. (adapted from Pritsker, 1990)

1.3 The Industrial Engineer Role

Industrial engineers many times encounter people who do not understand or are unfamiliar with the term *industrial engineer.* Indeed, probably the most commonly asked question of an industrial engineer in the workplace or outside may be, *What do industrial engineers really do?* IIE defines industrial engineering as being

> *concerned with the design, improvement, and installation of integrated systems of people, materials, information, equipment, and energy. It draws upon specialized knowledge and skill in the mathematical, physical, and social sciences, together with the principles and methods of engineering analysis and design to specify, predict, and evaluate the results to be obtained from such systems (Nadler, 1992)*

This definition certainly does not succinctly describe what industrial engineers do. One of the great challenges of the IE profession is communicating the distinct roles that industrial engineers play when the roles are so diverse and varied across organizations. From a historical viewpoint, and to some extent still today, industrial engineers are perceived to be stopwatch-and-clipboard-bound supervisors. A hope for the future is that they will come to be known and respected in more enlightened organizations for their roles as troubleshooters, productivity improvement experts, systems analysts, new project managers, continuous process improvement engineers, plant managers, vice presidents of operations, and CEOs. While confusion over the roles of industrial engineers can be a liability, it also presents opportunities that arise when expectations are allowed to evolve. In many organizations the roles of industrial engineers have become highly evolved and many industrial engineering departments have grown to fill a unique niche. Still, the term *industrial engineer* largely says more about the training and degree, and less about the actual role played in most organizations.

The industrial engineering education is an excellent foundation for careers of choice in today's business environment. It is comprised of a multitude of different skills and tools that enable the industrial engineer to act as a master of change and thus make a tremendous impact in any type of organization. The industrial engineer's ability to understand how activities contribute to cost and/or revenue give him or her an advantage in leading divisional or enterprise wide process improvement initiatives. The fact that industrial engineers will spend time to study and thoroughly understand the current activities of an organization and will be able to link changes to improvement in financial terms, makes the industrial engineer a valuable asset to the organization. Understanding the current activities, applying creative solutions to current problems, and measuring their impact in the context of strategy are some of the best contributions an industrial engineer can make.

The ability of many industrial engineers to relate to co-workers in different departments such as information systems, operations, and finance makes them great assets in many large organizations. The ability to understand the constraints and needs of different areas of the business and translate it to other participants in a change initiative is also something that not all professionals have. Industrial engineers with this ability are good candidates to facilitate different forces in an organization, a role that can make the difference between a successful change initiative and one that fails. In addition, the ability to learn the activities of an organization on a detailed level, coupled with a knowledge of finance and budgeting, helps to groom the industrial engineer to become the decision maker of tomorrow. These are some of the reasons a number of industrial engineers are reaching high levels in today's organizations.

1.4 Key Success Factors

While the role of industrial engineers can and does vary widely across modern organizations, certain factors are evident in those organizations in which industrial engineers have enjoyed much success. The following are several key success factors for ensuring the effectiveness of the industrial engineer's role.

Be Flexible, but Focused. Today's industrial engineer should be open to new assignments and look for opportunities to contribute in new ways. Expectations of industrial engineers change as the organization changes and the most successful ones respond by evolving their role to stay in sync with the overall organization. At the same time, in whatever role industrial engineers play, they should strive to maintain a focus on value-added work. Surveys of U.S. industries show that employees spend only 25 percent of their time on average doing value added tasks (Ronal, 1996).

Apply Industrial Engineering Concepts to Real-World Problems. To understand a theory is only part of the challenge; understanding how to use it in a real-life problem is the true challenge. Too often, younger engineers apply "recipes" without understanding their limitations, thus relying on flawed assumptions to justify new projects. The true understanding of how concepts are applicable makes a very important difference in the long-term success of projects or change initiatives. Another challenge is being able to explain to higher management how these theoretical concepts translate into bottom-line value for the organization. Most of the concepts taught in school rely on solid data; if not researched properly, incorrect data will invalidate expensive analysis (e.g., simulation modeling). Complex models can be built, but they will not mean anything if valid data is not used.

Understand the "Big Picture" - How Change Initiatives Impact the Overall Organization. System thinking is a skill that every industrial engineer should possess. Understanding how a change can impact an organization is essential in truly having a positive impact on the bottom line. It is easy to perform a process improvement on a subsystem, but understanding and conveying how it benefits the whole organization is what's really important.

Understand and Analyze the Current Processes Accurately. To understand current processes an industrial engineer must live the day-to-day reality of the shop floor. Only a true comprehension of current reality will enable the best process improvement alternative: not understanding presents the risk of pushing solutions that look great on paper, but don't answer the fundamental need of an operation. Often, simple changes yield large returns and allow for the discovery of the true long-term process improvement alternatives. It is also important to properly apply basic knowledge and techniques on a problem before implementing complex solutions. Failing to do so can generate problems for the sustainability of a solution.

Manage Change. People manage all processes. If the people affected by the changes are not convinced of the solution, there are many ways in which they can contribute to its failure. Helping key players understand the importance of the change and the benefits it will bring to the organization is a challenging but important task. Most failures in projects can be attributed to a poor change management process. Figuring out a new solution on paper is easier than predicting human reaction to the changes. Ask, *What does it mean for the people affected?* Not taking the time to understand what is at stake will likely result in project failure in the long run.

Follow Through on Implementation. Too often the mistake is made of assuming that if a project is implemented successfully, the benefits will be recovered. This is a mistake to avoid at all costs. The goal of an industrial engineer is to create value. Overlooking the securing of savings that are generated by a successful project is like forgetting to take home the groceries you paid for at the store. It is up to the industrial engineer to ensure that a measurement or tracking system is put into place, following a project implementation. Benefits as well as project costs should be tracked to the bottom line.

Be Creative. The ability to see current reality and generate new ideas is what brings the most value to any changing organization. The industrial engineering education provides useful skills and techniques that can be applied to any process, from manufacturing to the service industry. The industrial engineering profession is continuously growing in new areas because of the people who used their creativity to apply their knowledge outside of the traditional field of industrial engineering practice. The success of industrial engineers in non-traditional areas, such as logistics, health care, theme parks, banking, and retail, can be attributed to visionaries who could see the potential and convince decision makers to invest time and energy in these new change initiatives. By being creative, an industrial engineer can generate substantially more value to an organization than would be initially expected.

Communicate Clearly. To put ideas into practice, an industrial engineer must also possess excellent verbal and written communication skills. Most of the process improvements recommended by industrial engineers involve techniques or technologies that can be complex. These solutions could have a sizable impact on the business but may require significant investments. The ability to present recommendations to decision makers in a way that they can readily comprehend requires that industrial engineers work on creating clarity. Decision making has to be based on understandable facts that are supported scientifically. Reporting results and financial information in an understandable way is also critical in gaining and maintaining the trust level of senior management. Complex projects may take years to complete and ongoing communication of milestones is critical in ensuring continuous support for current and future projects. Many industrial engineers' education and experience position them well to make significant contributions to organizational performance improvement across most industries and sectors. Their unique combination of skills and thinking practices affords them opportunities to have a meaningful impact on how organizations operate and remain competitive. It is a rewarding role for both the individual and the organization.

1.5 Key Threats

A number of potential threats to the success of the industrial engineer exist that can come from within or without the organization. Avoiding the following pitfalls can go a long way toward protecting and growing the value of the industrial engineer's role.

Lack of Appreciation for the Discipline. Industrial engineering is a discipline that needs to be continually sold. Within their organizations, industrial engineers need to establish a reputation for recruiting and developing top talent. The success of the industrial engineering discipline will be greatly enhanced if this talent is able to develop and migrate into key leadership positions. Leaders who share an industrial engineering legacy will help fuel the demand for industrial engineering support and institutionalize a respect for the discipline.

Failure to Align with Key Business Challenges. If the industrial engineer's role within an organization does not adapt with the company and continue to serve the greatest need, it most likely will not thrive, and potentially, may not survive. Whether the business strategy involves growth or cost containment, industrial engineers need to position themselves to contribute the greatest value.

Failure to Evolve. Industrial engineers have the responsibility of marketing themselves. Those who do a good job of this are likely to reap the benefits of new opportunities that appear on the landscape before other so-called experts are called in.

1.6 Fundamentals of Industrial Engineering

This section presents the industrial engineering application areas for improvement and problem solving. Three application areas are identified and a list of topics for each of them is presented.

1. Operations analysis and design
    - Method Engineering;
    - Work Measurement and Time Standards;
    - Manufacturing Ergonomics and Workplace Design;
    - Facilities Planning and Design;
    - Material Handling.

2. Operations Control
    - Production;
    - Just-In-Time;
    - Inventory Control;
    - Quality control.

3. Operations Management
    - Team Based;
    - Continuous Improvement.

For a detailed description of each industrial engineering topics please refer to Zandin (2001).

Work measurement and time standards as well as manufacturing ergonomics and workplace design represent the core topics of the research activities related to the PhD thesis; so that sections 1.8 and 1.9 present a deeply description on their fundamentals, tools, and methods in order to get the reader more familiar with these topics.

1.7 Work Measurement and Time Standards

1.7.1 Introduction

Work measurement is used to develop standard times needed to perform operations (Karger and Bayh, 1987). *Time standards* have traditionally been defined as the time required by an average skilled operator, working at a normal pace, to perform a specified task using a prescribed method, allowing time for personal needs, fatigue, and delay (Aft, 2000). Time standards, work standards, and standards of all types are critical pieces of management information that apply to manufacturing, assembly, clerical, and other work. Standards provide information essential for the successful operation of an organization:

- *Data for scheduling:* production schedules cannot be set, nor can delivery dates be promised, unless times for all operations are known;
- *Data for staffing:* the number of workers required cannot accurately be determined unless the time required to process the existing work is known. Continuing management of the

workforce requires the use of labor variance reports. Labor variance reports are also useful for determining changes in work methods, especially the subtle or incremental changes;

- *Data for line balancing:* the correct number of workstations for optimum work flow depends on the processing time, or standard, at each workstation. Operation times and setup times are key pieces of this information;
- *Data for Materials Requirement Planning (MRP):* MRP systems cannot operate properly without accurate work standards;
- *Data for system simulation:* simulation models cannot accurately simulate operation unless times for all operations are known;
- *Data for wage payment:* to be equitable, wages generally must be related to performance. Comparing expected performance with actual performance requires the use of work standards;
- *Data for costing:* ultimately, the profitability of an organization lies in its ability to sell products for more than it costs to produce them. Work standards are necessary for determining not only the labor component of costs, but also the correct allocation of production costs to specific products;
- *Data for employee evaluation:* in order to assess whether individual employees are performing as well as they should, a performance standard is necessary against which to measure the level of performance.

1.7.2 Definition of Standard Time

To reiterate, the *standard time* is the time required by an average skilled operator, working at a normal pace, to perform a specified task using a prescribed method, allowing time for personal needs, fatigue, and delay (Aft, 2000). Some key factors of this definition are the understanding of an average skilled operator, the concept of normal pace, the reliance on prescribed method, and the designation of the allowance. An *average skilled operator* is an operator who is representative of the people performing the task. The average skilled operator is neither the best nor the worst, but someone who is skilled in the job and can perform it consistently throughout the entire workday. The *normal pace* is a rate of work that can be maintained for an entire workday. It is neither too fast nor too slow. It is the pace of an average skilled worker. Rarely any worker will perform at the normal pace for an entire workday. Sometimes the worker will perform faster than the normal pace. Sometimes the worker will perform slower than the normal pace. The normal pace represents an ideal that the industrial engineer judges the average worker should be able to maintain long term. Another key part of the definition is the phrase relating to *prescribed method.* Work standards measure the time required to correctly perform defined tasks. Part of the definition must include a statement regarding the quality of the work performed. All workers have personal needs that must be attended to. Workers sometimes become tired as the workday progresses. When developing a time standard, an *allowance* must be made for these factors. Additionally, there will be occasional unexpected and often uncontrollable delays, such as material shortages or equipment breakdowns, and these, too, must be allowed for. The personal, fatigue, and delay (PFD) factors, depending on the nature of the work being performed, can be significant, typically representing from 10 to 15 percent of the workday.

1.7.3 Measuring Work

Standards have traditionally been developed in one of three major ways.

1. The first of these is *estimation,* which can be done in either of two ways. Sometimes the time required is provided by an individual who is believed to be knowledgeable about the task examines the work to be completed and then states, "*It ought to take about that many hours to get all the pieces run*". The other commonly used method of estimation involves the use of historical data. Prior runs are examined and actual times and production quantities are used to develop a historical standard.

2. The second general way of setting work standards is through the use of *standard data systems.* Standard data are defined as “a compilation of all the elements that are used for performing a given class of work with normal elemental time values for each element. The data are used as a basis for determining time standards on work similar to that from which the data were determined without making actual time studies.” *Standard data* is the term used to describe time data for groups of motions rather than single motions. Such data are used to set standard times for new work without having to take complete and detailed studies of the work. They are compiled from existing detailed studies of manual work and are arranged in the form of tables, graphs, and formulas for ready use. Knowledge of how the new job must be done makes it possible to select the appropriate time data from these records to obtain the proper standard time for the job (Bailey and Presgrave, 1958). There are two types of standard data. One is what is often referred to as *macroscopic standard data.*

   Many operations in a given plant have several common elements. The element, “walking,” for example, is a component of many different jobs. Diverse activities such as painting, handling or working on a site invariably involve an element of “walking.”When these activities are timed, the same common element is in fact timed again and again. The job of the work study analyst would therefore be made much easier if the analyst had at the disposal a set of data from which he or she could readily derive standard times for these common work elements without necessarily going into the process of timing each one (International Labour Office, 1992)

   Macroscopic standard data takes advantage of similarities of activities within like families of operations and uses those similarities to develop standards for related activities. Standard data can reduce the time and labor required to set standards (Aft and Merritt, 1984).
   The other type of standard data is what might be called *microscopic standard data*. This type of standard data is also often referred to as *predetermined time systems(PTS).* It is a motion-based method of work measurement.

   By carefully describing all of the motions required to perform a particular job, the analyst will have to carefully study the method being used to perform the job. When the motions required to complete the work have been identified, the standard can be set. In predetermined time systems, each motion that is described and coded has a specific time allowed for its completion. By completely identifying all of the motions required, the entire time for a sequence of motions or for an entire operation can be synthesized. Once the allowance is applied, an accurate time standard can be issued. This procedure, of course, is based on the assumption that the correct motions have been identified before the times are assigned(Aft, 1992)

   A wide variety of predetermined time systems exist. The Predetermined Time Standard systems will be described in more detail in chapter 2.

3. Standards are also set using direct observation and measurement. The three common methods for setting standards using direct observation are *time study, work sampling,* and *physiological work measurement.* Time study is defined as follows:

   Time study is the analysis of a given operation to determine the elements of work required to perform it, the order in which these elements occur, and the times which are required to perform them effectively (Maynard, 1963)

   Time study involves the use of a timing device, study of the existing work method, recording observed times, rating the subject’s performance compared with normal pace, and adding the PFD allowance. Time study is most effective for developing standards for highly repetitive tasks that have relatively short cycle times. When work is non-repetitive and has relatively long cycle times (e.g., some clerical and maintenance tasks), then work sampling is an appropriate method for setting standards.

> *A work sampling study consists of a large number of observations taken at random intervals; in taking the observations, the state or condition of the object of study is noted, and this state is classified into predefined categories of activity pertinent to the particular work situation. From the proportions of observations in each category, inferences are drawn concerning the total work activity under study (Heiland and Richardson, 1957)*

A third way to directly measure work performed is by physiological means. This is based on the fact that work is equal to force times distance. Energy is required to perform work. Physical work results in changes in oxygen consumption, heart rate, pulmonary ventilation, body temperature, and lactic acid concentration in the blood. Although some of these factors are only slightly affected by muscular activity, there is a linear correlation between heart rate, oxygen consumption and total ventilation, and the physical work performed by an individual. Of these three, the first two - heart rate and oxygen consumption - are most widely used for measuring the physiological cost of human work (Barnes, 1980).

Many studies have shown that the difference between well-trained workers and beginners on a job is significant. The physiological cost to the beginner would be greater when the beginner attempts to produce at the normal pace. Physiological measurements are used to compare the cost to the worker for performing varying tasks (Brouha, 1960).

Time study, work sampling, and physiological work measurement methods are detailed described in sections 1.8.4 – 1.8.6.

1.7.4 Time Study

The major objective of this section is to present how to calculate a time standard based on stopwatch time study procedure. The procedure consists of the following steps:

1. Determining the job content;
2. Determining the element of the job;
3. Recording the actual time values;
4. Determining the average time to do the job by a certain operator;
5. Determining the base time for the job by rating or leveling;
6. Determining and applying allowances;
7. Applying the standard as determined by the time study.

- ***1. Determining the job content***

The determination of job content involves recording the method of doing the job exactly as it is done when the time study is taken. This should be done in such detail that the work can be reproduced at any time in the future. Details include recording:

1. The general information about the job;
2. The workplace description;
3. The conditions and environment surrounding the workplace;
4. The method used by the operator.

The record obtained is of the utmost importance for the administration of a sound time study system because it provides information for:

1. Determining the magnitude of job changes as they occur;
2. Training other operators in the standard method to enable them to meet the standard time;
3. Developing standard time data.

Before considering the methods description complete, two important questions should be asked:

1. Can the job be reproduced from the methods description?
2. Does the description include everything the worker has to do?

➢ *2. Determining the elements of the job*

Time values of a job can be secured in a number of different ways. Perhaps the two extremes would be (1) to secure the over-all time to do the whole job and divide this time by the number of pieces or pounds produced to get a unit measure and (2) to determine the time for each motion and a total of all the motion times for one unit produced to give a unit measure. Between these two extremes are any number of possibilities, and it is usually one of these other methods that is used. In other words, the job is broken down into parts and the parts are timed. The parts are known as elements.

There are no fixed regulations as to how a job should be broken down into elements, but there are a few guides which can be used. The rest has to be built up through experience. The guides are:

1. Contents of each element should be as homogeneous as possible. This means that a unit of work such as "insert a screw" should be in one element, but other units of work in the same job should be in other elements;
2. Hand and machine times should be placed in different elements. Hand time is under the operator's control and is subject to rating or leveling. Machine time, under automatic feed, is a definite value depending upon the physical characteristics of the part being made and equipment used. This can be determined without actual time study;
3. Each element should be either a relatively constant time value element or a variable time value element. The same element of work in one job will appear in many other jobs - especially in similar work. However, in some cases because of the physical characteristic of the part being made (such as size), the time value for the same element will be different from job to job. This is known as a variable element. In other cases, the varying work factors such as size, weight, shape, and difficulty of handling will not affect the time for the same element from job to job. If this is the case, the clement will be classified as a constant element. The value of having an element variable or constant is much more apparent when standard data, or standard time values, are being developed;
4. Each element should have a definite start and end point. In order to secure comparable time values for the same element, the start and end points should be fairly definite so the watch can be read at the right time each time the element occurs.

➢ *3. Recording the actual time values*

In recording the actual time values, two questions need to be answered:

1. What method of reading a stopwatch is going to be used?
2. When have an adequate number of stopwatch readings been secured?

With respect to the method of stopwatch reading, it can be said that the accuracy and reliability of the particular method depends entirely on the person handling the watch. Two fundamental methods of stopwatch reading are presented as follows:

- *Continuous Stopwatch Reading and Recording*. The stopwatch is started at the beginning of the first element of the job description and runs continuously until the study is completed. At the end of each element, in turn, the particular reading of the watch is recorded for the corresponding element;
- *Snapback or Repetitive Stopwatch Reading and Recording*. The stopwatch is started at the beginning of each element. At the end of each element, the watch is read and the hand is snapped back to zero. It starts again for the next element. They should be the same if the readings are accurate.

The second consideration when securing the actual time values involved in doing a job is to determine when an adequate number of values has been secured. In other words, how many time values must one secure to have a reasonable and sound sample to represent the job? There are two extreme possibilities here : (1) take a complete time study of the whole job from the first piece or pound to the last piece or pound (assuming a sizable number of pieces), or (2) take enough readings of time values until it is felt that a reasonable sample has been secured.

The first method is much too costly and the answer comes too late for use. It would mean issuing a production-standard-time-allowed after the job is done. The second method is most widely used, but the rationale of enough readings is left entirely up to the time study man. There is a way to overcome this disadvantage of the “feeling” of enough readings. By using statistics, actual limitations can be set. But for those who wish to make a reasonably rough check graphically, a simple means is available: Plot a frequency chart.

➢ *4. Determining the average time to do the job by a certain operator*

The previous step assumed that all time values secured during the time study were proper. But questions always come up as to the validity of certain so-called “abnormal” time values - those which are too high or too low. This question has to be settled on a rational basis. To hide behind the idea that a time is abnormal is not enough. A sound, workable policy that can be understood by anyone is necessary. To avoid the misuse of the idea of abnormal time values, consideration of this policy is suggested:

All time values for an element are to be included in determining the average time for an operator studied, unless a specific note is made in each case of a discarded time value that the job method was not followed. This means that if all the work called for in the element of the job is not done, the time value (which probably will be low) will be discarded. If the operator unnecessarily does more work than the element of the job calls for, the time value (which probably will be too high) also will be discarded.

➢ *5. Determining the base time for the job by rating or leveling*

The average time value secured for each element of the job was that displayed by a certain operator. But it must be remembered that in any field of human endeavor - whether it is housework, farming, or industrial work - observation will show that people differ in manner and speed at which they accomplish a task. The situation is not any different in time study work. It is reasonable to expect that no two persons will perform a given task at exactly the same speed, although this may happen occasionally. Yet, when a standard time is set for a job, the time study engineer is saying that a certain worker, following a certain method, working at a certain speed, and under certain conditions, should be able to do the job properly in at least the standard time.

The problem confronting the observer is how to watch different people doing work at different speeds and how to compare them to some person who is working at a certain speed already determined for a certain existing area, industry, or plant. The process of comparing a worker's rate of performance with the performance expected of a person working at the selected speed for the area, industry, or plant is called rating or leveling.

The rating process is a systematic attempt to relate the observed performance to the performance expected from a certain type of individual who has certain skill qualifications, who follows a certain method, and who works under certain conditions and at a certain pace.

Although many methods of rating have been devised, none has yet been able to remove the factor of human judgment satisfactorily. At the present time, rating based on sound judgment developed through extensive training is the best procedure to follow. Achieving satisfactory rating also means achieving equity for all employees affected by the time study program. If rating equity is not realized, a very unfavorable situation of unbalanced costs and employee dissatisfaction may develop.

Achieving equity of rating involves consideration of several rules:

1. All raters must practice fairness;
2. All raters in any one plant must use the same basic reference;
3. All raters must be consistent and accurate in their judgment;
4. Rating must be concrete and based on some observable, demonstrable basis;
5. It is desirable that both management and labor understand and agree to the basis of rating;
6. Rating judgment must involve the determination of the effect of the operator's skill, aptitude, and degree of exertion on his performance compared to the definition of standard performance. Consideration of these factors shows that:

    a) Skill determines how rapidly a job can be done by a certain method. Hence, skill is reflected in pace;
    b) Aptitude under a given method determines what speed of pace can be maintained. Hence, aptitude is reflected in pace;
    c) Exertion is a function of job difficulty and pace. Hence, exertion, which is the physical effort of work, is reflected in pace.

Therefore, it is suggested that the observer rate only pace or rate of activity. Selecting some physical representation of standard performance is an extremely important step which can influence the success of the rating program. The selection can be successful if a typical job is carefully chosen for the particular situation considered. Selecting a typical job satisfies the need for a basic reference that is concrete, observable, and demonstrable. Proper training of the raters can meet the need for consistency and accuracy. This usually can be done effectively by using a motion picture film loop of typical jobs for rating practice.

➢ *6. Determining and applying allowances*

Regardless of the occupation, certain interruptions will occur during a regular working day. No operator can be reasonably expected to work a full shift without some stoppages that are beyond his control. Interruptions vary from those of very short duration, which are difficult to measure, to those of moderate or long duration, which are fairly easy to measure. Delays which are caused by the nature of the work situation should not be permitted to act as a penalty upon the operator. Stoppages which are long enough to be recorded on a time card do not present a measurement problem because the time card is the measurement device in this case. However, a definite policy should establish which type and duration of delays are to be covered in the delay allowances in time study and which are to be covered by the time card.

Minor, varied delays of short duration present an extremely difficult measurement problem. They are often difficult to detect or determine properly without exhaustive study, and consequently they are overlooked in many cases. This should not be. A properly administered, workable time study system is based upon fair play. Proper allowances for delays - no matter how minor - are essential if fairness to all is to be achieved. These allowances can be determined only by careful, extensive studies taken on the job under regular working conditions. No attempt should be made to apply standard reference tables which may not fit the situation.

Although delay studies may not be absolutely accurate, they are valuable if carefully and conscientiously taken. Allowances for personal needs, such as food, drink, and toilet, and rest allowances can be determined by study and agreement between management and labor.

All studies made to determine the amount of delay that can be expected in various types of work have a definite relationship to the production time. Basically, the acceptable total work day is composed of net production time and acceptable delay times. The per cent allowance for delay for each class of delay can be computed from the studies made for the delay times expected.

*Per cent allowance for delay = (delay time/net production time) * 100,*

Then,

*Production-standard-time-allowed = base time * (1.00 + per cent allowance for delay).*

➢ *7. Applying the standard as determined by the time study*

The application and the administration of the time study program is perhaps the most vital part of the process. All of the other phases of the program may be technically correct and practiced with conscientious diligence. However, they may be unacceptable to the people affected by the program because the administration fails to instil a feeling of honesty and fair play, because everyone affected does not understand the program thoroughly, or because the administration lacks a systematic approach to the workings of a time study program.

If the trust, respect, and cooperation of the people affected by the time study program are to be gained and kept, a definite policy for systematic operation of the time study program and the various activities of that program must be formed, definitely stated, and widely understood. The statement of policy is vital to all phases of plant activity and must include a statement of procedures, aims, and rules by which the organization functions under varying or recurring situations.

A statement of policy for a time study program should answer clearly at least the following:

1. What does standard time represent? Because this is a unit of measurement it must be defined, and the definition must be generally known throughout the plant;

2. Who determines standard method? Responsibility for determining methods must be delegated so that standard times will be used only with the methods they were designed for and so that there will be a constant striving for better methods;
3. How will standard time be determined? Time study, rating, and allowance procedures should be specified as well as any deviations that will be allowed in unusual cases. This will establish uniform practice. Policy for standard time should indicate:

    a) Nature of the method record;
    b) The manner of timing and possible use of standard data;
    c) Basis of rating;
    d) Standard allowances,
    e) Manner of handling irregular elements;
    f) Designation of responsibility for above work and authority for procedure modification.

4. How will the standard method be installed?

    a) Standard method in written practice form is supplied to operator;
    b) Standard time is supplied to operator;
    c) Full value can be obtained by use of improved methods;
    d) The practice form can be designed for use by operator, group leader, foreman, or instructor - the more detailed the form, the better the control.

5. What are the conditions for change of standard time or method?

    a) Properly set standards are guaranteed against revision except in specified cases, whereas poorly set standards require constant revision and lead to industrial chaos;
    b) Only a change in job method, working conditions, or job materials above a certain per cent of the total standard justifies a change in the standard.

1.7.5 Work Sampling

Here it is presented a uniform procedure to be followed each time a work sampling study is performed (Barnes, 1957). The procedure consists of the following 10 steps:

1. Establish the purpose;
2. Identify the subjects;
3. Identify the measure of output;
4. Establish a time period;
5. Define the activities;
6. Determine the number of observation needed;
7. Schedule the observations;
8. Inform the personnel involved;
9. Record the raw data;
10. Summarize the data.

Each step will be in details described below and following the main advantages and limitations of work sampling are presented.

- ***1. Establish the purpose***

First, the objective of the study should be established. Work sampling can be used to determine an overall perspective on the work done. It can be used to determine a more precise analysis of the time spent on various work elements or it can be used in conjunction with production records to set performance standards. The analyst must establish the use of the results before making the study.

- ***2. Identify the subjects***

Second, the people performing the task under consideration must be identified. If general office work is being studied with the objective of determining overall productivity, the appropriate employees should be specified; in larger companies, specific job classifications should be identified. Likewise, if a study of machine tools utilization is to be performed, the specific tools that will be studied should be specified. The workers and supervisors involved must naturally be informed of the nature of the study.

- ***3. Identify the measure of output***

The third step in making the study is the identification of the measure of the output produced or the types of activities performed on the jobs being studied. This step is especially important if the objective of the study is to measure productivity with the intent of setting a standard.

- ***4. Establish a time period***

Fourth, the time period during which the study will be conducted must be established. Starting and stopping points for the study must be defined as well. The longer the period the better, but this constraint will be counterbalanced by the cost of making the study. Whatever period is specified, the time allowed should be sufficient to be representative of the work normally performed on the type of job that is being studied.

- ***5. Define the activities***

This step involves defining the activities that are performed by the people under study. This specification may be a very broad definition, such as the definition used in a machine utilization study, including only the categories of working, idle-not working and idle- mechanical breakdown. Or, it might include a listing of 10 or more specific work activities.

- ***6. Determine the number of observation needed***

After the work elements are defined, the number of observations for the desired accuracy at the desired confidence level must be determined The sample size, remember, is dependent on the percentage of time believed to be spent on the major work element requiring the smallest portion of the operator's time. If a reasonable guess cannot be made, then a trial study of perhaps 20 to 40 observations should be made to get an estimate of this portion. These initial observations should be included with the rest of the observations taken during the remainder of the work study.

- ***7. Schedule the observations***

Once the number of observations required has been determined, either from appropriate statistical calculations or from tables, the actual observations must be scheduled. Typically, the analyst will assign an equal number of observations each day during the course of the study. For example, if 800 observations are required and 20 work days are established as an appropriate observation time, 40 observations should be recorded each day. A random number table can be used to establish the random times for each observation.

- ***8. Inform the personnel involved***

Before the study is actually performed, the personnel involved should be informed about the objective of the study and the methodology that will be employed. As in any productivity measurement study, this part of the procedure is very important. Workers and their supervisors might think that they personally are being measured rather than the work they are doing.

- ***9. Record the raw data***

The next and perhaps the easiest part of any work sampling study is the actual recording of the raw data. Although this recording can be performed by anyone, it is desirable that a trained analyst be employed. It is also imperative that the observations be made at exactly the same location every time. Failure to be consistent in this manner may bias the results.

- ***10. Summarize the data***

After the data have been collected, they must be summarized. This process simply involves totaling the observations made for each work element and calculating the percentage of time actually spent on that particular task (this step may be easily adapted to computer analysis). If a standard is to be set, this percentage of time is compared with the output for the time of the study and the time per unit of output is calculated. Regardless of how the results of the work sampling study are expressed, the relative number of observations made of the particular activity divided by the total number of observations is the basic measure of the work performed during the work sampling study.

Advantage of work sampling. Work sampling has many advantages over some traditional direct measurement techniques used for setting time standards. Some of the claims presented in favor of work sampling include (Heiland and Richardson, 1957):

- Work sampling provides a procedure that can be used to measure the productivity contribution of a number of tasks that might not be measurable by other means. The high-cycle time and low-repetition-rate jobs are very suitable for this type of analysis;
- Work sampling studies can be performed on a number of different operators simultaneously. Proper planning of the path followed to make observations can reduce the number of analysts required for a particular study. In direct observation methods, one analyst is required for each job studied;
- When determining time utilization, as work sampling often does, it is more economical to randomly sample the work performed than it is to continuously observe the work done. Theoretically, the analyst can perform other work between observations;
- A work sampling study usually is conducted over a longer period of time than a direct observation study. A longer period of time spent making observations helps to ensure that there is no “faking it” for the sake of the study. The results are likely to be more representative of the work actually performed;
- Work sampling studies, because they are based on random observations, can be completed at the discretion of the analyst. There is no need to finish the study while a particular job is being run. The studies can be interrupted with no loss of validity if some other, more pressing need for the analyst comes along;
- Work sampling avoids the tediousness of time study and is, therefore, much easier on the observer;
- Many people feel very uncomfortable when they are watched for a continuous period of time. These self-conscious feelings are not only uncomfortable, but sometimes even distract from the work being performed. Because work sampling requires brief observations, it is often preferred by analysts making the study.

Limitations of work sampling. Although work sampling has many purported advantages, there are also a number of drawbacks. Some of the drawbacks often suggested include the following (Davidson, 1960):

- The results of a work sampling study are not quantifiable in the same sense that direct measurement results are. A work sampling observation, while it can be used in conjunction with historical production figures, is generally acknowledged to not give as good a standard set by a direct observation method such as time study. A work sampling study usually can only describe the general characteristics of operator performance, such as working or not working, or the general type work being performed. There is no way, in this method of study, to determine whether or not an operator is doing the proper work, working in the appropriate way, or using correct procedures.
- The economics of maintaining a study are questionable. Theoretically, anyone can make sample observations once the observation schedule has been established. On a practical basis, the observations are usually made by the engineer or the technologist who designed the study.
- Theoretically, a large number of operators performing different operations can be studied concurrently. However, as a practical matter, it is not cost-effective for one analyst to try to observe operators who are located all over the plant. The analyst can spend the entire working day journeying from one observation site to another.
- Work sampling cannot provide the detailed analysis of work performed that the elemental analysis prepared in time study can, nor can it compete in detail with the descriptions prepared when a predetermined time system is used to set the standard.
- Work sampling identifies the large components of specific jobs. No record is kept, however, of how the job is done or how the job should be done. When time study is used to set rates,

each time some small part of the method changes, the standard must be re-evaluated. When productivity is analyzed using work sampling, the standard methods are not well-defined. Any change in method can have an unknown effect on the time required to complete a job.

- Sometimes, the analyst gets sloppy or lazy. Although this limitation is possible in any work measurement system, it is far more likely to occur when work sampling is used. For work sampling to be effective and reliable, the proper sample size must be observed.

1.7.6 Physiological work measurement

Whatever measurement of physiological work is used, the objective of the measurement is to determine when a person is working and how hard the person is working. When people are resting, they have steady-state physiological characteristics. When physical work is performed, the observed characteristic, whether oxygen consumption, heart rate, or body temperature, increases. When work is completed, these characteristics take some time to return to normal or steady state. This period is commonly called *recovery*.

For workers to produce more effectively, it is necessary for them to either work at such a pace that the physiological measures stay close to normal or steady-state rates or that they be given sufficient time to recover, physiologically speaking, once a task has been completed. Physiological studies can be performed to determine the standards required to meet these conditions.

The three most frequently used measures are:

1. *Heart Rate Measurement*: heart rate, or pulse measurements, are recorded electrically via electrodes affixed to the human body. The rate is recorded at regular intervals and a picture of heart rate as a function of time is obtained. Beats per minute is the common measure of heart rate.
2. *Oxygen Consumption*: oxygen consumption is also a common way to physiologically measure the energy expended by a person at work. The amount of oxygen used indicates how hard the individual is working. This amount is determined by measuring the oxygen content of the air the worker is breathing and then measuring the oxygen content of the air that the worker expels. The difference is used to determine the oxygen consumption rate, which is generally expressed in terms of number of liters of oxygen consumed per minute. Samples of expired air can be taken in specially designed air bags connected to face masks and the relative amount of oxygen present can be determined. One problem of gathering data in this way is in the actual gathering of the sample data. The masks are somewhat burdensome to wear and may interfere with the worker's normal performance of the task.
3. *Metabolic Measurement*: metabolic measurement, performed similarly to the measurement of oxygen consumption, checks the expired air for other indicators of energy used, such as carbon dioxide content. Again, as with the other measures, the purpose of this type of measurement is to determine the energy expended by a worker while performing a task. Ideally, the worker can be trained to perform the task at near to normal or resting levels. If this level cannot be accomplished, tasks that require a large consumption of energy can be identified and appropriate recovery periods can be specified to permit the worker to recover, physiologically, before proceeding with additional work.

Uses of physiological work measurement. Davis et al. (1971), in work performed at Eastman Kodak, identified several potential uses of work physiology in the industrial setting. Some of the applications included:

1. Determining whether a particular job is within the physical capabilities of particular people. This application might be considered the extreme case of fitting the individual to the job. In this case, the physiological requirements of a job must be established, hopefully in terms of one of the common measures. It also requires that all potential workers have their physiological abilities and capabilities measured. Although a significant amount of measurement must be performed, once the data are collected and used in the manner described, the required work can be performed more productively.

2. Identifying the best method to perform a job. Other things being equal, it is better to select a method for performing a job that uses less energy than some comparable method that requires the expenditure of additional physiological energy. Of course, the traditional concepts of work design must be followed in designing alternative ways to perform the job under consideration.
3. Evaluating the work requirements of new or proposed jobs. Simulation of new jobs within a laboratory, while the jobs are being performed under a variety of controlled test conditions, can be helpful in determining the physical demands that may be placed on the worker in an actual production situation. These data can then be used in fitting the job to the best-suited person.
4. Ranking the jobs in terms of actual physical difficulty. This application can provide the basis for evaluation when wage and salary criteria are evaluated. Most job evaluation systems include a factor that pays at least lip service to the concept of evaluating jobs based on difficulty. Physiological measures can provide quantitative support to various assertions about jobs and their relative physiological ranking. They are based on the assumption that performing more difficult jobs requires more physiological energy. This assumption may be especially true of jobs that are categorized as straight physical work.

1.8 Manufacturing Ergonomics

1.8.1 Introduction and Background

Ergonomics can be defined as the study of work. Chaffin and Andersson (1984) further define ergonomics as *fitting the work to the person.* The primary goal of ergonomics is *improving worker performance and safety through the study and development of general principles that govern the interaction of humans and their working environment.* Rohmert (1985) states that ergonomics *deals with the analysis of problems of people in their real-life situations.*

Ergonomics is concerned with the problems and processes involved in designing systems and processes for effective human use, and in creating environments that are suitable for human living and work. Figure 1.3 illustrates how the relationship or "fit" between the worker and the workplace is defined by how the worker interacts with the workplace through tools and controls and how the workplace provides information back to the worker through displays or other instruments.

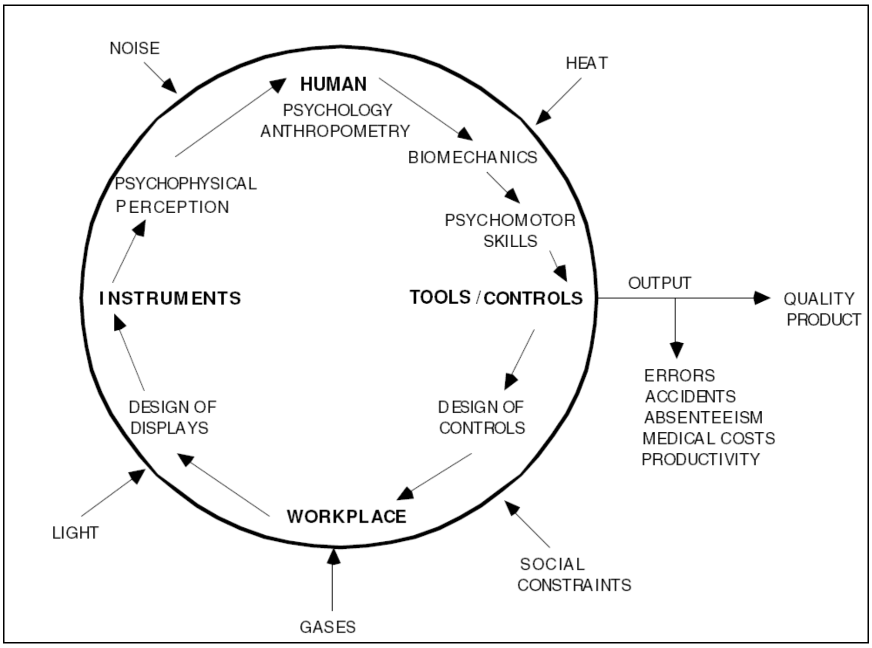


Figure 1.3 - Interface between the human and workplace

Properly designed workplaces, equipment, facilities, and tools can

- Reduce occupational injury and illness;
- Reduce worker's compensation, sickness, and accident costs;
- Reduce medical visits;
- Reduce absenteeism;
- Improve productivity;
- Improve product quality and reduce scrap;
- Improve worker comfort on the job.

Ergonomics can enhance the traditional industrial engineer's work measurement process by blending traditional time study information with health, safety, and worker capability data into a seamless measure of the contemporary workplace. Final productivity figures are often based on the data collected from time measurement studies and on the negotiation process between management and the worker representative. On the other hand, health, safety, and worker capability data are based in measurement of human performance in the workplace and in the laboratory. The ergonomist uses this data to identify elements of the job that reduce the quality of the interface between the human operator and the workstation. A poor interface can cause unnecessary stress to the operator, leading to an increased risk of injuries or an increased risk of errors (which may lead to an accident, poor product quality, or a loss in productivity).

In order to measure stress on the human body, the relationship between disease and exposure must be understood. This relationship is determined through analysis of various exposures and their effect on a target population through epidemiological studies. Measuring ergonomic stress is somewhat similar to collecting an air sample for toxins. An ergonomic analysis must include measurements of the environment, assessment of fatigue, and biomechanical modeling. Through this information, the analyst can *then* review the exposure data and attempt to quantify it into levels of ergonomic risk.

Section 1.8.2 provides a brief overview of key factors that affect the manufacturing workplace in the area of ergonomics.

1.8.2 Manufacturing Ergonomics – Risks

In many cases, ergonomic analysis looks at how the physical design of a particular workstation may affect human performance. In the area of manufacturing, ergonomic analysis often deals with three distinct types of work or activities:

1. Work involving *manual handling* of objects;
2. Work involving *assembly and/or disassembly;*
3. Work involving *machine operation.*

The human body can be thought of as a sophisticated mechanical system. The bones provide a framework to support the various loads on the body. The muscles provide the power to move the frame about the joints through muscle contraction. Tendons attach bone to muscle and convert the muscle contraction to mechanical energy. As muscles contract, the tendons pull the bone around the axis of the joint like a pulley.

The three main generic occupational risk factors associated with ergonomic stress are *force, frequency,* and *stressful postures.* Independently, each factor can lead to ergonomic stress if it exceeds human capability limits. However, combinations of these factors may lead to physical harm even if the independent levels of each risk factor are at or below their individual human capability limits.

- *Force* can be defined as the amount of work that the muscles, tendons, joints, and adjacent tissues must do in order to perform a particular action. The force exerted often depends on a variety of factors, including posture, weight, and friction.
- *Frequency,* often referred to as *repetitiveness,* is a measure of the time required in specific postures. Depending on the amount of force or the type of posture, repetitiveness can be harmful if repeated many times or if held for sustained periods of time.

- *Stressful postures,* when sustained or used repeatedly, can be harmful to the musculoskeletal structure, especially when force is exerted. There are many stressful postures, usually described by body part.

Figure 1.4 shows a simple decision tree that is useful for identifying potential physiological ergonomic stress. This decision tree can be translated into three basic questions that engineers need to ask before designing jobs:

1. *Is the population at risk strong enough to do the job without getting hurt?* This question addresses the instantaneous risk that a person may encounter in performing the job once. The resulting injury is typically biomechanical (strains or sprains) in nature;
2. *Is the population at risk strong enough to do the job long enough, and is there enough recovery time to do it again?* This question addresses the risk encountered performing the job over a period of hours, days, or weeks. The risk often manifests itself as local or whole-body fatigue and/or as biomechanical trauma;
3. *If the job is repeated often enough for an extended period of time, will the population at risk contract cumulative damage?* The current state of the science does not allow an accurate assessment of this question. However, because of the high correlation between questions 1, 2, and 3, reducing risk in 1 and 2 will result in substantial reduction in risk for 3.

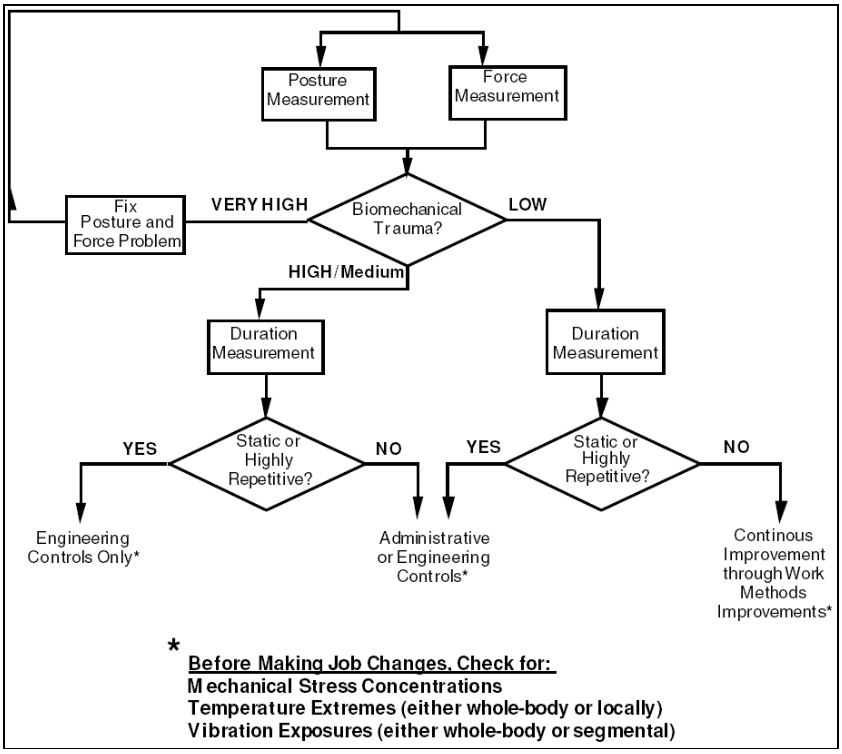


Figure 1.4 - Ergonomic decision tree for biomechanical stress (force/posture and repetition)

Activities Involving Manual Handling of Objects

- ***Fatigue.*** Fundamental to the concept of physical stress is fatigue. Whenever a machine performs work, energy is required. This might be in the form of electrical power, or could be gasoline or some other fuel if an internal combustion engine is used. Similarly, when the human body performs work, energy is also required. The muscles in the body are the "engines," and the "fuel" is the product of a complex chemical conversion process (metabolism) of the food that we eat. This fuel is supplied to the muscles by the cardiovascular system. When the muscles are active and demand more energy resources than can be supplied, fatigue results. There are two basic types of metabolism used by the body. One requires oxygen in the process and is known as *aerobic* metabolism. The other does not require oxygen and is known as *anaerobic* metabolism. The anaerobic process is much less efficient than the aerobic process, but it is usually the first source of energy used by the muscles when the cardiovascular system has not yet had enough time to respond to the muscles' needs with blood flow containing food-stuffs and oxygen to support their activity. There are also two basic types of fatigue experienced by the body. One is *localized muscle* fatigue and the other is *whole-body* fatigue. Localized muscle fatigue is often associated with the anaerobic process and is limited to a particular muscle group that has undergone a sustained (static) exertion or a very repetitive series of exertions with little or no rest. Whole-body fatigue is usually associated with aerobic metabolism and the inability of the person's cardiovascular system to supply enough food and oxygen to meet the energy expenditure rate demand of the working muscles throughout the entire body.

– *Description of Localized Muscle Fatigue.* The oxygen supply (via blood flow) to a muscle is usually sufficient to support aerobic metabolism during moderate activity. However, higher levels of activity may lack sufficient blood flow for aerobic metabolism to produce ATP (adenosine triphosphate) and to carry away anaerobic metabolism waste products. As anaerobic metabolism continues, lactic acid accumulates, foodstuffs in the muscle become depleted, needed ATP levels cannot be maintained, and muscle fatigue develops. For maintenance of muscle contraction without fatigue, sufficient oxygen must be present for aerobic metabolism of ATP. The mechanical action of muscle contraction actually restricts blood flow through the muscle and forces anaerobic metabolism. Figure1.5 displays the increase and then decrease in blood flow as grip contraction increases. Figure 1.6 illustrates that as a muscle is contracted toward its maximum strength, the endurance of its contraction decreases because of the development of localized fatigue. As muscle contraction increases above about 20 percent of its maximum voluntary contraction (strength), blood flow (and the corresponding oxygen supply) falls below muscle demand, requiring further anaerobic metabolism and shortening endurance time. In general, sustained or highly repetitive, forceful muscle contractions approaching or exceeding 20 percent of maximum muscle strength limit the flow of blood to the contracting muscle, resulting in local muscle fatigue and discomfort. Over time, this fatigue will diminish a worker's ability to perform a certain function job.

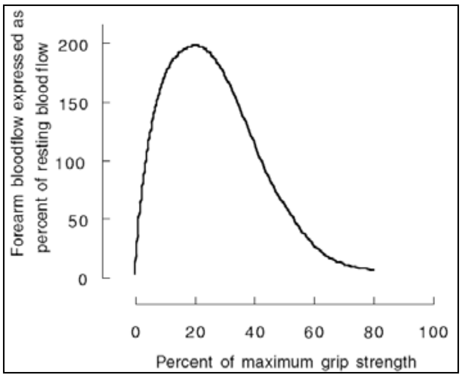


Figure 1.5 - Muscle blood flow versus static contraction level
(adapted from Armstrong, 1983)

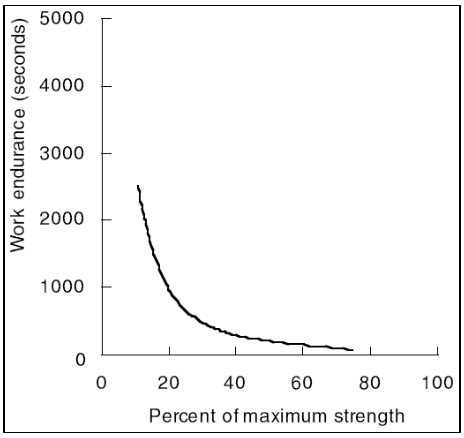


Figure 1.6 - Static endurance time versus load held (expressed as a percent of maximum strength)

- *Description of Whole-Body Fatigue.* Dynamic movements such as walking, load carrying, and repeated load lifting utilize many different muscle groups simultaneously. Unlike static loads or sustained postures, the muscles involved often allow enough blood flow to keep localized muscle fatigue from occurring. However, these dynamic activities requiring many active muscles groups can require large energy expenditures from the body as a whole. When the metabolic energy expenditure rate demand exceeds the body's energy-producing capability (the work capacity of the individual), whole-body fatigue develops and it will diminish a worker's ability to perform a certain function job.

- ***Back Pain.*** Every year, over 2.5 million low back injuries and 1.2 million disabling low back injuries were occurring each year in the United States, and low back pain was the diagnosis of 10 percent of all chronic health conditions (Kelsey et al., 1978; Kelsey and White, 1980). An average 28.6 workdays per 100 workers with low back pain were lost for each case of low back pain (Pope et al., 1984). The overall cost for low back pain has been estimated to be between $4.6 and $11 billion per year (Snook and Jensen, 1984).This cost represents a tremendous loss in productivity, as measured in dollar output per worker, and extremely high levels of human suffering. Anything that can be done to minimize the risk factors and so to reduce the associated incidence of disease will greatly reduce human suffering and costs to industry.

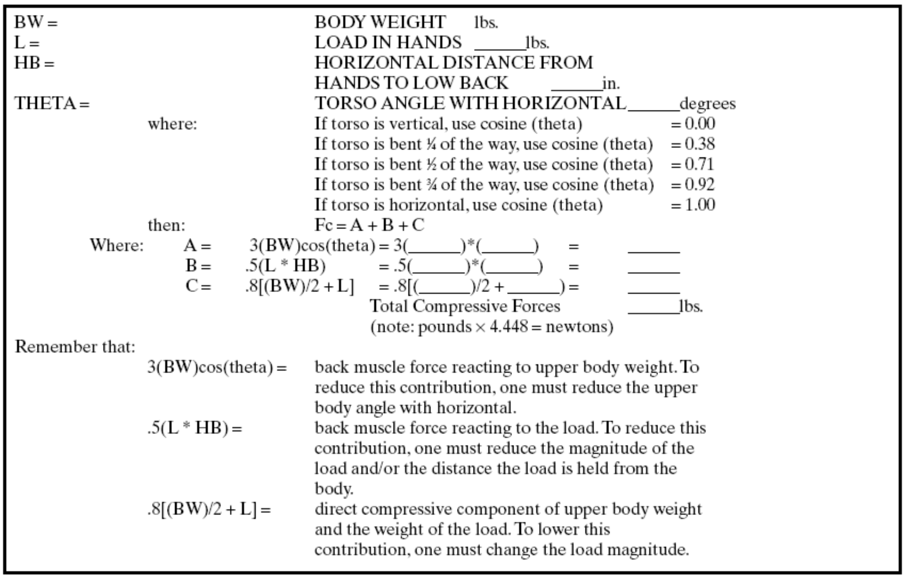
  - *Industrial Risk Factors.* Manual exertions associated with lifting tasks can require excessive strength. Recent studies have shown that the risk of musculoskeletal injuries (e.g., strain, sprains, and back pain) increases when the strength demands of a task exceed the strength capabilities of a worker. These studies also have shown that the risk of low back pain increases when the magnitude of the compressive forces acting on the vertebra and the first sacral vertebra (L5/S1) spinal disk exceeds a threshold level of 770 pounds (Snook and Ciriello, 1991; Keyserling et al., 1980; Waters et al. 1993). Several workplace factors have been shown to contribute to low back pain. These variables are separated into two groups: (1) personal characteristics and (2) task, object, or workplace characteristics. Personal characteristics include age, gender, anthropometry, muscle strength, previous medical history, fatigue, trauma, socioeconomic and emotional status, personality, congenital defects, and genetic factors (Waters et al., 1993; Yu et al. 1984). Workplace factors associated with low back pain include lifting, bending, static work posture, slips and falls, vibration, and trauma (Yu et al., 1984). NIOSH (Waters et al., 1993) lists the following factors as important to low back pain:

    1. Lifting of heavy objects
    2. Lifting and moving bulky objects
    3. Lifting objects from the floor

4. Lifting objects frequently
5. Twisting with loads
6. Poor coupling between the hands and the loads

The six factors suggest four types of risk: (1) the weight or force required to lift the object, (2) the distance the object is located from the body at the beginning and during the lift, (3) the frequency of lifts, and (4) the amount of lateral twisting when moving loads. Additionally, manual material handling jobs that require excessive amounts of strength, regardless of the weight of the object moved, can increase the risk of injury (Chaffin et al., 1978). These risk factors indicate that excessive loads on the back are a primary cause of injury.

- ***Shoulder Pain/stress***. Stresses at the shoulder are also frequently of concern in manual material handling tasks. The shoulder moment resulting from a particular load (and resulting shoulder stress) can be estimated if some simplifying assumptions are made. The moment at the shoulder depends on the weight of the load, body weight (arm weight), and the distance that these two weights are located in front of the point of rotation (shoulder). Figure 1.7 is a worksheet that can be used to calculate shoulder moment using this simple model (English units only). Substitute BW, D, L, into the equation to estimate the total moment required at the shoulder (M_{task} expressed as in-lb).



BW = BODY WEIGHT lbs.
L = LOAD IN HANDS ______lbs.
HB = HORIZONTAL DISTANCE FROM
HANDS TO LOW BACK ______in.
THETA = TORSO ANGLE WITH HORIZONTAL______degrees
where:
If torso is vertical, use cosine (theta) = 0.00
If torso is bent ¼ of the way, use cosine (theta) = 0.38
If torso is bent ½ of the way, use cosine (theta) = 0.71
If torso is bent ¾ of the way, use cosine (theta) = 0.92
If torso is horizontal, use cosine (theta) = 1.00
then: Fc = A + B + C
Where: A = 3(BW)cos(theta) = 3(______)*(______) = ______
B = .5(L * HB) = .5(______)*(______) = ______
C = .8[(BW)/2 + L] = .8[(______)/2 + ______) = ______
Total Compressive Forces ______lbs.
(note: pounds × 4.448 = newtons)

Remember that:
3(BW)cos(theta) = back muscle force reacting to upper body weight. To reduce this contribution, one must reduce the upper body angle with horizontal.
.5(L * HB) = back muscle force reacting to the load. To reduce this contribution, one must reduce the magnitude of the load and/or the distance the load is held from the body.
.8[(BW)/2 + L] = direct compressive component of upper body weight and the weight of the load. To lower this contribution, one must change the load magnitude.

Figure 1.7 - Simple low back compressive force prediction model worksheet.

There are no generally accepted limits with which the estimated shoulder moment may be compared. Two of the variables that determine the shoulder moment that individuals may be able to generate on a task are *gender* and *arm posture.*
The metric proposed as a measure of the stress at the shoulder is the ratio of the shoulder moment required by the task, as calculated by the worksheet (M_{task}), and the maximum strength of an average male/female in that posture (M_{cap} - calculated on the basis of specific tables).While there are no empirically determined acceptable limits for this ratio, it is proposed that ratios below 0.5 (task-required shoulder moment is less than half of the maximum for the average male/female) will not present a hazard for most workers unless the frequency is quite high, while ratios above 1.0 (task-required shoulder moment exceeds the maximum for the average male/female) will present a hazard for many members of the workforce..

Activities Involving Assembly and/or Disassembly Activities
When designing or redesigning jobs to control *cumulative trauma disorders* (CTDs), one must measure the risk factors associated with the design for two reasons: first, it is important to analyze the

jobs to identify the problems that need intervention to correct. Second, once corrections have been made, it is important to determine the effectiveness of the redesign in reducing the degree of risk. Since very little research has been completed showing which risk factors or interaction of factors contributes most to the development of disease, the most reliable way to measure the risk of injury is to measure all the risk factors. A summary of the major risk factors and corresponding measurement systems for the upper extremity follows.

- ***Risk Factors.*** Although there are a large number of cumulative trauma disorders, many are caused by the same or similar work activities. In general, the occupational factors that can increase the risk of CTDs include: repetitiveness, forcefulness, awkward postures, vibration, mechanical stress concentrations, and cold temperatures. Of these factors, the first three are probably the most important. The more risk factors that are present in a single job, the greater the potential for injury. Although it may not always be possible to eliminate all of the risk factors from the job, the more that can be eliminated or reduced, the better. The impact of each of these factors is as follows:

  - *Repetitiveness:* the traditional way to measure repetitiveness is simply to count the number of cycles occurring during a shift. On the basis of this definition, jobs with short cycle times are more repetitive than jobs with longer cycle times because they require the operator to repeat the operation more often. A study conducted by Armstrong et al. (1985) considered cycle times shorter than 30 seconds (jobs with 1000 or more cycles per shift) as being highly repetitive. Jobs with cycle times greater than 30 seconds often require the operator to make many similar repeated motions within the cycle. In such cases, measuring the number of cycles per shift may not be an adequate method of measuring job repetitiveness. Consequently, the concept of *fundamental cycles* was developed. Fundamental cycles are defined as a repeated set of motions or elements within a cycle. Jobs with a high percentage of the cycle time (50 percent or more) spent performing the same fundamental cycles are considered as repetitive as jobs with a cycle time of less than 30 seconds (Armstrong et al., 1985). Cycles and fundamental cycles together constitute one classification system for repetitiveness. But this system considers only the speed at which the operator is performing the job, not the actual movements. Repetitiveness could also be measured in terms of the number of movements or posture changes per shift. Several studies have associated movements with the prevalence of CTDs. Hammer (1935) found that jobs requiring greater than 2000 hand manipulations per hour were associated with the development of tendonitis. Repeated wrist flexion and extension have been correlated with carpal tunnel syndrome (Armstrong and Chaffin, 1979; Brain and Wilkinson, 1947; Phalen, 1966; Tanzer, 1959).
  - *Forcefulness:* forcefulness is the amount of effort required to maintain control of materials or tools. A number of factors will affect the amount of force that an individual can exert:

    - *Type of Grip:* the two basic types of hand grips are the *power grip,* or *full hand grip,* and the *pinch* or *fingertip grip,* as shown in Fig. 1.8 the strength of a power grip is four or more times greater than a pinch grip;
    - *Type of Activity:* types of effort activity include *lifting, lowering, pushing, pulling, carrying,* and *holding.* The forces that can be maintained for these activities are highly dependent on body posture, type of grip, duration, and repetitiveness of the activity;
    - *Posture:* effects of posture on forcefulness include the location of the hands with respect to the body when a force must be exerted, whether one or both hands are used, and the direction in which the force is applied.

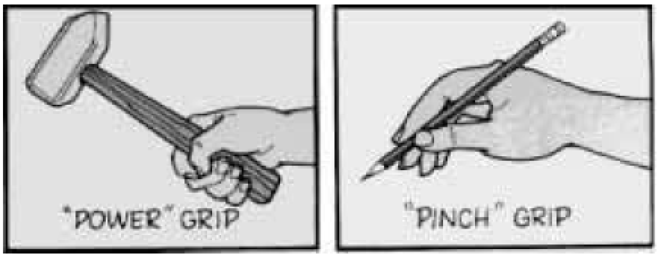


Figure 1.8 - Power versus pinch grip

- *Duration and Repetitiveness:* the longer the duration or length of time that the force must be exerted, along with the more repetitions required, the lower the exertion force that can be maintained without injury and fatigue. Force can be measured in a variety of ways—most simply by weighing objects. But depending on the size of the object, the grip type, grip surface, and other factors, the force requirements may change. Consequently, this method does not give any indication of the actual force required to hold the object in the hand. Therefore, a system that directly measures actual hand force is necessary. One such system incorporates the use of *electromyography* to measure muscle activity in the finger flexor muscles of the forearm. Electromyography (EMG) essentially measures the motor unit potential of twitching muscle fibers (Chaffin and Andersson, 1984). As muscle tension increases, EMG activity increases concurrently (Lippold, 1952; DeVries, 1968; Bouisset, 1973). Because of this relationship, it is possible to make a reasonable estimate of muscle force (in this case grip force) by measuring EMG activity.
- *Awkward Postures:* the ideal working posture shown has the elbows at the sides of the torso, the wrists straight, and a power grip (figure 1.9).Working postures that involve reaching up, out, or behind the body and bending or twisting of the wrists will increase the potential for CTDs.

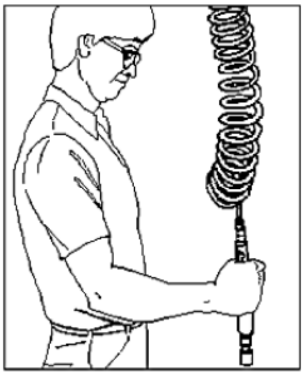


Figure 1.9 - Optimum working posture

The measurement of the number of movements or posture changes during a shift requires the accurate recording of postures during a job cycle. A system for posture targeting developed by Armstrong (1983) and based on the work of Corlett et al. (1979) divides the upper extremity into its individual joints and defines their position in space with reference to the body. The positions of the joints are analyzed for each degree of freedom of movement, including three degrees of freedom for the shoulder and two for the elbow and wrist. Because it is impossible to analyze the angles of each joint to the nearest degree, zones or ranges of angles are used to estimate the position within a specific range. This analysis allows the categorization of postures into zones of stressfulness..

- *Vibration:* the prolonged use of many types of vibrating tools, especially in combination with awkward postures and cold environments, can adversely affect worker health, potentially causing damage to nerves, blood vessels, and bones.

- *Mechanical Stress Concentrations:* stress concentrations over the soft tissue structures of the hand can result from poorly designed hand tools that dig into the base of the palm or fingers, the handling of sharp objects, or using the hand as a hammer. These activities compress the nerves and blood vessels in the hand, contributing to a number of CTDs. Likewise, mechanical stress concentrations can also occur at the elbow if it is resting on or rubbing against a hard surface for long periods of time.
- *Cold Temperatures:* cold temperatures can decrease the sensory feedback to the hands. This in turn increases the force or strength requirements of the job. This can also increase the risk of operators dropping or losing control of tools or materials, creating a potential hazard for the individual or other workers in the area.

1.8.3 Manufacturing Ergonomics - Cost and Benefit

Currently, in most manufacturing facilities, all business projects must go through normal purchasing channels to be approved for funding. Unless costs are nominal, these projects must be reviewed for cost/benefits. Funding is awarded based on traditional cost/benefit analysis calculations and expected savings due to either work standards, work practices, or quality.

It may be difficult to use traditional cost systems to justify an ergonomics project. This is because ergonomics projects often do not show significant savings, in the traditional sense, immediately after installation. Instead, the type of savings often seen in ergonomic projects are reductions in health care costs. And these can be difficult to justify if the relationship between injuries and the responsible jobs is not well established.

This lack of an obvious link between an injury and a job yields two results: first, medical costs associated with worker accidents and chronic musculoskeletal disorders are usually not charged directly to the production department responsible for causing the injury. Instead, they are charged to a separate central account in the plant's Industrial Relations Department (or equivalent), thereby partitioning the true costs over the entire plant. This makes it difficult to justify a job change because the benefits are hidden. Second, projects often have to be justified on the basis of traditional cost/benefit analysis and computed in terms of plant wide and area productivity (e.g., completed pieces per hour).

The following is a list of some of the costs involved in installing new equipment. All these costs should be considered in order to accurately determine the costs of implementing ergonomics projects and changes on the plant floor. It is recommended that a form be developed that records these costs for later analysis.

1. *Design time:* the time and resources involved in designing projects;
2. *Engineering time:* the time and resources involved in engineering the project;
3. *Tool change:* the fabrication costs and time necessary to fabricate a set of tools for the project;
4. *Skilled trades time:* manpower needs for installing, testing, and maintaining the project;
5. *Materials:* cost of materials for the new project;
6. *Machine downtime:* if the project is going to directly affect an existing line, that line may have to schedule downtime to properly install the project. Therefore, downtime and lost production must be budgeted into the installation costs;
7. *Training:* when new equipment and/or processes are implemented on the plant floor, operators responsible for running and maintaining the equipment must receive training.

In summary, figure 1.10 depicts the relationship between the cost and benefits of ergonomics. Because of the problems of using traditional cost/benefit analysis, it becomes more important to document all of the costs associated with poor job design and all the benefits after ergonomic intervention. Therefore, it is often best to make simple, inexpensive changes first. As poorly designed jobs are identified, the data (as previously outlined) should be collected and analyzed before and after the proposed job changes. As more data is collected and the cost/benefit equation becomes better defined, it should be easier to justify job changes.

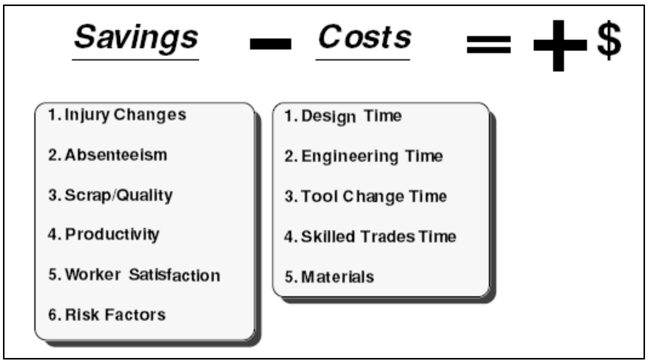


Figure 1.10 – Cost/benefit summary

1.8.4 Overall Ergonomic Program

A well-defined and documented ergonomics program should be in place for any manufacturing system. This program can vary in size and scope depending on the size of the company. However, each part of the program should be considered as to how it would be handled within the context of the manufacturing system.

There are seven main steps to a comprehensive ergonomics program:

1. Employee and workplace audit;
2. Ergonomic evaluation;
3. Ergonomic redesign of workplaces, methods;
4. Ergonomic program organization;
5. Education and training program;
6. Fitness and rehabilitation program;
7. Reporting, feedback, and follow-up.

The second step, ergonomic evaluation, will be discussed in detail in a subsequent section.

A brief description of each element or step is presented as follows. The second and the third steps (ergonomic evaluation and ergonomic redesign of workplace, methods) will be discussed in detail in the section 1.9.5 and 1.9.6.

1. Employee and Workplace Audit

The audit will document work practices of the employees through the aid of employee feedback and by the physical observation of the design and method. The relationship between employee feedback and workplace design observation, versus injury history, will be determined from this audit. From the audit, a list of operations that should receive immediate attention regarding improvements will be made.

2. Ergonomic Stress Evaluation

The ergonomic stress evaluation of the operations on the list will be made using a variety of tools. Ergonomic problems can then be identified and pinpointed during this step. This topic will be discussed in great detail later in this chapter (section 1.9.5).

3. Ergonomic Redesign of Workplaces and Jobs

Based on the results of the audit and ergonomic stress evaluation, the products, workplace, and jobs may have to be redesigned or controlled to meet human aspects and requirements. This activity will integrate the ergonomic component with an engineered process for productivity improvement. A combined effort to improve both the job ergonomics and economics could result in synergistic effects and attractive cost reductions.

To the greatest possible extent, the objective of this phase is to adapt the physical and organizational work conditions to better fit the human physiology. Ideal operator positions (sitting and standing) can be defined and applied in the design and modification of workplace. Some ergonomic methods for ergonomic redesign of workplace and job are presented in section 1.9.6.

4. Ergonomics Program Organization

It is critical to obtain the commitment and support of top management to implement an ergonomics program. Such a program will affect all employees in an organization, so it is essential to establish a project organization to support this.

A steering committee will set the direction, review the project, and make necessary decisions. An ergonomics coordinator will be responsible for the projects and activities relating to ergonomic evaluations and improvements. This person will report to the steering committee. Involvement by the safety, union, engineering, maintenance, and medical departments is required.

5. Education and Training Program

To increase the awareness and understanding of ergonomics in the workplace, training on all levels of the organization will be structured and carried out. The relationship between job design and employee health will be reviewed as well as methods to reduce the risk of injury. The employees will be encouraged to discuss problems and improvement ideas pertaining to their own workplaces and jobs with management and/or the ergonomics coordinator. It is important to make training sessions and training material simple and understandable for all employees.

6. Fitness and Rehabilitation Program

By consulting with a human kinetics or a kinesiology professional in a medical department, a fitness program will be developed to improve individuals' physical capability as well as their psychological awareness and motivation to participate in the program.

The human kinetics or a kinesiology professional will also prescribe rehabilitation procedures for those individuals who have experienced a CTD or any other injury.

7. Reporting, Feedback, and Follow-up

The ergonomics program is a continuous improvement program linked to other industrial engineering programs such as productivity improvements and is based on methods engineering.

To assess the progress and results of ergonomic efforts, a reporting and feedback system is developed to include employee feedback and injury monitoring. To ensure a safe work environment, a comprehensive approach to ergonomics must be established within a facility. This approach will ensure that

- Proper avenues for employee involvement and feedback are developed;
- Problems are properly identified, evaluated, and remedied;
- All of the effected parties (human resources, employees, engineering, union) can be involved in the process.

By following this program organization, all aspects of the ergonomic process will be considered. Problems and concerns will be properly identified, evaluated, and remedied, thus providing the company with valuable means to protect the workforce.

1.8.5 Ergonomic Evaluation

Previously in an employee and workplace audit, a list of potential jobs associated with an ergonomic problem would have been identified through injury history, workers' complaints, and absenteeism records. *An ergonomic problem exists when there is a poor match between a person's physical capability and job demands.* This is why we need to perform an ergonomic evaluation. Ergonomic problems can be very simple to identify, and other times very difficult. Even for what may appear simple, there may be many remedies.

For example, if *a package the operator is lifting is too heavy,* preliminary observation will provide some obvious remedies. One may be to reduce the package size to within operator capability; this may reduce the severity of each single lift. However, the impact on the rest of the system may be an increase in quantity of packages, packing material, and more labor to handle more packages, therefore raising the overall product cost in terms of labor and material. Another remedy may be to use a material-handling device (lift assist) to reduce the weight of the package to the operator. This remedy does not increase the number of packages and packing material in the rest of the system, but still may use more labor since these devices generally slow the operator down as compared with the manual method.

To thoroughly investigate possible remedies to an ergonomic problem, a structured approach should be taken to ensure that the proper consideration is given to the problem. Based on the diverse and complex nature of the problem, some aspects will be more thorough than those for less complex problems.

There are six basic steps to performing a thorough ergonomic evaluation:

1. Preliminary information gathering;
2. Instruments for data collection;
3. On-the-job observation, operator self-evaluation, data collection, and posture analysis;
4. Ergonomic analysis;
5. Documentation.

All of these steps are essential to performing a thorough ergonomic evaluation. The difference between a simple and a more complex problem is the quantity of work for the analyst at each step. A detailed breakdown of each step is presented as follows:

- **1. Preliminary Information Gathering**

This is a preparation step to a good analysis and is many times overlooked. Here we need to collect information about the job:

- First, develop a layout of the job from the top and side views as required. The layout should be to scale and include all operator interfaces, buttons, switches, levers, heights, and locations of all items that the operator needs to perform the task;
- Next, detail the job instruction demonstrating a proper method. This method should include all the tools the operator needs to perform the job, corresponding frequencies, and the time it takes to do each task. This method may be available from the predetermined time system (such as MOST® or MTM) used to develop the labor standard;
- Understand the history of the job. Are there medical reports with cases of injuries relating to this job? What are the details of injuries? Is this a new employee just getting used to the job?
- Gather information on operator-specific issues. What is the current history of the operator to be observed? Does the operator have an injury or restrictions?

- **2. Instruments for Data Collection**

From preliminary information gathering, determine what tools to use to collect good data. Some of the tools are:

- Force gauge - to measure the push, pull, lift, and carry forces;
- Temperature gauge - to record ambient temperature (environmental condition);
- Grip strength gauge - an indirect way of measuring grip force;
- Light meter - to measure available light to do the task (environmental condition);
- Measuring tape - probably the most important instrument to verify all workstation dimensions (e.g., heights, reach, the height of the employee);
- Stop watch - to verify the cycle time of the tasks;
- Video or still camera - to assist method and posture analysis by others away from the actual job.

- **3. On-the-Job Observation, Self-Evaluation, Data Collection, and Posture Analysis**

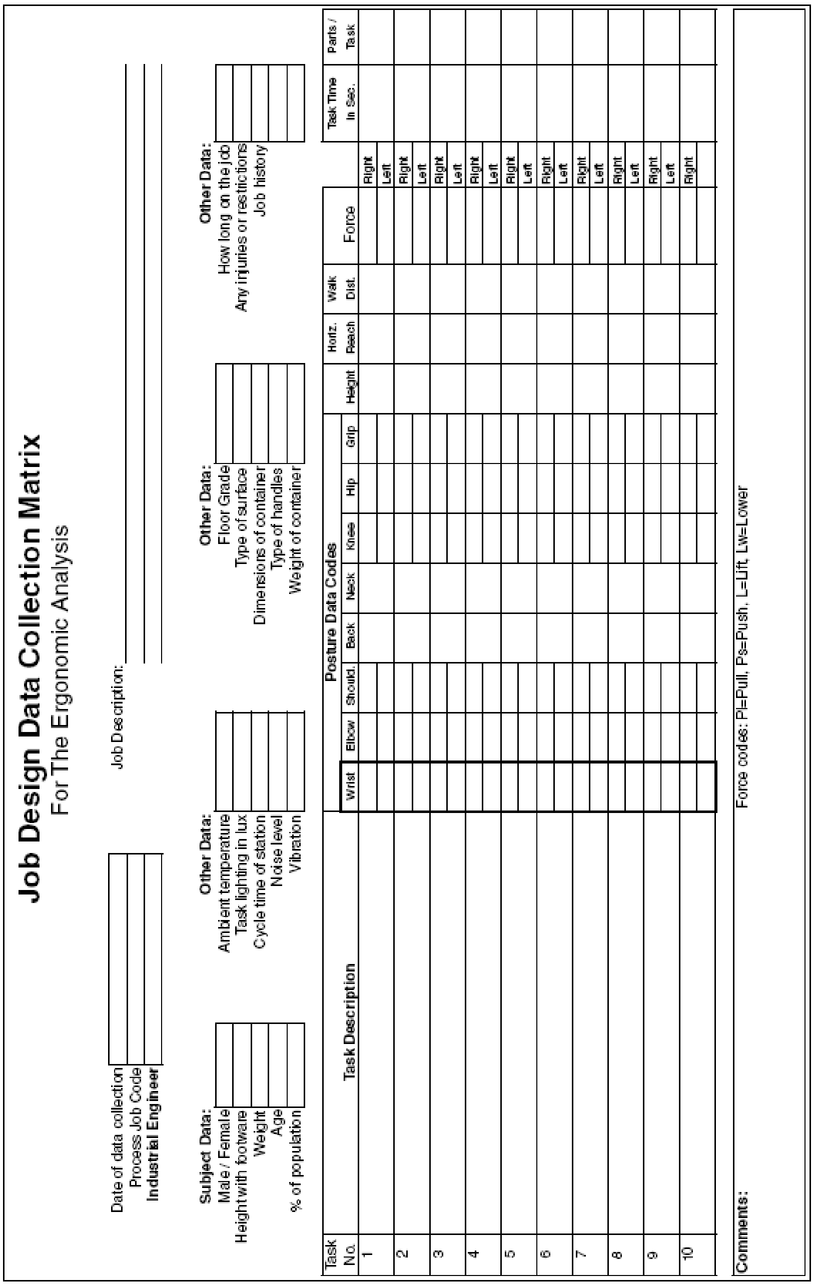
On-the-Job Observation. This is probably the most important step. When recording postures, it is very important to know the operator overall height (stature), anthropometric data, elbow height, and shoulder height. Depending on the severity and resources available, it is a good idea to take still pictures or to videotape the job so that it can be used in laboratory analysis later. Here you could have others observe the job without disrupting it. Some care should be taken in making a video to ensure the camera is level and pointed perpendicular to the operator. It would also be helpful to have some dimension markers on objects.

Operator Self-Evaluation. Every analyst should talk to multiple operators and get their input. You may discover that the problem is other than ergonomic such as a problem with the supervisor or a home recreational physical activity. The operator will tell you where it hurts, when it hurts, and how much effort they perceive it takes to do each step of the job. One possible tool here could be the overall rating of the perceived exertion or the overall rating of physiological effort: Borg Scale (Wilson and Corlett, 1990).

Data Collection. The Job Design Data Collection Matrix, as shown in figure 1.11, is used to aid in an ergonomic analysis. This data collection matrix allows a user to collect information for the ergonomic evaluation tools used in this study, which are explained later.

The evaluation tools that will use this data collection matrix are:

- RULA (rapid upper limb assessment) (McAtammey and Corlett, 1993);
- NIOSH's two-handed dynamic lifting (Waters et al., 1994);
- University of Michigan's 2D, 3D static analysis (University of Michigan Center for Ergonomics, 2D Static Strength Prediction Program, 3D Static Strength Prediction Program);
- Snook and Ciriello's push/pull/carry tables (Snook and Ciriello, 1991);
- ErgoMOST (Maynard and Company, Inc.);
- University of Michigan's Energy Expenditure Prediction Program (University of Michigan Center for Ergonomics, Energy Expenditure Prediction Program).



Job Design Data Collection Matrix
For The Ergonomic Analysis

Date of data collection	
Process Job Code	
Industrial Engineer	

Job Description: ____________________

Subject Data:

Male / Female	
Height with footware	
Weight	
Age	
% of population	

Other Data:

Ambient temperature	
Task lighting in lux	
Cycle time of station	
Noise level	
Vibration	

Other Data:

Floor Grade	
Type of surface	
Dimensions of container	
Type of handles	
Weight of container	

Other Data:

How long on the job	
Any injuries or restrictions	
Job history	

Task No.	**Task Description**	**Posture Data Codes**								Height	Horiz. Reach	Walk Dist.	Force		Task Time In Sec.	Parts / Task
		Wrist	Elbow	Should.	Back	Neck	Knee	Hip	Grip							
1														Right Left		
2														Right Left		
3														Right Left		
4														Right Left		
5														Right Left		
6														Right Left		
7														Right Left		
8														Right Left		
9														Right Left		
10														Right		

Force codes: Pl=Pull, Ps=Push, L=Lift, Lw=Lower

Comments:

Figure 1.11 - Blank data collection matrix

Posture Analysis. Posture analysis is a very important part of an ergonomic evaluation because there is a great variation in what type of force the body can handle due to the posture that the body is in. Posture analysis is probably the most difficult step in the data collection process, and having a video or still pictures for further analysis would make this step easier.

- **4. Ergonomic Analysis**

After you have filled in the Job Design Data Collection Matrix, you need to do an ergonomic analysis. The following is a list of some major and most widely used tools industrial engineers should consider for their ergonomics toolbox:

- Anthropometric data analysis;
- Upper limb checklist: RULA method;
- Load limits for lifting: NIOSH 81 and NIOSH 91 lifting equations, Burandt Schultetus analysis;

- Lumbar spine forces and strength demands analysis: University of Michigan’s 2D, 3D analysis;
- Push/pull/carry analysis: Snook and Ciriello method;
- Force, posture, repetition, grip, and vibration ergonomic analysis: ErgoMOST;
- Metabolic energy cost analysis: University of Michigan’s Energy-Expenditure, Garg analysis;
- Posture analysis: Ovako Working Posture Analyzing System (OWAS);
- Occupational Repetitive Action methods (OCRA).

These tools will be discussed in further detail in Chapter 2.

- **5. Documentation**

In today’s competitive market, companies are striving to achieve different levels of ISO [14] certification. This is one of many reasons to have a documented ergonomic process. If the first step in the ergonomic evaluation is to fill out the Job Design Data Collection Matrix, then it is important to control this document and have a central location for all records of evaluations. This documentation will prove to be beneficial if you have more than one analyst, and also give you the ability to correlate future injuries to job design parameters. To demonstrate a good process you need to document what you do, and do what you have stated in your documentation.

1.8.6 Methods for ergonomic redesign of workplace and job

The aim of this section is twofold: to present (1) some existing *ergonomic methods* that may be used by the engineer to predict mechanical exposure and (2) some *production analysis methods with ergonomic inferences* to suggest an approach for combining ergonomic and engineering methods.

Ergonomic redesign method

- *Anthropometrics in Workplace Design***.** By use of anthropometric data (figure 1.12), the physical dimensions of a workplace can be matched to human requirements. Anthropometric data for different populations may be found in the literature (NASA, 1978; Pheasant, 1996). In addition, sets of drawing templates exist to help the workplace designer. Anthropometrics is often used in workplace design to create a healthy workplace and to increase efficiency. The use of anthropometry may result in a well-designed workplace from a static viewpoint. *Dynamic* anthropometric data (e.g., concerning functional strength in different body regions) may also be included (Chaffin and Andersson, 1991). However, these procedures are directed only toward the exposure level and do not consider the duration and repetitiveness of the work performed.

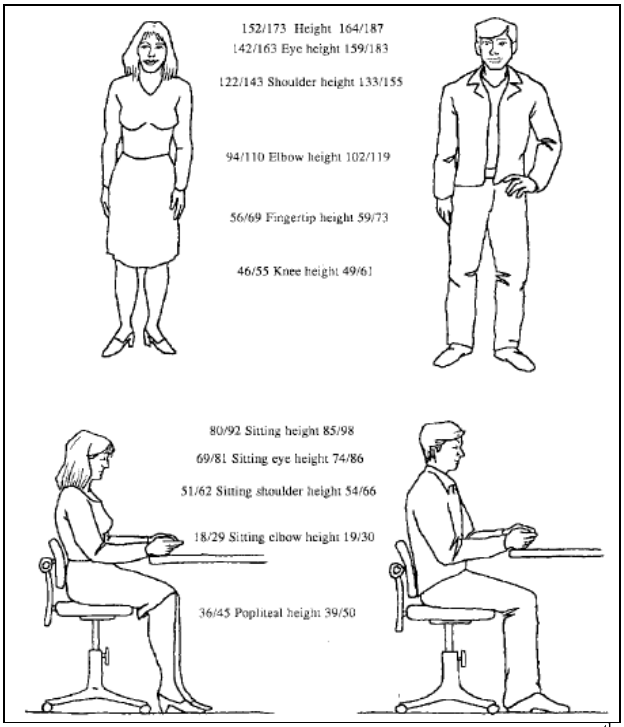


Figure 1.12 - Anthropometric measures for average U.S. adults (5th/95th percentiles for women and men in cm)

- *Biomechanics.* In simple biomechanics, methods from mechanical physics are applied to the human body. It may be seen as an extension of anthropometrics, since it combines information on external loads with data on body dimensions and posture (Chaffin and Andersson, 1991). Simple biomechanical models provide estimates of loads and torques to the body that may be useful in assessing ergonomic demands. In principle, biomechanical data can be obtained continuously during a work operation as a basis for assessing the level, duration, and repetitiveness of the exposure. Most often, however, biomechanical calculations are restricted to snapshot situations that are considered to be representative. In this case, only the exposure level is obtained. More elaborate biomechanical models that predict the activity in individual muscles during work have been developed. So far, however, these techniques are complicated and of questionable practical value.

- *Checklist Methods*. Workplaces may be designed and evaluated by use of checklists (Kuorinka and Forcier, 1995). Many checklists are intended for trained ergonomists, however, and may be less useful for engineers without ergonomic experience. The Nordic Council of Ministers has published a model for evaluation of exposure (Hedén and Bjurvald, 1995). Checklists may be a valuable tool for highlighting ergonomic problems, but normally are not useful at a detailed level.

- *Computer-Aided Design (CAD) Models.* During the last 10 years many computer-based mannequin models have been developed (Karwowski et al., 1990). The mannequins are based on the same anthropometric data as may be found in printed tables, but they offer many advantages. Most important, the mannequin may be integrated in an ordinary CAD drawing and included in the visualization of the final result. Another advantage is the option of incorporating biomechanical evaluations in the program. As in the case of classical anthropometry and biomechanics, a drawback is that most programs consider only the static mechanical exposure level, disregarding the aspects duration and repetitiveness.

- *Task Analysis.* Task analysis is a common procedure in ergonomics, as it is assumed that different tasks are associated with different mechanical exposures. Thus, the job exposure of an individual worker may be assessed by decomposing the product cycle into well-defined tasks with known exposure. The assessment of the prevalence, frequency, duration, and distribution of different tasks may be accomplished by observation techniques or by analyzing video recordings, or it may be made by the workers themselves (e.g., in a diary). Tasks may be categorized at different levels of detail depending on the aim of the analysis.

- *Estimated Oxygen Uptake.* A task analysis may be combined with data on energy demands in each task in order to estimate the total energy demand associated with a job. Task exposure data may be obtained from the literature (Garg et al., 1978) and weighted according to the occurrence of the task in the job or product cycle. This method will consider repetitiveness only at a very crude level and is relevant only for heavy work requiring activity involving large muscle groups.

- *Direct Technical Recordings.* Direct technical recordings (i.e., methods based on measurement devices fixed to the body) can be used if detailed information on mechanical exposure is required [9].All three exposure dimensions - level, duration, and repetitiveness - can be assessed in this way, since direct methods can provide continuous recordings of exposure. Some of these methods are presented as follows:

  - ***Electromyography.*** Surface electrodes picking up muscle electricity can be used for assessing muscular load in field studies. Computer programs for signal quality control and normalization are available. Typical exposure variables are load distributions, durations of muscular rest, and patterns of load variation.
  - ***Goniometry.*** Joint angles (independent of gravity), for instance at the wrist, can be assessed by goniometers (angle transducers). By means of computer programs, it is possible to derive distributions of wrist angles and angular velocities, as well as power spectrums. These data, in turn, can provide information on extreme positions, median and peak velocities, and measures of repetitiveness. Information on joint angles can also be obtained by optical systems. For example, reflectors are placed on the body and followed on a videotape.
  - ***Inclinometry.*** Angles of body parts relative to the line of gravity are measured as an expression of working postures, using transducers based on pendulums or electrolyte solutions. A common approach is to arrange two inclinometers perpendicular to each other to get angles in the three-dimensional space. Dynamic accelerations can be assessed by accelerometers, which will also provide information on positions and movements of, for example, the head, back, and upper arms.

Production analysis methods with ergonomic inferences

- *Zero-Based Analysis.* One method for designing production systems is the so-called zero-based analysis (Engström et al., 1996), originally based on work by Wild (1975) in which performance aspects of the assembly line were quantified. Traditionally, engineers use mean operation times based on time-and-motion studies when determining work cycle times and do not pay sufficient regard to the effects of the variation between and within workers in pace and efficiency when performing repetitive work. Furthermore, the amount of work to be performed at each workstation will vary between work cycles and workstations on account of differences in product variants. There will also be process variation caused by, for example, tools and mechanized equipment. These variations introduce losses into the production system in the form of rework, waiting times, extra space, low quality, and so on. The principle of zero-based analysis is that the actual resource consumption (for example, in the form of human work) is estimated and, compared with the consumption required in an ideal production system, free of losses. Thus, this method highlights the important resources from a value-adding perspective. It allows a determination of rationalization potentials, as well as comparisons between different manufacturing system designs. Zero-based analysis may be founded on different types of data, including *secondary data* (e.g., budget figures or figures from method-time measurement [MTM] analyses) and *primary data* (e.g., video recordings). In the latter case, the video-recorded work is decomposed into tasks and operations, which are then analyzed in terms of necessary and excessive time consumption. Since tasks and operations may be associated with known mechanical exposures, as outlined previously, the consequences of intervention may in principle be predicted by combining the mechanical exposures of tasks remaining after, for instance, a change.

- *Predetermined Time Systems.* Predetermined time systems (PTS), for example MTM, have been developed to assess the duration of work operations and tasks on the basis of movement times. Since, however, several of the factors influencing the duration of movements (e.g., distance and object weight) are known also to affect mechanical exposure, it seems reasonable to expect that an MTM categorization may also produce valuable ergonomic information. Preliminary studies have indicated that this is indeed the case. In addition, work pace as quantified by an MTM analysis has been shown to influence mechanical exposure - a higher pace giving larger exposure levels and faster load changes. On the other hand, several factors known to influence exposure are not taken into consideration in the MTM system (e.g., working height).Thus, more diversified PTS, including operation categories with an ergonomic rationale, might become a powerful and easy tool for ergonomic assessment of systems in the planning phase. A similar idea has been adopted in the ErgoMOST system, in which ergonomic information quantifying and evaluating the stress of operations is linked to the MOST analysis (Zandin et al., 1996).

Chapter 2

Effective Workplace Design: A State of the Art Overview

Over the last two decades, researchers and practitioners have devoted considerable resources to solve the problems associated with the effective design of the working environment. Many theories, principles, methods and data relevant to the workplace design have been generated through research activities. It is the intent of this chapter to provide the reader with an accurate overview on the main scientific approaches proposed by researchers and scientists working in this specific area. In particular, three main scientific approaches have been identified: the first and the second are based on the use of ergonomic and work measurement methodologies; while the third one deals with the integration of ergonomic and work measurement methodologies with the most widely used Modeling & Simulation (M&S) tools. The identification of several research shortages on this area concludes the chapter.

2.1 Introduction

An ergonomic approach for the design of industrial workstations is the attempt to achieve an appropriate balance between the worker's capabilities and worker's requirements as well as provide the worker with physical and mental well-being, job satisfaction and safety (Das and Sengupta, 1996). Designers of workplaces have usually three major tasks: one, integrating information about processes, tools, machines, parts, tasks, and human operators; two, satisfying design constraints which often conflict; and three, generating a design acceptable to all parties involved. However, while completing these tasks, designers often have difficulty incorporating ergonomics information about the human operators into their designs. Note that, although today the tasks or processes are being mechanized or automated as the technology has advanced, many tasks are still performed manually in several industrial settings (Chung and Kee 2000). In this context, it seems to be clear that matching the abilities of the operator with the task requirements as well as with working environment physical constraints are important aspects to be faced within the effective workplace design.

This chapter supplies an accurate overview on the main scientific approaches proposed for facing the workplace design issue. Each scientific approach will be presented through a detailed description of the research works and articles it involves.

2.2 Ergonomics for Effective Workplace Design

A number of studies in literature try to achieve the ergonomic workplace design by using ergonomic methodologies for investigating and analyzing the interaction of the operators with their working environment and the work methods. Among the ergonomic methodologies, the following has to be regarded as the most widely used: (1) anthropometric data analysis, (2) RULA method, (3) NIOSH 81 and NIOSH 91 lifting equations, (4) Burandt Schultetus analysis, (5) University of Michigan's 2D, 3D analysis, (6) Snook and Ciriello method, (7) ErgoMOST, (8) University of Michigan's Energy-Expenditure, (10) Garg analysis, (11) Ovako Working Posture Analyzing System (OWAS), (12) Occupational Repetitive Action methods (OCRA).

A detailed description of the above mentioned ergonomic methodologies is reported in section 2.2.1.

Examples of research works that aims at achieving the ergonomic design of manufacturing system workplace by using a single ergonomic methodology are Carrasco et al. (1995), Van Wendel de Joode et al. (1996), Temple and Adams (2000), González et al. (2003), Massaccessi et al. (2003), Choobineh et al. (2004) Mäkelä and Hentilä (2005)[1].

The integration of two or more ergonomic tools was the successive step carried out by the researchers working in this specific area for achieving multiple and simultaneous ergonomic improvements. Examples of ergonomic methodologies integration can be found in Jones et al. (2005), Jones and Kumar (2007), Russell et al. (2007)[2].

---

[1] *Carrasco et al. (1995)* use the OWAS analysis for evaluating three different designs of checkout workstation, which require the operator to stand when they scan the products, pack them into the plastic bags and transfer the packed bags to the customer. The evaluation points out significant musculoskeletal load and exertion associated with the different checkouts and several suggestions have been presented for an improved workstation design in terms of postural load reduction and productivity increase as well.

Van Wendel de Joode et al. (1996) use the OWAS analysis in order to quantify workers physical load within two ship maintenance companies. Postural load was measured and awkward postures affecting workers back, neck/shoulder and arms were identified. On the light of such results, the authors reduced workers physical load by proposing several technical adaptations and applications as well as by enlarging task rotation.

Temple and Adams (2000) use the NIOSH analysis in order to establish ergonomic acceptable limits for an industrial lifting station. Through the analysis of several factors the authors define a cumulative lifting index and use such index for detecting ergonomic problems during lifting tasks. They successively modify the lifting station for reducing ergonomic risks and preventing lower back related injuries.

González et al. (2003) apply the RULA method for the ergonomic evaluation of industrial workplace. The authors propose a methodology that consists of three steps: the first includes the selection of the profile of the firm to study, while the second and the third will, respectively, consist in the choice of the workplace and the gathering and treatment of the representative data of the levels of ergonomics and quality. Having identified the ergonomic problems within a metalworking firm, a series of improvements were then implemented, analyzing whether significant alterations in quality levels took place in parallel as a result of these ergonomic improvements.

Massaccessi et al. (2003) investigate work-related disorders in truck drivers using the RULA method. Such method allowed to perform a rapid and correct evaluation of the loading to which neck and trunk are exposed while driving. RULA evidences that the posture adopted in street washing trucks during cleaning operations was associated with a major risk for back pain, especially with non-adjustable seats. On the light of the analysis results, the authors recommend ergonomic interventions aiming at modifying the truck's workstation with a view to prevent musculo-skeletal disorders.

Choobineh et al. (2004) use the RULA technique for carrying out ergonomic intervention in carpet mending operation. The authors identify several ergonomic problems affecting workers knees, back and shoulders and propose a new workstation configuration improving working postures noticeably.

Mäkelä and Hentilä (2005) estimate the physical workload and strain of dairy farming in loose housing barns. The authors use the OWAS analysis for evaluating workers postures during the feeding and removing manure and spreading of bedding activities. On the basis of the OWAS results, the authors provide some recommendations for building new loose-housing barns providing enough space for automated feeding and cleaning systems.

[2] *Jones et al. (2005)* use the RULA method and the NIOSH lifting equation in order to examine three common pub occupations (bartending, waitressing and cooking) with the aim of determining the biomechanical loads of job tasks, assessing the potential risk of musculoskeletal injury, and recommending injury prevention measures.

Jones and Kumar (2007) compare the results of 5 ergonomic risk assessment methods (RULA, REBA, ACGIH TLV, Strain Index and OCRA) in a repetitive high-risk sawmill occupation, examine the effect of multiple definitions of the posture and exertion variable on the risk assessment methods, describe the variability

2.2.1 Ergonomic methodologies

Here a detailed description of each ergonomic methodology is presented.

- ***1. Anthropometric Data Analysis***

Anthropometric data is the measurement of human body external characteristics such as the functional forward reach, stature (overall height), and elbow height. This is probably the most powerful tool in the industrial engineer's ergonomics toolbox. Anthropometric data forms the foundation in the design of the ergonomically sound workstation.

Each industrial engineer needs to establish anthropometric data for the population in their environment. This data may be different from one manufacturing facility to another or from one country to another. If data is not available from the human resources department, then do some sampling and make adjustments to data from other populations. Design parameters need to be established as to what percentage of the population we want to protect. The most common approach is to design for the 5^{th} to 95^{th} percentile of the population, which means that the job will not fit 10 percent of the population. Following are some critical design parameters:

- The forward-reach distance should be designed for the capability of the 5^{th} percentile person;
- Clearance dimensions should be based on the 95^{th} percentile person;
- Manual work is best performed just below the elbow height;
- Physical load carrying is best around waist height.

- ***2. RULA***

The rapid upper limb assessment is a survey method for the investigation of work-related upper limb ergonomic problems. It is a simple method to use since all it requires is a trained eye, analysis forms, and a pencil. This assessment divides the posture analysis into two groups:

1. Arm and wrist analysis - sagittal plane or side view

    a) Score the upper arm posture;
    b) Score the lower arm posture;
    c) Score the wrist posture;
    d) Combine the arm and wrist scores from a table based on the individual scores;
    e) Add a muscle score, which is based on the type of posture. Is it static or does it repeat the same action more than four times a minute (repetitive)?
    f) Add a force load score;
    g) Subtotal the arm and wrist score;

2. Neck, trunk, and leg analysis - sagittal plane or side view

    a) Score the next posture;
    b) Score the trunk posture;
    c) Score the leg posture;
    d) Combine the neck, trunk, and leg scores from a table based on the individual scores;
    e) Add a muscle score, which is based on the type of posture. Is it static or does it repeat the same action more than four times a minute (repetitive)?
    f) Add a force load score;
    g) Subtotal the neck, trunk, and leg score;
    h) Total the final score, which is the overall rank for that task.

---

in risk assessment scores between workers, examine the ability of risk assessment component scores to differentiate between facilities with significantly different levels of exposure, and examine the association between risk output and recorded incidence rates.

Russell et al. (2007) compare the results of NIOSH, ACGIH TLV, Snook, 3DSSPP and WA L&I methodologies for evaluating ergonomic risks in lifting operations. Each ergonomic methodology is applied to a uniform task (lifting and lowering two different types of cases) with the aim of choosing the best work methods by appropriately interpreting the results of the ergonomic analysis.

The overall score can range from 1 to 7. A job with a score of 1 is acceptable and a score of 7 requires an immediate redesign. Further information about the RULA method can be found in McAtammey and Corlett (1993).

➢ 3. NIOSH 1981 and revised NIOSH 1991 Lifting Equations

The NIOSH 81 method calculates the Action Limit (AL) and the Maximum Permissible Limit (MPL). AL is the weight value, which is permissible for 75% of all female and 99% of all male workers. MPL is the weight value, which is permissible for only 1% of all female and 25% of all male workers. Three different cases can be distinguished:

- Case A: If the AL exceeds the MPL, then an ergonomic intervention is required;
- Case B: If the AL is equal to the MPL, then a corrective intervention is necessary in the near future;
- Case C: The actual limit is lower than the MPL, then no ergonomic intervention is required.

Concerning the NIOSH 91 analysis, additionally to the NIOSH 81, it includes the Recommended Weight Limit (RWL) and the Lifting Index (LI). The RWL is the load that nearly all healthy workers can perform over a substantial period of time for a specific set of task conditions. The LI is calculated as a ratio between the real object weight and the RWL. Three different cases can be distinguished:

- If LI value is less than 1, the lifting task is not hazardous for some of the population
- If the LI value is equal to 1, the lifting task could be hazardous for some of the population
- If the LI value is greater than 1, the lifting task is hazardous for some of the population.

The LI is the approximate value of the relative level of strain. Note that NIOSH 81 and NIOSH 91 require as input

parameters data regarding worker postures at the origin and destination of the lift, object coupling and the duration of

the specified task. Further information about the cited ergonomic standards can be found in NIOSH Technical Report (1991) and Waters et al. (1994).

➢ 4. Burandt Schultetus analysis

The analysis detects the maximum weight that a working person can lift (maximum permissible force). The maximum permissible force can be evaluated by using the following equation:

$$PF = G*C*AJ*RF$$

where,
G: coefficient for the worker's gender,
C: coefficient for the worker's health condition,
AJ: coefficient for worker's age and type of job,
RF: reference force.

Note that the *AJ* (Age and Job factor) depends on the effort type (i.e., static or dynamic), the worker's age, the shift time (i.e., 8 h) and the effort frequency. The *RF* takes into consideration the torso weight movement, the hands use (i.e., one or two hands), the number of persons performing the operation (i.e., one or two persons), the effect of secondary jobs and the maximum force. In turns, the torso weight movement depends on the lower and upper grasp height and motion frequency; the maximum force depends on body size class (anthropometric measure), upper grasp height and distance of grasp from the body. Moreover, the analysis requires several input parameters regarding the physical conditions, age and gender of the worker, the load weight, the lifting frequency (measured in lifts per minute) and the total task duration. The maximum permissible force is then compared with the current Actual Force (AF) being exerted. Three different cases can be distinguished:

- Case 1: If the maximum permissible force does not exceed the AF, then an ergonomic intervention is required;

- Case 2: If the maximum permissible force is equal to the AF, then a corrective intervention is necessary in the near future;
- Case 3: If the AF is lower than the maximum permissible force, then no ergonomic intervention is required.

Further information can be found in Schultetus (1980).

5. University of Michigan's 2D and 3D Static Strength Prediction Model Programs

The model programs will analyze the back compressive forces required to perform the task (lifts, presses, pushes, and pulls). Neither program is appropriate for analyzing risk in highly dynamic or repetitive tasks. They are used for low frequency high force demand tasks.

- Worker body posture (arms, back, and legs), or preset postures in the sagittal plane assumes symmetrical motions;
- Force magnitude, direction, and one- or two-handed task;
- Worker anthropometry or preset values.

2D OUTPUT:

- Percent of the male and female population that have the strength in each of the joints (elbow, shoulder, L5/S1 back, hip, knee, ankle) required to perform the task;
- Percent of the male and female population that can tolerate the back compressive forces required performing the task. The 2D program is relatively easy to use compared to the 3D program.

The 3D program has many more posture inputs because the analysis and inputs are in three dimensions. 3D analysis
is better since most lifts in the real world are not symmetrical. More information on these programs is reported in Norman et al. (1994).

6. Push, Pull, and Carry Tables - Stover H. Snook and Vincent M. Ciriello

Pushing carts is a two-handed, manual-handling dynamic task using the whole body (arms, back, legs). Push/pull tables are available from Snook and Ciriello (1991). These tables provide data for:

- Pushing/pulling at six different heights;
- 10 to 90 percent of the male and female population;
- Task frequencies from once per 6 seconds to once per 480 minutes;
- Distance of push from 2.1 m (6.8 ft) to 61 m (200 ft);
- Initial forces - force required to put the cart in motion;
- Sustained forces - force required to keep the cart in motion.

To analyze the job, you need a push/pull type force gauge with peak value freeze capability. You should have enough attachments to be able to push/pull many different objects. Take at least three different samples and use the average value. Compare this value to the value in one of the push/pull tables. If the value you sampled is greater than the one in the table, then there is a concern for endurance or the whole-body strength.

7. ErgoMOST

ErgoMOST, a software tool developed by H. B. Maynard and Company, Inc., is designed to allow a user to analyze a defined method from an ergonomic standpoint. This analysis is then interpreted by ErgoMOST and presented to the user in easily understood terms. This tool is intended to provide some of the expertise of the ergonomist to the methods analyst so that ergonomic analysis can be performed as methods are developed. This feature allows for a greater coverage of jobs with ergonomic analysis.

ErgoMOST combines the analysis of a number of different ergonomic factors. They include force, posture, repetition, and grip and vibration stress. The goal of ErgoMOST is to allow the user to model an operator's work content for an entire shift. This is extremely helpful because the whole job is evaluated, not just one isolated piece of the job.

ErgoMOST requires that the method be defined. A group of method steps defining a job is analyzed in the Analysis module of the system creating an element known as an *Analysis.* ErgoMOST allows the user to combine these analyses together in the Process Module. The Process Module provides feedback for a job rotation or for operations performed on a product mix. For each method step in an Analysis, the following information is required. This set of information can be captured in an element called an ErgoSet so that it may be reused as the same activity recurs in the method.

- INPUT:
  - *Method:* a method description is required. They can be methods used to develop labor standards. The essential elements are the method description, the time, and the frequency of occurrence per cycle;
  - *Force:* the force required to perform the method;
  - *Action:-* the action for each method description is defined as a Lift, a Push or a Pull;
  - *Posture Input :* postures for each body member are defined per method description. The body members are:
    - Wrists;
    - Elbows;
    - Shoulders;
    - Back;
    - Neck;
    - Knees;
    - Hip.
  - *Vibration:* vibration rating for the right or left hand;
  - *Population:* the population of the operator is defined as male or female with the percentile (5th, 50th, or 95th);
  - *Job Information:-* at the job level, the shift hours and the cycles per shift - product quantity - are needed to provide feedback for the operator's entire day of work.

- OUTPUT: After the information has been entered and saved, the ErgoMOST tool will then provide the evaluation of this job. The Analysis Summary output is a textual or graphical display of Ergonomic Stress Index (ESI) for each body member by ergonomic factors summarized for the whole job. The Ergonomic Stress Index is a five-point scoring system. These ratings indicate potential risk for each body member in the following manner:
  - 1 - 2 low risk
  - 3 medium risk
  - 4 - 5 high risk

The goal of the system is to highlight higher risk methods so that the analyst can identify them and target them to be redesigned to reduce potential risk. Further information about ErgoMOST is availabroe from Maynard and Company, Inc..

➢ ***8. Energy Expenditure Prediction Program - University of Michigan Center for Ergonomics.*** The energy expenditure analysis needs only to be performed if the worker

- appears to be out of breath,
- is breathing heavily,
- is sweating,
- can't talk to you because they cannot keep up with the line rate.

Energy expenditure equations have been developed for the following types of tasks:

- Walking - on level or inclined surface;
- Lifts/lowers with following postures (stoop, squat, semisquat, one hand);
- Loads carried at waist or thigh level with one or both hands;

- Loads held at waist or thighs, one or both hands;
- Pushes and pulls at any height from the floor;
- Handwork, light and heavy;
- General arm work (light, less than 2.3 kg and heavy, more than 2.3 kg).

Other inputs are weight of the worker, gender of the worker, and body postures with each task. The output of the program will provide incremental energy expenditure at every task and a total job energy expenditure of all the tasks. By analyzing the output, one can redesign tasks with the highest incremental energy expenditures to reduce the total energy expenditure. More information can be obtained from the University of Michigan Center for Ergonomics.

- ***9. Garg analysis***

The Garg analysis calculates the total amount of energy spent during the manual operations. The analysis splits up a specified operation into smaller steps calculating for each of them the Energy Expenditure (EE); the sum of these separate steps represents the total Energy Expenditure for the activity. As input parameters, such analysis requires information concerning load weight and body weight as well as gender of the working person. Further information can be found in Garg (1976).

- ***10. Ovako Working Posture Analyzing System (OWAS)***

The OWAS analysis carries out a qualitative analysis of the worker's movements during a working process. The analysis calculates the stress associated to each body posture and classifies them in one of the following four stress categories:

- Category 1: the stress level is optimum, no corrective interventions are required;
- Category 2: the stress level is almost acceptable, corrective interventions are necessary in the near future;
- Category 3: the stress level is high, corrective interventions are required as soon as possible;
- Category 4; the stress level is very high, corrective interventions must be carried out immediately.

Further information about the cited ergonomic standard can be found in Kharu et al. (1981).

- ***11. Occupational Repetitive Action methods (OCRA)***

The Occupational Repetitive Action methods (OCRA) analyze worker’s exposure to tasks featuring various upper limb injury risk factors (repetitiveness, force, awkward postures and movements, lack of recovery periods). The OCRA methods are the OCRA index and the OCRA checklist. The OCRA index can be predictive of the risk of upper extremity work related musculoskeletal disorders in exposed populations. It is generally used for the (re)-design or in depth analysis of workstations and tasks (Colombini et al. 1998, 2002). The OCRA checklist, based on the OCRA index, is simpler to apply and is generally recommended for the initial screening of workstations featuring repetitive tasks (Occhipinti et al. 2000; Colombini et al. 2002).

The OCRA method is based on a consensus document of the International Ergonomics Association (IEA) technical committee on musculoskeletal disorders (Colombini et al. 2001). Further information regarding OCRA methods can be found in Occhipinti and Colombini (1996).

2.3 Ergonomics and Work measurement for Effective Workplace Design

Another important issue to take into consideration in the effective workplace design is the relation between the concepts of work measurement and ergonomics. To reiterate, the measurement of the work aims at evaluating the time standard for performing a particular operation. On the contrary, the concept of ergonomics is often indicated as study of work (Zandin, 2001) and studies the principles that rule the interaction between humans and their working environments. Actually the work measurement and the ergonomics affect each other: ergonomic interventions affect the time required for performing the operations as well as any change to the work method affects the ergonomics of the workplace.

The methodologies reviewed in section 2.2.1 have been developed for ergonomic purposes; however, they may be also accessible to the engineer and compatible with work measurement methodologies to consider both efficient workplace productivity and good ergonomics simultaneously. At the same time, the work measurement methodologies may be powerful instruments for assessing ergonomic risks within the workplace. Among the work measurement methodologies, predetermined time systems are the most widely used. Broadly speaking, there are three main predetermined systems sets:

1) *Motion-based* encompasses all those systems that are made up of basic motions - time elements that cannot be broken down into smaller elements;
2) *Action-based* are such systems that consist of combining basic motions into actions;
3) *Activity-based* are systems consisting of elements that are combinations of basic motions or (in most cases) action elements. Activity-based elements are then put together in a sequence representing a complete activity, such as "move object from A to B" or "fasten screw with screwdriver".

Among the others, the following are the most widely used predetermined time systems:

1. Methods Time Measurement (MTM-1), Work Factor (WF) system, Basic Motion Time (BMT) study and MODAPTS, as motion-based systems;
2. General Sewing Data (GSD), MTM-MEK, Andard Data (USD), Master Standard Data (MSD), MTM-2 and MTM-3, as action-based systems;
3. Maynard Operation Sequence Technique (MOST), as activity-based systems.

The aforementioned predetermined time systems are detailed described in section 2.3.1.

Examples of research works using ergonomic and work measurement methodologies for achieving the ergonomic workplace design can be found in Resnick and Zanotti (1997) and Laring et al. (2002)[3].

2.3.1 Work Measurement Methodologies

Motion-based predetermined time systems

- ***1. Methods Time Measurement (MTM-1)***

The most widely publicized system of performance rating was presented in *Time and Motion Study* by Maynard et al. (1948). The rating system was based on four factors: skill, effort, consistency, and performance. Maynard and Stegemerten teamed with John Schwab to expand this idea into *Methods Time Measurement* (MTM) (Maynard et al., 1948) - this is now known as MTM-1. According to Robert Rice, this method is the most widely used system of predetermined times (Rice, 1977). Maynard and associates performed many micro-motion studies to come up with their standard elements and times. Because MTM was readily available, it is not surprising that it is the most frequently used - and the most frequently imitated - of all the systems.

MTM-1 is a procedure for analyzing any manual operation or method by breaking out the basic motions required to perform it and assigning to each a predetermined standard time based on its nature and the conditions under which it is made (Karger and Bayh, 1987). The total time for a manual

---

[3] *Resnick and Zanotti (1997)* underline that ergonomic principles can potentially be used to improve productivity as well. The authors propose an application example for remarking that a workstation can be designed to maximize performance and reduce costs by considering both ergonomics and productivity together.

Laring et al. (2002) develop an ergonomic complement to a modern MTM system called SAM that gives the production engineer a first insight into the future ergonomic quality of a planned production. In particular, the authors propose a tool that gives the possibility to estimate simultaneously the consumption of time in the envisaged production and the biomechanical load inherent in the planned tasks. The method was tested at the Torslanda final assembly plant of Volvo Car Corporation and at the ITT Flygt plant.

operation is then calculated as sum of the time of each basic motion it is consists of. *Reach* is the most common or basic MTM-1 motion. Other motions include the following:

- *Move:* the predominant purpose is to transport an object to a destination;
- *Turn:* the hand is turned or rotated about the long axis of the forearm;
- *Position:* motion is employed to align, orient, and/or engage one object with another;
- *Grasp:* the main purpose is to secure sufficient control of one or more objects with the fingers or the hand;
- *Release:* the operator relinquishes control of an object;
- *Disengage:* contact between two objects is broken;
- *Eye times:* the eyes direct hand or body motions;
- *Body motions:* motions are made by the entire body, not just the hands, fingers, or arms.

➢ 2. Work Factor (WF) System

The first predetermined time system was developed around 1925 by Segur, one of the first to recognize the association between motion and time. He formulated the principle, that, within allowances for normal variation, the time required by experts to perform a fundamental motion is consistent. He believed that work factors could be used to set standards for all manual and mental work. Segur developed *methods time analysis,* which could be used to analyze manual and manual/machine operations. Segur emphasized that the time required for work depended on how the work was done and stressed that a complete description of the work performed was necessary.

In the early 1930s, union workers in Philadelphia were dissatisfied with the quality of the stopwatch time standards set for their highly controlled incentive jobs. This protest led to one of the first published predetermined time systems, called *Work Factor* (Karger and Bayh, 1987).The Work Factor System (Quick et al., 1962) makes it possible to determine the normal time for manual tasks by using motion time data.

The definition of *basic motion* is that which involves the least amount of difficulty or precision for any given distance and body member combination. Work factor is used as the index of additional time required over and above the basic times for motions involving manual control and weight or resistance. Four variables affect the time of manual motions in the work factor system:

1. Body member used;
2. Distance moved (measured on a straight-line basis);
3. Degree of manual control required;
4. Weight or resistance of body member used and sex of operator.

The eight standard elements of work factor are transport, grasp, preposition, assemble, use, disassemble, mental process, and release.

➢ 3. Basic Motion Time study (BMT)

In 1951, the Canadian firm of Woods and Gordon made the first significant contribution to predetermined time system literature by a foreign source. The Canadians developed basic motion time study from systems already available. The major advantage of BMT is its brevity. It is best used for factory jobs that follow fairly rigid motion patterns. In BMT, a *basic motion* is defined as a single complete movement of a body member. A basic motion occurs every time a body member, being at rest, moves and comes to rest again. Basic motion time study takes the following five factors into consideration in determining times:

1. Distance moved;
2. Visual attention needed to complete motion;
3. Degree of precision required in grasping or positioning;
4. Amount of force needed in handling weight;
5. Simultaneous performance of two motions.

The motions of BMT fall into one of three classifications:

- *Class A:* stopped without muscular control by impact with a solid object;
- *Class B:* stopped entirely by use of muscular control;

- *Class C:* stopped by use of muscular control both to control the slowdown and to end it in a grasping or placing action.

A force factor is recognized, because handling heavy objects or overcoming friction require added muscular effort. Additional information about BTM systems is reported in Bailey and Presgrave (1958).

➢ *4. MODAPTS*

MODAPTS is a relatively easy-to-use predetermined time system (Griffith, 1970). MODAPTS stands for *mod*ular *a*rrangement of *p*redetermined *t*ime *s*tandards.

MODAPTS is an Australian-developed time system based on the premise that larger body sections take longer to move than smaller sections. For example, in this system it takes twice as long to move a hand as it does to move a finger. It takes three times as long to move the forearm as it does a finger, and it takes four times as long to move the whole arm outward. From this simple framework, MODAPTS has built an entire system of predetermined macro time standards (Masud et al., 1985)

Because it describes work in human rather than mechanical terms, it has many more potential applications than earlier work analysis systems. The application is integrated with desktop computer processing capabilities, which simplifies its use.

MODAPTS is a recognized industrial engineering technique, meeting all criteria of the U.S. Defense Department and Department of Labor for developing industrial standards. Performance times are based on the premise that motions will be carried out at the most energy efficient speed.

MODAPTS is used to analyze all types of industrial, office, and materials-handling tasks. Data from MODAPTS studies are used for planning and scheduling, cost estimating and analysis, ergonomic evaluation of manual tasks, and the development of labor standards. Additional information about MODAPTS is available from the International MODAPTS Association, Inc.

Action-based predetermined time systems

➢ *1. General Sewing Data (GSD)*

General sewing data (GSD) uses a specially developed database that was derived from MTM core data. GSD was developed by Methods Workshop Limited of Lancashire, England. The originators recognized that most apparel (sewing) operations followed a well-defined and repeating sequence of operations:

1. Get parts;
2. Put parts together;
3. Sew parts together with various alignments and repositions;
4. Trim thread;
5. Put parts aside.

When combined with batching operations, most of the tasks for sewing have been defined. GSD permits the user to rapidly analyze methods and generate time standards based on those methods. The major categories of GSD are as follows:

- *Obtaining and matching part or parts:* this includes matching and getting two parts together, matching and getting two parts separately, matching parts to foot, and matching and adding parts with either one or two hands;
- *Aligning and adjusting:* this includes aligning or adjusting one or two parts, aligning and repositioning assembly under foot, and aligning or adjusting parts by sliding;
- *Forming shapes:* this includes forming fold, forming crease in folded part, and forming unfold or layout;
- *Trimming and tool use:* this includes cutting with scissors, cutting thread with fixed blade, and dechaining parts with scissors;
- *Asiding:* this includes pushing away parts and putting parts aside with one or two hands;

- *Handling machine:* this includes machine sewing and different stops within half an inch, using the machine handwheel to raise or lower the needle, and manipulating the machine lever to backtack at the beginning or end;
- *Getting and putting:* this includes getting parts and putting parts under various conditions, such as the use of one or two hands, contact only, getting part from the other hand, and putting the part onto the stack.

In addition to these elements, additional MTM elements are incorporated (reaches, moves, sit, stand, etc.).

➢ *2. MTM-MEK*

With the increasing emphasis on one-of-a-kind and small-lot production in the 1970s, the need for effective MTM work measurement in these areas became apparent. Development of a predetermined time system to deal effectively with these areas presented unique problems as a result of the methods' variability of this type of work. In response, the German MTM Association formed a consortium to develop an effective system for measuring highly variable work. The research and work was carried out by member companies of the German and Swiss MTM Associations and the Austrian MTM Group. The result was a data system developed for the specific needs of one-of-a-kind and small-lot production: the MTM-MEK data system. In order to provide a system with the broadest range of application, only variables that could be readily identified in both the production and planning stages were utilized. Thus the MTM-MEK system can be readily applied in the preproduction stages of product development. The action elements were broken down in such a way as to ensure that they can be definitely recognized and clearly coordinated. Furthermore, a distinction was made between the activity and specific characteristics (e.g., handling of a construction part or handling of a tool). Additional variables are limited to those that can be identified from the external conditions surrounding the work process.

Analysis showed that one-of-a-kind production results in very complicated and complex motion sequences. At the same time, one-of-a-kind production rarely repeats the motion sequences with each repetition of the job. Without historical information or documentation of existing methods, the strategy for MTM-MEK uses the following:

- Variables affecting the elements are not derived from the motion sequence but rather from the peripheral conditions under which the motion sequence takes place;
- Therefore, the degree of complexity of a get-and-place sequence is not given, only that it takes place, how exact the place must be, over what distance the move takes place, and the weight or bulkiness of the objects.

This strategy results in those consequences:

1. The total time applicable to a given operation can no longer be accounted for by a detailed method sequence prepared by an analyst, but rather it must be statistically accounted for within the analyzing system.
2. The application of such analyzing systems requires that a statistical match has to be determined in advance. The commonly used concepts of one-of-a-kind, batch, and mass production are much too vaguely defined for the purpose of determining the presence of this statistical match.

The utilization of statistical techniques to develop element times results in element classifications that are general in nature. Thus, the system contains no specific process or object related data.

The development of data into general element classifications results in a minimum number of application elements. The small number of elements required results in quick access, which leads to high analyzing speed. The MTM-MEK analyzing system uses the following element groups:

- *Get and place:* get one or more objects and place at a certain destination.
- *Handle tool:* get tool, apply tool, and place tool aside after use.
- *Place:* place one or more objects at a certain destination.

- *Operate:* operate control devices (levers, switches, handwheels, cranks, stops, etc.) that are attached to machines, appliances, and fixtures.
- *Motion cycles:* at least two applications or movements of tools, levers, switches, or turning of cranks, repeated in succession. Also covered is the rotational portion of the turning of bolts by hand or with the fingers.
- *Body motions:* includes the elements walk, bend, and stoop as well as sit. Walk is analyzed as a separate element only if a distance of 2 m (80 inches) is exceeded. Bend and stoop are analyzed separately only if more than one of these occur within the elements get and place, place, and operate. Sit must always be analyzed if it occurs within a work process.
- *Visual control:* eye travel and inspection in independently occurring control or inspection operations. This includes the necessary eye travel to and from the place of inspection.

➢ *3. ANDARD DATA (USD)*

Universal standard data is a modification of MTM-1. It was developed not only to supply specific time data that can be applied relatively quickly, but also to provide a concept of standard data application.

The basic concept of USD was formulated in 1954 when it became necessary to develop a large number of standards in a plant assembling a number of different models of farm tractors on a common progressive assembly line. The cycle time at each workstation was rather long, and there were a number of variations in the assembly procedures for each of the many different styles of tractors involved (Maynard, 1963)

All of the USD motions are constructed from the basic MTM-1 data. The result is a shortcut method. The basic motions of USD are as follows:

- *Get object:* used for gaining possession or control of an object. The variables used include distance reached, the case of reach from MTM-1, and the case of grasp from MTM-1;
- *Place object (nominal weight):* used for placing, disposing, or positioning an object. It is based on the MTM-1 motions move, position, and release. The variables involved include the distance moved, the case of move, and the class of fit. Nominal weight is defined as 1 kg (2.5 pounds) or less;
- *Place object (significant weight):* as with the place-object-nominal-weight motion, this is used for placing, disposing, or positioning an object based on move, position, and release. Additionally, it uses three weight ranges;
- *Get turn and place turn:* this is a special case of get and place. It is used for motions that involve turning dials, knobs, and hand tools. It uses the MTM-1 motions grasp, turn, and release. The variables involved are the degrees of the turn and the force required to complete the turn. There are four categories for degrees turned and three categories for resistance or force;
- *Walk displacement:* involves a body turn and a walk to another location. It is based on the MTM-1 motions of turn body (case 1) and walk. The variables include the distance walked and whether there is any obstruction in the walk;
- *Miscellaneous body:* this is a consolidation of the MTM-1 body, leg, and foot motions. It includes three classes of body displacement and individual foot and leg motion classifications;
- *Crank:* motion employed to turn a handwheel or crank. It is based on the MTM-1 cranking formula. Variables include the crank diameter, force required to operate the crank, and number of revolutions. There are two classifications for crank diameter, two classifications for required force, and 20 classifications for number of revolutions. Continuous cranking is also addressed with three classifications.

4. Master Standard Data (MSD)

Master Standard Data (MSD) was developed by the Serge A. Birn Co. in the 1950s to set standard MTM-based data on manually controlled operations in which production was less than 100,000 units per year, or a few thousand units per week.

Between production runs, the operator would lose most of the skill he or she had developed. Statistically, a very high percentage of industrial work falls within this limited practice category. MSD was developed by statistically studying all motions. Because many motions studied occur rarely, they can be ignored (Maynard, 1963). Since MSD was developed for tasks that essentially have to be relearned, the likelihood of simultaneous motions is small. The exceptions are those motions that can be performed simultaneously without practice. MSD includes a simultaneous-motion chart along with tables for the following motions:

- Obtain;
- Place;
- Rotate;
- Use;
- Finger shift;
- Body motions.

5. MTM-2

MTM-2 is based on MTM-1. It consists of both basic MTM-1 motions and combinations of MTM-1 motions.

According to the MTM Association for Standards and Research, MTM-2 was designed to fulfill the needs of practitioners who do not need the high precision of MTM-1 but where speed of analysis is important. Like MTM-1, it is useful for methods analysis, work measurement, and estimating. It was developed in Sweden (MTM association, 1978). There are nine elements in MTM-2. Just two of the nine elements have variable categories, which means that only 39 time values appear on the MTM-2 card.

- *Get:* this is the motion with the predominant purpose of reaching for an object with the hand or fingers, grasping the object, and subsequently releasing it. Three variables influence the appropriate value. The case is determined by the nature of the grasping motions used. The distance reached is the actual path of travel. The third variable is the weight of the object being grasped;
- *Put:* this is the motion used when the predominant purpose is to move an object to a destination with the hands or fingers. Three variables influence the appropriate value. The case is determined by the nature of the grasping motions used. The distance reached is the actual path of travel. The third variable is the weight of the object being grasped;
- *Apply pressure:* this is used to describe the action of exerting muscular force on an object;
- *Regrasp:* this describes the actions required when the purpose is to change the grasp on an object;
- *Eye action:* this is used when focusing on an object or when shifting the field of vision to a different viewing area;
- *Crank:* this is used when the fingers or hand move an object in a circular path of more than half a revolution;
- *Step:* this applies to leg motions that are used to move the body or are longer than 30 cm (12 inches);
- *Foot motion:* this describes a short foot or leg motion where the major purpose is not to transport the body;
- *Bend and arise:* this applies to bending, stooping, or kneeling on one knee and the subsequent arise.

➢ *6. MTM-3*

MTM-3 is intended to be used where the product is manufactured in small batches and where the methods and motion distances can vary considerably from cycle to cycle. It is not appropriate for measuring highly repetitive work cycles (MTM Association, 1978). MTM-3 has a total of only four motions, with only 10 time values specified. *Handle* and *transport* are the first two motions. The cases are determined by the degree of control required and the distance moved. The other two motions are *step* and *bend and arise.*

Activity-based predetermined time systems

➢ *1. BASICMOST®*

BasicMOST® concentrates on the movement of objects (Zandin, 1990). Efficient, smooth, productive work is performed when the basic motion patterns are tactically arranged and smoothly choreographed. This provides the basis for the BasicMOST sequence models. The primary work units are no longer basic motions, but fundamental activities (collections of basic motions) dealing with moving objects. These activities are described in terms of sub-activities fixed in sequence. In other words, to move an object, a standard sequence of events occurs. Objects can be moved in only one of two ways: either they are picked up and moved freely through space or they are moved and maintain contact with another surface. The use of tools is analyzed through a separate activity sequence model that allows the analyst the opportunity to follow the movement of a hand tool through a standard sequence of events, which, in fact, is a combination of the two basic sequence models.

Consequently, only three activity sequences are needed for describing manual work. The BasicMOST technique is made up of the following basic sequence models:

- The general move sequence (for the spatial movement of an object freely through the air)
- The controlled move sequence (for the movement of an object when it remains in contact with a surface or is following a controlled path during the movement)
- The tool use sequence (for the use of common hand tools)

1. *General move* is defined as moving objects manually from one location to another freely through the air. To account for the various ways in which a general move can occur, the activity sequence is made up of four sub-activities:

A	Action distance (mainly horizontal)
B	Body motion (mainly vertical)
G	Gain control
P	Place

2. *Controlled move* sequence is used to cover such activities as operating a lever or crank, activating a button or switch, or simply sliding an object over a surface. In addition to the A, B, and G parameters from the general move sequence, the sequence model for controlled move contains the following sub-activities:

M	Move controlled
X	Process time
I	Align

3. *Tool use* (equipment use) sequence covers the use of hand tools for such activities as fastening or loosening, cutting, cleaning, gauging, and writing. Also, certain activities requiring the use of the brain for mental processes can be classified as tool use. The tool use sequence model is a combination of general move and controlled move activities.

Whereas the three manual sequences comprise the BasicMOST technique, three other sequence models were designed to simplify the work measurement procedure for dealing with heavy objects.

- *Manual crane sequence* covers the use of a manually traversed jib or monorail crane for moving heavier objects;

- *Powered crane sequence* covers the use powered cranes, such as bridge cranes, for moving the heaviest objects;
- *Truck sequence* covers the transportation of objects using riding or walking equipment such as a forklift, stacker, pallet lift, or hand truck.

BasicMOST is appropriate for any work that contains variations from one cycle to another. While BasicMOST is the most widely used system, MOST Systems was expanded in 1980 to include MiniMOST, MaxiMOST and AdminMOST. MiniMOST provides detailed analysis of highly repetitive activities, such as small assembly and the packing of small items. MaxiMOST is used for longer cycle activities, such as setups, maintenance, material handling, heavy assembly and job shop work. AdminMOST is used for analyzing general office and administrative activities.

2.4 Ergonomics, Work Measurement and Simulation for Effective Workplace Design

In the past, a number of research works in literature try to achieve the effective workplace design by directly analyzing the real workplace; in particular such studies make use of based observation methods for collecting data, i.e. observation of the worker performing the manufacturing operations is used for collecting information about the work methods. Examples of research works using based observation methods can be found in Das and Sengupta (1996), Kadefors and Forsman (2000), Neumann et al. (2001) and Forsman et al. (2002)[4]. The possibility to integrate based observation methods and specific ergonomic methodologies was also investigated by researchers. Even in this case the based observation methods were used as data collection tools, while the ergonomic standards allowed the researchers to investigate and analyze the ergonomics of the workplace. Scott and Lambe (1996), Vedder (1998), Herman et al. (1999), Shuval and Donchin (2005), Lin and Chan (2007) take into consideration in their research works both ergonomic methodologies and based observation methods[5].

---

[4] *Das and Sengupta (1996)* provide the conceptual basis for a good workstation design by presenting a systematic ergonomic approach capable of determining the workstation dimensions and layout. The workstation design procedure starts off with the collection of the workstation relevant data through direct observation and videotaping and ends up with constructing a prototype workstation based on the final design. Moreover the authors apply the systematic ergonomic approach to the design of a supermarket checkstand workstation.

Kadefors and Forsman (2000) present a method for ergonomic evaluation of complex manual work based on interactive operator assessment of video recordings. The video recordings are displayed on a computer terminal, and the video recorded operators assess the work by clicking on virtual controls on the screen, whenever a situation inducing pain or discomfort appears. The application of the method to a workshop belonging to Volvo Cars shows it is easy to understand and operate by practitioners as well as it provides structured information on the high priority tasks that are relevant and useful for instance in industrial interventions and industrial workstation design.

Neumann et al. (2001) identify the trunk position and movement velocity as important parameters to be considered and measured in industrial settings design. To this end, the authors present a video-based posture assessment method capable of measuring trunk angles and angular velocities in industrial workplaces. The video analysis workstation consists of a desktop computer equipped with digital video capture and playback technology, and a computer game type joystick. An application example confirms the importance of these factors and demonstrates the utility of a video based method to measure them.

Forsman et al. (2002) present a method to amalgamate technical and human aspects in the industrial workstation design. The technical aspects are represented by results from a computer- and video based observation method for time data collection. The human aspects comprised physiological measurements of muscular activity, and of body postures and movements. The integrated procedure allows work activities to be assigned significantly different levels of physical work load. These different levels may be used to predict physical work load in the design and change of reduction systems.

[5] *Scott and Lambe (1996)* implement the OWAS methodology in a perchery system. The workers have been video recorded performing normal duties within the perchery and the positions of the body have been assessed. Several wrong working postures have been identified and suggestions, in light of the OWAS results, have been proposed for an improved perchery design.

In addition to the previous studies, Grant et al. (1995), Grant et al. (1997), Chung and Kee (2000) and White and Kirby (2003) use interviews as further based observation method for the workplace data collection[6]. The use of based observation methods together with work measurement methodologies was also a further research issue researchers and scientists have addressed (Engström and Medbo, 1997; Vedder and Hellweg, 1998)[7].

Vedder (1998) presents an easy-to-use video based posture analysis method for workplaces where task interference has to be minimized and postures have to be observed over a longer period of time. The different worker postures have been video recorded by using a stationary camera and then evaluated by using the OWAS posture methodology. Such method allows to identify hazardous postures and their causative factors so that appropriate re-design measures can be taken.

Herman et al. (1999) propose a practical methodology to analyze the influence of material handling devices on the physical load during the end assembly of cars. First, the worker under observation describes the manual actions in detail while performing the task and explains why he does or does not use the tool, then the NIOSH methodology (1991) is used to analyze the lifting and lowering aspects of each task. Finally the authors, according to objective and subjective results of the data analysis, propose several recommendations to the company regarding the use of existing tools for the end assembly of cars.

Shuval and Donchin (2005) examine the relationship between ergonomic risk factors and upper extremity musculoskeletal symptoms at a Hi-Tech company in Israel. Ergonomic risk factors were assessed through direct observation of employees' postures at their workstations using the rapid upper limb assessment (RULA) tool. Results of the RULA observations indicate excessive postural loading with no employee in acceptable postures so that the authors point out the need for implementing an intervention program.

Lin and Chan (2007) evaluate the effect of ergonomic workstation design on musculoskeletal risk factors and musculoskeletal symptoms reduction among female semiconductor fabrication room worker. By means of walk-through observations of the working environment, discussing with company's managers and using NIOSH analysis, the authors identify the most prevalent and urgent ergonomic issues to be resolved and modify the layout of the workplace for reducing ergonomic hazards.

[6] *Grant et al. (1995)* describes an investigation conducted to identify and evaluate possible causes of back and lower extremity pain among the workers of a day care facility. The investigation is based on the use of questionnaire, video tape systems and NIOSH lifting equations. Questionnaire results indicated that back pain discomfort was a common musculoskeletal complaint. Observation and analysis of the work activities indicated that employees spend significant periods of time kneeling, sitting on the floor, squatting, or bending at the waist. The revised NIOSH lifting equation indicated that several employed performing lifting tasks may be at increased risk of low back pain and lower extremity injury. Finally the authors present recommendations for reducing or eliminating these risks by modifying the workplace and changing the methods of work.

Grant et al. (1997) analyze lifting tasks at a cabinet company. Workers interviews have been used to assess the magnitude of the musculoskeletal problems. Videotape systems have been used for observing material handling activities and finally the revised NIOSH lifting equation has been used for analyzing representative lift tasks. The research study identifies several lifting hazards and specific recommendations for reducing physical workload have been suggested.

Chung and Kee (2000) propose a procedure based on the use of a questionnaire survey as well as the 1991 revised NIOSH lifting equations for the evaluation of lifting tasks frequently performed during fire brick manufacturing processes. A questionnaire survey shows that weight of the load significantly influence the incidence of back injuries. The NISOH lifting equation identifies risk factors that may cause musculoskeletal disorders among the operators. The research results suggest that several tasks should be redesigned ergonomically simply by making horizontal locations closer to a worker or by reducing the asymmetric angles.

White and Kirby (2003) propose an ergonomic evaluation of health-care workers in a rehabilitation center. The authors present a procedure based on the integration of questionnaire, video tape systems and OWAS methodology. Workers completed a brief questionnaire that elicited information on the subject's age, gender and occupation. The videotape system was used to ensure relevant qualitative data, as well as providing data that could be coded and scored. The OWAS methodology was used for identifying the wrong working postures. The research study reveals that health-care workers use a variety of methods, many of which include bent and twisted back postures that may carry a risk of injury. Note that the authors do not provide any information concerning the improvement of the operators work methods.

[7] *Engström and Medbo (1997)* develop a video based observation method for time data collection and analysis of work time consumption. The method allows to measure the efficiency of the production system by separating between value and not value adding works activities. In this regards, the method can be used for increasing manufacturing systems productivity.

Vedder and Hellweg (1998) recorder twenty day and night shifts in a fibbre spinning area of a chemical plant by means of a stationary camera. A very long analysis of the videotapes allows them to provide the guidelines for redesigning the system under consideration in order to achieve higher productivity levels.

The approach proposed by the aforementioned studies have often been reactive, time-consuming, incomplete, sporadic, and difficult. In effect, usually the direct analysis of the real workstations is quite expensive (in terms of money and time) because it requires to "disturb" processes and activities of the manufacturing system. For this reason, researchers and practitioners very often use simulation as problem solving tool for creating an artificial history of the system, analyzing its behaviour, choosing correctly, understanding why, diagnosing problems and exploring possibilities (Banks, 1998). Moreover, simulation can be jointly used with virtual three-dimensional environments in which observe the system evolution over the time and detect ergonomic and work measurement problems that otherwise could be difficult to detect. Wilson (1997) proposes an overview on attributes and capabilities of virtual environments devoted to support effective workplace design[8]. Examples of research work using virtual environment as support tool for effective workplace design are Jayaram et al. (2006) and Chang and Wang (2007)[9].

At present various simulation commercial software are available for ergonomic analysis of human posture and workplace design. Among the others, the following has to be considered as the most widely used: (1) Jack, (2) SAFEWORK, (3) RAMSIS and ANTHROPOS, (4) SAMMIE, (5) Boeing Human Modeling System, (6) EM-Workplace. A detailed description of these simulation commercial software is reported in section 2.3.1. Gill (1998), Eynard (2000), Feyen et al. (2000), Hanson (2000), Sundin (2000) and Marcos (2006) faced the effective workplace design research issue by using simulation commercial systems[10].

---

[8] According to *Wilson (1997)*, virtual environment has potential as a tool to support many types of ergonomics contribution, including assessments of office and workplace layouts giving egocentric viewpoints for testing consequences for reaching and accessing, reconfiguring and testing alternative interface designs, training for industrial and commercial tasks, and teaching in special needs or general sectors.

[9] *Jayaram et al. (2006)* propose two distinct approaches to link virtual environments (VE) and quantitative ergonomic analysis tools in real time for occupational ergonomic studies. The first approach aims at creating methods to integrate the VE with commercially available ergonomic analysis tools for a synergistic use of functionalities and capabilities. The second approach aims at creating a built-in ergonomic analysis module in the VE. The authors present the two integration strategies and test them using case studies conducted with real industrial company.

Chang and Wang (2007) propose a method of conducting workplace ergonomic evaluations and re-design in a digital environment for the prevention of work-related musculoskeletal disorders. First, the real workplace and human task can be converted into the digital environment through building digital mock-ups and using a motion capture technique. Second, the ergonomics evaluation models can be applied to evaluate the assembly task in the digital environment. The method has been applied to evaluate automobile assembly tasks and some ergonomic improvements have been implemented during assembly tasks in the automotive sector.

[10] *Gill et al. (1998)* provide an analysis of the Jack (a simulation software used for human simulation and ergonomic evaluation of car interiors) to highlight the usefulness for applications in the manufacturing industry.

Eynard et al. (2000) describe a methodology using Jack to generate and apply body typologies from anthropometric data of Italian population and compare the results with a global manikin. The study identified the importance of using accurate anthropometric data for ergonomic analysis.

Feyen et al. (2000) propose a PC-based software program that allows a designer to quantify a worker's biomechanical risk for injury based on a proposed workplace design. The program couples an established software tool for biomechanical analysis, the Three-Dimensional Static Strength Prediction Program (3DSSPP), with a widely used computer-aided design software package, AutoCAD. The software program allows the authors to study ergonomic issues during the design phase taking into consideration different design alternatives. The use of this 3DSSPP/AutoCAD interface in the proactive analysis of an automotive assembly task is described and the results compared with an independent assessment using observations of workers performing the same task.

Hanson (2000) presents a survey of the following three tools: ANNIEErgoman, JACK, and RAMSIS, used for human simulation and ergonomic evaluation of car interiors. The tools are compared and the comparison shows that all three tools have excellent potential in evaluating car interiors ergonomically in the early design phase.

Sundin et al. (2000) present two case studies to highlight benefits of the use of Jack analysis, one in the design phase of a new Volvo bus and the other in the design phase of the Cupola, a European Space Agency (ESA) module for manned space flights for the International Space Station.

Marcos et al. (2006) aim at reducing the stress and strain of the medical staff during laparoscopic operations, and, simultaneously, at increasing the safety and efficiency of an integrated operation room (OR) by an ergonomic redesign. This was attempted by a computer simulation approach based on the integration of the CAD software (CATIA) and the simulation software (RAMSIS).

2.4.1 Simulation Commercial Software

- ***1. Jack***

Jack human simulation model, which is now supported as part of UGS-PLM Solutions was developed from research into real-time manipulation of complex kinematics systems (Badler et al., 1993), and has since evolved into a commercial product incorporating a great deal of published human modeling data

The tool can be used by engineers to ask questions of their designs regarding how well the design accommodates the range of human sizes that might be interacting with it, and how a proposed design might affect human performance in terms of comfort, efficiency, and injury risk prediction. These analyses can be animated and exported as movies, providing graphic content for management review, training, and service materials. An overview providing some of the fundamental technologies comprising the Jack human figure model is presented as follows.

- ***Kinematic Representation in Jack***

  For physical ergonomics investigations in digital environments, human models need to mirror the structure, shape, and size of people in sufficient detail to allow the figures to realistically assume the static postures observed of actual individuals performing similar tasks. Such human form models typically consist of an underlying kinematic linkage system that closely parallels our own skeletal structure, and an attached geometric shell that duplicates our surface shape. The Jack human figure is an articulated, linked system that is similar to our own skeletal makeup. The joints of the skeleton obey physiological range of motion restrictions, keeping the user from posturing the Jack avatar in poses that are not typically achievable by the population. Particular attention is paid to the construct of the skeleton, to make sure that it represents reality as much as possible. This is critical, as it has been shown that the biomechanical models used for subsequent analyses of human performance are sensitive to the avatar's posture. The Jack figure has a fully articulated spine below the neck of 17 segments, fully articulated hands, and a sophisticated shoulder complex. Manually adjusting this large number of joints individually (68 of them in Jack) to define a posture would be intractable for a user, so degree of freedom reduction methods, called “behaviors” have been implemented.

  These behaviors are kinematic models created from observations of how people often move. For example, most of us cannot move individual vertebrae of the spine. The skeleton is held together with ligaments and tendons that couple the movement of skeletal bones. These motion couplings can be modeled to dramatically reduce the number of degrees of freedom the user needs to adjust, making Jack easier to posture than would be the case if all 68 links had to be set in a particular posture.

- ***Anthropometry in Jack***

  The internal skeletal structure and surface topography of a digital human model influences both the qualitative and quantitative use of the figures. As an engineering tool, the accuracy of the internal link structure affects the dimensional measures made between the environment and the human figure, such as viewpoint and reach. Similarly, the ability of the figure to acquire a physiologic surface shape directly adds to the perception of reality when viewing a simulation. While both of these aspects are important, to date effort has concentrated on improving scaling of the link lengths. This bias is in part a result of the large amount of traditional, one-dimensional anthropometric data available (i.e., stature, sitting height, shoulder breadth, etc.), in contrast to the largely non-existent three-dimensional surface contour data. Second, a driving factor of human modeling in visualization environments has been to produce a system that works in near real time (Badler et al., 1993). The complexity of the figure surface description presents a computational burden on real-time simulation performance, so a balance is sought in which there is sufficient surface detail for visual reality without undue computational load. A variety of anthropometric databases can be used in Jack to represent the dimensions of a population. Primarily, the ANSUR 1988 U.S Army database is used (Gordon et al., 1988). This very detailed database includes more than 120 measures per person from a collection of about 1700 males and 2200 females of the U.S. Army Multivariate statistical models of the proportions of individuals can be derived from these data. While it is collected on Army personnel, it included clerical and support personnel, and the dimensions have been estimated to be within a few percent of the civilian population as a whole (Roebuck, 1995). Often there are proprietary databases or country specific anthropometric databases that are desired. Unfortunately these are almost always only summary statistics, containing mean and standard deviation values of a subset of dimensions, which do not provide sufficient information to specify the many dimensions or proportions necessary to create a comprehensive human figure model. Jack includes advanced anthropometric interfaces to allow users to create figures scaled from these incomplete data, while drawing on statistical models from more complete data to provide missing proportionality information.

In response to the recent availability of three-dimensional body scan data through the CAESAR (Civilian American and European Surface Anthropometry Resource) project, Jack also is able to utilize these data figure surface polygons to match the surface topography defined by these scans. Although these latter data and their application to design are in their infancy, they are expected to enhance the visual look of the human figures and allow for additional analyses, such as more comprehensive accommodation and clothing studies.

- ***Posturing and Motion in Jack***

  As mentioned earlier, the Jack human figure has the concept of postural behaviors to help collapse the many degrees of freedom of the figure into a few that adhere closely to the parlance of the human factors community, such as shoulder abduction, adduction, and humeral rotation or torso flexion, axial rotation, and lateral bending. Even with a substantial reduction degrees of freedom that are provided by coupled joint motions, there still are far too many degrees of freedom remaining to allow rapid and accurate posturing by a user.

  To address this, Jack uses inverse kinematics (IK) to help specify joint kinematics based on a desired end-effector position. IK operates on a linked chain of segments, for example, the torso, shoulder, arm, forearm, and wrist, which provides, when given the location of the distal segment (e. g., hand), all of the joint postures along this chain based on a chosen optimization criterion. For Jack, the optimization criteria include that the joints do not separate and that the joint angles remain within their physiological range of motion. The IK also operates through the coupled joint behavior definitions, so that the empirical rules defining the motion of these complexes is preserved. Using IK, the practitioner is able to grab Jack's hand in the three-dimensional visualization environment, and manipulate its position in real time, while the rest of the figure modifies its posture (e.g., torso, shoulder, arm) to satisfy the requested hand position.

- ***Motion in Jack***

  Although static posturing is often sufficient to analyze many ergonomic issues, such as reach, vision, clearance, and joint loading, there are often times when figure motion in the form of animation is important. Examples include simulated training material managerial presentations, and analyses that depend on observations of a person performing an entire task cycle, such as when assessing the efficiency a workplace layout. The Jack animation system provides a variety of methods to create simulations, from operations that interpolate the joint locations between two postures, such as is commonly used in robotic interpolation, to constraint-based methods operating through use of the IK system.

- ***Virtual Reality in Jack***

  Often a designer might ask how a person will move to perform an operation, or ask if there is sufficient clearance for a person to grasp a part within the confines of surrounding parts. Situations that require non-typical, complex motions currently cannot be answered adequately with the movement prediction algorithms available. Although there are numerous promising efforts under way to model natural human movement, currently the use of immersive Virtual Reality (VR) technology provides the best solution to create complex human movement sequences rapidly. For these reasons, immersive is increasingly used in both design and manufacturing applications. The Jack system supports a variety of immersive hardware, including gloves, head-mounted displays, and whole-body motion trackers. As will be described later, many of the human performance models available with

Jack can work in real time while the figure postures are being manipulated. Motions can be captured and then played back for human performance analysis or presentation purposes.

- ***Performance Models with Jack***
  One of the major application areas of Jack is in the analysis of manufacturing workplaces, where issues of assemble ability, work cell layout, work adjustability and worker risk of exertion injury can be evaluated. A wide variety of human performance tools are available in Jack that provide assessments of worker risk of injury, strength capability, fatigue potential, and task timing. To facilitate the use of these tools, many have been integrated in such a way that they can run in the background, allowing the designer to concentrate on the design and only be flagged by situations that may be potentially injurious to the worker.

- ***Low Back Injury Risk Assessment in Jack***
  The low back analysis tool in Jack builds on the Jack skeleton and posturing capabilities, adding a biomechanical model to estimate the forces and moments at the joints, and a sophisticated muscle recruitment model that estimates the activity of the torso muscles in response to these forces and moments (Raschke et al., 1996). These internal muscle contributions to the overall spinal forces can be an order of magnitude larger than the applied loads. NIOSH (1981) has recommended guidelines against which the predicted compression forces can be compared, and job design decisions made. The implementation of this tool in Jack works in real time as the Jack figure is manipulated with an alert to the user if a high back-stress level is predicted.

- ***Population Strength Assessment in Jack***
  Strength assessments are a typical human performance analysis, regardless if the application involves manual handling tasks, serviceability investigations, or product operation. Questions of strength can be posed in a variety of ways. Designers may want to know the maximum operating force for a lever, dial, or wheel, such that their target demographic population will have the strength to operate it. Asked in a slightly different way, the engineer may create a job design, and might ask what percentage of the population would be expected to have the strength to perform the required tasks within the job. Jack provides a variety of strength tools, both based on psychophysical methods (Ciriello and Snook, 1991) and on maximum voluntary exertion empirical data models (Chaffin, 1998).

- ***Fatigue Assessment in Jack***
  Jack also has tools that predict possible fatigue of the worker, making sure that there is sufficient rest time in the work cycle to avoid worker fatigue during the workday. Although there are only sparse data available for fatigue assessment, the implementation in Jack draws on the University of Michigan three-dimensional strength data to identify the level of muscle group strength required by a loading situation, and then uses this with empirical endurance models to estimate the recovery time required by this exertion.

➢ 2. SAFEWORK

SAFEWORK is developed by the Safework, Inc. Business Unit of Dassault Systemes. SAFEWORK structures multiple human modeling systems to facilitate detailed investigation into human centered design issues. It is intended to provide very accurate simulation of people from many different populations, and their physical interactions with the environment, to ensure they can perform naturally in a workplace tailored to their tasks.

- ***Enterprise-Wide Human Modeling in SAFEWORK***
  In the same way that CATIA and other such computer-aided design systems facilitate the design of digital geometrical object models, SAFEWORK provides a digital geometrical representation of humans and allows a designer to evaluate humans in terms of the products they must use and tasks they must perform. However, humans are the most complex system components to be considered due to the diversity of size, the number of body segments, the degrees of freedom in movements, the complex limitations of these movements, the muscle forces that people can produce, and the various behaviors that have to be modeled.

Any software solution is only as strong as the foundations and assumptions on which it is built. For SAFEWORK, these foundations consist of skeletal definition, anthropometry, posture, and movement.

- ***Anthropometry in SAFEVVORK***

  The importance of anthropometry in design is to provide a highly scalable graphic human form in which, for example, a global automotive vehicle manufacturer can optimize its designs for a target audience consisting of millions of potential consumers across a worldwide marketplace. Detailed anthropometry surveys can record more than 100 variables that become extremely useful input variables in the development of a human form model. The effectiveness and validity of human modeling analysis tools, however, are directly correlated with the accuracy with which the human models represent the population they are simulating. As such, the SAFEWORK solution defines the human body in terms of 104 anthropometric variables, including a fully articulated spine, shoulder, and hand models. This attention to detail is intended to minimize erroneous assumptions often associated with the definition of anthropometric variables used in human models, and to ensure that the multi-factored variations in "population" size are represented in life-cycle design applications. For underlying cost-benefit trade-off reasons, a traditional general rule of thumb for designers has been to accommodate 90% of the population (from 5th to 95th percentile). This concept, in itself, is multidimensional, in that it involves the analysis of multiple anthropometry variables simultaneously. Unfortunately, anthropometry variables are often analyzed individually in a univariate manner. Confusion regarding the appropriate application of anthropometric data is well documented (Zehner et al., 1993). Brandenburgh (1999) noted that MIL-STD-1472D states:

  "*Design limits shall be based upon a range from the 5th percentile female to the 95th percentile male values for critical body dimensions.... a design range from the 5th to 95th percentile values will theoretically provide coverage for 90 percent of the user population for that dimension*."

  However, MIL-STD-1472 qualifies this statement where more than one variable is to be considered, by stating:

  "*Where two or more dimensions are used simultaneously as design parameters, appropriate multivariate data and techniques should be utilized*"

  MIL-HDBK-759c concedes that the univariate approach is inadequate in scenarios where two or more anthropometry variables are used simultaneously as critical design parameters. This standard further indicates:

  "Extreme caution should be used when two or more dimensions are simultaneously used as criteria for design. Percentile values are not additive between different dimensions.... For example, it is incorrect to assume that the combination of the 5th percentile values will describe the dimensions of a 5th percentile man"

  Brandenburgh's intent is clear. When two or more dimensions are required as design parameters, a multivariate approach should be employed. The multivariate approach used by SAFEVVORK generates a population of manikins that statistically represent the identified target audience. Each manikin in the population possesses a distinct set of anthropometric relationships that must be analyzed in unison. The exact number of "boundary" manikins increases with the number of critical design criteria. Thus, the user specifies "critical design variables" upon which a special boundary manikin algorithm unique to SAFEWORK automatically adjusts all other manikin anthropometric variables, based on the statistical correlations of individual variables. Resultant manikins are then "created" using links, ellipses, lines, and flat and gouraud shading. Gender and morphological profile can be specified including seven somatotype choices ranging from ectomorph to mesomorph. In addition to six default size manikins produced in a simulation, SAFEWORK can create, by means of an anthropometry module known as the "Human Measurement Editor", any human size or shape from published population data. Users can manually define any of the 104 anthropometric variables on the manikin by inputting desired measurements in terms of percentile values or unit measurements. SAFEWORK also affords users the capacity to define the mean and standard deviation for each variable. The multivariate algorithm then generates a manikin corresponding to the most probable human being in the target population.

SAFEWORK allows users to access up to 94 recently completed male and female population surveys containing data relating to anthropometric variables, including their standard deviations, percentile values, and correlations. Functional anthropometry, by its very definition, is domain and application specific. As such, SAFEWORK's Human Measurement Editor presents anthropometry data derived from both standing and seated reference postures. In addition, SAFEWORK permits the intuitive construction of user-defined, or proprietary, anthropometric databases for truly global human modeling requirements.

– ***Realism of Skeletal Structure and Movement in SAFEWORK***

Ensuring that a human model moves and behaves in a realistic, task-oriented fashion is the next "foundation" element required for validity of a human modeling solution. SAFEWORK defines the human body with 100 links and segments representative of the skeletal structure, with 148 degrees of freedom ensuring realistic joint movement capability. The SAFEWORK human model can be manipulated using a number of posturing techniques including direct kinematics, IK, custom movement libraries, low-level simulation primitives, or VR motion capture technology.

IK is employed by SAFEWORK to define the final position of an end-effector at the end of a kinematics chain (for example, hands on steering wheel). IK techniques require the system to "inverse" all joint positions to determine what joint angles are required to reach the desired postural goal. SAFEWORK possesses seven default IK handles to control manikin motion and predict postures. In addition, the user can define up to 20 end-effectors as scenario-specific constraints. The manikin's 148 degrees of freedom take into account joint limits, and support a coupled range of motion for enhanced realism of movement.

IK chains can also be extended to include tools, clothing, objects, or accessories that are manipulated by the human model. For example, a power tool attached to the hand of the manikin can serve as the end-effector for the IK calculations, and would drive the movement of the manikin. Simultaneous multiple end-effectors enable the designer to describe a task as a series of goals and geometrical constraints. In contrast, direct kinematics can be employed to accurately fine-tune manikin postures by manipulating individual segments in each available degree of freedom. For example, changing the degree of forearm flexion would result obviously in a new hand position, without affecting the position of the upper arm segment in space.

Both direct kinematics and IK play an important role in determining the predicted posture of the manikin. All manipulation and posturing techniques need to ensure that the resulting posture lies within the functional limitations of the human model segments. The challenge is to try to make sure that the resulting posture will be as natural as possible. To that effect, SAFEWORK permits all movements to be defined not just by absolute physical limits, but also by "preferred angles", which may reference joint comfort angle data (range of angles between segments where the least discomfort is observed). Range of motion data representing task-specific functional limitations can also be applied to each segment so that each available degree of freedom (flexion/extension, rotation, abduction/adduction, etc.) conforms to best practice, as outlined by general human factors principles or task-specific criteria. The concept of "population accommodation" does not relate uniquely to anthropometry data. In the same way that anthropometry data can be normalized around a mean, flexibility should also be subject to accommodation analysis. For example, some demographic elements of the population are more flexible than others and, as such, will enable a certain percentage of the population to perform certain tasks that others could not. SAFEWORK permits users to utilize available population statistical data that can be used in conjunction with coupled range-of-motion limitations to analyze the range of motion of a given segment, not just in an isolated sense, but also according to the position of neighboring segments.

- ***Analysis Tools in SAFEWORK***

  The ability to define, create, and manipulate human models that represent the appropriate target audience is, in itself, merely establishing the foundation for "adding value" to the design process. SAFEWORK possesses a range of analysis tools for evaluating task-specific human factors criteria. For example, gaining an understanding of what an operator or maintenance person could "see" in a task environment is a fundamental element of a human factors analysis. The SAFEWORK Vision Module, derived from the NASA 3000 standard (1989), contains an accurate vision behavior model to replicate the realistic movement of the human eyes, so that "what the manikin sees, the designer sees". Four types of vision simulation are provided: binocular, ambinocular, monocular left, and monocular right (stereoscopic viewing with advanced depth perception is available in the Virtual Reality Feature). Visual characteristics are displayed as peripheral cones, central cones, blind spot cones, and central spot cones that permit the user to gain an insight into the manikin's view.

- ***Human Modeling Data Interoperability in SAFEWORK***

  The SAFEWORK architecture is based on the concept of libraries. Manikin oriented libraries, containing variables, such as angular limitations, comfort angles, maximum force exertion, and other preferred variables are provided, as well as global posture libraries and local posture libraries (grasp, pinch, grip, hook, etc.). Libraries of clothing (part of the Clothing Module) can be used to indicate the functional limitations of the manikins are also provided. No single source of data in SAFEWORK is "hard coded" so a user can edit, modify, or create new data sets as appropriate.

➢ *3. RAMSIS and ANTHROPOS*

RAMSIS is meant to provide efficient design of interiors of cars, trucks and airplanes within existing computer-aided design systems (Seidl, 1997). VR developers would have enlivened their virtual scenes with these human figure models long before now if such models had been available to them with high graphic quality, and with biomechanical intelligence. These developers and users of VR techniques require an efficient tool with an adaptable interface within their VR systems. For this purpose the ANTHROPOS was developed. What follows is a brief description of both RAMSIS and ANTHROPOS TECHNOLOGIES.

- ***Anthropometrical Realization in RAMSIS***

  At the beginning of RAMSIS development it was realized that the amount and types of anthropometric data were insufficient for the complete definition of a comprehensive three-dimensional human figure model. At present anthropometrical data are obtained by two- and three-dimensional body scanners of test subjects in a number of select postures. The data images are read into the computer, where they are overlaid with RAMSIS. The simulated length, thickness, and circumference of each human body element are then varied until the scanned data are completely congruent with the corresponding digital human form.

  The heart of the tool RAMSIS is a three-dimensional human form model with its archives containing data regarding postures and seated comfort, as well as an anthropometric database. While the appearance of a human being is completely described by its body surface, the mobility is largely determined by the skeleton. In a similar way, RAMSIS is represented on two levels: an internal and an external modeling level. The internal RAMSIS model plays the role of a "human skeleton" and is the basis for the definition of RAMSIS kinematics. The external RAMSIS model represents the body surface. In contrast to most existing human models, the body surface of RAMSIS is not modeled by rigid, geometrically simple objects (prismatic bodies or ellipsoids) but rather by use of a set of posture-dependent control points. These control points (about 1200 in the standard model) are attached to the internal RAMSIS model. The attachment is not static, but varies in accordance with the joint positions. The statistical results of the process of overlaying measured postures onto a digital surface are realized in the anthropometric database module RAMSIS/BodyBuilder. Using a classification scheme it is possible to describe the human population in a realistic way. From 90 real physique types obtained from scanned populations of people, the user chooses statistically defined population groups by providing key measurements of height, proportion, and corpulence. The database of BodyBuilder provides the size of a defined population segment by borderline typologies. This functionality is combined with standard anthropometric databases from Germany, France, USA, Canada, Japan, Korea, South America, and Mexico.

- ***Research of Posture and Movement Simulation for Cockpit Design with RAMSIS***
  RAMSIS includes a three-dimensional posture and movement simulation. Postures of different analysis tasks of test subjects were measured by cameras located at arbitrary positions. In addition to posture measurement with the pedals, steering wheel and seat placed m various locations, typical functions such as reach and entering and exiting the car have been included in the test range. Based on the distribution of postures with respect to various body dimensions and various tasks, a multidimensional "postural function" has been developed for each joint (Seidl, 1994). The measurement of postural discomfort has been performed with the aid of a vehicle mockup. The position of the controls may be varied in this mockup to such a large extent that the dimensions o nearly any vehicle - from a sports car to a small truck - can be simulated. In addition, the mockup has been extended to include simulations of driving views and acoustics. For the measurement of discomfort, the test subjects were requested to maintain different postures. A standardized questionnaire was used for evaluating the feeling of discomfort of the test subjects. The questionnaire data for each test subject were compiled with the corresponding recorded postures. Thus, it was possible to calculate regression coefficients, which when applied to postures of the RAMSIS model can then predict the expected postural discomfort of a given seated position. In practice, the designer describes the task to be fulfilled by RAMSIS by interactively defining complex model restrictions, for example hands on the steering wheel, feet on the pedals, drive looking backward, including a chosen viewing posture. These restrictions can be stored and reused with other human simulations. Additional constraints, such as avoiding penetration of body parts, also are provided.

- ***Modeling of Vehicle Seating Spinal Postures and Belt Factors with RAMSIS***
  Accurately predicting driver posture in a new vehicle/seat design allows for efficient planning and verification of what an occupant can reach, see, and access while in a specific posture. Additionally, proper occupant posture prediction allows for better determination of safety restraint locations and compliance with regulations. Based on the Michigan State University JOHN model, which provides a biomechanical simulation of the lower torso posture, experiments were conducted to examine the change of postures due to seat and interior package factors. This research provided a biomechanical simulation of the torso posture and the postural effects due to current seat and interior package factors (Gutowski et al., 2001). For example, many new seat designs include aggressive side bolsters and/or lumbar support which did not exist when prior standards and occupant prediction methods were developed. The results are integrated into the posture prediction model of the RAMSIS program to give a more detailed prognosis of the spine curvature, and thus can be used to refine the model-seat interactions.
  Seat belt efficacy to prevent injuries in a collision is directly related to how well the seat belt design matches occupant body dimensions. Research by Transport Canada developed a Belt Fit Test Device (BTD) to forecast potential occupant injuries resulting from discrepancies between seat belt designs and occupant sizes. The digital eBTD module is integrated with RAMSIS and allows vehicle manufacturers to use computer-aided design data to evaluate seat belt designs before a vehicle is produced. It positions the computer-aided design data representation of the physical BTD in a three-dimensional vehicle interior, including vehicle geometry, for a given driver (Pruett et al. 2001). Users specify the location and types of anchor points for various seat belt configurations. The software module then simulates the predicted routing over the eBTD, and measures the belt position over the clavicle, sternum, and lap scales, with respect to belt width and contact to the surface.

- ***Additional Functions in RAMSIS***
  Similar to other simulation commercial software, a variety of functions are integrated into RAMSIS. A reach analysis tool makes it possible to determine a predicted surface envelope of reachable limits for any chain of body elements set in various seated postures. These surfaces are actually calculated, taking into consideration the kinematics of the model. A line-of-sight simulation allows the user to sit inside the model and look at the proposed

design of the workplace through the eyes of the manikin. The user can switch from the left eye to the right eye, or a combined eye view with a “shadow” function for covered objects. A mirror simulation allows a simple method of detecting hidden or partially hidden objects. Complex cockpit analysis and design are possible with these ergonomic tools in RAMSIS. In addition, some specialized automotive technologies are integrated in RAMSIS. For example, a parametric package designer or the most important checking procedures of national and international car regulations are integrated.

- ***Design of ANTHROPOS***
  The ANTHROPOS graphic models consist of 90 parts of the body and a corresponding number of joints, some of which have five axes. The surface is constructed internally from 3200 skin points and as many as 40,000 reference points, which are also used for recognition of collisions. The resulting human figure can be displayed with various graphic qualities, from wire frame to shading, depending on the computer-aided design system being used. The movement intelligence of the models is integrated in the internal support and movement apparatus (skeleton) including a 24-part spine and five-finger hands. By deforming the outer skin or clothing layers in the model, the skin or clothes adapt to the skeleton movement. One also can select the reference points that are to make contact with the environmental graphic.

- ***Working Posture Animation and Simulation with ANTHROPOS***
  The primary movement simulation process in ANTHROPOS is called Auto Animation. This algorithm recognizes the various movement limits of the joints, and the movement dependencies of pelvis and thigh when sitting, as well as the movement in the shoulder region when lifting the arms. Body postures believed to be injurious to health cannot be generated with auto animation. To generate specific or very awkward postures, as still occur at many workplaces, manual direct postural manipulation is used, during which each joint can be moved separately. With this method, however, the mobility of the spine, depending on age and fitness, can also be influenced. All settings are made dynamically by entering angles or with potentiometer settings. Standard body postures (bending, kneeling, crouching, sitting, climbing, etc.) can be generated. Also, pelvis rotation with fixed foot positions and walking to a distant goal are possible. When the floor and seat height are given, along with the angle of the seat and backrest, the optimum foot position is computed and the model assumes this sitting position. In parametric animation the user can construct relationships to a reference point, and mutual relationships to touch points and objects (lever, steering wheel, car door). In addition to touch points and touch planes, restriction surfaces can be defined; ANTHROPOS recognizes them as collision surfaces relating to parts of the body with the help of its numerous skin points. It positions the manikin to avoid these. If restriction angles have been entered, then it records the magnitude of the variation from these values. For the hands, gripping postures with the hand straightened and slack, and in an adjustable gripping diameter, forefinger straight and bent, with dynamic movement of single fingers are available. Rotational and lateral movements of the kinematical chains can be carried out in free space, but also to defined points within the environmental graphic. Direct movements to the chosen point and motion capture gathering of several points are possible. Using Newtonian mechanics, the kinematic chains move in different ways, depending on age, to goal points where they remain fixed until further notice. During these movements, the joint at the end of the chain (hip) tests whether and how the following joint (knee) has already been moved, and computes the biomechanical correct limiting angles to be derived from it. To specify the position of the hands and feet end target or goal, exact touch planes can be specified. The combination of the different animation algorithms of ANTHROPOS allows the analysis of a complex lifting movement. ANTHROPOS automatically tests the physical loading of the joints caused by an animation (movement space used in percent, joint point resistance, torque, and normal force) and compares them with an alternative movement specified by the user. The values can be displayed alphanumerically and graphically. Using the Burandt method (Burandt, 1978), load limits for lifting and carrying are computed with the person standing, facing the load. Sex and age, body height and fitness, load weight and frequency, as well as distance lifted, are included in the calculation (Seidl, 2000). Depending on a person's anthropometry and sitting posture, ANTHROPOS computes the static and dynamic leg forces.

- ***Additional Ergonomic Functions in ANTHROPOS***
  To recognize reach capabilities, not only after single animations, a reachability module for hands and feet is available with which all defined goal points are tested simultaneously, and (if necessary with offset values for tools) are noted as “reachable, only just reachable, or unreachable”. The reachability curves are displayed in defined planes. ANTHROPOS can provide sight line analysis in various ways. With the “eye” switched on, it shows its graphic environment in a separate window on each animation as a person would see it with a given head position. Angle of sight and distance seen can be specified by the user. The various sight functions, however, also include projection of points on defined planes (road, house front, etc.). Objects that hinder sight (steering wheel in front of instrument panel) are projected as shadows on the visual environment, and anything seen in a rearview mirror to be defined with curvature factors can be displayed on the mirror.

➢ *4. SAMMIE*

SAMMIE (System for Aiding Man Machine Interaction Evaluation) is a computer-aided human modeling, ergonomics design, and evaluation system. Since its conception in the late 1960s, SAMMIE has been continuously employed in research, and as a consultancy tool (Bonney et al., 1979; Case et al., 1980, 1990a, 1990b; Porter et al., 1991, 1993, 1996, 1999). This section details the functionality of the SAMMIE system, and the SAMMIE team’s approach to supporting the use of computer-aided ergonomics throughout the product development process.

- ***Functionality with SAMMIE***
  SAMMIE's primary goal is facilitated through the provision of the following:

  - A fully articulated human model capable of representing people of the required gender, age, and nationality;
  - A knowledge base of maximal and comfort limits for the major joints of the body to represent realistic human reach capability;
  - The ability to model/import graphical models from other computer-aided design systems of the product or environment concepts together with the ability to simulate model functionality, such as ranges of adjustment, control limits, and the structural and functional relationships between model elements;
  - The ability to assess the kinematic interaction between the human model and the product or environment in terms of fit, reach, vision and detection of surface collisions;
  - The ability to assess concept designs and subsequent modifications to ensure good ergonomics before physical mockups and user trials are required.

  The SAMMIE human model is a fully articulated manikin capable of utilizing standard published anthropometric data or custom data obtained or taken by the user. The system then provides the flexibility to modify the human models size through the percentile range from below 1st to above 99th percentile for the whole body, or for individual limb dimensions. In addition the technique of somatotyping is used to control the shape of the avatar allowing the user to represent the degree of endomorphy (fatness), mesomorphy (muscularity), and ectomorphy (thinness) as described in Sheldon (1940). SAMMIE has its own equipment/workplace modeling capability, in addition to supporting the importation of graphic data from the user’s preferred computer-aided design system. Assessment focuses on whether or not the human models can work efficiently with the product or in the environment and can adopt “comfortable” postures. The human model may be “driven” trough direct manipulation of individual limb positions, but also through a library of postures and automated reach and vision checks. Additionally, lifting and materials-handling risk evaluation is supported by linking to the NIOSH lifting equation and RULA risk assessment tools for given postures (NIOSH 1981, McAtamney and Corlett, 1993).
  Finally, the SAMMIE system provides a macro command language that allows processes to be automated and assessments to be chained together.

- ***Development and Application of SAMMIE in Achieving Design for All***

  Recent work has focused on the concept of design for all or what some professionals refer to as "universal design". While young and able people are often considered to be able to "adapt" to a poor design, there is typically an associated human cost. For example, a poor posture that has to be maintained for prolonged periods will result in a high incidence of musculoskeletal complaints and possibly sickness absence. If important displays are not clearly visible or controls are difficult to operate, then safety will be compromised. People who are older or disabled have less opportunity to adapt to a poor design. In many cases, they are effectively "designed out" and cannot use the product or service. The design for all philosophy aims to reduce, if not eliminate, this problem. Attempting to design for all, including people who are older or who have disabilities, exposes a number of limitations of current anthropometric and biomechanics databases. It is believed that there is a need for a new approach to effectively support designers when attempting to design for all, be it in the workplace, at home, or in public areas. The main limitations of current anthropometric and biomechanics databases for this purpose include (1) their mode and format of presentation, (2) their lack of support for investigating multivariate issues, and (3) the lack of holistic information including specific task and environmental factors (Porter et al., 2002). In essence, designing for all requires access to a large library of publications to compile information on the physical size and abilities of people of all ages. Current anthropometric and biomechanics databases and guidelines present information typically as univariate percentiles with a separate table of numbers for each variable, such as eye height, arm reach, or hand grip strength. These percentile tables are prepared for either a healthy population, often aged 19 to 65 years, or for specific populations, such as people who are older and with specific disabilities. Sadly, most of these databases do not promote the need for multivariate analysis. Statistical methods exist that can be used by specialists to conduct multivariate analysis, such as principal component analysis and Monte Carlo simulation. Both are complex and often lack face validity. Although many designers have doubts about the validity of combining different percentile body segments based on statistical calculations, the fact that there are no actual faces that can be put to these anonymous statistical creations is a bigger problem. Designers need to have empathy with the people they are designing for - they find it difficult to design for statistical calculations. Empathy comes from seeing people and getting to know and understand their needs and desires. The data also need to be task and environment specific. For example, an assessment of an oven design will require the user to hold the hot baking tray in two hands using oven gloves, not just with a simple one-arm reach, as sometimes presented in existing guidelines. In addition, it is likely that users will have developed some "coping strategies", which help them to carry out the various tasks in the kitchen despite certain impairments. It would be most beneficial to record these and be able to pass this knowledge to the designer. The approach to supporting design for all in SAMMIE includes two main elements. First is the creation of a novel computer database of "individuals", so that multivariate analysis can be conducted on a wide range of people of all ages, abilities, shapes, and sizes. The database initially comprises 100 individuals, including a large proportion that is older and/or disabled. This sample, while not intended to be representative of the whole population, provides a useful measure of the extent of variation in physical characteristics and capabilities and provides a preliminary database for the development and validation of the predictive tool. Design relevant information concerning each individuals task behavior (including coping strategies) and environmental issues have been recorded using test rigs to simulate typical activities of daily living that are known to be problematic for people who are older or disabled (Oliver et al., 2001).

  The second element is the development of a computer-based tool to support the use of the database in design situations. Thus, the database of individuals also is supported by an integrated ergonomics analysis tool. HADRIAN (Human Anthropometric Data Requirements Investigation and Analysis) is a computer-aided design tool that integrates the database of individuals, including their anthropometry, mobility, capability, disability, coping strategies, and a wealth of background data with a simple task analysis tool. HADRIAN has been developed to work in conjunction with the SAMMIE system. Together these systems provide the capability to investigate data on individuals in addition to allowing task analysis and virtual fitting trials to be carried out on a design without the need for prototypes and user trials. However, it is not the intention to replace physical models and user trials, but rather to complement them. The two systems HADRIAN and SAMMIE provide the designer with the ability to accomplish the following:

- Model a product/environment, or import a model generated on another computer-aided design system;
- Select a target user base, which should be the whole database when designing for all;
- Create a task description with as much or as little data as wished (e.g., viewing distances, which hand to use, etc.);
- Run the task analysis with the chosen user base;
- Inspect the results of the analysis including:

  - Estimation of the percentage of the individuals in the database who are accommodated by the product/workstation/environment, which informs the designer of the extent to which design for all has been achieved, and is a useful metric for comparing alternative designs;
  - Identification of those individuals who were designed out because they failed certain parts of the analysis, which should promote an understanding of why the failure occurred and lead to the development of design improvements.

- Modify the design/task parameters and rerun the analysis, which promotes iterative design and evaluation until the design solution has been optimized.

– ***Task Analysis in SAMMIE***

HADRIAN's task analysis features are aimed at providing designers with a simple and flexible mechanism for constructing a task description for the use of, or interaction with, their chosen product or environment design. Although most of the actual tools for performing individual elements of a task analysis are part of SAMMIE's inherent functionality, HADRIAN attempts to simplify their use and remove the overhead of driving the system, while concentrating on the application of sound ergonomics principles. To construct a task description the designer first loads the graphic model to be assessed, from which the system extracts the interactive objects; those elements that will be sat on, reached to, viewed, activated, etc. The designer then decides what the user is to do by selecting the type of task element (e.g., reach) and then selecting the object to be reached for (e.g., keys). While the system provides users with ability to enter as much detail as they wish, it does not require it. Information that may be supplied includes which hand should be used, the duration of the reach, the importance of this task element, any maximum viewing distances, and orientation information for objects. Any information that the system needs to perform the analysis that is not explicitly specified by the designer will be set to a default that is task specific. Thus, the system may decide to use the nearest hand to perform a reach, but this may be overridden if the individual being assessed has a limited capability with that particular hand or has specified a preference to only use a particular hand for a particular type of task. The techniques behind the analysis have been developed to be as robust as possible, allowing for the multivariate nature of the analysis. The system also employs a framework that overlies the task description in an attempt to more accurately represent a dynamic process (performing the task) from a sequence of static task elements (reach x, view y, etc.) (Marshall et al., 2002). Such features have little or no impact on the designer, but lead to a much more flexible and realistic analysis.

– ***Feedback and Result Reporting from SAMMIE***

One of the most important aspects of the HADRIAN tool with SAMMIE concerns the results obtained from an analysis. Again, the designer is able to configure exactly how the tool behaves, and thus is able to customize the level and format of the feedback obtained. At one extreme, the system can perform the analysis without any user intervention, logging results, making assumptions where required, and skipping any failures. The final results are then presented when the analysis is complete for the designer to examine. The other extreme allows the designer to be involved in any decision-making processes where the system has to resolve some issue. Such issues may include what to do in the event of a failed task element or an inconsistent task definition, such as explicitly specifying a hand for a reach task when the hand is already holding an item. The flexibility of being able to intervene during an evaluation allows the designer to refine the task analysis during early runs and then run more autonomous analyses when the process is more robust. Alternatively, this facility allows the designer to run through the analysis in a more step-by-step approach to understand the issues faced by a particular user at every stage and actively think about how all aspects of the design can affect its usability. Although HADRIAN is not an intelligent design system, it can highlight some of the key variables that are involved in the failure and direct the designer's attention to the fundamental reasons for the problem. A large range of results may be examined to determine who has successfully completed the task analysis, and potentially more importantly, who has failed, or been designed out, and why. A particular statistic presented is the percentage accommodated by the design. Although this is a very complex metric, it provides a powerful indicator of the usability of the design when compared against alternative design concepts.

➢ *5. Boeing Human Modeling System*

The Boeing Human Modeling System (BHMS) was developed starting in 1987 as a tool for human factors engineers to analyze proprietary product data for human fit, reach, and vision in aircraft cockpit design and, generally, workplace design, using three-dimensional computer-aided design data. It has evolved based on user requirements to include a manikin with a 24-link flexible spine. More than 100 input measures can be accessed with the capability to analyze new designs, maintenance, and assembly scenarios for various populations of individuals, while supporting a variety of computer-aided design formats. Through the years, many analysis features have been incorporated into BHMS, such as the capability to sweep three-dimensional volumes of body segment motions through space in order to define human motion paths and three-dimensional engineering "stay-out" volumes. This capability allows a manikin's arm/hand/tool to define a required three-dimensional volume for a population while performing such operations as maintenance tasks with various hand tools.

– *Torso Modeling in BHMS*

Another advance in human modeling analysis within BHMS was the development of the full 24-link spine and spine motion algorithms. The spine can be driven through its range of motion via a forward kinematics interface where the motion of the spine is split into groups: (1) head/neck, (2) lumbar, (3) torso, and (4) full spine. Control points on the geometry representing the manikin torso/shoulder/neck skin enfleshment allow the surface to stretch as a normal torso would as the spine moves. The motion and reach range of the manikin was greatly extended by adding the spine motion algorithms to BHMS.

– *Predicting Reach Envelopes in BHMS*

The ability to create "population union" reach envelopes with BHMS allows engineers to determine predicted maximum reach for all manikins in the "design to" population. This feature combines the maximum reach of any number of manikins, and then creates a reach envelope that will accommodate all those in the targeted design group.

– *Hand Tool Modeling in BHMS*

Another analysis feature of BHMS is the ability to simulate the use of special tools, such as the speed wrench. This feature allows the full range of animation of the tool by keeping the left hand attached to the tool in a fixed location while the tool motion drives the inverse kinematics for the right hand, thus rendering a real-time evaluation of manikin-tool use.

➢ *6. EM-Workplace*

eM-Workplace is a 3D-simulation software tool used for designing, analyzing and optimizing manual workplaces and operations. It simulates human tasks using human models of appropriate gender and body size. It also optimizes the workplace by using various ergonomics analysis methods, including posture, energy expenditure and lifting force, as well as manual cycle times by using MTM-methods. The human operations can be simulated together with robotic and mechanical tasks once inserted in the same sequence of operations chart.

eM-Workplace is the simulation software utilized for carrying out the research activities related to this PhD thesis and it will be presented to the reader contextually to its use (please refer to chapters 3 and 4).

2.5 Research Shortages Identification

The literature overview on the effective workplace design research area remarks the huge efforts carried out by researchers and scientists. Although significant, relevant and high quality scientific results have been achieved, it seems to be clear that further developments are still possible. In effects, the accurate analysis of the literature points out two deep research lacks that can be listed as follows:

1. Simulation commercial software are often used in combination with either ergonomic or work measurement methodologies: the final ergonomic design of the workplace does not consider simultaneously ergonomic and time issues.
2. Researchers and scientists usually design the final workplace configuration following their experience and/or knowledge: the workplace design is usually based on trial and error methodology and does not follow any standard one.

This PhD thesis comes in help of such research shortages: it is the intent of this study to develop a standard methodology that can be used by production engineers for the effective design of workplace within industrial environments. The design methodology aims at considering both the interaction of the operators with their working environment (ergonomic issues) and the work methods (time issues). As support tool for applying the design methodology Modeling & Simulation (M&S) and virtual three-dimensional environments are used for recreating, with satisfactory accuracy, the evolution over the time of the real industrial workplaces. In particular the effective design of the workplaces is achieved by using the simulation model for comparing workplaces' alternative configurations (in terms of workplaces layout, tools disposition and operators' work methods). The generation of the alternative configurations comes out from the variation of multiple design parameters that affect multiple performance measures (ergonomic and time performance measures). The evaluation of the effects of the multiple design parameters on the multiple performance measures allows to choose the final configuration of the workplace. A detailed description of the proposed methodology is presented in Chapter 3.

Chapter 3

Effective Workplace Design: A Methodology

To be effective, industrial engineers need a methodology to design effectively industrial workplaces. This methodology has to be practical and designed to be used in the workplace to achieve ergonomic and time improvements. The objective of this chapter is to introduce and present a design methodology that can be used by industrial engineers for achieving the effective design of workplaces within industrial environments. The chapter will bring clarity to the foundational understanding of the methodology placing specific emphasis on its principles and procedures. To this end, the methodology steps will be deeply discussed.

3.1 Introduction

The PhD thesis focuses on the development of a multi-measure based methodology that can be used by industrial engineers for achieving the effective design of workplaces within industrial environments. The design methodology is based on multiple design parameters and multiple performance measures and aims at considering both the interaction of the operators with their working environment (ergonomic issues) and the work methods (time issues). Such methodology must take into account all the design parameters affecting the performance measures related to work measurement and ergonomics. However an industrial workplace is a quite complex system characterized by different design parameters (i.e. objects dimensions, tools position, operator work methods). As a consequence, the design methodology has to be supported by an approach capable of recreating the complexity of a real industrial workplaces. To this end, Modeling & Simulation (M&S) tools are used for recreating, with satisfactory accuracy, the evolution over the time of the real industrial workplaces. Moreover, simulation can be jointly used with virtual three-dimensional environments in which observe the system and detect ergonomic and work measurement problems that otherwise could be difficult to detect. The 3D simulation model of the industrial workplaces is used for investigating and comparing different workplaces configurations in terms of workplaces layout, tools disposition, and alternative operators' work methods. The generation of the alternative configurations comes out from the variation of multiple design parameters that affect multiple performance measures (ergonomic and time performance measures). The evaluation of the effects of the multiple design parameters on the multiple performance measures allows to choose the final configuration of the workplace.

The design methodology consists of the following 6 steps:

- **STEP 1**: Problem Formulation and Objectives Definition;
- **STEP 2**: Performance Measures and Design Parameters Definition;
- **STEP 3**: Data Collection;
- **STEP 4**: Simulation Model Development;

- **STEP 5**: Effective Workplace Design;
- **STEP 6**: Results Presentation and Implementation.

Sections 3.2-3.7 present a detailed description of the aforementioned steps.

3.2 STEP 1 – Problem Formulation and Objectives Definition

The problem formulation and objectives definition is the most important step in the process and guides all others methodology steps. Nothing is less productive than finding the right solution to the wrong problem. Every study begins with a statement of the problem. If the statement is provided by those that have the problem (client), the analyst must take extreme care to ensure that the problem is clearly understood. If a problem statement is prepared by the analyst, it is important that the client understand and agree with the formulation. After the problem formulation, establishing sound objectives is critically important. Obscure objectives make it difficult to succeed, while objectives that are precise, reasonable, understandable, measurable, and action oriented convey a proper sense of direction and allow to distinguish between primary and subordinate issues. The definition of the objectives is based on the generation and the analysis of several key questions. These key questions serve to support the their definition and to identify (within the system under consideration) all the aspects that need to be analyzed.

Considering the effective workplace design, representative questions in support objectives definition could be the following:

- Is the worker strong enough to do the job without getting hurt?
- Is the worker strong enough to do the job long enough, and is there enough recovery time to do it again?
- If the job is repeated often enough for an extended period of time, will the worker contract cumulative damage?
- Are there any lifting tasks to be carried out?
- How many times are the lifting tasks repeated within a shift?
- Are the objects to be moved too heavy for the operators?
- Are the objects positions easily reachable by the workers?
- Can the sequence of the workplaces operations be changed?
- Can the workplaces operations be combined?
- Can the work itself be simplified?
- etc..

Listing all questions, ranking them in importance, and selecting the key ones helps to further direct the objectives definition process.

3.3 STEP 2 - Performance Measures and Design Parameters Definition

At this point the objectives are set. Next step is to decide what performance measures are necessary to answer the key questions defined in the previous step and, in turn, to monitor the objectives achievement. As stated before the design methodology is based on multiple ergonomic and time performance measures. A list of ergonomic performance measures (indexes) is reported as follows:

- Working postures indexes evaluated by using the OWAS methodology;
- Upper limb stress indexes evaluated by using the RULA method;
- Load indexes for lifting tasks evaluated by using NIOSH 81 and NIOSH 91 lifting equations and/or Burandt Schultetus methodology;
- Lumbar spine forces and strength demands indexes evaluated by using the University of Michigan's 2D, 3D analysis;
- Push/pull/carry indexes evaluated by using Snook and Ciriello method;

- Force, posture, repetition, grip, and vibration ergonomic indexes evaluated by using the ErgoMOST methodology;
- Operators' metabolic energy consumption evaluated by using University of Michigan's Energy-Expenditure Garg methodologies;
- Action limits indexes evaluated by using the OCRA methodology.

Further information about the cited ergonomic indexes can be found in Chapter 2.

The time performance measures could be the process time evaluated by using any of the work measurement methodologies deeply discussed in Chapter 2.

Moreover, validity, reliability, and accessibility criteria have to be followed in order to choose the correct performance measures. The following questions help industrial engineers to effectively define performance measures:

- Is the measure clearly defined? *(validity and reliability);*
- Is the data easy to obtain? *(minimize burden);*
- Is there a tracking/reporting system? Is it easy to access and use? *(accessibility);*
- Is the measure useful to whoever can act on it to improve performance? *(validity);*
- Does the measure accurately reflect what is happening in the system? *(validity).*

After the output indexes are set, the design parameters, that could have an impact on the ergonomic and time performances measures, have to be identified. Distances and angles associated to objects and tools positions, objects dimensions (length, width, and height), operations sequence of work methods could be significant factors for industrial workplaces design.

3.4 STEP 3 - Data Collection

To reiterate, the proposed methodology uses 3D simulation models of industrial workplaces for comparing different workplaces configurations in terms of time and ergonomic issues; such comparison is carried out by means of the time and ergonomic performance measures evaluated by using work measurement and ergonomic methodologies. In this context, it has to be pointed out that all simulation models require data to be developed as well as ergonomic and time methodologies need input data to be carried out. Therefore, in order to correctly apply the design methodology collecting such data, or estimating it if they are not available, is a necessity.

Good data are critically important. If the data are limited in some way, so are the results of the study. Moreover, if the data appear in error, inconsistent, or irrelevant, it undermines the results goodness. Challenging all data collected, doing a quick audit, considering the source, what was collected, when it was collected, and how it was collected are all important activities to be carried out in order to complete correctly the data collection step. The following questions come in help of a good data collection process:

- Do the data make sense?
- Are the data at an appropriate level of detail?
- Are the data within the scope of the study?
- How are the data going to bias the results?

There are two general types of data: descriptive and judgmental.
Considering the effective workplaces design, descriptive data could include the following examples,

- Workers characteristics (age, gender, height, weight and physical condition);
- Objects dimensions (length, width and height);
- Objects weight;
- Work methods operations sequence;
- Operation basic motions list;
- Lifting tasks frequency;
- Workers' postures at the origin and destination of the lift;

- Objects coupling, i.e. grip quality;
- Duration of specific tasks;
- etc..

while, examples of judgmental information could be the following:

- Opinions from experts or consultants;
- Workers' well being;
- Workers' satisfaction;
- Workers' beliefs and values;
- etc..

Examples of different data collection methods are given below.

- *Based observation methods:* video based systems, walking-through observation, video capture and playback technology, etc.;
- *Behavior Observation Checklist*: a list of behaviors or actions among participants being observed. A tally is kept for each behavior or action observed;
- *Knowledge Tests*: information about what a person already knows or has learned;
- *Opinion Surveys*: an assessment of how a person or group feels about a particular issue;
- *Performance tests:* testing the ability to perform or master a particular skill;
- *Delphi Technique:* a method of survey research that requires surveying the same group of respondents repeatedly on the same issue in order to reach a consensus;
- *Q-sorts:* a rank order procedure for sorting groups of objects. Participants sort cards that represent a particular topic into different piles that represent points along a continuum;
- *Self-Ratings:* a method used by participants to rank their own performance, knowledge, or attitudes;
- *Questionnaire:* a group of questions that people respond to verbally or in writing;
- *Time Series:* measuring a single variable consistently over time, i.e. daily, weekly, monthly, annually;
- *Case Studies:* experiences and characteristics of selected persons involved with a project;
- *Individual Interviews:* individual's responses, opinions, and views;
- *Group Interviews:* small groups' responses, opinions, and views;
- *Wear and Tear:* measuring the apparent wear or accumulation on physical objects, such as a display or exhibit;
- *Physical Evidence:* residues or other physical by-products are observed;
- *Panels, Hearings:* opinions and ideas;
- *Records:* information from records, files, or receipts;
- *Logs, Journals:* a person's behavior and reactions recorded as a narrative;
- *Simulations:* a person's behavior in simulated settings;
- *Advisory, Advocate Teams:* ideas and viewpoints of selected persons;
- *Judicial Review:* evidence about activities is weighed and assessed by a jury of professionals.

Below are some issues to remember when choosing a data collection method:

- *Availability:* information and data may be already available. It is advised to review information in prior records, reports, and summaries;
- *Need for Training or Expert Assistance:* some information collection methods will require special skill on the part of the evaluator, or perhaps staff will need to be trained to assist with the evaluation;
- *Pilot Testing:* the information collection instrument may be tested, no matter the form or structure. It is needed to plan time for this step and for any revisions that may result from this testing;
- *Interruption Potential:* the more disruptive an evaluation is to the routine of the project (i.e. it could "disturb" workplaces processes and operations), the more likely that it will be unreliable or possibly sabotaged by those who feel they have more important things to do;

- *Protocol Needs:* in many situations, appropriate permission or clearance to collect information from people or other sources need to be obtained. Time is needed to work through the proper channels;
- *Reactivity:* **r**eactivity may also be a concern if your presence during data collection may possibly alter the results. For example, if you as a supervisor are administering an opinion survey about a specific project, the responses your employees give may be influenced by their desire to please you as their supervisor, rather than based on their true feelings;
- *Bias:* bias means to be prejudiced in opinion or judgment. Bias can enter the evaluation process in a variety of ways. For example, if you use a self-selected sample (when a person decides to participate in a study, rather than being picked randomly by the researcher), how might these respondents be different from the people that chose not to participate?
- *Reliability:* will the evaluation process you have designed consistently measure what you want it to measure? If you use multiple interviews, settings, or observers, will they consistently measure the same thing each time? If you design an instrument, will people interpret your questions the same way each time?
- *Validity:* will the information collection methods you have designed produce information that measures what you say you are measuring? Be sure that the information you collect is relevant to the evaluation questions you are intending to answer.

The amount of data to be collected is a critical issue to face while carrying out this step. Requiring more data can easily delay the design methodology application. Two distinct approach can be followed. The first and the more prudent approach is to start with the data that are available, and then to request additional information once it is needed. The second refers to sampling technique. Such technique is often used for gathering information concerning a population (i.e. workers population). Sampling refers to select a portion of subjects in order to learn something about the entire population without having to measure the whole group, which in many cases might be quite large. There are two general types of sampling methods: random and purposive. Random methods are used to produce samples that are, to a given level of probable certainty, free of biasing forces. In a random sample, each individual in the population has an equal chance of being chosen for the sample. Purposive methods are used to produce a sample that will represent specific viewpoints or particular groups in the judgment of those selecting the sample. The purposive sample consists of individuals selected deliberately by the researcher. Here are some questions to consider when deciding whether to sample:

- Should you use a sample of a population or a census (an entire population)?
- Should you use a random or purposive sample?
- How large a sample size do you need?
- Is your sample likely to be biased?

3.5 STEP 4 - Simulation Model Development

The design methodology utilizes simulation, 3D visualization and human modelling for developing workplaces simulation models. Then, simulation models are used for recreating in virtual environment workplaces operations, executing time and ergonomic methodologies and allowing the comparison of alternative workplaces configurations (effective workplace design). The simulation model development usually consists of the following three phases:

1. *Workplaces Layout Development*: creating the three-dimensional geometric models representing the workplaces objectives and tools being used during the manufacturing process. The completion of this phase requires to import the geometric models into a virtual environment in order to exactly recreate, the real workplace plant-layout;
2. *Digital Human Modeling*: selecting human models as similar as possible to the real workers, and “training” them in order to perform workplace operations in the digital environment;
3. *Simulation Model Verification, Validation and Testing*: determining if the simulation model is an accurate representation of the real workplaces.

Workplaces Layout Development

The implementation of the geometric models of the workplaces can follow three different developing approaches: (i) geometric models implementation by using CAD tool; (ii) geometric models implementation by using the simulation software internal CAD (if available); (iii) geometric models imported from simulation software libraries (if available).

CAD tools allow to hand-create 3D objects even setting attributes such as colour, materials, and textures in order to add realism to the geometric models. As regards (ii) the internal CAD software and (iii) the use of the simulation software libraries two concerns often arise: internal CAD software usually does not support parametric modelling (a brief description of the CAD tool parametric feature is discussed later on), while geometric models imported by the simulation software libraries usually have general shapes and sometimes do not represent the real system with satisfactory accuracy.

If you decide to develop geometric models by means an external CAD tool, the choice of the right one is a very important issue to be faced. There are many different CAD software available on market; they all have various strengths and weaknesses, however when making the choice, the following criteria have to be considered:

1. *File formats*: they mostly save their drawing file in their own particular file formats, variously called .DWG, .DGN, .CTA etc. Because the file format differs, moving data from one CAD software either to another one or to another software type (i.e. simulation software) is not necessarily a trivial task, so it is needed to “get it right” when making the choice;
2. *Parametric features*: parametric CAD software support the geometric model modification; considering the proposed design methodology such aspect becomes more and more important because it is required to test different workplaces configurations and each workplace new configuration requires different geometric models;
3. *Vendor stability*: make sure that the company chosen has a stable financial base. One of the worst things that can happen to CAD customers is to lose the support and upgrade path for their software, because their CAD software vendor has gone out of business;
4. *Features and functionality*: many prospective CAD customers try to calculate the value of their software based on a long list of features, and try to compare to other systems. The difficult of this is that the terminology used to describe certain functions varies from system to system. Vendors may also unintentionally or intentionally obfuscate this point, by claiming unique functionality which is really just a question of semantics. Features and functionality have to be deeply evaluated in order to assure the software meet the specific intended application;
5. *Cost*: this is the easiest criteria to evaluate, but one caveat emptor needs to be addressed. Most CAD software is sold on a modular basis. No company should purchase more CAD modules than they need. There should always be an upgrade path open for a later purchase of additional modules if needs expand or change. Buyers also take note that this industry is extremely competitive, and in general customers really do get what they pay for. Prices are stable and well established, and there really are no fire sales, or steep discounts available;
6. *Maintenance, upgrades, training and support*: users should not be shocked to find that software is regularly upgraded, at additional cost. This is true across the entire software industry. Since CAD software is generally more costly than other type of software, it should also be no surprise that software upgrades are also more expensive than other types of software. Upgrades should be available on a regular basis. It is good to ask what the time period was between the last several upgrades. Users should not be penalized for failure to upgrade. They may find, however, that reasonable restrictions may be placed on support for badly outdated software. Support hours should be reasonable, and at cover business hours, with some consideration to start and finish times within the time zones. Training costs should not be exorbitant. Group training for several employees at one time, or on-site training may also be available.

Obviously, the evaluation and the importance of these criteria depends on several factors such as money availability, customers’ needs, software specific intended applications, etc.. However, considering the effective workplace design area, and, in particular the proposed design methodology, file formats and parametric features criteria could strongly affect the effective application of the design methodology.

After the developing approach has be chosen, next step regards the geometric models implementation. It requires an accurate collection of data, such as objects types, dimensions and weights, to be used for designing geometric models with high level of detail (please refer to Step 3 for further information concerning the data collection process).

The final step of the workplace layout generation phase requires to import the geometric models into the virtual environment provided by any of the simulation software utilized (simulation tools of various types have existed since the 1960s; a detailed description of the most widely used is reported in Chapter 2). The geometric models, created by using an external CAD tool have to be imported and positioned into the simulation software virtual environment (geometric models created by using internal CAD or imported from the software libraries are directly created and positioned into the virtual environment). Note that each object has to be located in the same position it takes place in the system under consideration in order to exactly recreate, in the virtual environment, the real workplace plant layout.

In developing the workplaces simulation models for applying the design methodology, the integrated and parametric 3D Cad tool Pro-Engineer and the simulation software eM-Workplace have been utilized.

Digital Human Modeling

The Workplace Layout Development is followed by the Digital Human modeling phase. Digital human models insertion and training are needed for reproducing correctly in the virtual environment all the operations performed in the real workplaces. Digital human models in the context of this section are computer-generated representations of human beings used in the most widely used simulation software (see Chapter 2). These models are increasingly being used by ergonomists and other engineers to design both equipment and work environments to meet the needs of human operators. They have the advantage of allowing the designer to explore the potential advantages and disadvantages of different design configurations without requiring the construction of expensive physical mockups used in the past. Using a digital human model, design engineers can position and manipulate operators of varying anthropometry within the simulated work environment.

The digital human modeling phase usually consists of two distinct steps:

(1) digital human modeling selection: the objective is to select and import, from the simulation software libraries, human models representing as much as possible the real workers The selection of the human models type has to consider an accurate analysis of operators' characteristics (age, gender, height, weight and health conditions);
(2) digital human training: the objective is to train the human model in order to make it correctly perform in the simulation environment the real workplace operations. The most common simulation software (see Chapter 2) provides the user with a programming language for teaching different types of activities and recreating correctly each type of operation. The human model training requires an accurate analysis of the real operations in terms of basic motions. In effect, any simulation software usually provides the user with specific commands for teaching basic motions (i.e. reach, grasp, release, move, etc.). Consequently, each operation has to be subdivided in basic motions. Note that a simple operation is usually made by of multiple basic motions therefore the human model training procedure is a time consuming task.

The main programming language commands provided by eM-Workplace (simulation software used for developing workplaces simulation models - please refer to Chapter 4 for the application examples) are described below.

In eM-Workplace the human model is a complex kinematics consisting of 60 joints. The human model can be moved by either changing his individual joint values or, more conveniently, by means of an inverse kinematics operation for a certain body part. At the same time the most frequently used motions (walking, sitting, etc.) as well as body and hand postures (home posture, sitting posture, grasping cylindrical objects, etc.) are available as macros.

The simulation program of the human model is defined by a teach-in procedure. Each taught position can be either set directly – through the adjustment of joint values – or indirectly by moving a specified body part towards a given layout frame and having the rest of the body move to accommodate this move.

The following options are available for moving and teaching the human model:

- *Walking*: by entering a "walk" command into the simulation program the user can program the human model to go to any desired layout position. In the command line this target position is defined by the name of a coterminous frame, which the user must have created at the specific position beforehand. Whenever the human model has reached the frame of a "walk" command, it will stop there;
- *Updating Location*, *Sitting* and *Standing up*: the "update_loc" command causes the human model to move to a position previously defined by a frame without walking. If no time frame is specified for this motion, the human model will be seen to "jump" from the start to the target position. Inasmuch as a time frame has been defined, the human model will seem to "glide" to the target frame the specified number of seconds. This command is especially useful, when certain sequences of a simulation program have already been defined and successfully tested. In this case the "update_loc" command offers an effective means of skipping a sequence and thus prevent an unnecessary and time-consuming repetition of it whenever the program is run. The "Sit" command causes the human model to assume a sitting posture at the position of the identified frame, on the seat of a chair, for example. A "Standup" command is usually inserted after a "Sit" command to deactivate the sitting stance of the human model's legs;
- *Body Posture Macros*: there are three pre-defined postures for the entire body, the so-called "Home posture", "Sitting posture", "Home posture (all)". When in the "Home posture", the human model is standing upright, while his extremities maintain their previous joint settings. When in the "Sitting posture", the human model bends his elbows and knees at right angles. When in the "Home posture (all)", the human model not only stands upright, but his legs are kept straight and his arms are held straight to his side as well;
- *Teaching Current Posture*: teaching a current posture, i. e. adjusting the human model's stance to the desired posture, can be executed in one of three ways: (1) using the macro posture command, as aforementioned; (2) adjusting the human model joints directly (if the desired posture cannot be defined by using the numerous body and hand posture macros, there is the option of moving the human model by adjusting the value of each body joint separately. Each joint is designated according to the respective body part and the direction of motion), and (3) adjusting the human model joints indirectly by means of inverse kinematics (by defining target frames the motion of the human model can be programmed more flexibly. Thus a frame located in one of the human model kinematics parts is made to coincide with a target frame, the rest of the human's joints adjust automatically to this motion. Before using these so called inverse kinematics, however, the parameters governing the human model's motion has to be opportunely set);
- *Hand Macros*: there are macros for a number of hand shapes which enable the user to define a grasp or task posture for the hand. The hand posture can either be set for the left or right hand only or for both hands simultaneously. Several hand shape options are available so that every object which is to be grasped should have a corresponding type.

Further information concerning the eM-Workplace programming language can be found in the eM-Workplace Training Manual (2000).

Simulation Model Verification, Validation and Testing

The last step of the simulation model development is the Verification, Validation and Testing (VV&T) that aims at determining if the simulation model is an accurate representation of the real manufacturing system workplace. While performing the VV&T of a simulation model several principles have to be considered. The principles presented herein are established based on the experience described in the published literature. The principles are listed below in no particular order:

1. VV&T must be conducted throughout the entire simulation model development process. Conducting the VV&T for the first time when the simulation model is complete is analogous to a teacher who gives only a final examination (Hetzel, 1984) (no opportunity is provided throughout the semester to notify the student that he or she has serious deficiencies). The VV&T activities throughout the entire simulation model development process are intended to reveal any quality

deficiencies that might be present as the process progresses from the objectives definition to the presentation of the results. This allows the developers to identify and rectify quality deficiencies during the simulation development phase in which they occur.

2. The outcome of the simulation model VV&T should not be considered as a binary variable where the model is absolutely correct or absolutely incorrect. Since a model is an abstraction of a system, perfect representation is never expected. Shannon (1975) indicates that “it is not at all certain that it is ever theoretically possible to establish if we have an absolute valid model; even if we could, few managers would be willing to pay the price”. As depicted in figure 3.1 (Shannon, 1975; Sargent, 1996), as the degree of model credibility increases, so will the model development cost. At the same time, the model utility will also increase, but probably at a decreasing rate. The point of intersection of two curves changes from one model to another.

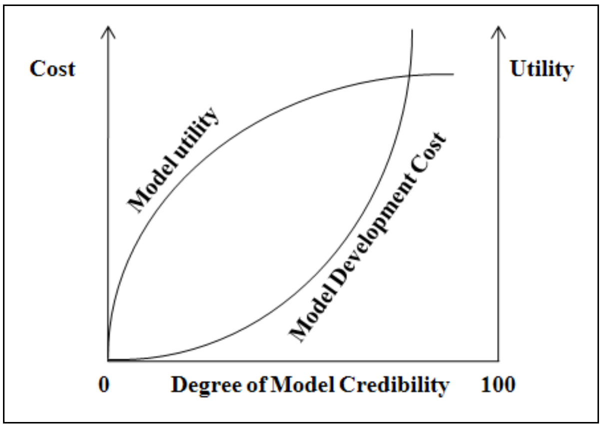


Figure 3.1 - Model credibility versus cost and utility

3. A simulation model is built with respect to the study objectives and its credibility is judged with respect to those objectives. The objectives are explicitly and clearly specified in the objectives definition step (design methodology Step 1). The simulation model is either developed from scratch or an existing model is modified for use or an available one is selected for use as is, all with respect to the study objectives. The study objectives dictate how representative the model should be. Sometimes, 60% representation accuracy may be sufficient; sometimes, 95% accuracy may be required, depending on the importance of the decisions that will be made based on the simulation results. Therefore, model credibility must be judged with respect to the study objectives.
4. Simulation model VV&T requires independence to prevent developer’s bias. Model testing is meaningful when conducted in an independent manner by an unbiased person. The developers are often biased because they fear that negative testing results can damage the credibility of the organization. The independence in model VV&T can be achieved in two ways: (1) establishing a VV&T group within the organization conducting the study, and (2) using an independent third party hired by the sponsor of the study.
5. Simulation model VV&T is difficult and requires creativity and insight. One must thoroughly understand the entire simulation model so as to design and implement effective tests and identify adequate test cases. Knowledge of the problem domain, expertise in the modeling methodology and prior modeling, and VV&T experience are required for successful testing. However, it is not possible for one person to fully understand all aspects of a large and complex model, especially if the model is a stochastic one containing hundreds of concurrent activities. Hence testing a complex simulation model is a very difficult task that requires creativity and insight.
6. Simulation model credibility can be claimed only for the conditions for which the model is tested. The accuracy of the input-output transformation of a simulation

model is affected by the characteristics of the input conditions. The transformation that works for one set of input conditions may produce absurd output when conducted under another set of input conditions.

7. Complete simulation model testing is not possible. Exhaustive (complete) testing requires that the model is tested under all possible input conditions. Combinations of feasible values of model input variables can generate millions of logical paths in the model execution. Due to time and budgetary constraints, it is impossible to test the accuracy of millions of logical paths. Therefore, in model testing, the purpose is to increase our confidence in model credibility as much as dictate by the studies objectives rather than trying to test the model completely.
8. Simulation model VV&T must be planned and documented. Testing is a continuous activity throughout the entire simulation model development process. The tests should be identified, test data or cases should be prepared, tests should be scheduled, and the entire testing process should be documented.
9. Errors should be detected as early as possible in the simulation model development process. Direction and correction of errors as early as possible must be the primary objective. Nance (1994) points out that detecting and correcting major modeling errors during the process of model implementation and in the later phases is very time consuming, complex, and expensive.
10. Successfully testing each sub-model (module) of the main simulation model does not imply overall model credibility. Suppose that a simulation model is composed of sub-models representing subsystems respectively. Each sub-model can be tested individually using many of the VV&T techniques. The credibility of each sub-model is judge to be sufficient with some error that is acceptable with respect to the study objectives. We may find each sub-model to be sufficiently credible, but this does not imply that the whole model is sufficiently credible. The allowable errors for the sub-models may accumulate to be unacceptable for the entire model. Therefore, the entire model must be tested even if each sub-model is found to be sufficiently credible.
11. Double validation problem must be recognized and resolved properly. If data can be collected on both system input and output, model validation can be conducted by comparing model and system outputs obtained by running the model with the "same" input data that drives the system. Determination of the "same" is yet another validation problem within model validation. Therefore, this is called the double validation problem. This is an important problem that is often overlooked. It greatly affects the accuracy of model validation. If invalid input data models are used, we may still find the model and system outputs sufficiently matching each other and conclude incorrectly on the sufficient validity of the model.
12. Simulation model validity does not guarantee the credibility and acceptability of simulation results. Model validity is a necessary but not a sufficient condition for the credibility and acceptability of simulation results. We assess model validity with respect to the study objectives by comparing the model with the system as it is defined. If the study objectives are identified incorrectly and/or the system is defined improperly, the simulation results will be invalid; however, we may still find the model to be sufficiently valid by comparing it with improperly defined system and with respect to the incorrectly identified objectives. A distinct difference exists between the model credibility and the credibility of simulation results. Model credibility is judged with respect to the system (requirements) definition and the study objectives, whereas the credibility of simulation results is judged with respect to the actual problem definition and involves the assessment of the system definition and identification of study objectives. Therefore, model credibility assessment is a subset of credibility assessment of simulation results.

More than 50 VV&T techniques are currently available. Most of these techniques come from the software engineering discipline and the remaining are specific to the modeling and simulation field. The VV&T techniques can be classified into four primary categories:

- *Informal techniques* are among the most commonly used. They are called informal because the tools and the approaches used rely heavily on human reasoning and subjectivity without stringent mathematical formalisms. The “informal” label does not imply a lack of structure or formal guidelines for the use of the techniques. In fact, these techniques are applied using well-structured approaches under formal guidelines and they can be very effective if employed properly;
- *Static techniques* are concerned with accuracy assessment on the basis of characteristics of the static model design and source code. Static techniques do not require machine execution of the model, but mental execution can be used. The techniques are very popular and widely used, with many automated tools to assist in the VV&T process. Static VV&T techniques can obtain a variety of information about the structure of the model, modeling techniques and practices employed, data and control flow within the model, and syntactical accuracy (Whitner and Balci, 1989);
- *Dynamic techniques* requires model execution and are intended for evaluating the model based on its execution behavior. Most VV&T techniques require model instrumentation (the insertion of additional code into the executable model for purpose of collecting information about model behavior during execution is called *model instrumentation*). Dynamic VV&T techniques are usually applied using the following three steps. In step 1 the executable model is instrumented, in step 2 the instrumented model is executed, and in step 3 the model output is analyzed and dynamic model behavior is evaluated.
- *Formal techniques* are based on mathematical proof of correctness. If attainable, proof of correctness is the most effective means of model VV&T. Unfortunately, “if attainable” is the overriding point with regard to the formal VV&T techniques. Current state of the art proof of correctness techniques are simply not capable of being applied even to reasonably complex simulation model.

The complete list of such techniques is reported in table 3.1 (for further information concerning such techniques please refer to Banks, 1998), while the techniques used for the VV&T of the workplaces simulation models developed for applying the design methodology (please refer to Chapter 4 for the application examples) are described below.

Verification, Validation and Testing Techniques			
Informal	**Static**	**Dynamic**	**Formal**
Audit	Cause-Effect Graphing	Acceptance Testing	Induction
Desk Checking	Control Analysis	Alpha testing	Inductive Assertion
Documentation Checking	Data Analysis	Assertion Checking	Inference
Face Validation	Fault/Failure Analysis	Beta Testing	Lambda Calculus
Inspections	Interface Analysis	Bottom-Up Testing	Logical Deduction
Reviews	Semantic Analysis	Comparison Testing	Predicate Calculus
Turing Test	Structural Analysis	Compliance Testing	Predicate Transformation
Walkthroughs	Symbolic Evaluation	Debugging	Proof of Correctness
	Syntax Analysis	Execution Testing	
	Traceability Assessment	Fault/Failure Insertion Testing	
		Field Testing	
		Functional Testing	
		Graphical Comparisons	
		Interface Testing	
		Object-Flow Testing	
		Partition Testing	
		Predictive Validation	
		Product Testing	
		Regression Testing	
		Sensitivity Analysis	
		Special Input Testing	
		Statistical Techniques	
		Structural Testing	
		Submodel/Module Testing	
		Symbolic Debugging	
		Top-Down Testing	
		Visualization/Animation	

Table 3.1 - Verification, Validation and Testing Techniques

1. *Face Validation* (informal technique): the project team members, potential users of the model, people knowledgeable about the system under study, based on their estimates and intuition, subjectively compare model and system behaviors under identical input conditions and judge whether the model and its result are reasonable. Face validation is useful as preliminary approach to validation (Hermann, 1967);
2. *Walkthroughs* (informal technique): walkthroughs are conducted by a team composed of a coordinator, model developer, and three to six members. All members other than the model developer should not be directly involved in the development effort. A typical structured walkthrough team consists of:

    - *Coordinator*: most often the VV&T group representative who organizes, moderates, and follows up the walkthrough activities;
    - *Presenter*: most often the model developer;
    - *Scribe* that documents the events of the walkthrough meetings;
    - *Maintenance Oracle* that considers long term implications;
    - *Standard Bearer* that concerns with adherence to standards;
    - *Client Representative* that reflects the needs and concerns of the client;
    - *Other Reviewers* such as simulation project manager and auditors.

For further information concerning such techniques, please refer to Adrion et al. (1982), Deutsch (1982), Myers (1978), Myers (1979), Yourdon (1985);

3. *Debugging* (dynamic technique): it is an iterative process whose purpose is to uncover errors or misconceptions that cause the model's failure and to define and carry out the model changes that correct the errors (Banks, 1998). This iterative process consists of four steps. In step 1 the model is tested, revealing the existence of errors (bugs). Given the detected errors, the cause of each error is determined in step 2. In step 3 the model changes believed to be required for correcting the detected errors are identified. The identified model changes are carried out in step 4. Step 1 is re-executed right after step 4 to ensure successful modification because a change correcting an error may create another one. This iterative process continues until no errors are identified in step 1 after sufficient testing (Dunn, 1987).
4. *Graphical Comparison* (dynamic technique): it is a subjective, inelegant, and heuristic, yet quite practical approach, especially useful as a preliminary approach to model VV&T. The graphs of values of model variables over time are compared with the graphs of values of systems variables to investigate characteristics such as similarities in periodicities, skewness, number and location of inflection points, logarithmic rise and linearity, phase shift, trend lines, and exponential growth constants (Cohen and Cyert, 1961; Forrester, 1961; Miller, 1975; Wright, 1972).
5. *Visualization/Animation* (statistical techniques): this techniques greatly assists in model VV&T (Sargent, 1996; Bell and O'Keefe, 1994. Displaying graphical images of internal and external dynamic behavior of a model during execution enables the developer to discover errors by seeing. Seeing the animation of the model as it executes and comparing it with the real system can help the developer identify discrepancies between the model and the system. Observing that the animation of the model behavior is free of errors does not guarantee the correctness of the model results.

3.6. STEP 5 – Effective Workplace Design

As already stated in the section 3.1, the generation of workplaces alternative configurations comes out from the variation of multiple design parameters that affect multiple time and ergonomic performance measures. Identification of the right parameters and definition of the most suitable performance measures is clearly discussed in section 3.3. Here the main concern regards the variation of the multiple design parameters in order to generate new workplace configurations. Within the proposed methodology the variation of the design parameters is achieved by using the following approaches:

1. Trial and Error based approach;
2. Design of Experiment based approach;

As follows a detailed description of such approach is presented.

Trial and error based approach

The variation of the design parameters is led to the engineer. The engineer generates a number of workplaces configurations by simply varying the design parameters values according to the experience and/or knowledge about the problem under consideration. Such workplaces configurations are implemented within the simulation model and compared each other on the basis of the ergonomic and time performance measures.

The purpose of the trial and error based approach is not to find out the reasons that cause the problem, but it is primarily used to solve the problem. While this may be good in some fields, it may not work so well in others. For example, while trial and error may be excellent in finding solutions to mechanical or engineering problems (i.e. effective workplace design), it may not be good for other applications where understanding why a specific solution works is particularly important. Moreover, trial and error approach can proceed where there is little or no knowledge of the subject; however, sometimes, it may require to have large amounts of patience in order to identify an effective solution to the problem.

Application examples developed by using this approach are deeply described in Chapter 4.

Design of Experiment based approach

Here the design methodology is well supported by a well defined factorial design. First of all, let us introduce some basic definition and principles concerning the factorial design in order to make the reader more familiar with this topic.

- *Factor*: a factor is a variable over which you have direct control in an experiment. Factors can be classified into design factors, held-constant factors, and nuisance factors. The design factors are the variables actually selected for study in the experiment. Held-constant factors are variables that may exert some effect on the responses, but for purposes of the present experiment these factors are not of interest, so they will be held at specific level. Nuisance factors may have large effects that must be accounted for, but the investigator is not interested in them in the context of the present experiment;
- *Level*: the value to which a factor should be set in an experiment.
- *Responses*: the outputs of a process.

Many experiments involve the study of the effects of two or more *factors* on several *responses*. By a factorial design, it is meant that in each complete trial or replication of the experiment all possible combinations of the *levels* of each *factors* are investigated. This is an experimental strategy in which *factors* are varied together. For example if there are a levels of factor A and b levels of factor B, each replicate contains all ab treatment combinations.

In the context of the effective workplace design, the design parameters are the factors, the factors levels represent the values each factor can assume, and the responses are the time and ergonomic performance measures. Each design parameter is characterized by different values and all the combinations of the values of each design parameters generates a comprehensive set of workplace alternative configurations to be compared by means of the workplaces simulation model.

Examples of design methodology application based on the factorial design approach are reported in Chapter 4.

3.7. STEP 6 - Results Presentation and Implementation

This step aims at establishing the right strategy to communicate and especially to convince workers and managers about the effectiveness and improvements related to the design methodology application. However, sometimes, selling the improvements can be more difficult than devising the improvements. Even if the workplaces ergonomic and time improvements are really valuable, some resistance to the new workplace configuration and/or work methods has to be faced. Much has been written about this problem, some of the best of it by Krick (1962). People resist change for a number of reasons. To minimize, or eliminate, this resistance and sell the new changes, these reasons for resistance must be understood and, perhaps more important, remembered when changes are to be made. As follows, a brief description of the main reasons for it are described. Successively, some suggestions followed to overcome the resistance to change while applying the design methodology are presented.

The main reasons that may generate resistance to the change can be listed as follows:

- *Inertia*: people become very content with the way things have always been done. People often resist changes simply because they don’t want to change;
- *Uncertainty*: change brings with it some unknown consequences;
- *Need*: more precisely, this reason should be called failure to see the need for making a change. Before people are willing to make a change, they must be convinced that something really needs changing;
- *Understanding*: failure to understand the change is a common reason for rejecting the change. If people don’t understand what is happening they won’t accept it. Most people have a tremendous fear of what they don’t understand;
- *Obsolescence*: after a long period of time, individuals usually become skilled at a task. A change means they will not be able to regain their skill level;

- *Downgrading*: changes in work methods often result in a work that is simpler to perform. When this simplification happens, the operator may be afraid that he will be replaced by a less talented worker or that, because he is now performing a work requiring less skill, he will lose status with his coworkers;
- *Tactlessness*: the method of presentation is important. Nothing will kill an idea more quickly than a "know-it-all" attitude;
- *Timing*: the resistance can be generated just because the operator is having a bad day;
- *Economics*: a change in work method might cause an operator believe that there will be economic, i. e., pay, changes to follow. An improved work might require less skill and the job classification and pay rate might be lowered. The time required would possibly be less, or at least different, and operators generally fear that the new time standard would be tighter and require more work to maintain the same pay.
- *Social*: alteration of work groups is a major source of resistance to change. As Roy (1960) pointed out, even the most boring jobs can be satisfying when the informal organization is pleasing to the workers. Redesign of a job or set of jobs can change work groups and lead, at least in the workers' minds, to perceived horrors. Change is often fought for this reason.

As concerns the suggestions considered while applying the design methodology, the following represent the most important ones:

1. *Explain the need for the change*. Don't overlook the worker in this respect. The change will directly affect the worker; if the worker is convinced that there is a good reason for making the change, then there is a better chance to change will be accepted;
2. *Explain the nature of the change*. Use straightforward, clear, well-organized language to ensure that everyone understands the method or policy. Tailor your written and oral reports for the audience receiving it;
3. *Facilitate participation or the perception of participation in the formulation of the proposed changes*. People are concerned about making their own ideas and recommendations succeed. The feeling of participation can be imparted in several ways:

   a. Consult operators, inspectors, supervisors, tool makers, maintenance men, managers, etc. to ask for information, opinions, and suggestions. Remember that the people who do the work on a regular basis know the procedures far better than any other. Show a real interest in what these people say. Seek advice even if you do not think you will need it. Merely by being given opportunity to express himself, the person will have a feeling of participation.
   b. Whenever possible, suggestions should be incorporated into the final proposal with credit being given to the originator of the idea. Suggestions from these individuals need to be used on a regular basis.

4. *Be tactful in introducing your proposal*. Watch your wording and mannerisms. Above all, avoid criticisms or anything that could even be construed as such. Just because a more productive procedure is being developed does not mean the old way was necessarily bad.
5. *Watch your timing*. in attempting to gain adoption of your proposal, avoid presenting it when the recipient is busy, upset, or otherwise distracted. Allow sufficient time for concept to be thought about. Patience is indeed a virtue. Also, provide ample advance warning. Finally, changes should not be made during times of labor unrest. Any changes from the usual during such a time like would most likely add to the unrest.
6. *Introduce major changes in stages*. The size of some changes may frighten some people and cause resistance. Also, when people see how well the first stage of a proposed change works, they may be more receptive to later changes.
7. *Emphasize personal benefit*. In attempting to gain acceptance, capitalize on the features that provide the most personal benefit to the person or people you are trying to convince.
8. *Show a personal interest in the welfare of the person directly affected by the change*. Be aware of the social relationships and implications that changes will have on the relationships. If skilled workers will no longer need the skills formerly required, rather than underutilize talented people, try to find the person a job that will make the maximum use of his or her

previously developed skills. If possible, try to guarantee continuing work at previous developed skills. If possible, try to guarantee continuing work at the previous income level.

9. *It is best to have the supervisor announce changes*. Suggestions by the supervisor are much more likely to be accepted than those made by an "outsider".

Chapter 4

Effective Workplace Design: Methodology Applications and Case Studies

This chapter presents a series of case studies related to the application of the design methodology deeply discussed in Chapter 3. Practical examples are provided that allow to understand the use of the methodology for improving ergonomics and productivity within industrial workplaces. The case studies mainly regard existing workplaces characterized by operations entirely manually performed as well as operations where the interaction man-machine is needed to produce goods. The methodology's entire development process as well as the quantitative and the qualitative results are explained. Finally, the chapter will address the application of the methodology for designing workplaces still not in existence.

4.1 Introduction

To reiterate, the design methodology can be used by industrial engineers to effectively design industrial workplaces. Here, several practical examples are provided to make industrial engineers better understanding the use of the methodology. All the application examples regard either industrial workplaces where highly manual tasks are performed or industrial workplaces characterized by man machine operations. The first ones belong to an industrial plant producing leather goods such as leather bags, leather planner cases, leather handbags, leather pockets, etc., while the second ones belong to an industrial plant that manufactures high pressure hydraulic hoses. A detailed description of the industrial plants aforementioned is reported in section 4.2.

The case studies are listed according to the design approaches, (*trial and error and design of experiments based approaches*), used for generating workplaces alternative configurations. Section 3.9, Chapter 3 provides an excellent summary of these design approaches. Section 4.4 presents application examples related to the trial and error based approach, while section 4.5 regards the case studies concerning the design of experiments based approach.

In addition, for each case study a detailed description of each methodology step is presented. Such steps are reported as follows in order to provide the reader with enough information for understanding the structure of this chapter:

- **STEP 1**: Problem Formulation and Objectives Definition;
- **STEP 2**: Performance Measures and Design Parameters Definition;
- **STEP 3**: Data Collection;
- **STEP 4**: Simulation Model Development;

- **STEP 5**: Effective Workplace Design;
- **STEP 6**: Results Presentation and Implementation.

Considering STEP 4, the simulation models of the industrial workplaces, being presented later on, will follow all the same development process and the same CAD and simulation software will be used; so that, the description of such step will not be included within each application example in order to avoid repetitiveness in explanations. Section 4.3 is specifically developed for presenting this methodology step. Then, for each case study, figures and images concerning the specific simulation model will be placed at the end of the Data Collection phase (STEP 3).

Finally, in the last part of the chapter, section 4.6 proposes the application of the design methodology to industrial workplaces still not in existence. An assembly line for heaters production and an industrial plant that manufactures mechanical parts for agricultural machineries engines are considered.

4.2 The Industrial Plants

Since the methodology aims at achieving the effective workplace design by considering the interaction of the operators with their working environment and the operators' work methods, emphasis is given to industrial situations in which human presence is necessarily needed (considering completely automated workplaces would be nuisance).

The case studies regard two different types of workplaces: workplaces characterized by highly manual operations (*manual workplaces*) and workplaces characterized by man machine operations (*man-machine workplaces*). In the proposed examples, *manual workplaces* belong to an industrial plant manufacturing leather goods (Barca Leather Goods Ltd) while *man-machine workplaces* belong to an industrial plant manufacturing high pressure hydraulic hoses (AlfaTechnology Ltd). Section 4.2.1 and section 4.2.2 provide a detailed description of the industrial plants under consideration.

4.2.1 Barca Leather Goods Ltd.

Barca Leather Goods Ltd. was established in 1977, with over 30 years of experience in manufacturing leather goods. The manufacturing plant is located in the South of Italy (Calabria) and covers a total floor area of 660 m^2. The plant is specialized in designing and manufacturing handbags, wallets, briefcases, travel goods, business accessories and small leather goods. Figure 4.1 shows examples of the manufacturing plant main products.

Figure 4.1 - Leather Products

The plant is subdivided into five different areas:

1. Raw Material Warehouse;
2. Production area;
3. Final Products Warehouse;
4. Offices;
5. Exhibition and Sales area.

The production area consists of 4 different workplaces and employs 10 workers. A brief description of the operations performed by the workers in each workplace is presented as follows:

- *Cutting workplace*: herein the operator picks up leather rolls in the raw material warehouse and, according to Shop Order requirements, cuts sheets of leather in appropriate dimensions and shapes;
- *Assembly and Gluing workplace*: the operator assembles different parts with glue to form the components for sewing operations;
- *Sewing and Final Assembly workplace*: after sewing operations all the components are assembled to form the final product;
- *Quality Control and Packaging workplace*: in this workplace the operator performs visual controls to check the final product quality, performs packaging operations by using specific boxes, and, finally, stores final products in the products warehouse.

The different workplaces are connected each other by using manual operating dollies and all the operations within each workplace are entirely manually performed. Further and detailed information on operators' work methods and workplaces layout will be provided later on while applying the design methodology (please refer to section 4.4).

The actual manufacturing plant layout is showed in figure 4.2.

Figure 4.2 - Manufacturing plant layout

4.2.2 AlfaTechnology Ltd.

AlfaTechnology Ltd. was established in 1984, with over 25 years of experience in manufacturing high pressure hydraulic hoses. The manufacturing plant is located in the South of Italy (Calabria) and covers a surface of about 3750 m^2. The plant is specialized in designing and manufacturing flexible hoses for hydraulic high-pressure fluid applications, fittings adapters, ring nuts and valves. Figure 4.3 shows the final products. Each hydraulic hose is made up of a rubber hose, two fittings and two ring nuts.

Figure 4.3 - High pressure hydraulic hoses

The plant-layout is subdivided into 4 different areas:

1. Raw materials warehouse;
2. Mechanical area;
3. Assembly area;
4. Final products warehouse.

Figure 4.4 shows the whole industrial plant layout.

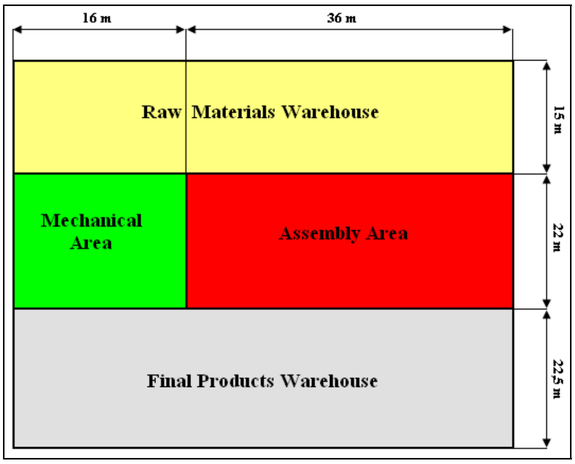


Figure 4.4 - Industrial plant layout

A brief description of each area is reported as follows.

The Raw Materials Warehouse
Here the raw materials for manufacturing ring nuts, fittings and high pressure hydraulic hoses are stored in shelves and pallets located along the whole area. Note that the pallets are placed on the bottom level of each shelf in order to full use the warehouse area. The raw materials are manually moved by means of a multi order picking cart as well as several forklifts are used for the pallets placement. The storage area is 10 m high and covers a surface of 930 m^2. Figure 4.5 and figure 4.6 show respectively a panoramic view and the plant layout of the warehouse.

Figure 4.5 - Panoramic view of the raw materials warehouse

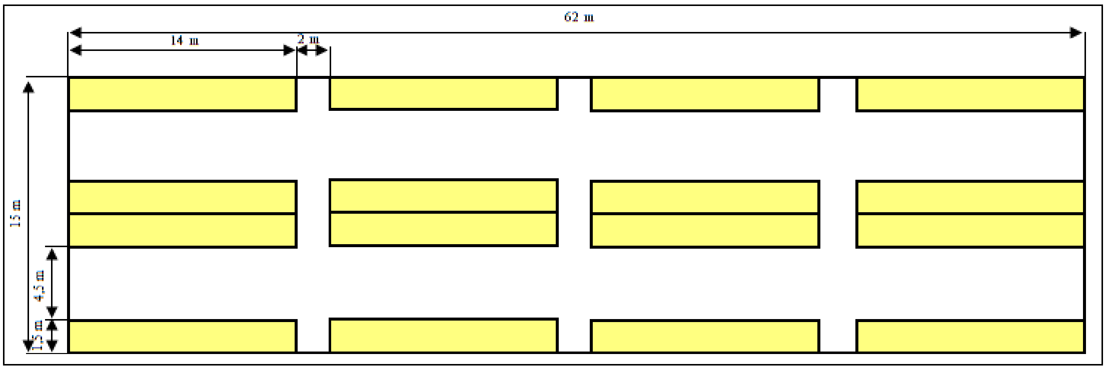


Figure 4.6 - Plant layout of the raw materials warehouse

The Mechanical Area

In this area fittings and ring nuts are manufactured; some of them are used for manufacturing the high pressure hydraulic hoses, the others represent final products of the industrial plant. In the mechanical 5 operators are employed and 5 numerically controlled machines are used. The area layout covers a surface of 350 m^2.

The Assembly Area

Here, rubber hoses, ring nuts and fittings are assembled together in order to obtain the final high pressure hydraulic hoses. Note that each hydraulic hose is made by a rubber hose, two fittings and two ring nuts. The assembly area consists of 6 different workplaces each one performing specific operations of the hydraulic hoses assembly process. The operations performed in each workplaces are described as follows:

1. *Seal Press workplace*: the operator prints on ring-nuts and fittings the quality and traceability identifying numbers by using the Seal Press machine;
2. *Skinning workplace*: the operators eliminate a part of rubber at the ends of each hose in order to guarantee a good junction with the fittings;
3. *Assembly workplace*: the operators manually assemble the rubber hoses with fittings and ring-nuts;
4. *Stapling workplace*: the operators tighten the ring-nuts on the hoses by using the stapling machine;
5. *Pressure Test workplace*: the operators test the hydraulic hoses by using a pressure machine (setting a pressure value higher than the nominal value);
6. *Check and Packaging workplace*: the operators compare the Shop Orders requirements and the hoses' characteristics (quality controls), they also put the hydraulic hoses in the shipping containers.

At the end of each operation, the operators set the status ''end of the operation'' on the company informative system and move the materials to the successive workplace by using a manual dolly. In addition, most of the workplaces are characterized by man-machine performed operations. Further and detailed information on operators' work methods and workplaces layout will be provided later on while applying the design methodology (please refer to sections 4.4-4.6). Figure 4.7 shows the flow chart of the manufacturing processes.

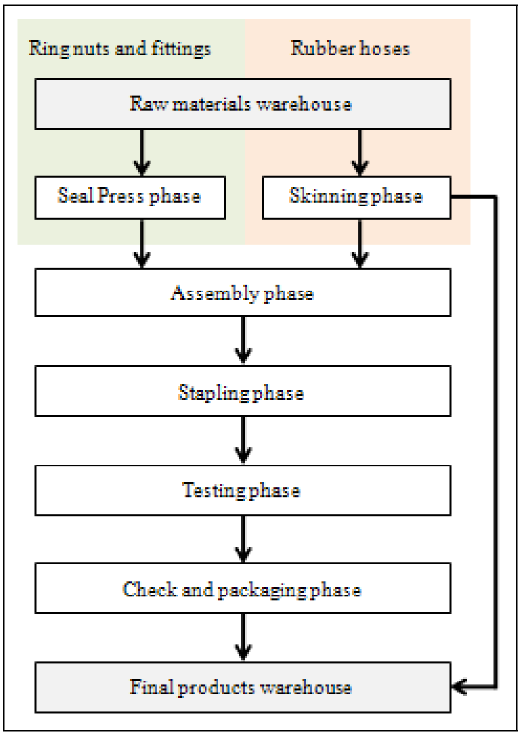


Figure 4.7 - Flow chart of the manufacturing process

The assembly area employs 12 operators and covers a surface of about 1110 m^2. Table 4.1 reports the industrial plant surface (m^2) covered by each workplace, while figure 4.8 provides a view of the assembly area plant layout.

Workplace	Surface (m^2)
Seal Press Workplace	49
Skinning Workplace	182
Assembly Workplace	221
Stapling Workplace	56
Pressure Test Workplace	110
Check and Packaging Workplace	88
Offices	63

Table 4.1 - Industrial plant surface of each workstation

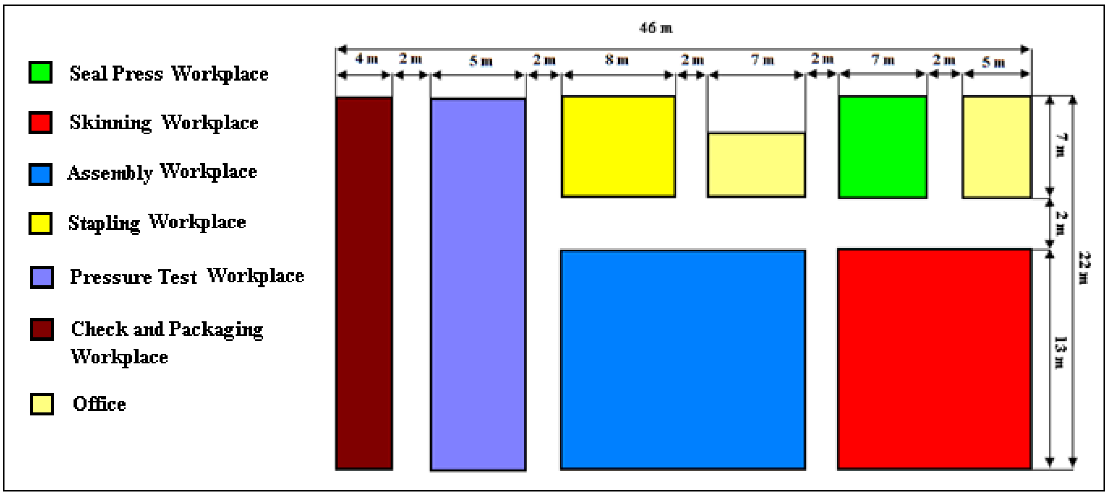


Figure 4.8 - Plant layout of the assembly area

The design methodology will be applied to several workplaces belonging to the Assembly area due to the fact that a preliminary analysis carried out by the company top management shows that the productivity (evaluated on monthly basis) falls always below the target level causing, as a consequence, delays in Shop Orders (S.Os) completion.

The Final Products Warehouse

Here the final products (ring nuts, fittings, rubber hoses and high pressure hydraulic hoses) are stored in shelves and pallets located along the whole area. As the *Raw Materials Warehouse,* the pallets are placed on the bottom level of each shelf in order to full use the warehouse area and the final products are moved by means of a multi-order picking cart as well as by using several forklifts. The storage area is 10 m high and covers a surface of about 1395 m^2. Figure 4.9 shows the plant layout of the warehouse.

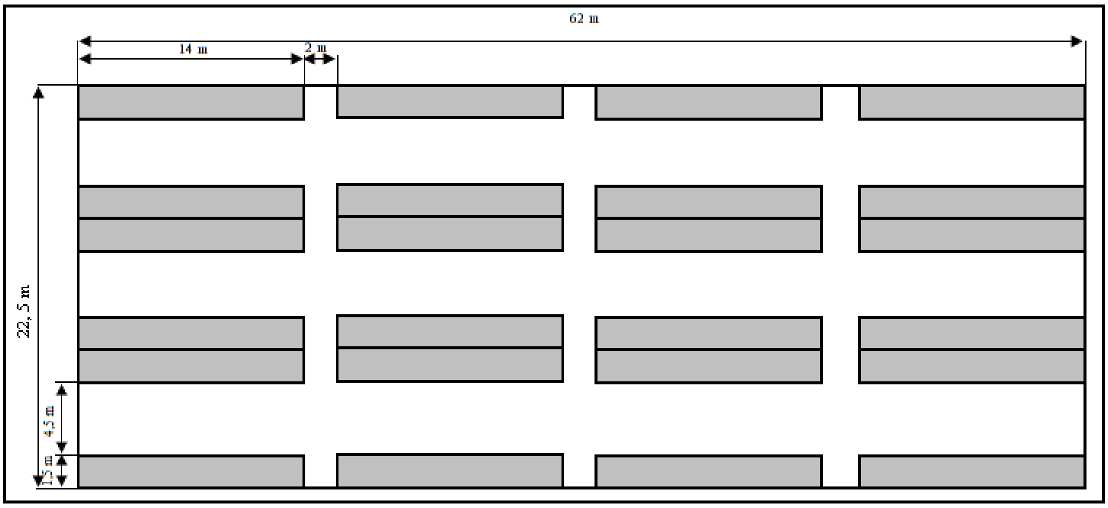


Figure 4.9 - Plant layout of the final products warehouse

4.3 STEP 4: Simulation Model Development

The Modeling & Simulation tools, used for developing the workplaces simulation models, are the CAD software Pro-Engineer by PTC (further information can be found at http://www.ptc.com/products/proengineer/) and the simulation software eM-Workplace by Tecnomatix Technologies (further information can be found at http://www.plm.automation.siemens.com/en_us/products/tecnomatix/assembly_planning/process_simulate_human/index.shtml).

As reported in Chapter 3, section 3.5, the most important steps of the simulation models development can be summarized as follows: (1) the first phase is the creation of the three-dimensional geometric models representing the objects and tools being used during the manufacturing process (*Workplace Layout Development*). The completion of this phase requires to import the geometric models into the virtual environment provided by the simulation software; (2) the second phase regards the selection of human models as similar as possible to the real workers, and their "training" in order to correctly reproduce workplace operations in the digital environment (*Digital Human Modeling*); (3) the last phase is the *Simulation Model Validation, Verification and Testing* in order to check the simulation model accuracy in recreating the real workplace. Further information concerning the simulation models development phases is reported as follows.

Workplace Layout Development

The implementation of the geometric models of the industrial workplaces follows three different approaches: (i) geometric models implementation by using the CAD software Pro-Engineer; (ii) geometric models implementation by using the eM-Workplace internal CAD software; (iii) geometric models imported from eM-Workplace libraries. Note that, in the cases proposed, most of the geometric models (i.e. geometric models of machines, worktables and hand operated dollies) have been created by using Pro-Engineer (in order to have parametric and features based geometric models); in effect this software supports the geometric models modification; such aspect becomes more and more important because the design methodology requires to test different workplace configurations (each workplace new configuration requires different geometric models). Note that the internal CAD software provided by eM-Workplace (a CAD software based on Boolean operators) does not support the geometric models modification (a Boolean CAD tool does not support the parametric Modeling). Finally, geometric models provided by the eM-Workplace usually have general shapes and sometimes do not represent the real system with satisfactory accuracy.

The geometric models implementation requires an accurate data collection on objects types, dimensions and weights. Data regarding objects dimensions and weight have been inserted into the CAD software as input data for designing geometric models with high level of detail.

As next step, the geometric models, created by using the CAD software Pro-Engineer, have to be imported and positioned into the eM-Workplace virtual environment (geometric models created by using the eM-Workplace internal CAD software or imported from the software libraries are directly created and positioned into the virtual environment). Note that each object has to be located in the same position it takes place in the system under consideration in order to exactly recreate, in the virtual environment, the real workplace plant layout.

Digital Human Modeling

The selection of the human models type is based upon an accurate analysis of operators' characteristics (age, gender, height, weight and health conditions). The objective is to select and import, from eM-Workplace libraries, human models representing as much as possible the real workers. After the insertion into the virtual environment, the human model is only able to stand in the waiting position; the model has to be trained to perform workplace operations. eM-Workplace provides the user with a programming language for teaching different types of activities and recreating correctly each type of operation (please refer to Chapter 3, section 3.5 for further information concerning the eM-Workplace programming language).

The human model training requires an accurate analysis of the operations (performed in the industrial workplaces) in terms of basic motions. In effect, the programming language provides the user with specific commands for teaching basic motions (i.e. reach, grasp, release, move, etc.). Consequently, each operation has to be subdivided in basic motions. Note that a simple operation consists of multiple basic motions, therefore the human model training procedure is a time consuming task. Furthermore the simulation model requires additional information (successively used for carrying out ergonomic and time analysis) such as, working postures at the beginning and end of each lifting task, frequency and duration of lifting tasks, process and set-up times of operations not performed by the human model.

Simulation Model Verification, Validation and Testing

The simulation models VV&T phase has been carried out by using the following techniques: face validation, walkthroughs, debugging technique, visualization/animation and graphical comparison. Further and detailed information about these VV&T techniques can be found in Chapter 3, section 3.5.

All these methodologies have been applied with the help of the workplaces operators and production engineers: some wrong working postures, wrong motions and redundant motions were corrected or deleted and the simulation models have been correctly validated.

4.4 Trial and Error based Approach Case Studies

Here the application examples using the trial and error based approach are presented. A brief description of the trial and error based approach is reported as follows in order to make the reader better understanding the proposed case studies. Anyhow a detailed explanation of this approach is reported in Chapter 3, section 3.9.

According to the trial and error based approach, the engineer generates a number of workplaces configurations by simply varying the design parameters values on the basis of his/her experience and/or knowledge about the problem under consideration. Such workplaces configurations are implemented within the simulation model and compared to each other on the basis of the ergonomic and time performance measures.

4.4.1 Barca Leather Goods Ltd.: Assembly and Gluing Workplace

STEP 1: Problem Formulation and Objectives Definition

In the assembly and gluing workplace, the operators assemble different parts with glue to form the components for sewing operations. The workplace includes a single worktable and 4 workers positioned around. The operations performed by 2 workers are presented as follows (the other workers perform exactly the same operations):

1. The first worker takes a leather block from a manual operating dolly and put it on the worktable;
2. The first worker glues each leather layer;
3. The first worker places the glued leather layer on a cardboard to let it dry;
4. The first worker puts the cardboard on a mobile tray and moves it towards the second worker;
5. The second worker takes the cardboard from the mobile tray;
6. The second worker takes the dried leather layer from the cardboard and piles it up on the worktable;
7. The second worker takes another leather layer type from a raw material shelf and puts it on the worktable;
8. The second worker puts the two different leather layers by using a hammer and tacks;
9. The second worker puts the assembled leather layers on a manual operating dolly to be moved towards the next workplace.

In the workplace the nearness of workers reduces their productivity because of the narrow spaces and the opportunity to speak each other. Moreover, at the end of the shift, workers continuously complain arms and back pains due to the stand up position while performing the operations. In this context, it seems to be clear that a new workplace configuration is needed in order to improve workers productivity as well as to eliminate any ergonomic problem.

STEP 2: Performance Measures and Design Parameters Definition

The time and ergonomic performance measures used for applying the design methodology to this workplace are listed as follows:

1. *Process Time (PT)* evaluated by means of the Methods Time Measurement methodology;
2. The *Action Limit (AL)* and the *Maximum Permissible Limit (MPL)* evaluated by using the NIOSH 81 lifting equation. AL is the weight value, which is permissible for 75% of all female and 99% of all male workers. MPL is the weight value, which is permissible for only 1% of all female and 25% of all male workers
3. The *Recommended Weight Limit (RWL)* and the *Lifting Index (LI)* evaluated by means of the NIOSH 91 lifting equation. The RWL is the load that nearly all healthy workers can perform over a substantial period of time for a specific set of task conditions. The LI is calculated as a ratio between the real object weight and the RWL.
4. The *stress level (SL)* associated to the workers' body posture evaluated by using the OWAS methodology.

Further and detailed information concerning the aforementioned performance measures can be found in Chapter 2.

As concerns the design parameters definition, objects positions and weights have be identified as significant factors for the effective workplace redesign.

STEP 3: Data Collection

As first step, the company top management was asked for all the data needed for the application of the design methodology. However, only the data regarding the industrial workplace plant layout and objects dimensions (length, width and height) and weights were available. Data concerning operators' characteristics has been collected by using the *individual interview method*, while *walk-trough observation method* has been used for collection information on the operators work methods. Table 4.2 reports operators' characteristics such as age, gender, height, weight and physical condition. Table 4.3 proposes description, type, dimensions, weights, and quantity of the objects mainly used while performing the workplace operations.

Operator ID	Age	Gender	Height (cm)	Weight (Kg)	Workplace
Op-1	36	Male	178	76	Assembly and Gluing
Op-2	34	Male	175	80	Assembly and Gluing
Op-3	41	Female	164	60	Assembly and Gluing
Op-4	38	Female	165	68	Assembly and Gluing

Table 4.2 - Operators' physical characteristics

Object Description	Object Type	Weight (Kg)	Dimensions (cm) L x W x H	Quantity
Worktable	Equipment	68	300 x 140 x 86	1
Hammer	Equipment	0.650	31 x 4 x 2	4
Glue stick	Equipment	0.250	3 x 3 x 10	4
Raw material bin	Equipment	0.400	30 x 20 x 15	8
Manual operating dolly	Equipment	22	80 x 100 x 76	4
Raw material shelves	Equipment	32	100 x 40 x 200	8
Leather block	Raw material	9.5	40 x 30 x 60	Depending on the shop order

Table 4.3 - Objects' data

Figure 4.10 shows the actual configuration of the Assembly and Gluing workplace.

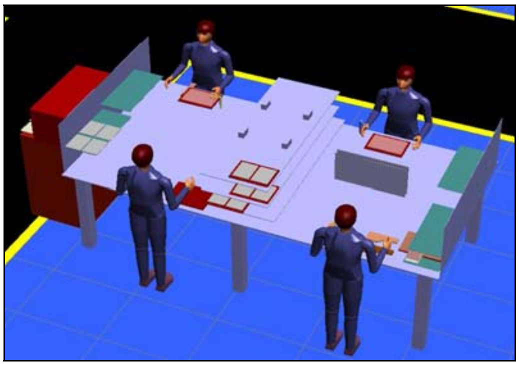


Figure 4.10 - Assembly and Gluing Workplace

STEP 5: Effective Workplace Design

The objective of this step is twofold: (1) calculate productivity and evaluate ergonomic risk levels related to the actual workplace configuration by means of the time and ergonomic methodologies; (2) propose a new workplace configuration trying to increase the operators productivity and improve the ergonomics of the working environment as well.

Actual workplace configuration

First of all, time and ergonomic analysis are carried out through the workplace simulation model in order to calculate the process time and to evaluate the ergonomic issues related to the actual configuration. The analysis takes into consideration one of the most important set of products: the leather desk set (please refer to figure 4.11). The set includes the following items: the desk pad, the business card holder, the letters tray, the pencil cup, the letters holder with letters opener and the double pen stands.

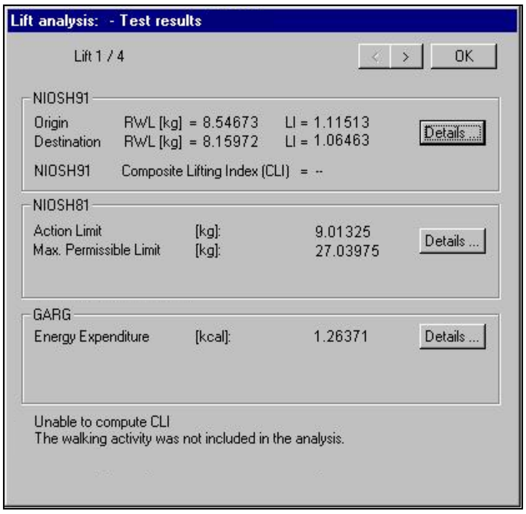
Figure 4.11 - Examples of leather desk sets

The process time has been calculated by using the MTM methodology. Table 4.4 reports time analysis results for each item of the leather desk set.

MTM Methodology Time [seconds]	Assembly and Gluing Workplace
Desk Pad	201
Business Card Holder	167
Letters Tray	193
Pencil Cup	185
Letters Holder	162
Letters Opener	153
Double Pen Stands	165

Table 4.4 - MTM analysis results for the leather desk set

As concerns the ergonomic analysis, the NIOSH 81 and NISH 91 lifting equations identify an ergonomic risk when the worker takes a leather block from a manual operating dolly (please refer to figure 4.12). In effect, both at origin and destination point of this lifting task the LI, evaluated by using the NIOSH 91 lifting equation, is greater than one (respectively 1.15 and 1.06) (a LI value greater than 1 poses an ergonomic risk). The AL and the MPL, evaluated by using the NIOSH 81 lifting equation, are respectively equals to 9.01 Kg and 27.03 Kg. Usually weights lower than the AL does not pose an ergonomic risk, weight between AL and MPL pose an ergonomic risks (that should be monitored in the near future) and weights greater than MPL pose ergonomic risks to be immediately eliminated. In this case the weight of the object being lifted is about 9.5 Kg, therefore it causes an ergonomic risk to be kept under control in the near future.



Lift analysis: - Test results

Lift 1 / 4

NIOSH91

Origin RWL [kg] = 8.54673 LI = 1.11513

Destination RWL [kg] = 8.15972 LI = 1.06463

NIOSH91 Composite Lifting Index (CLI) = --

NIOSH81

Action Limit	[kg]:	9.01325
Max. Permissible Limit	[kg]:	27.03975

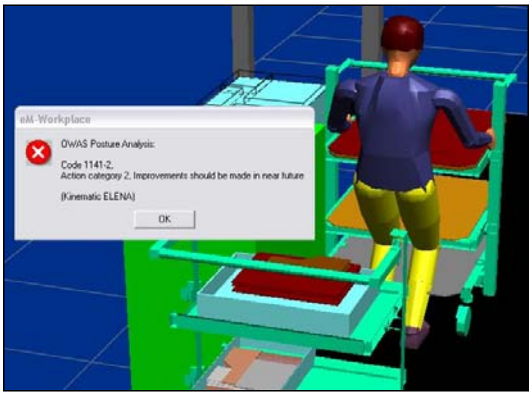
GARG

Energy Expenditure	[kcal]:	1.26371

Unable to compute CLI
The walking activity was not included in the analysis.

Figure 4.12 - NIOH 81 and NIOSH 91 lifting equations results

When the OWAS methodology is applied to the workplace, the SL related to each worker body postures is evaluated. Figure 4.13 shows a category 2 ST associated with the working posture of the operator while picking the leather block up from a manual dolly, while figure 4.14 shows the category 2 ST when the worker performs the gluing operation. A category 2 SL means that improvements should be made in the near future. The OWAS shows that workers' back and legs are the most stressed body parts.



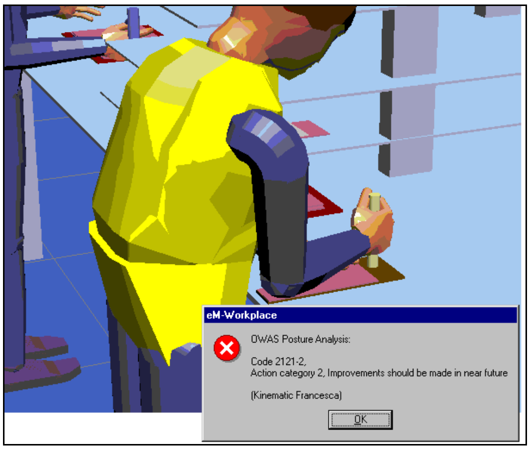
eM-Workplace

OWAS Posture Analysis:

Code 1141-2.
Action category 2. Improvements should be made in near future

(Kinematic ELENA)

Figure 4.13 - OWAS methodology results



OWAS Posture Analysis:

Code 2121-2,
Action category 2, Improvements should be made in near future

(Kinematic Francesca)

Figure 4.14 - OWAS methodology results

Final workplace configuration

Here, the redesign of the Assembly and Gluing workplace is presented. The new workplace configuration has been developed trying to increase the operators productivity, to improve workers ergonomics and keeping in mind top management requests. In fact, the management asked for a redesign of the workplace based on a modular structure that should avoid workers to talk each other.

Figures 4.15, 4.16 and 4.17 show three different views of the final workplace configuration.

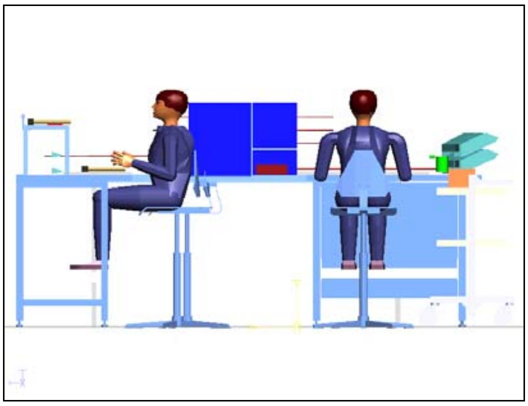


Figure 4.15 - Workplace final configuration

Figure 4.16 - Workplace final configuration

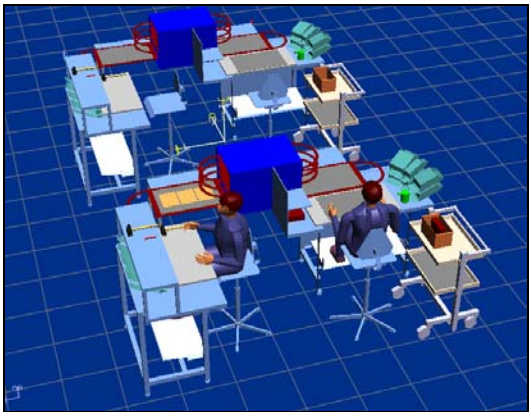


Figure 4.17 - Workplace final configuration

Such configuration allows workers to perform all the operations while seated (eliminating the stress associated to the working postures), operators do not work in frontal position (they cannot speak and look each other), temporary products storage is assured by multi shelf trays accessible by each operator and, finally, the workplace has a modular structure.

As concerns the ergonomic problems related to the lifting operations, the manual operating dolly (on which the leather block is placed on) has been replaced with a higher one (figure 4.18 shows, in the left side, the old manual dolly, and, in the right side, the higher one) and it has been asked to the operators to pick up simultaneously a smaller number of leather sheets. The higher manual operating dolly guarantees a more comfortable position during the grasping operation; this increases the RWL (the equation of the RWL includes among others two terms that consider the origin and destination points of the lifting activity) and, in turn decrease the LI. In addition, the smaller is the number of leather sheets to be simultaneously picked up, the smaller is the weight to be lifted (the object weigh is lower than the AL). Anyhow, all the ergonomic methodologies (NIOSH 81, NIOSH 91 and OWAS) have been repeated on the final workplace configuration and no ergonomic problems have been detected.

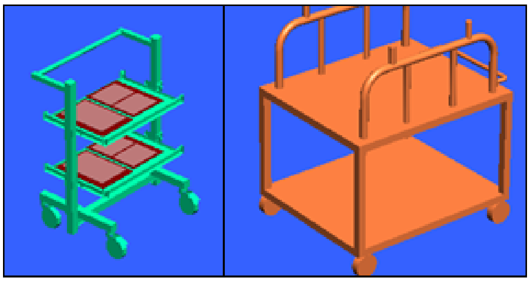


Figure 4.18 - Manual operating dollies

Finally the results of the MTM methodology related to the new configuration show lower process times for each leather desk set component (on the average the reduction is about 9%). Such reduction is mostly due to the use of the multi shelf trays (that allows a better disposition and movement of components) and to the improved disposition of tools used by operators. Moreover additional improvements are expected due to the fact that operators cannot talk to each other.

STEP 6: Results Presentation and Implementation

The final workplace configuration has been proposed to the company top management by presenting in a clear manner the ergonomics and productivity improvements. An ad hoc oral presentation has been developed and several progress reports as well as a final report have been written, giving a chronology of work done, decisions made and achieved results. The top management appreciates the research results and the final workplace configuration has been implemented in the real industrial plant.

4.4.2 AlfaTechnology Ltd.: Skinning Workplace

STEP 1: Problem Formulation and Objectives Definition

In the skinning workplace, the operators eliminate a part of rubber at the ends of each hose in order to guarantee a good junction with the fittings. The workplace employs 2 workers and includes the following elements: scanners, empty bins, rubber hoses, pallets, skinning machines, pc worktables, support table, PC and manual hand charts. The workplace plant layout is reported in figure 4.19.

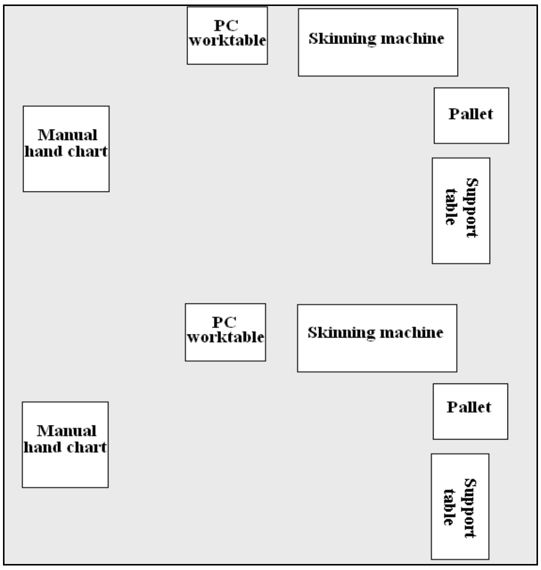


Figure 4.19 - Skinning workplace plant layout

The workplace workers perform the following operations:

1. The workers pick up the Shop Order sheet, read the information they need and put it back;
2. The workers set the skinning machine up;
3. The workers pick a rubber hose up located on a pallet 15 cm high;
4. The workers insert the rubber hose into the skinning machine, perform the security procedure and start the skinning phase;
5. The workers remove the rubber hose from the skinning machine and put it on a bin placed on a manual hand chart 30 cm high;
6. The workers set the status “end of the operation” on the company informative system;
7. The workers move the rubber hoses to the successive workplace by means of a manual hand chart.

Note that the skinned rubber hoses are used for manufacturing the high pressure hydraulic hoses and directly sold to the final customers as well; in this context, some of them is moved to the next workplace, the others are moved to the final product warehouse.

According to the company management, the workplace is characterized by low productivity levels and several harmful working postures occur while performing the operations. Moreover the management believes that the workplace should be not affected by the ergonomic problems related to the lifting tasks, since no heavy objects have to be grasped and moved by the workers.

STEP 2: Performance Measures and Design Parameters Definition

The application of the design methodology to the Skinning workplace considers the following time and ergonomic performance measures:

1. *Process Time (PT)* evaluated by means of the Methods Time Measurement (MTM) and Maynard Operation Sequence Technique (MOST) methodologies;
2. The *Action Limit (AL)* and the *Maximum Permissible Limit (MPL)* evaluated by using the NIOSH 81 lifting equation. AL is the weight value, which is permissible for 75% of all

female and 99% of all male workers. MPL is the weight value, which is permissible for only 1% of all female and 25% of all male workers;

3. The *Recommended Weight Limit (RWL)* and the *Lifting Index (LI)* evaluated by means of the NIOSH 91 lifting equation. The RWL is the load that nearly all healthy workers can perform over a substantial period of time for a specific set of task conditions. The LI is calculated as a ratio between the real object weight and the RWL.
4. The *Maximum Permissible Force (MPF)* evaluated by means of the Burandt Schultetus methodology. The MPG detects the maximum weight that a working person can lift;
5. The *Stress Level (SL)* associated to the workers' body posture evaluated by using the OWAS methodology;
6. The total amount of energy (*Energy Expenditure – EE*) spent during the manual operations evaluated by means of the Garg methodology.

Further and detailed information concerning the aforementioned performance measures can be found in Chapter 2.

As concerns the design parameters definition, objects positions within the workplace have be identified as significant factors that can affect the aforementioned performance measures.

STEP 3: Data Collection

As first step, a schedule of data requirement was submitted to the company top management. However no data were currently available. Therefore a three months period was spent at the Skinning workplace for collecting data and information about operators' characteristics (age, gender, height, weight and physical condition), dimensions (length, width and height) and weights of all the objects being modeled and for analyzing the work methods used by operators for performing the manufacturing operations. *Video based systems*, *walking-through observation methods*, and *individual questionnaires* were used as supporting tools for gathering all the required information. Table 4.5 reports description, dimensions (length, width and height), weights, and quantity of all the objects being used within the Skinning workplace, while table 4.6 consists of operators' physical characteristics.

Objects description	**Dimensions (cm) (L x W x H)**	**Weight (Kg)**	**Quantity**
Scanner	12 x 7 x 18	0,4	2
Empty bin	60 x 40 x 30	0,3	4
Rubber hose	Depending of Shop Order	Depending of Shop Order	Depending of Shop Order
Pallet	80 x 120 x 15	25	2
Skinning Machine	300 x 150 x 250	142,5	2
PC Worktable	100 x 65 x 95	47,54	2
Support Table	180 x 60 x 95	49,1	2
PC	30 x 35 x 50	7	2
Manual hand chard	100 x 140 x 15	35,3	2

Table 4.5 - Objects' data

Operator ID	**Age**	**Gender**	**Height (cm)**	**Weight (kg)**	**Workplace**
Op-1	32	Male	172	73	Skinning
Op-2	29	Male	175	71	Skinning

Table 4.6 - Operators' physical characteristics

Figures 4.20 shows the geometric models of the PC and PC worktable; figure 4.21 depicts the rubbers hoses and a pallet; finally, figure 4.22 provides the reader with a panoramic view of the Skinning workplace.

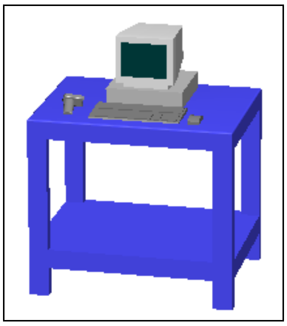


Figure 4.20 - PC and PC worktable geometric models

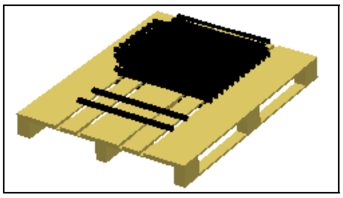


Figure 4.21 - Rubber hoses and pallets geometric models

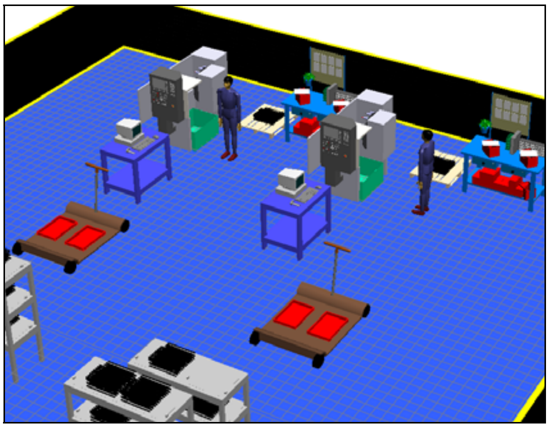


Figure 4.22 - Panoramic view of the Skinning workplace

STEP 5: Effective Workplace Design

Herein, firstly the actual workplace configuration is analyzed and studied in terms of time and ergonomic issues, and, secondly an improved workplace configuration is proposed. The analysis are performed considering a typical shop order made by 20 hydraulic hoses.

Actual workplace configuration

The activities performed by the operators do not require heavy lifting tasks; in effect, Burandt Schultetus, NIOSH 81 and NIOSH 91 methodologies do not reveal any particular lifting problem. On the contrary, relevant results have been obtained in terms of uncomfortable working postures and EE respectively for the OWAS and the Garg methodologies. When the OWAS analysis is applied to the Skinning workplace, the program assigns a category 3 (body posture characterized by high SL) to the following operations:

1. Picking manually up a rubber hose located on a pallet 15 cm high before the skinning operation (please refer to STEP 1, operation 3);
2. Putting a rubber hose on a bin located on a manual hand chart 30 cm high after the skinning operation (please refer to STEP 1, operation 5).

In both cases, the most affected body part is the workers' back.

The Garg methodology completes the ergonomic evaluation process calculating about 2340 Kcal as the total amount of energy spent during the whole shift.

As concerns time issues affecting the workplace, the operations herein performed have been subdivided in 4 different groups (each group has to be regarded as a macro-activity), described as follows.

- *Macro-activity 1* – the operators set the workplace for starting the skinning operations;
- *Macro-activity 2* – the operators move the component (rubber hoses) into the skinning machine and start the skinning phase;
- *Macro-activity 3* – after the skinning phase the operators remove the components from the skinning machine and put them into a bin;
- *Macro-activity 4* – the operators complete the shop order and move the rubber hoses to the successive workplace.

The macro-activities were grouped together into two different categories: preparation operations (performed just once for the entire shop order) and cyclic operations. The macro-activities 1 and 4 (workplace set-up and shop order completion) belong to the first category. The macro-activities 2 and 3 belong to the second category. Table 4.7 and table 4.8 consist of process times for each macro-activity (expressed in seconds and evaluated respectively by using the MTM and the MOST methodologies).

MTM methodology	
Preparation operation	**Time (sec.)**
Macro-activity 1	6.19
Macro-activity 4	184.97
Total Preparation Time	191.16
Cyclic operation	**Time (sec.)**
Macro-activity 2	222.04
Macro-activity 3	415.12
Total Cyclic Time	637.16
Total time for completing the Shop Order	**828.74**

Table 4.7 - Process time evaluated by using the MTM methodology

MOST methodology	
Preparation operation	**Time (sec.)**
Macro-activity 1	7.01
Macro-activity 4	185.52
Total Preparation Time	192.53
Cyclic operation	**Time (sec.)**
Macro-activity 2	222.94
Macro-activity 3	416.24
Total Cyclic Time	639.18
Total time for completing the Shop Order	**831.71**

Table 4.8 - Process time evaluated by using the MOST methodology

As concerns the MTM, the total process time is 828.74 sec. (about 12 min and 8 sec.). As concerns the MOST, the total process time is 831.71 sec (about 12 min and 11 sec).

Let us focus on the Skinning workplace productivity. It has been evaluated by taking into account the total time required for completing a shop order (PT), an 8 hours shift and the operators' allowance for physiological needs, fatigue and delay (calculated as 20% of the process time). Regardless of the work measurement methodology (MTM or MOST), the workplace productivity is about 29 shop orders per day.

Final workplace configuration

This section presents the final workplace configuration developed for reducing ergonomic risks as well as increasing workers' productivity. The following three main modifications have been indentified:

1. A manual dolly replaces the pallet being used for locating the rubber hoses before the skinning operations. This change allows the operators to avoid the continuous bending needed for picking the rubber hoses up. Figure 4.23 shows, on the left side, the initial configuration, and, on the right side, the final one.

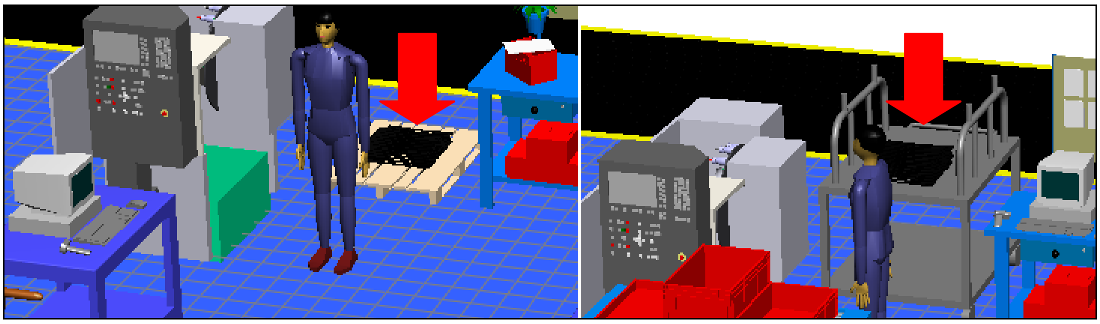


Figure 4.23 - Final workplace configuration

2. The PC being used by the operator for setting the status "end of operation" on the company informative system, has been moved to the support table. Note that such change allows to reduce the number of steps required by the operator for reaching the PC worktable; figure 4.24 shows the initial (left side) and the final (right side) workplace configurations.

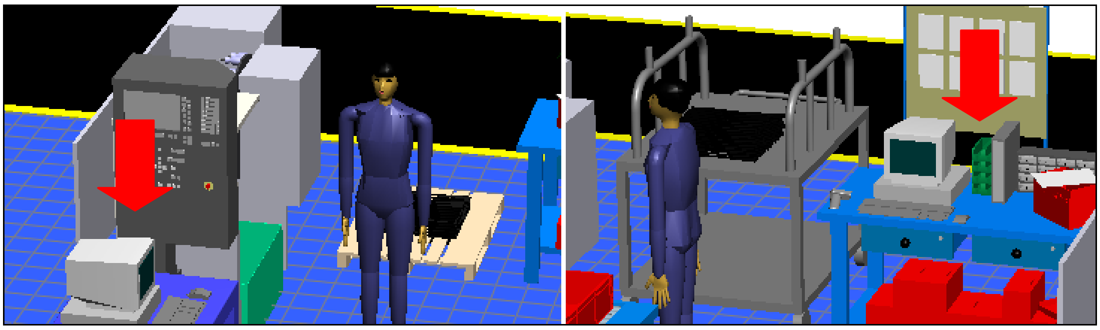


Figure 4.24 - Final workplace configuration

3. A manual conveyor replaces the manual hand chart for moving the skinned rubber hoses to the successive workplace. Such change allows to notably save time for moving the skinned rubber hoses to the next workplace. After the skinning phase, the workers put the skinned rubber hoses on a bin located on the manual conveyor and then, by providing a slight push to the bin, move the rubber hoses to the Assembly workplace. Moreover the new configuration consents to effectively manage rubber hoses inventory between the Skinning and the successive workplace; in effect, the rubber hoses can be directly stored into the bins placed on the manual conveyor, instead of use several shelves located between the workplace. Figure 4.25 depicts the initial configuration (left side) and the final one (right side).

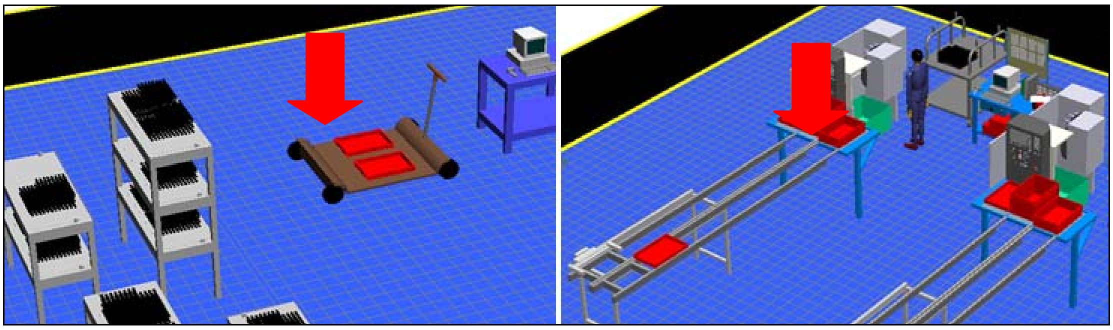


Figure 4.25 - Final workplace configuration

Ergonomic and time performance measure have been re-evaluated for the final workplace configuration. No ergonomic issues have been identified and the EE has been reduced from 2340 to 1780 Kcal (a 24% reduction). As regards time analysis, table 4.9 and table 4.10 report the process times for each macro-activity performed within the final configuration. MTM and MOST methodology calculate, respectively, 523,51 sec. (about 8 min and 43 sec.) and 528,9 sec. (about 8 min and 48 sec.) as total time required for completing a Shop Order. In both cases the PT reduction is about 58% and the workplace productivity improvement is about 56% (from 29 to 45 shop orders per day).

MTM methodology	
Preparation operation	**Time (sec.)**
Macro-activity 1	6.19
Macro-activity 4	70.16
Total Preparation Time	76.35
Cyclic operation	**Time (sec.)**
Macro-activity 2	192.04
Macro-activity 3	255.12
Total Cyclic Time	397.16
Total time for completing the Shop Order	**523.51**

Figure 4.9 - Process time for the final workplace configuration evaluated by using the MTM methodology

MOST methodology	
Preparation operation	**Time (sec.)**
Macro-activity 1	7.01
Macro-activity 4	72.56
Total Preparation Time	79.57
Cyclic operation	**Time (sec.)**
Macro-activity 2	193.01
Macro-activity 3	256.32
Total Cyclic Time	449.33
Total time for completing the Shop Order	**528.9**

Figure 4.10 - Process time for the final workplace configuration evaluated by using the MOST methodology

STEP 6: Results Presentation and Implementation

A history of the study has been provided by writing progress reports. Reporting has occurred at least monthly in order to make the top management directly and deeply involved in the application of the methodology. A study log has been also kept. The log has provided a comprehensive record of accomplishments, noteworthy problems, change requests, key decisions, ideas for follow-on work, and anything else of major or even minor importance.

Moreover, a final ad hoc oral presentation has been developed trying to point out and remark the ergonomic and time improvement achieved by applying the design methodology.

4.5 Design of Experiment based Approach Case Studies

This section presents several case studies related to the design methodology application by using the design of experiment based approach. Although a detailed description of such approach can be found in Chapter 3, section 3.9, few lines are here reported in order to make the reader better understanding the proposed case studies.

According to this approach, the engineer generates a number of workplaces configurations by using a well defined Design of Experiments (DOE). Each design parameter is characterized by different values and all the combinations of these values generates a comprehensive set of workplace alternative configurations to be compared by means of the workplaces simulation model.

4.5.1 AlfaTechnology Ltd.: Assembly Workplace

STEP 1: Problem Formulation and Objectives Definition

In the Assembly workplace, the operators manually assemble the rubber hoses with fittings and ring-nuts. The workplace employs 2 workers and includes the following elements: scanners, ring nuts and fittings bins, rubber hoses, pallets, worktables, pc worktables, PC, and manual hand charts. The workplace plant layout is reported in figure 4.26.

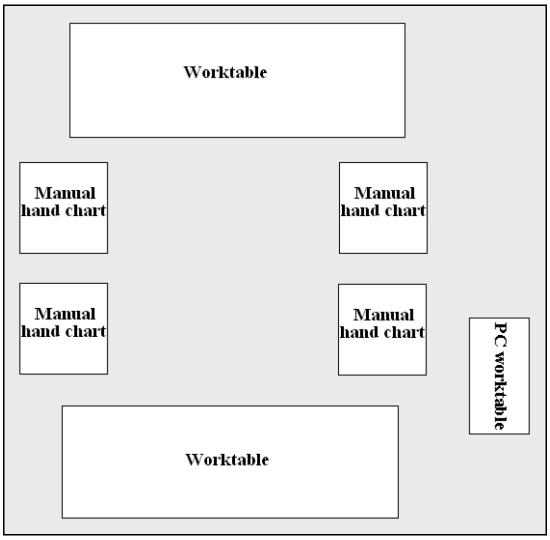


Figure 4.26 - Assembly workplace plant layout

The workplace workers perform the following operations:

1. The workers pick up the shop order sheet, read the information they need and put it back;
2. The workers picks manually up a rubber hose located on a manual dolly and bring it to the work table;
3. The workers pick manually two ring nuts and two fittings up from bins located on a manual hand chart and bring them to the work table;
4. The workers manually perform the assembly operation;
5. The workers place the assembled hydraulic hoses on a manual hand chart;
6. The workers set the status “end of the operation” on the company informative system;
7. The workers moves the hydraulic hoses to the successive workplace by means of a manual hand chart.

A preliminary analysis carried out by production managers shows that the productivity of the Assembly workplace (evaluated on monthly basis) always falls below target levels causing delays in shop orders completion. In this context, the design methodology aims at achieving workplace productivity improvement. Moreover ergonomic methodologies will be also used in order to evaluate the ergonomic issues within the current workplace configuration.

STEP 2: Performance Measures and Design Parameters Definition

The application of the design methodology to the Assembly workplace considers the following time and ergonomic performance measures:

1. *Process Time (PT)* evaluated by means of the Methods Time Measurement (MTM) methodology;
2. The *Maximum Permissible Force (MPF)* evaluated by means of the Burandt Schultetus methodology. The MPG detects the maximum weight that a working person can lift;
3. The *Stress Level (SL)* associated to the workers' body posture evaluated by using the OWAS methodology;
4. The total amount of energy (Energy Expenditure – EE) spent during the manual operations evaluated by means of the Garg methodology.

Further and detailed information concerning the aforementioned performance measures can be found in Chapter 2.

As concerns the design parameters definition, distances and angles (associated to objects and tools) could be significant factors for the Assembly workplace. The design parameters definition for the Assembly workplace is as follows:

- Let *b* be the worktable angle; it defines the orientation of the worktable respect to the actual position (please refer to figure 4.27);
- Let *sp* be the air blower position; it defines the position of the air blower equipment respect to the actual position (please refer to figure 4.27);
- Let *cp* be the computer position; it defines the position of the computer respect to the actual position (please refer to figure 4.27).

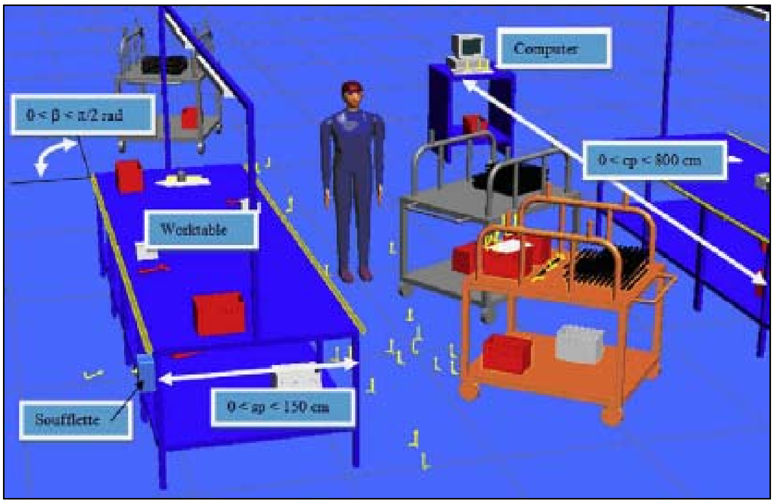


Figure 4.27 - Actual configuration of Assembly workplace with design parameters

Table 4.11 consists of factors and levels for the Assembly workplace. The design parameters levels combination generates 8 different configurations to be tested trough the simulation model.

Assembly workplace				
Design parameters	**Factor ID**	**Level 1**	**Level 2**	
Worktable angle	β	0	π/2	rad
Air blower	sp	0	150	cm
Computer position	cp	0	800	cm

Table 4.11. Design parameters and levels of the Assembly workplace

STEP 3: Data Collection

A two-months period was spent at the Assembly workplace for collecting data and information about operators' characteristics (age, gender, height, weight and physical condition), dimensions (length, width and height) and weights of all the objects being modeled and analyzing the work methods used by workers for performing the manufacturing operations. *Questionnaires* and *walking-through observation methods* were used for collecting all the data required for carrying out the design methodology. Table 4.12 reports description, dimensions (length, width and height), weights, and quantity of all the objects being used within the Assembly workplace, while table 4.13 consists of operators' physical characteristics.

Objects description	Dimensions (cm) (L x W x H)	Weight (Kg)	Quantity
Scanner	12 x 7 x 18	0,4	2
Ring nuts and fittings bins	20 x 15 x 15	0,3	Depending of Shop Order
Rubber hose	Depending of Shop Order	Depending of Shop Order	Depending of Shop Order
Worktable	400 x 150 x 95	150,62	2
PC Worktable	180 x 60 x 95	47,54	1
PC	30 x 35 x 50	7	1
Manual dolly	100 x 140 x 90	35,3	4

Table 4.12. Objects' data

Operator ID	Age	Gender	Height (cm)	Weight (kg)	Workplace
Op-1	44	Male	169	74	Assembly
Op-2	39	Male	178	78	Assembly

Table 4.13. Operators' physical characteristics

Figure 4.28 shows the real manual dolly (left side) and its geometric model (right side), while figure 4.29 depicts the real (left side) and the virtual (right side) Assembly workplace.

Figure 4.28 - Real and virtual manual hand chart

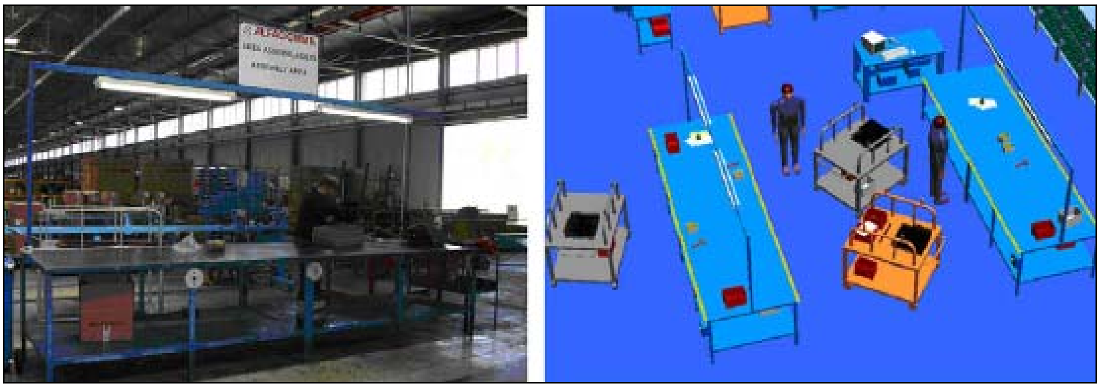


Figure 4.29 - Real and virtual Assembly workplace

STEP 5: Effective Workplace Design

In this section the simulation model is used for comparing the workplace's alternative configurations obtained by considering all the design parameters levels combinations (as mentioned in the previous step). Then the multiple performance measures defined in STEP 2 allow to choose the workplace's final configuration. Note that the methodology is carried out by considering a typical shop order made by 12 hydraulic hoses.

Within the Assembly workplace, the activities performed by the operators do not require heavy lifting tasks or uncomfortable working postures. In effect, the Burandt Schultetus methodology and the OWAS do not reveal any particular lifting or posture problem. Significant results for the effective design have been obtained in terms of EE and PT respectively for the Garg and MTM methodologies. Table 4.14 reports simulation results for each factors levels combination.

			Assembly Workplace	
			MTM	**Garg**
β	**sp**	**cp**	**Process Time (sec)**	**Energy Expenditure (Kcal)**
0	0	0	1118.36	1736.0
0	0	800	1104.64	1701.3
0	150	0	986.66	1466.9
0	150	800	972.94	1432.2
π/2	0	0	1107.38	1710.0
π/2	0	800	1096.41	1675.2
π/2	150	0	975.68	1440.9
π/2	150	800	964.71	1406.2

Table 4.14 - Simulation results for the Assembly workplace

The variation of the worktable angle *b* (*0 <b < π/2*, considering fixed the remaining factors levels) affects both the EE and the PT. Note the reduction of the EE and the PT in the case of b = π/2 (EE = 1710.0 kcal and PT = 1107.39 sec reductions respectively 1.5% and 1.0%). The variation of the air blower position (*sp*) and the computer position (*cp*) shows a similar behavior in terms of the EE and the PT. The variation of the *sp* causes a reduction of both the EE and the PT (EE = 1466.9 kcal, PT = 986.66 sec reductions respectively 15.5% and 11.8%). Similarly the variation of the *cp* causes a reduction of both the EE and the PT (EE = 1701.3 kcal, PT = 1104.64 sec reductions respectively 2.0% and 1.2%). The results in table 4.14 show that such positive effects are amplified by the interaction among the factors levels (i.e. the interaction between the *sp* and the *cp* causes a reduction of the EE and the PT respectively equals to 17.5% and 13.0%). The variation of all the factors levels guarantees the best workstation performances both in terms of ergonomics and work measurement (EE = 1406.2 kcal, PT = 964.71 sec reductions respectively 19.0% and 13.7%). The process time reduction guarantees higher productivity levels: 49 additional hydraulic hoses per day (1083 additional hoses per month). Concerning the final configuration of the assembly workstation, the design methodology suggests the following interventions (respect to the actual configuration):

1. a T-shape configuration for the worktable (one operator at each side);
2. a computer position closer to the worktable;
3. an air blower position closer to the area of the worktable where the hoses are assembled.

Figure 4.30 shows the final configuration of the assembly workplace.

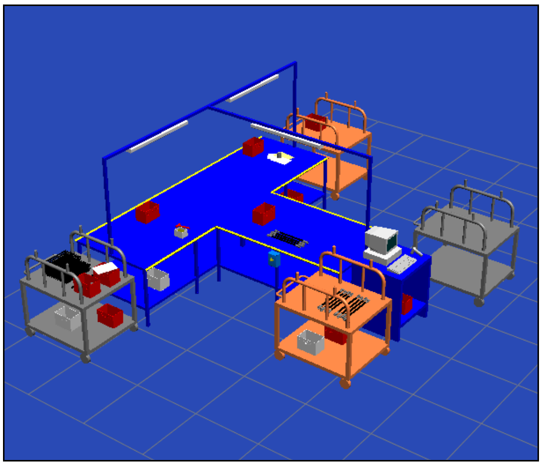


Figure 4.30 - Workplace final configuration

STEP 6: Results Presentation and Implementation

An ad hoc final oral presentation has been developed and a final report has been given to the company top management. Moreover several progress oral presentations have been proposed in order to involve the top management through the entire application of the methodology. The company top management really appreciates the work done as well as the achieved results, and the proposed configuration has been implemented in the real system.

4.5.2 AlfaTechnology Ltd.: Pressure Test Workplace

STEP 1: Problem Formulation and Objectives Definition
In the Pressure Test workplace, the operators test the hydraulic hoses by using a pressure machine (setting a pressure value higher than the nominal value). The workplace employs 2 workers and includes the following elements: scanners, ring nuts and fittings bins, rubber hoses, worktables, pc worktables, PC, support tables, pressure test machines and manual hand charts. The workplace plant layout is reported in figure 4.31.

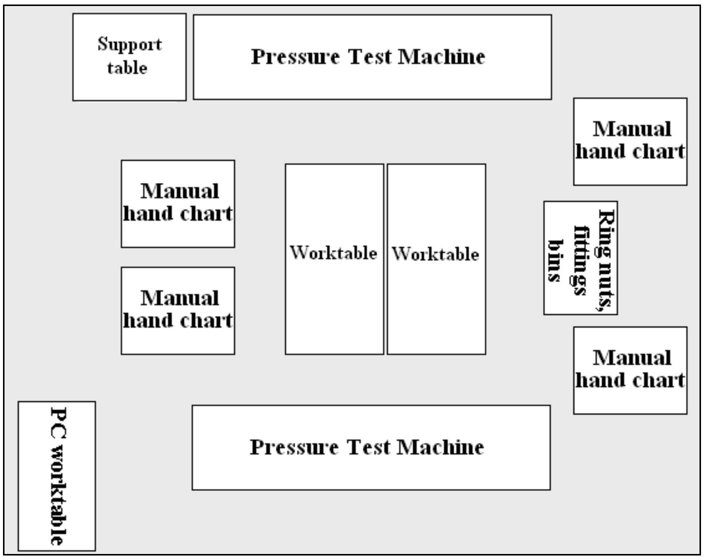


Figure 4.31 - Pressure Test workplace plant layout

The workplace workers perform the following operations:

1. The workers pick up the Shop Orders sheet, reads the information they need and puts it back;
2. The workers take the hydraulic hoses from a manual dolly and bring it on the work table;
3. The workers pick up the joints for connecting the hydraulic hoses to the pressure test machine;
4. The workers connect joints and hydraulic hoses;
5. The workers move the hydraulic hoses from the work table to the testing machine;
6. The workers connect the hydraulic hoses to the testing machines, performs the security procedures and starts the testing phase;
7. The workers disconnect the hydraulic hoses from the testing machine, perform the visual checks and moves the hoses on the work table;
8. The workers disconnect the joints from the hydraulic hoses;
9. The workers put the joints back in the proper bins and come back to the work table;
10. The workers bring the tested hydraulic hoses to a manual dolly;
11. The workers complete the Shop Order by setting the status “end of the operation” on the company informative system;
12. The workers move the materials to the successive workplace by using a manually operated dolly.

STEP 2: Performance Measures and Design Parameters Definition
The application of the design methodology to the Pressure Test workplace considers the following time and ergonomic performance measures:

1. *Process Time (PT)* evaluated by means of the Methods Time Measurement (MTM) methodology;
2. The *Maximum Permissible Force (MPF)* evaluated by means of the Burandt Schultetus methodology. The MPG detects the maximum weight that a working person can lift;

3. The *Stress Level (SL)* associated to the workers' body posture evaluated by using the OWAS methodology;
4. The total amount of energy (*Energy Expenditure – EE*) spent during the manual operations evaluated by means of the Garg methodology.

Further and detailed information concerning the aforementioned performance measures can be found in Chapter 2.

Concerning the design parameters definition, distances and angles associated to objects and tools cannot be easily modified (because the pressure test on the hydraulic hoses is executed by using an automated machine). Consequently it was decided to consider, as design parameters, four different work methods. Each work method is characterized by a different number of hydraulic hoses to be simultaneously tested within the pressure test machine. By using the first work method the operator executes the pressure test on a single hydraulic hose, by using the second work method, the operator executes the pressure test simultaneously on two hydraulic hoses, by using the third work method on three hydraulic hoses and by using the fourth on four hydraulic hoses.

STEP 3: Data Collection

Table 4.15 and table 4.16 report, respectively, data concerning all the objects being used within the workplace and information about operators' physical characteristics.

Objects description	Dimensions (cm) (L x W x H)	Weight (Kg)	Quantity
Scanner	12 x 7 x 18	0,4	1
Ring nuts and fittings bins	20 x 15 x 15	0,3	Depending of Shop Order
Rubber hose	Depending of Shop Order	Depending of Shop Order	Depending of Shop Order
Worktable	400 x 150 x 95	100,8	2
PC Worktable	180 x 60 x 95	47,54	1
PC	30 x 35 x 50	7	1
Manual hand chart	100 x 140 x 90	35,3	4
Support table	110 x 130 x 100	49,1	1
Pressure Test Machine	368 x 90 x 150	1020,04	2

Table 4.15 - Objects' data

Operator ID	Age	Gender	Height (cm)	Weight (kg)	Workplace
Op-1	48	Male	176	81	Pressure Test
Op-2	51	Male	173	76	Pressure Test

Table 4.16 - Operators' physical characteristics

Figure 4.32 shows the real and the virtual ring bins, while figure 4.33 depicts the real and the virtual Pressure Test workplace.

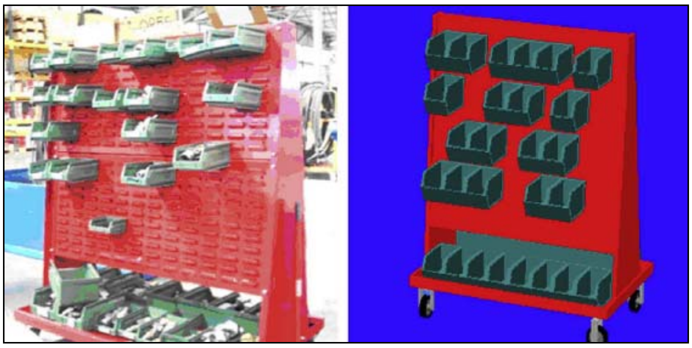


Figure 4.32 - Real and virtual ring bins

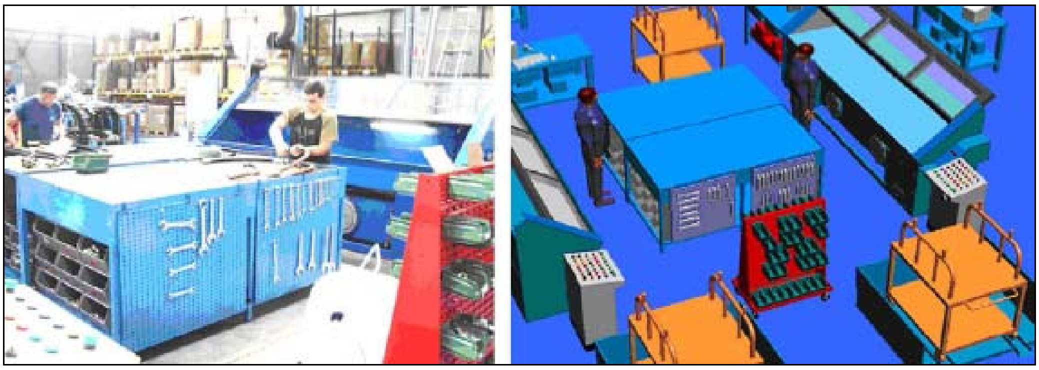


Figure 4.33 - Real and virtual Pressure Test workplace

STEP 5: Effective Workplace Design

In this section the simulation model is used for comparing the workplace's alternative work methods. Note that the methodology is carried out by considering a typical shop order made by 12 hydraulic hoses.

The operations performed in this workplace have been subdivided into 6 different groups (each group has to be regarded as a macro-activity), described as follows.

1. *Macro-activity 1* – the operator sets the workplace for starting the testing operations;
2. *Macro-activity 2* – the operator prepares the hydraulic hoses to be tested;
3. *Macro-activity 3* – the operator moves the hydraulic hoses from the worktable to the testing machine;
4. *Macro-activity 4* – the operator connects the hydraulic hoses to the testing machine, performs the security procedures and starts the testing phase;
5. *Macro-activity 5* – after the test the operator performs the visual checks and moves the hoses on the worktable;
6. *Macro-activity 6* – the operator completes the shop order.

Table 4.17 consists of process times for each macro-activity (expressed in seconds and evaluated by using the MTM methodology).

Pressure Test Workplace	1 Hose	2 Hoses	3 Hoses	4 Hoses
Macro-activity 1	4.89	5.32	7.12	8.25
Macro-activity 2	26.86	36.75	50.53	68.13
Macro-activity 3	15.70	14.44	13.28	14.36
Macro-activity 4	29.06	39.07	54.57	74.54
Macro-activity 5	31.06	45.54	60.61	80.88
Macro-activity 6	19.96	23.36	25.37	26.28
Total (sec.)	127.53	164.48	211.48	272.45

Table 4.17 - Simulated times for each macro-activity in the Pressure Test workplace

It was supposed to subdivide the macro-activities into two different categories: preparation operations (performed just once for the entire shop order) and cyclic operations (cyclically performed for each hydraulic hose). The macro-activities 1 and 6 (workplace set-up and shop order completion) belong to the first category. The macro-activities 3 - 5 belong to the second category. Note that the frequency of such macro-activities depends on the work method used by the operator. The macro-activity 2 is cyclically performed but the PT of the macro-activity 2 affects the shop order total completion time just once (in other words it is cyclically repeated during the macro-activity 4). Therefore, the macro-activity 2 should be inserted in the first category and considered as preparation time. Consider now the four different work methods in terms of hydraulic hoses simultaneously tested: one single hydraulic hose (scenario 1) two, three or four hoses simultaneously tested (respectively scenario 2, scenario 3 and scenario 4) by taking into consideration a shop order made up by 12 hydraulic hoses.

As concerns the ergonomic performance measures, for each scenario the Burandt Schultetus methodology and the OWAS do not reveal any particular lifting or posture problem. However, the Garg and MTM analyses give significant results that can be used for the effective design of the workstation (in terms of energy expenditure, EE, and process time, PT). Table 7 consists of the MTM and Garg analysis results for each scenario. Table 7 reports the PT (in seconds) for preparation operations (macro-activities 1, 2 and 6) and for cyclic operations (macro-activities 3–5). In addition, the last 4 rows of Table 4.18 report the total amount of energy expended for each scenario (EE) and the total time required for completing the Shop Order. The optimal work method in terms of EE is the third scenario. In particular the amount of energy expended for completing the Shop Orders is 1504.06 kcal. The third scenario (three hydraulic hoses simultaneously tested) is also characterized by the minimum Shop Order PT. In this case the total PT is 596.9 s (about 9 min and 57 s). Note that the PT improvement is about 38% respect to the first scenario, 9.6% respect to the second scenario and 2.5% respect to the fourth scenario. As in the case of the assembly workstation the methodology proposed by the authors allows to achieve the effective design of the workstation both in terms of energy expenditure and process time.

	Preparation			
	Macro-Activity 1 (sec.)	**Macro-Activity 2 (sec.)**	**Macro-Activity 6 (sec.)**	**Total Preparation time (sec.)**
Sc1	4.9	26.9	20.0	51.7
Sc2	5.3	36.7	23.4	65.4
Sc3	7.1	50.5	25.4	83.0
Sc4	8.3	68.1	26.3	102.7
	Cyclic			
	Macro-Activity 3 (sec.)	**Macro-Activity 4 (sec.)**	**Macro-Activity 5 (sec.)**	**Total working time (sec.)**
Sc1	188.4	348.7	372.7	909.8
Sc2	86.7	234.4	273.2	594.3
Sc3	53.1	218.3	242.5	513.9
Sc4	43.1	223.6	242.7	509.3
		Energy Expenditure (Kcal)		**Total Time for completing the Shop Order (sec.)**
Total Time - Scenario 1		2165.67		961.5
Total Time - Scenario 2		1521.95		659.7
Total Time - Scenario 3		1504.93		596.9
Total Time - Scenario 4		1644.84		612.0

Table 4.18 - MTM and Garg analysis results for the Pressure Test workplace

STEP 6: Results Presentation and Implementation

The final workplace work methods has been revealed to the company top management by presenting in a clear manner the productivity improvements. An ad hoc oral presentation has been developed giving a chronology of work done, decision made and achieved results.

4.5.3 AlfaTechnology Ltd.: Seal Press Workplace

STEP 1: Problem Formulation and Objectives Definition

In the Seal Press workplace, the operator prints on ring-nuts and fittings the quality and traceability identifying numbers by using the seal press machine and places the components inside apposite boxes. The workplace employs 2 workers and includes the following elements: scanner, ring nuts and fittings bins, rubber hoses, worktable, pc worktable, PC, support table, and seal press machine. The workplace plant layout is reported in figure 4.34.

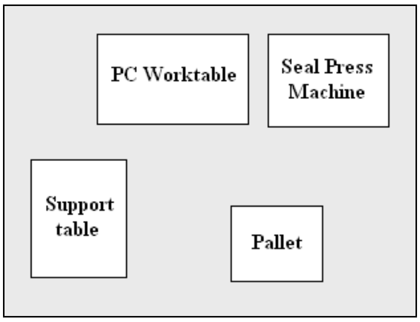


Figure 4.34 - Seal Press workplace plant layout

The workplace workers perform the following operations:

1. The operators set the seal press machine up;
2. The operators position components (ring nuts or fittings) within the machine;
3. The operators carry out the printing operations (quality and traceability identifying numbers on the component);
4. The operators remove the components from the machine and place them in a box;
5. The operators update the operation status on the company informative system (end of the operation);
6. The operators transport the components to the successive workplace by using a manual dolly.

Moreover, note that the worker can perform the above mentioned operations by using 4 different work methods each one characterized by a different number of ring nut/fitting to be simultaneously positioned into the seal press machine (operation 2). By using the first work method the operator inserts one ring nut/fitting into the seal press machine, by using the second work method, the operator inserts two ring nuts/fittings into the seal press machine, by using the third and the fourth work methods, three and four ring nuts/fittings, respectively.

STEP 2: Performance Measures and Design Parameters Definition

The application of the design methodology to the Seal Press workplace considers the following time and ergonomic performance measures:

1. *Process Time (PT)* evaluated by means of the Methods Time Measurement (MTM) and Maynard Operation Sequence Technique (MOST) methodologies;
2. The *Maximum Permissible Force (MPF)* evaluated by means of the Burandt Schultetus methodology. The MPG detects the maximum weight that a working person can lift;
3. The *Stress Level (SL)* associated to the workers' body posture evaluated by using the OWAS methodology;
4. The total amount of energy (Energy Expenditure – EE) spent during the manual operations evaluated by means of the Garg methodology.

Further and detailed information concerning the aforementioned performance measures can be found in Chapter 2.

As concerns the design parameters definition, a preliminary analysis reveals that some distances and angles (associated to objects and tools position) could be significant factors for the Seal Press workplace. The following design parameters have been considered:

- *Support table angle*: let us indicate this angle with α, it defines the orientation of the support table respect to the actual position (please refer to figure 4.36);
- *Raw materials bin height*: let us indicate this height with *rmh*, it defines the height of the bin containing the raw materials (please refer to figure 4.36);
- *Ring nuts bin height*: let us indicate this height with *rnh*, it defines the height of the bin containing ring nuts exiting from the seal press machine (please refer to figure 4.36).

Note that the figure 4.35 shows the real Seal Press workplace (left side) and a 3D visualization reporting the design parameters under consideration (right side).

Table 4.19 reports design parameters and levels.

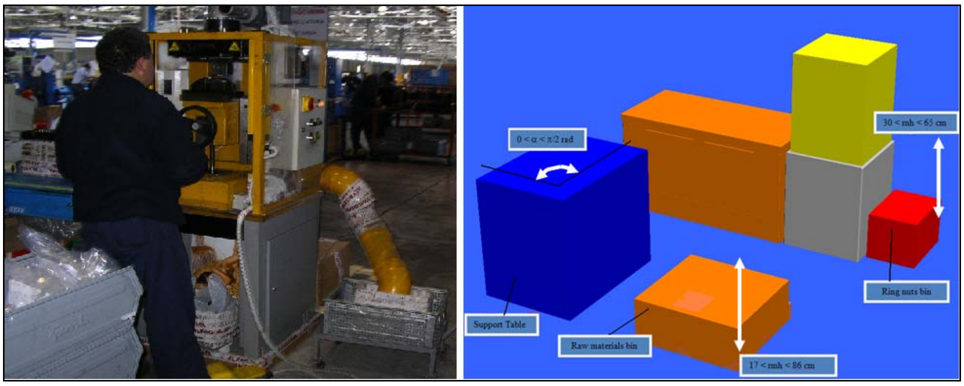


Figure 4.35 - Real and virtual Seal Press workplace with design parameters

Seal Press Workplace				
Design parameters	**Factor ID**	**Level 1**	**Level 2**	
Support Table Angle	*α*	0	π/2	rad
Raw Materials bin height	*rmh*	17	86	cm
Rings nuts bin height	*rnh*	30	65	cm

Table 4.19 - Design parameters and levels of the Seal Press workplace

The design parameters levels combination generates 8 different configurations, so the design of experiments will investigate 8 different workplace configurations.

STEP 3: Data Collection

The data collection includes the following elements of the Seal Press workplace: machine, equipment and tools, worktables, manual operated dollies, raw materials, containers and bins. Table 4.20 reports the objects description, dimensions, weights, and quantity, while table 4.21 report workers' physical characteristics.

Object Description	Dimensions (cm) L x W x H	Weight (Kg)	Quantity
Ring nut	Depending on S.O.	0.168	Depending on S.O.
Fitting	Depending on S.O.	0.336	Depending on S.O.
Marking die	Depending on S.O.	1.800	Depending on S.O.
Workstation stamp	Depending on S.O.	0.100	Depending on S.O.
Scanner	12 x 7 x 18	0.400	1

Empty bin	30 x 20 x 15	0.300	4
Rubber hose	Depending on S.O.	1.020	Depending on S.O.
Manual operated Dolly	100 x 120 x 76	35.300	1
Rings bin	30 x 20 x 15	0.300	1
Worktable	150 x 70 x 86	52.700	1
Support table	106 x 76 x 94	50.120	1
PC Worktable	180 x 60 x 95	47,54	1
PC	30 x 35 x 50	7	1
Seal Press machine	65 x 65 x 160	131.250	1
Pallet	80 x 120 x 15	25.000	1

Table 4.20 - Objects' data

Operator ID	Age	Gender	Height (cm)	Weight (kg)	Workplace
Op-1	42	Male	170	68	Seal Press
Op-2	50	Male	165	69	Seal Press

Table 4.21 - Operators' physical characteristics

Figure 4.36 shows the real Seal Press workplace and figure 4.37 shows the workplace geometric models imported into the eM-Workplace virtual environment and the human model.

Figure 4.36 - Real Seal Press workplace

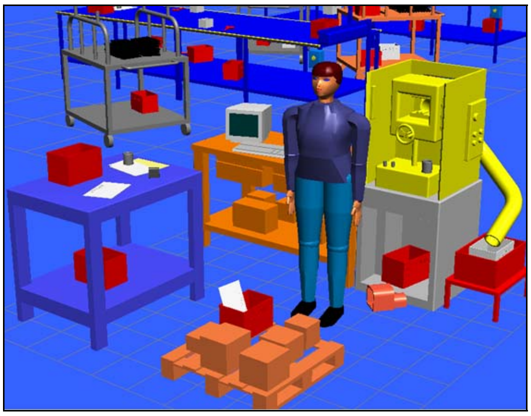


Figure 4.37 - Seal Press workplace simulation model

STEP 5: Effective Workplace Design

In this section the effective design of the Seal Press workplace is achieved. In particular the simulation model has been used for comparing the 8 workplace configurations obtained by considering all the design parameters levels combinations (as mentioned in the previous step). The analysis of the multiple performance measures defined in the STEP 2 will determine the workplace final configuration. Table 4.22 reports the results of the simulation experiments: in correspondence of each combination of the design parameters level, four ergonomic performance measures are reported: the permissible force and the actual force (Burandt Schultetus methodology), the stress level (OWAS methodology), the energy expenditure (Garg methodology).

Seal Press Workstation						
α	**rmh**	**rnh**	**Burandt Schultetus**		**OWAS**	**Garg**
			PF - Permissible Force (N)	**AF - Actual Force (N)**	**SL - Stress Level**	**EE-Energy Expenditure (Kcal)**
0	17	30	121.3	147.2	3	1480.0
0	17	65	135.0	147.2	2	1438.8
0	86	30	137.7	147.2	2	1403.6
0	86	65	151.4	147.2	1	1362.4
π/2	17	30	121.3	147.2	3	1439.4
π/2	17	65	135.0	147.2	2	1398.3
π/2	86	30	137.7	147.2	2	1363.0
π/2	86	65	151.4	147.2	1	1321.9

Table 4.22 - Simulation results for the Seal Press workplace

First, let us consider separately the effect of each design parameter on the performance measures. The variation of the support table angle α ($0 < \alpha < \pi/2$ keeping fixed the remaining factors levels) does not affect the Burandt Schultetus and the OWAS performance measure. In effect, in both cases ($\alpha = 0$ and $\alpha = \pi/2$) the PF and the SL remain unchanged (PF = 121.3 N and SL = 3). The variation of the support table angle does not affect lifting tasks and working postures. However, the support table rotation causes an ergonomic improvement: the higher is the angle α the lower is the EE. Note that for $\alpha = 0$ the EE = 1480.0 Kcal, for $\alpha = \pi/2$ the EE = 1439.4 Kcal (the reduction is about 2.7%). As additional information, table 3 reports the AF; the AF is the same for each scenario and it is the weight of the objects being handled during the operations. For each scenario, the Burandt Schultetus analysis compares PF and AF: if PF > AF than the ergonomic risk can be accepted otherwise a corrective intervention is required for increasing the PF (or reducing the AF). For both $\alpha = 0$ and $\alpha = \pi/2$ it results PF < AF, it means that the ergonomic risk cannot be accepted.

The variation of the raw material bin height, *rmh* (17 < *rmh* < 86 cm, keeping fixed the remaining factors levels) affects all the performance measures. The greater is the *rmh* the higher is the PF, the lower are the SL and the EE. By increasing the *rmh*, the operator can easily reach and grasp the bin of the raw materials without torso and legs bending (see figure 4.39). The stand up position during grasping operations guarantees greater PF values (PF = 137.7 N, note that PF is still lower than AF) as well as more comfortable working postures (SL = 2, however such stress level could create ergonomic problems in the near future). Furthermore by avoiding torso and legs bending, smaller amount of energy is required for performing the same operations (EE = 1403.6 Kcal). In this workstation configuration (please refer to the right part of figure 4.38), the increase of the PF is about 13.5 %, the SL falls now into the second category, the reduction of the EE is 5.2%.

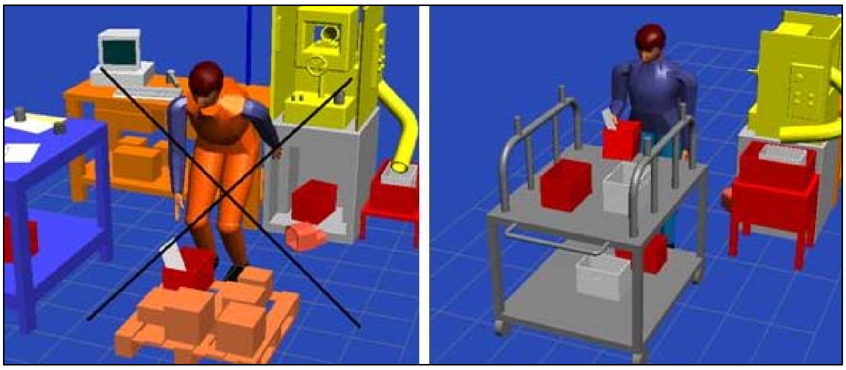


Figure 4.38 - Alternative workplace configuration (raw material bin height)

Let us consider now the variation of the ring nuts bin height *rnh* (30 < *rnh* < 65 cm, keeping fixed the remaining factors levels). As in the previous case, the greater is the *rnh* the higher is the PF, the lower are the SL and the EE. By increasing the *rnh*, the operator reaches and grasps the bin of the ring nuts (exiting from the seal press machine) without torso and legs bending (please refer to figure 4.40). Consequently, he can exert a greater permissible force (PF = 135.0 N), he works in a more comfortable position (SL = 2) and performs the operations with a smaller amount of energy (EE = 1438.8 Kcal). The increase of the PF is about 11.3 %, the SL falls now into the second category (as before mentioned) and the reduction of the EE is about 2.8%. Figure 4.39 shows the modified configuration of the workstation in case of *rnh* = 65 cm.

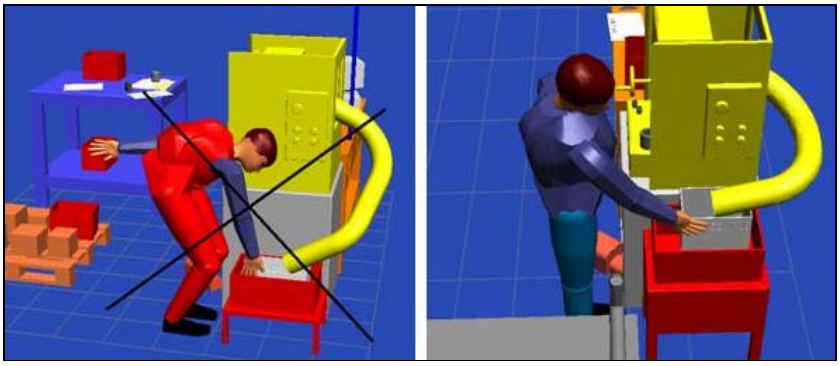


Figure 4.39 - Alternative workplace configuration (ring nuts bin height)

Let us consider now the factors levels interactions. Table 4.22 reports the following results:

- The interaction between α and *rmh* gives, as result, a greater PF (PF = 137.7 N, increase 13.5%), the second category stress level for the working postures and a smaller EE (EE = 1363.0 Kcal, reduction 7.9%). Note that the PF is still lower than the AF and the SL associated to the working postures still falls in the second category.
- The interaction between α and *rnh* gives as result a greater PF (PF = 135 N, increase 11.3%), the second category stress level for the working postures and a smaller EE (EE = 1398.3 Kcal, reduction 5.5%). As in the previous case, the PF is still lower than the AF and the SL still falls in the second category.
- The interaction between *rmh* and *rnh* gives as result a greater PF (PF = 151.4 N, increase 24.8%), the first category stress level for the working postures and a smaller EE (EE = 1362.4 N, reduction 7.9%). Note that the PF is now greater than the AF (it means no ergonomic risks during lifting activities) and the SL falls in the first category (it means the SL associated to working postures is optimum).
- The interaction among all the factors levels guarantees the best workstation ergonomic performances. In effect, table 4.22 reports the following results: the PF = 151.4 N (the highest value, the increase is 24.8%), the SL for the working postures falls into the first category and the EE = 1321.9 Kcal (the lowest value, the reduction is 10.7%). Note that by choosing this workstation configuration the PF > AF (the ergonomic risks related to lifting

activities can be accepted), the working postures are characterized by the first category stress level (no further ergonomic interventions are required).

Figure 4.40 shows the real Seal Press Workplace, the simulation model actual configuration and the ergonomic design (final design) respectively on the left, middle and right part. Note that the support table has been completely removed and the length of the main worktable has been slightly increased. In addition, the raw materials are now placed on a hand-operated dolly and the height of the bin containing the ring nuts exiting from the Seal Press machine is greater than the initial height in the actual workstation configuration.

Figure 4.40 - Effective redesign of the Seal Press workplace

The final workplace configuration was then used for comparing the four different workplace work methods. As already stated in section STEP 1, each work method is characterized by a different number of ring nuts/fittings to be simultaneously inserted into the seal press machine: one single ring nut/fitting (scenario 1) two, three and four ring nuts/fittings simultaneously inserted (respectively scenario 2, scenario 3 and scenario 4) by taking into consideration a typical shop order made by 12 ring nuts/fittings.

As follows the application of MTM and MOST to the Seal Press final configuration is proposed.

The operations performed in the Seal Press workplace have been subdivided in 4 different groups (each group has to be regarded as a macro-activity), described as follows.

- *Macro-activity 1* – the operator sets the workstation for starting printing operations.
- *Macro-activity 2* – the operator moves the component (ring nut/fitting) into the Seal Press machine and starts the printing phase.
- *Macro-activity 3* – after the printing phase the operator performs visual checks and place the components into a bin;
- *Macro-activity 4* – the operator completes the Shop Order (setting the status of "end of the operation" on the informative system, moving all the components to the successive workplace).

Then the macro-activities were grouped together in two different categories: preparation operations (performed just once for the entire shop order) and cyclic operations. The macro-activities 1 and 4 (workplace set-up and shop order completion) belong to the first category. The macro-activities 2 and 3 belong to the second category. Note that the number of the ring nuts/fittings being simultaneously inserted into the seal press machine does not affect the time of the preparation operations. On the contrary, the work method used by the operator affects both frequency and time of cyclic operations. In effects, higher number of ring nuts/fittings inserted into the seal press machine, correspond to: (1) lower frequency of the cyclic operations, (2) higher time for inserting components into the machine, (3) higher time for the printing phase, (4) higher time for removing the components from the machine. On the contrary, lower number of ring nuts/fittings inserted into the seal press machine, correspond to: (1) higher frequency of the cyclic operations, (2) lower time for inserting components into the machine, (3) lower time for printing phase, (4) lower time for removing the components from the machine. In this context, the authors aims at achieving the optimal trade off between the number of ring nuts/fittings to be inserted into the seal press machine and the time required for performing cyclic operations.

Table 4.23 and table 4.24 consist of process times for each macro-activity (expressed in seconds and evaluated respectively by using MTM and MOST).

MTM methodology				
Seal Press Workplace	**1ring nut/fitting**	**2ring nuts/fittings**	**3ring nuts/fittings**	**4ring nuts/fittings**
Macro-activity 1	3.19	3.19	3.19	3.19
Macro-activity 2	9.42	11.23	15.48	23.84
Macro-activity 3	17.76	23.44	31.21	49.24
Macro-activity 4	11.97	11.97	11.97	11.97
Total (s)	42.34	49.83	61.85	88.24

Table 4.23 - MTM results for each macro-activity in the Seal Press Workplace

MOST methodology				
Seal Press Workplace	**1ring nut/fitting**	**2ring nuts/fittings**	**3ring nuts/fittings**	**4ring nuts/fittings**
Macro-activity 1	3.41	3.41	3.41	3.41
Macro-activity 2	9.54	11.48	16.01	23.78
Macro-activity 3	17.54	23.22	32.14	49.51
Macro-activity 4	12.81	12.81	12.81	12.81
Total (s)	43.30	50.92	64.37	89.51

Table 4.24 - MOST results for each macro-activity in the Seal Press Workplace

Table 4.25 and table 4.26 consist of process times for each scenario expressed in seconds and evaluated respectively by using MTM and MOST (a scenario includes a shop order made up by 12 ring nuts/fittings).

MTM methodology			
Preparation	**Macro-activity 1**	**Macro-activity 4**	**Total Preparation Time (s)**
Scenario 1	3.19	11.97	15.16
Scenario 2	3.19	11.97	15.16
Scenario 3	3.19	11.97	15.16
Scenario 4	3.19	11.97	15.16
Cyclic	**Macro-activity 2**	**Macro-activity 3**	**Total Cyclic Time (s)**
Scenario 1	113.04	213.12	326.16
Scenario 2	67.38	140.65	208.03
Scenario 3	61.92	124.84	186.76
Scenario 4	71.52	147.72	219.24
	Total time for completing the Shop Order (s)		
Scenario 1	341.32		
Scenario 2	223.19		
Scenario 3	201.92		
Scenario 4	234.4		

Table 4.25 - MTM results for each scenario of the Seal Press Workplace

MOST methodology			
Preparation	**Macro-activity 1**	**Macro-activity 4**	**Total Preparation Time (s)**
Scenario 1	3.41	12.81	16.22
Scenario 2	3.41	12.81	16.22
Scenario 3	3.41	12.81	16.22
Scenario 4	3.41	12.81	16.22
Cyclic	**Macro-activity 2**	**Macro-activity 3**	**Total Cyclic Time (s)**
Scenario 1	114.48	210.48	324.96
Scenario 2	68.88	139.32	208.2
Scenario 3	64.04	128.56	192.6
Scenario 4	71.34	148.53	219.87

	Total time for completing the Shop Order (s)
Scenario 1	341.18
Scenario 2	224.42
Scenario 3	208.82
Scenario 4	236.09

Table 4.26 - MOST results for each scenario of the Seal Press Workplace

The third scenario (three ring nuts/fittings simultaneously inserted into the Seal Press machine) is characterized by the minimum Shop Order process time (according to both MTM and MOST). As concerns the MTM, the total PT is 201.92 sec (about 3 min and 22 sec). Note that the PT improvement is about 41% respect to the first scenario, 9.6% respect to the second scenario and 13.9% respect to the fourth scenario. As concerns the MOST, the total PT is 208.82 sec (about 3 min and 28 sec). Note that the PT improvement is about 38,8% respect to the first scenario, 7% respect to the second scenario and 11.6% respect to the fourth scenario. Figure 4.41 shows the scenarios comparison in terms of PT evaluated by means of MTM (left side) and MOST (right side).

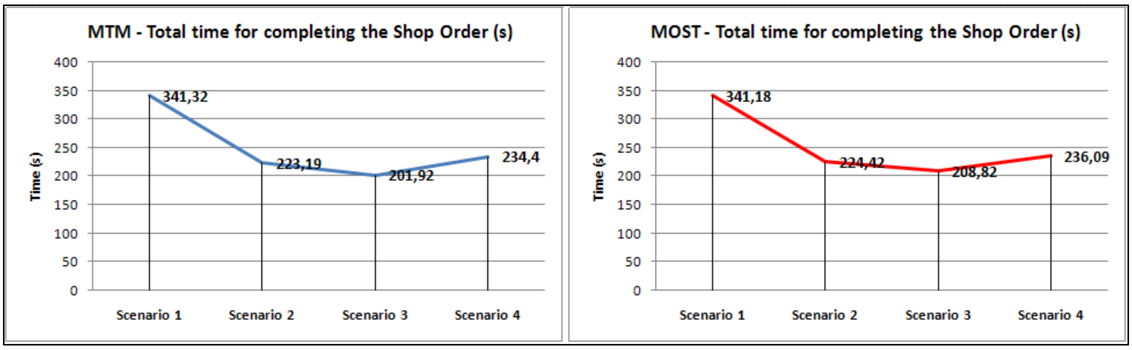


Figure 4.41 - Scenarios comparison

Let us focus on the Seal Press workplace productivity and let us consider the total time required for completing a shop order (PT), the 8 hours shift time and the operators' allowance for physiological needs, fatigue and delay (calculated as 20% of the process time). Regardless of the work measurement methodologies (MTM or MOST), the workplace productivity (in the third scenario) is about 118 shop orders per day. The productivity enhancement is about 69% respect to the first scenario, 11% respect to the second scenario and 16 % respect to the fourth scenario.

STEP 6: Results Presentation and Implementation

The final workplace configuration has been presented by writing progress and final reports. Moreover, a final ad hoc oral presentation has been developed trying to point out and remark the ergonomic and time improvement achieved by applying the design methodology.

4.6 Applications to support preliminary Workplaces Design

Manufacturing organizations continue to design and develop workplaces that are capable of performing better, faster, and longer. An increasingly important design consideration is to ensure that workplaces are being designed from the perspective of the people who actually build, maintain, and operate them. Today's manufacturers must consider this aspect before building the real workplace. In this context, the proposed methodology comes to help engineers for a more operational workplace design. Before the real workplace is built, the proposed methodology can also be used to check plant layout design, objects positions, and operators work methods against human factors limitations such as reach, line of sight as well as safety factors such as clearances and suspended loads when performing the manufacturing operations. Moreover, workplace productivity levels can also be calculated and improved. It means that the engineer is capable of diagnosing and solving ergonomic and time problems before any real workplace implementation is done saving a huge amount of money and time for future redesign.

As follows the application of the design methodology to industrial workplaces still not in existence is proposed. An assembly line for heaters production (section 4.6.1) and an industrial plant that manufactures mechanical parts for agricultural machineries engines (section 4.6.2) are considered.

4.6.1 Assembly line for heaters production

STEP 1: Problem Formulation and Objectives Definition

The assembly line is still in the design phase. One of the main goals at this stage is to explore possibilities for improving the overall efficiency of the system being considered. The first step was to design the assembly line in terms of number of workstations. Considering that no data were available in terms of assembly times, it was decided to subdivide the heater main components into four different groups:

1. heat exchangers, combustion chamber and related components;
2. tank for combustible and related components;
3. electric circuits, control and security systems;
4. shell and protective covering.

Figure 4.42 shows the geometric model of the heater, the geometric model of some heater main components as well as some technical drawings.

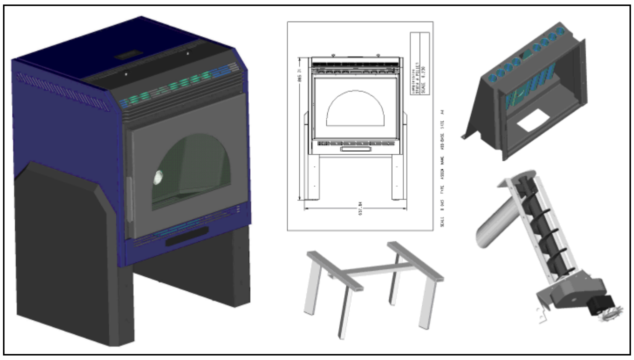


Figure 4.42 - Heater geometric model

The assembly operations related to a specific group of components are performed in the same workstation. Therefore the assembly line is made up of four workstations:

1. *First workstation*: the operator places the heat exchanger inside the main frame, adds the door framework and inserts the combustion chamber;
2. *Second workstation*: the operator places the tank for combustible in the heater mainframe. The operation is quite difficult because the combustible transportation system must be opportunely assembled in correspondence of the tank hole in order to move the

combustible from the tank to the combustion chamber during the heater normal functioning;

3. *Third workstation*: the worker performs all the operations required to assemble electric circuits, control systems and security systems;
4. *Fourth workstation*: here the worker adds all the shells and protective covering.

In addition to the operations performed in each workstation, two different transportation tasks are required to complete the heater assembly process. The first one regards the transportation of the heater main frame in correspondence of the first workstation. By using a manual dolly, a worker moves the heater main frame from the warehouse shelves to a position accessible by the overhead travelling crane. The overhead travelling crane moves the heater main frame in correspondence of the first workstation of the assembly line. The second one is the movement of the combustible tank from the warehouse shelves to the second workstation, once again executed performing a manual lift, using a manual dolly and the overhead travelling crane.

Moreover, it was supposed that the assembly line is made up of eight workstations (two assembly lines, each one with four workstations), different warehouse shelves, two manual dollies, an overhead travelling crane and different tools used during the assembly operations.

STEP 2: Performance Measures and Design Parameters Definition

The application of the design methodology to the Assembly line considers the following time and ergonomic performance measures:

1. *Process Time (PT)* evaluated by means of the Methods Time Measurement (MTM) methodology;
2. The *Maximum Permissible Force (MPF)* evaluated by means of the Burandt Schultetus methodology. The MPG detects the maximum weight that a working person can lift;
3. The *Action Limit (AL)* and the *Maximum Permissible Limit (MPL)* evaluated by using the NIOSH 81 lifting equation. AL is the weight value, which is permissible for 75% of all female and 99% of all male workers. MPL is the weight value, which is permissible for only 1% of all female and 25% of all male workers;
4. The *Recommended Weight Limit (RWL)* and the *Lifting Index (LI)* evaluated by means of the NIOSH 91 lifting equation. The RWL is the load that nearly all healthy workers can perform over a substantial period of time for a specific set of task conditions. The LI is calculated as a ratio between the real object weight and the RWL;
5. The *Stress Level(SL)* associated to the workers' body posture evaluated by using the OWAS methodology;
6. The total amount of energy (Energy Expenditure – EE) spent during the manual operations evaluated by means of the Garg methodology.

Further and detailed information concerning the aforementioned performance measures can be found in Chapter 2.

As concerns the design parameters definition, objects positions and weights as well as operators work methods have be identified as significant factors for the effective workplace design.

STEP 3: Data Collection

Since the assembly line is still not in existence, no data were available. In this context, the data required for applying the design methodology, i.e. objects positions, dimensions and weight, operators physical characteristics, and operators work methods, were either supposed or adapted to the scope from the analysis and study of the related literature as well as from other manufacturing systems working in the heater production industrial field.

Figure 4.33 shows the Assembly line simulation model. Figure 4.44 shows the operations performed in the first workstation while figure 4.45 shows components transportation from the warehouse to the assembly line (manually performed by an operator).

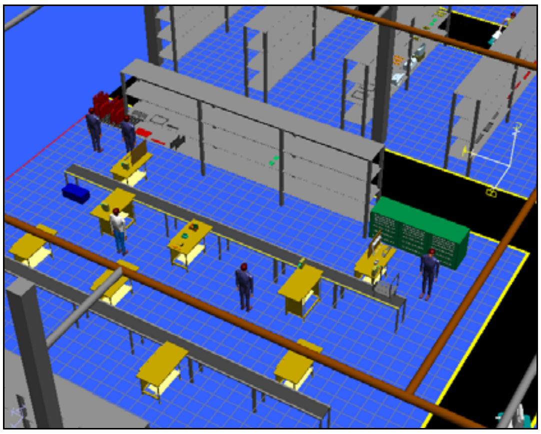


Figure 4.43 - Assembly line simulation model

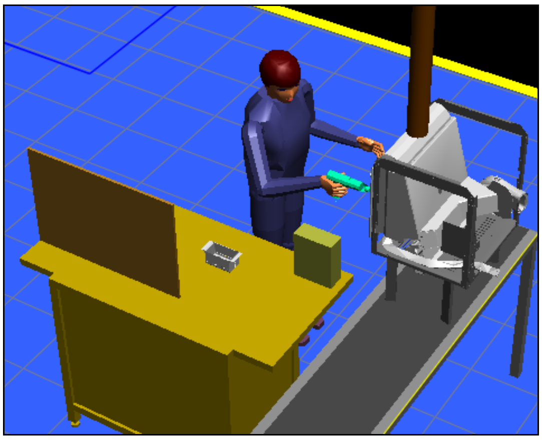


Figure 4.44 - Assembly operations in the first workstation

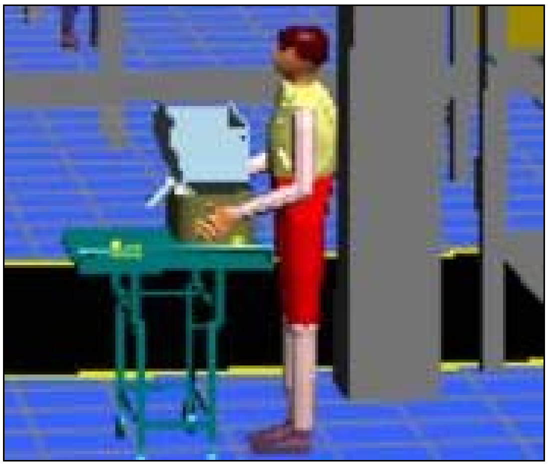


Figure 4.45 - Lifting task manually performed

STEP 5: Effective Workplace Design

Here, the trial and error based approach is used in order to achieve the effective design of the assembly line. In particular, firstly, an assembly line configuration is proposed on the basis of experience and knowledge concerning the manufacturing system and the heater production industrial field (please refer to figures 4.43-4.45 for the initial configuration). Secondly, such configuration is analyzed in terms of ergonomic and time issues in order to evaluate ergonomic risks and productivity levels within the configuration; and, finally, a new assembly line configuration is proposed in order to prevent workers health as well as to increase the overall productivity.

Initial Workplace Configuration

This section present the time and ergonomic analysis carried out for evaluating ergonomic risks and productivity levels within the initial configuration. Note that such analysis consider the production of one single heater.

As concerns the time analysis, table 4.27 shows MTM methodology results for the first workstation.

ID	**Description (left hand)**	**Code left hand**	**TMU left hand**	**TMU**	**TMU right hand**	**Code right hand**	**Description (right hand)**
1	………………………	……..	…….	………..	………	…………	**…………………………**
2				30,00	30,00	W2P	*Basic Motion – type walking*
3				18,60	18,60	TBC1	*Basic Motion – type turn*
4	*Reach component 1A*	R45B	17,00	17,00	17,00	R45B	*Reach component 1A*
5	*Grasp component 1A*	G1A	2,00	2,00	2,00	G1A	*Grasp component 1A*
6				37,20	37,20	TBC2	*Basic Motion – type turn*
7				18,60	18,60	TBC1	*Basic Motion – type turn*
8				15,00	15,00	W1P	*Walk toward the main frame*
9				18,60	18,60	TBC1	*Basic Motion – type turn*
10	*Basic Motion – type move*	M4C	4,50	4,50	4,50	M4C	*Basic Motion – type move*
11	*Release Component 1A*	RL1	2,00	2,00	2,00	RL1	*Basic Motion – type release*
12				15,00	15,00	W1P	*Basic Motion – type walking*
13				9,20	9,20	R28A	*Basic Motion – type reach*
14				2,00	2,00	G1A	*Grasp tool 1*
15				17,00	17,00	SS0C1	*Basic Motion – type position*
16				9,80	9,80	M14C	*Basic Motion – type move*
17				2,00	2,00	RL1	*Release tool 1*
18				37,20	37,20	TBC2	*Basic Motion – type turn*
19				18,60	18,60	TBC1	*Basic Motion – type turn*
20				15,00	15,00	W1P	*Basic Motion – type walking*
21				18,60	18,60	TBC1	*Basic Motion – type turn*
22				6,10	6,10	R10A	*Basic Motion – type reach*
23				2,00	2,00	G1A	*Grasp component 2A*
24				37,20	37,20	TBC2	*Basic Motion – type turn*
25				18,60	18,60	TBC1	*Basic Motion – type turn*
26				15,00	15,00	W1P	*Basic Motion – type walking*
27				18,60	18,60	TBC1	*Basic Motion – type turn*
28				15,00	15,00	W1P	*Basic Motion – type walking*
29				11,70	11,70	M20C	*Basic Motion – type move*
30				2,00	2,00	RL1	*Release component 2A*
31				37,20	37,20	TBC2	*Basic Motion – type turn*
32				18,60	18,60	TBC1	*Basic Motion – type turn*
33				15,00	15,00	W1P	*Basic Motion – type walking*
34				18,60	18,60	TBC1	*Basic Motion – type turn*
35	*Basic Motion – type reach*	R10B	6,30	6,30			
36	*Grasp component 3A*	G1A	2,00	2,00			
37				37,20	37,20	TBC2	*Basic Motion – type turn*
38				18,60	18,60	TBC1	*Basic Motion – type turn*
39				15,00	15,00	W1P	*Basic Motion – type walking*
40				18,60	18,60	TBC1	*Basic Motion – type turn*
41				17,00	17,00	SS0C1	*Basic Motion – type position*
42	*Basic Motion – type*	M16C	10,50	10,50	15,00	W1P	*Basic Motion – type walking*
43	*Basic Motion – type release*	RL1	2,00	2,00	15,00	W1P	*Basic Motion – type walking*
44	………………………	……..	…….	………..	………	…………	**…………………………**
				24261,8			

Table 4.27 - MTM methodology results for the first workstation

The meaning of each column of the table is as follows:

- *ID*, identifying number for the combined basic motion (the combined basic motion is the union of the basic motions performed by both the hands or is the basic motion of one hand when the other hand does not perform any basic motion);
- *Description (left hand)*, brief description of the basic motion performed by the left hand of the operator;
- *Code (left hand)*, MTM identifying code for the left hand;
- *TMU (left hand)*, normal time in TMU of the basic motion performed by the left hand of the operator;
- *TMU*, normal time in TMU of the combined basic motion;
- *TMU (right hand)*, normal time in TMU of the basic motion performed by the right hand of the operator;
- *Code (right hand)*, MTM identifying code for the right hand;
- *Description (right hand)*, brief description of the basic motion performed by the right hand of the operator.

Consider that all the operations of the first workstation generate a huge number of basic motions; as a matter of space table 4.27 does not report all the basic motions performed by the operator in the first workstation (note that in correspondence of the first and last row no basic motions are reported). The total time for performing all the assembly operations in the first workstation is 24261.80TMU (14min and 33 sec) reported in the last row of Table 4.27. The MTM methodology for the remaining workstations gives as results the following assembly times:

- *Second workstation*: 30055.56TMU (18 min and 2 sec);
- *Third workstation*: 40444.45TMU (24 min and 16 sec);
- *Fourth workstation*: 63611.12TMU (38 min and 10 sec).

Note the high accuracy of the MTM results. In addition to the assembly time of each workstation, the MTM gives as result the time associated to each operation and the time associated to each basic motion. Consider, for instance, the following operation performed in the first workstation: grasp, move and release component 2A. Table 4.27 describes such operation (performed by the operator of the first workstation with the right hand) from row 23 to row 30. The normal time required for performing the operation is the sum of the times standard reported in the column TMU (right hand) starting from row 23 to row 30, that is 120.1TMU (4.32 s). In addition, the table gives the times standard of each basic motion: consider the row 29 of Table 4.27, the basic motion M20C (M = Move, 20 is the distance in centimeters of the movement, C means the object is being moved toward an exact position) requires 11.70TMU (0.42 s).

The results of the MTM methodology will be used later on for proposing a different work assignment with the aim of obtaining a better line-balancing (note that the assembly line bottlenecks are the third and the fourth workstations).

Before getting into details of system modifications, let us give a look at the results of ergonomic analysis.

The ergonomic analysis is based on the evaluation of the ergonomic performance measures presented in the STEP 2. The lift, the Burandt Schultetus and the Garg methodologies have been carried out on workers who manually move the heater main components from the warehouse shelves to the manually operated dolly (please refer to figure 4.45). The lift analysis based on NIOSH 81 gives as results acceptable weights to be handled in terms of AL and the MPL.

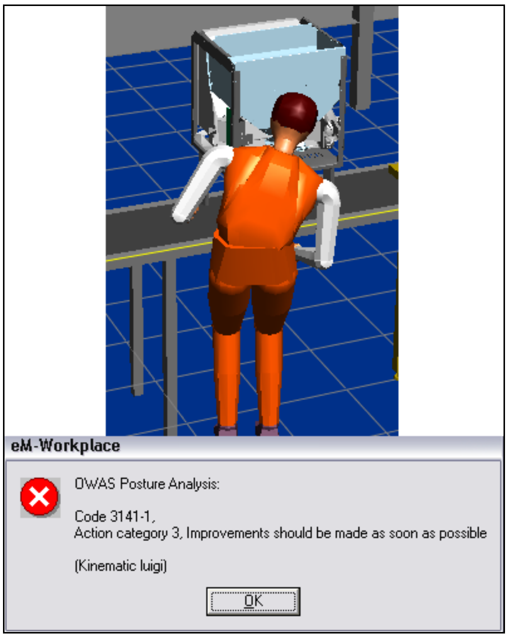
$$\text{AL} = 12.30 \text{ kg} \qquad (1)$$

$$\text{MPL} = 36.92 \text{ kg} \qquad (2)$$

Psychophysical studies suggest that over 75% of women and over 99% of men can lift loads equal to the AL and about 25% of men and 1% of women are capable of lifting loads greater than MPL. NIOSH 81 results assess that, for the described context, lifting tasks above the MPL cannot be accepted, lifting tasks in the range of AL and MPL must be kept under control (for instance alternating lifting tasks with recovering times), while lifting tasks under AL can be accepted as normal ergonomic risks. The lift analysis based on NIOSH 91 estimates the physical stress of two hands manual lifting tasks in terms of RWL and LI. The LI is defined as the ratio between weight of the object being lifted and the RWL. The ergonomic risk cannot be accepted if the LI is greater than 1. A lifting task is defined as grasping an object with two hands and lifting it vertically through space without any assistance (Zandin, 2001) as in Figure 4.45. In correspondence of the origin point (lifting and transportation from the warehouse shelves) the LI is 1.242 (greater than 1). An analogous problem has been found at the destination point (in correspondence of the manual dolly). In this case the LI is 1.054 (slightly greater than 1). The composite lift index (CLI, the average value at the origin and destination point) is obviously greater than 1 (CLI = 1.242). The lift analysis (based on NIOSH 81 and NIOSH 91) highlights unacceptable ergonomic risks during the lifting tasks regarding the movement of the heater main components from the warehouse shelves to the manual dolly. In effect the weight of some objects being lifted is greater than the AL (AL = 12.93 kg) and lower than the MPL (MPL = 36.92 kg); thus, the ergonomic risk must be kept under control (as suggested by the NIOSH 81). Similar results come up by the NIOSH 91; the LI is always greater than 1 both at the origin and at the destination point. The Burandt Schultetus analysis studies two hands lifting activities in which a large number of muscle groups are involved (as in the case analyzed, please refer to figure 4.55). It gives as result the maximum weight (permissible limit, PL) that the worker can lift. The PL is equal to 140.4N. As in the previous case the Burandt Schultetus analysis states that the ergonomic risks related to the lifting tasks being considered cannot be accepted. The PL (expressed in kilograms) is 14.33 kg. In effect the weight of some heater main components is greater than 14.33 kg. One of the basic assumptions of the revised NIOSH 91 lifting equation is that activities other than lifting tasks must not require excessive energy expenditure (Waters et al., 1994). In the motions sequence being analyzed, the lifting tasks must be the most important movements. To verify such assumption the Garg equation for assessing the metabolic demand (the amount of energy expended during the manual activities) was used. In the case of figure 4.45 the energy expenditure is 1.80 kcal that is 7.53 kJ. Consider that the energy expenditure for walking inside the plant during a period of time up to 8 h is about 1.70 kcal. Walking activities cannot be regarded as the most important activities of a worker during the work shift, so the Garg methodology states that the NIOSH 91 results can be accepted.

As concerns the OWAS methodology, it has highlighted the following problems:

1. Third workstation (operations for assembling electrical circuits, control and security system): the problem is due to the position of electrical cables located in the lower part of the heater main frame causing as a consequence a continuous legs and torso bending. The stress level is equal to 3, it means that a high stress level and a corrective intervention to the working posture is required as soon as possible (please refer to figure 4.46).
2. Warehouse shelves: some heater components are positioned on the first level of the shelves near the floor causing a continuous legs bending. The stress level is equal to 2; thus, the worker could have some problems in the near future.



OWAS Posture Analysis:

Code 3141-1,
Action category 3, Improvements should be made as soon as possible

(Kinematic luigi)

Figure 4.46 - Legs and torso bending in the third workstation

As in the case of the time analysis the results of the ergonomic analysis will be used in the next section for proposing system modifications with the aim of obtaining for each operation acceptable ergonomic risks and stress levels.

Final Workplace Configuration

Here the final assembly line configuration is presented. The MTM methodology shows different assembly times for each workstation. However, the assembly times of the first and second workstations are quite similar (about 15 and 18 min, the difference does not cause an excessive delay in the assembly operations), while the third and fourth workstations are characterized by higher and quite different assembly times (about 24 and 38 min, that cause as consequence a double bottleneck and reduce the assembly line productivity). The analysis of each basic motion can be used for modifying the initial list of operations assigned to each workstation. A better assembly line configuration in terms of work assignment and line balancing has been obtained proposing the following changes:

1. The operations regarding the assembly of junction box (an electrical component), initially performed in the third workstation, have been assigned to the second workstation (the worker of the third workstation must execute the remaining operations);
2. The operations regarding the combustion chamber positioning, initially performed in the second workstation, have been assigned to the first workstation;
3. An additional worker has been added to the last workstation (please refer to figure 4.47).

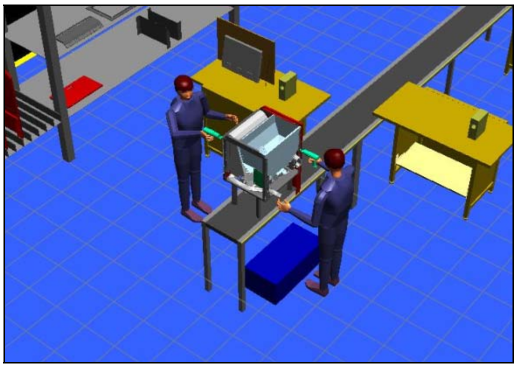


Figure 4.47 - Additional worker in the last workstation

The MTM methodology, carried out once again after assembly line modifications, gives as result the following assembly times:

- *First workstation*: 18 min and 43 sec;
- *Second workstation*: 18 min and 38 sec;
- *Third workstation*: 19 min and 30 sec;
- *Fourth workstation*: 20 min and 15 sec.

Note that the new work assignment neither affects the results of the ergonomic analysis nor introduce new ergonomic risks. In effect both the assembly of the junction box and the assembly of the combustion chamber (operations subjected to work re-assignment) do not cause any ergonomic problem. The repetition of the ergonomic analysis just after the implementation of the system modifications does not detect additional ergonomic problems. The initial assembly line productivity was about one heater every 38 min; the final configuration provides a productivity of one heater every 20 min. The improvement of the assembly line productivity is about 47%.

Let us now consider the system modifications for reducing/deleting ergonomic risks, starting with the ergonomic risks related to lifting tasks. The lifting tasks manually performed by the operator for moving components from warehouse shelves to the manually operated dolly must be avoided. As a solution to this ergonomic problem, a forklift was introduced for performing the required lifting operation. Note that the use of the forklift eliminates the ergonomic problem (legs bending) detected by the OWAS in correspondence of the warehouse shelves. Consider legs and torso bending of the operator of the third workstation, it was proposed to increase conveyor height. By increasing the height of the conveyor, the electrical circuits can be assembled without an excessive legs and torso bending. Such modifications have been implemented in the simulation model and the ergonomic analysis have been repeated once again. The LI associated with lifting tasks is always lower than one, neither Garg or Burandt Schultetus analysis reveal any particular ergonomic risk and the OWAS methodology does not detect any wrong working posture. Note that the greater conveyor height does not allow the assembly of heater superior protective coverings. This last problem has been fixed providing the operators of the last workstation with a step to be used during the previously mentioned operation. Moreover, the ergonomic modifications do not affect the normal time required for performing assembly operations in each workstation.

STEP 6: Results Presentation and Implementation

The final assembly line configuration is presented within a specific business plan developed for establishing the production heaters manufacturing system. Chronology of the work done, decisions made, and achieved results has been pointed out and remarked.

4.6.2 Agricultural machineries engines industrial plant

STEP 1: Problem Formulation and Objectives Definition

Here the design methodology is applied to an assembly workplace still not in existence for an industrial plant manufacturing mechanical parts for agricultural machineries engines. Within the assembly workplace, a final mechanical component for agricultural machineries engines has to be assembled; the final product consists of a basic mechanical component, a flange and several screws. Before going into the details of the workplace work method, let us provide the reader with several information concerning the industrial plant.

The industrial plant is located in the South part of Italy and covers a surface of 11,000 m^2. It consists of three different areas:

- *The raw materials warehouse*. Here raw material for screws and flanges production are stored in pallets loaded into pallet racks. The pallets and the raw materials are moved by means of a system of automated conveyors, automated storage and retrieval machines. The storage area is 11 m high and covers a surface of 2000 m^2.
- *The production area*. It consists of the flange workplace and the screws workplace.
    - The flange workplace manufactures flanges to be sold to the final market. It employs 4 operators and contains four motorized ball control lathes characterized by the same productive process. The workstation layout covers a surface of 2500 m^2.
    - The Screws workplace manufactures ten different screw types directly sold to the final customers. The workplace employs 5 operators and it is made by a broaching machine, a slotting machine, a machine for worm screws, a numerically controlled machine for worm screws with robot and a shaving machine. The workplace layout covers a surface of 2500 m^2.
- *The final products warehouse*. Here the final products (screws and flanges) are stored in pallets loaded into pallet racks. As the Raw materials warehouse, pallets and final products are moved by means of a system of automated conveyors and automated storage and retrieval machines. The storage area covers a surface of 2000 m^2 and is 12 m high.

The company top management aims at establishing a new workplace, the *Assembly Workplace*, within the production area in order to manufacture a new final product to be sold to other manufacturing plants. As already stated, the new mechanical part consists of a basic mechanical component, a flange and several screws. Note that the basic mechanical component has to be purchased from the market, while flanges and screw are already available within the industrial plant.

As concerns the Assembly workplace work method, the operations to be performed have been identified on the basis of the company top management and workers experience on this specific industrial sector. The supposed work method consists of the following operations:

1. The worker picks up manually the basic mechanical component and puts it on a workbench;
2. The worker drills the basic mechanical component 5 times by means of a hand drill;
3. The worker brings the basic mechanical component to a second workbench;
4. The worker takes a flange, puts it on the mechanical component and makes them adhering by means of a hammer;
5. The worker fixes together the basic mechanical component and the flange by using three hexagonal screws;
6. The worker gets the assembled mechanical part and puts it on a pallet;
7. The worker activates a mechanical arm for moving the assembled mechanical part to the final product warehouse.

STEP 2: Performance Measures and Design Parameters Definition

The application of the design methodology to the Assembly workplace considers the following ergonomic performance measures:

1. The *Maximum Permissible Force (MPF)* evaluated by means of the Burandt Schultetus methodology. The MPG detects the maximum weight that a working person can lift;
2. The *Action Limit (AL)* and the *Maximum Permissible Limit (MPL)* evaluated by using the NIOSH 81 lifting equation. AL is the weight value, which is permissible for 75% of all female and 99% of all male workers. MPL is the weight value, which is permissible for only 1% of all female and 25% of all male workers;
3. The *Recommended Weight Limit (RWL)* and the *Lifting Index (LI)* evaluated by means of the NIOSH 91 lifting equation. The RWL is the load that nearly all healthy workers can perform over a substantial period of time for a specific set of task conditions. The LI is calculated as a ratio between the real object weight and the RWL;
4. The *Stress Level (SL)* associated to the workers' body posture evaluated by using the OWAS methodology;
5. The total amount of energy (*Energy Expenditure - EE*) spent during the manual operations evaluated by means of the Garg methodology.

Further and detailed information concerning the aforementioned performance measures can be found in Chapter 2.

As concerns the design parameters definition, objects positions and weights as well as operators work methods have be identified as significant factors for the effective workplace design.

STEP 3: Data Collection

Since the Assembly workplace is still not in existence, no data were available. In this context, the data required for applying the design methodology, i.e. objects positions, dimensions and weight, operators physical characteristics, and operators work methods, were supposed and/or adapted to the scope from the analysis and study of the related literature as well as from other manufacturing systems working in the related industrial sectors.

Figure 4.48 shows the Assembly workplace simulation model.

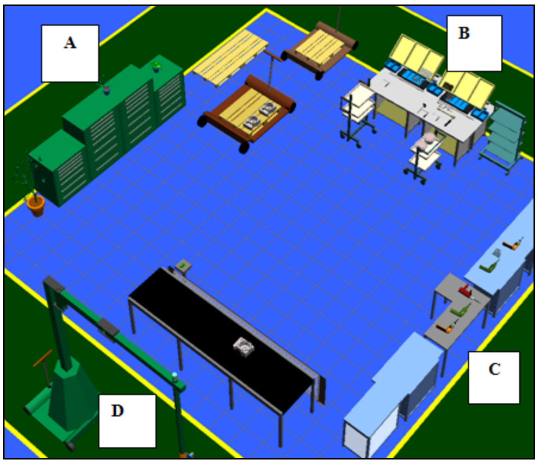


Figure 4.48 - Assembly workplace simulation model

The side *A* consists of some office furniture and the basic mechanical components located on pallets. The side *B* consists of a workbench, a screws bin, a hexagonal wrench, a hammer and flanges; in this part of the workplace, the basic assembly operations are performed. The side *C* consists of several workbenches and hand drills used for drilling the basic mechanical component. Finally, the side *D* consists of a mechanical arm, a workbench and a conveyor.

Figures 4.49 and 4.50 show, respectively, the basic mechanical component and the workbench used for the assembly operations.

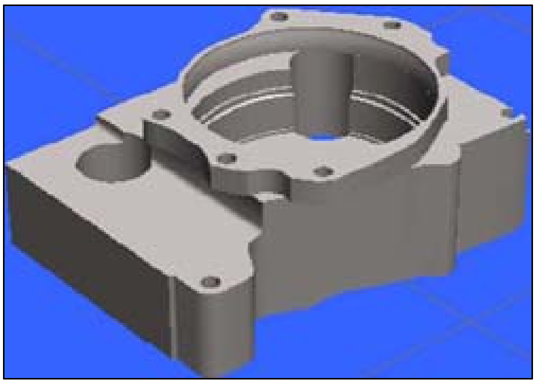


Figure 4.49 - Basic mechanical component geometric model

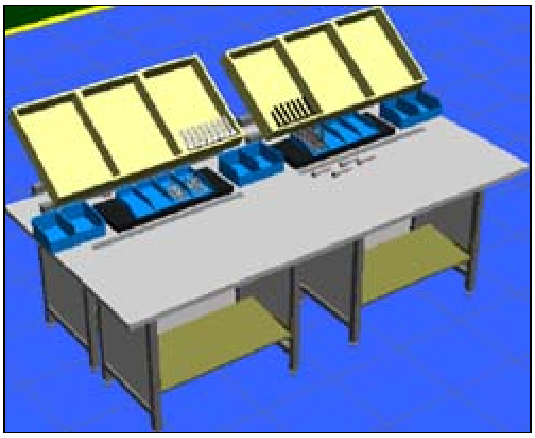


Figure 4.50 - Workbench geometric model

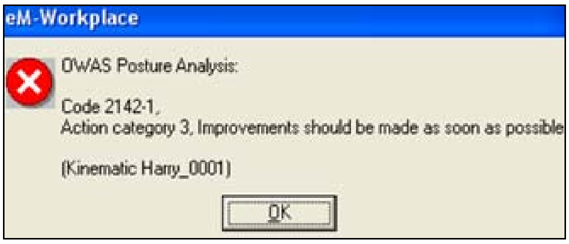
STEP 5: Effective Workplace Design

Here, the trial and error based approach is used in order to achieve the effective design of the assembly workplace. In particular, firstly, an assembly workplace configuration is proposed on the basis of experience and knowledge concerning the manufacturing system and the specific industrial field. Secondly, such configuration is analyzed in terms of ergonomic issues in order to evaluate ergonomic risks levels within the configuration; and, finally, a new assembly workplace configuration is proposed in order to prevent workers health and increase the overall safety of the assembly workplace.

Initial Workplace Configuration

This section presents the ergonomic analysis carried out for evaluating ergonomic risks level within the initial configuration. Note that the ergonomic analysis considers a typical shop order made by 25 mechanical parts.

Let us consider the OWAS methodology. As soon as the software eM-Workplace identifies a harmful working posture, a message window appears reporting the category it belongs to (please refer to figure 4.51). Moreover, the most affected worker body parts are pointed out by the program (please refer to figure 4.52).



OWAS Posture Analysis:

Code 2142-1,
Action category 3, Improvements should be made as soon as possible

(Kinematic Harry_0001)

Figure 4.51 - Message window for OWAS Category 3 working posture

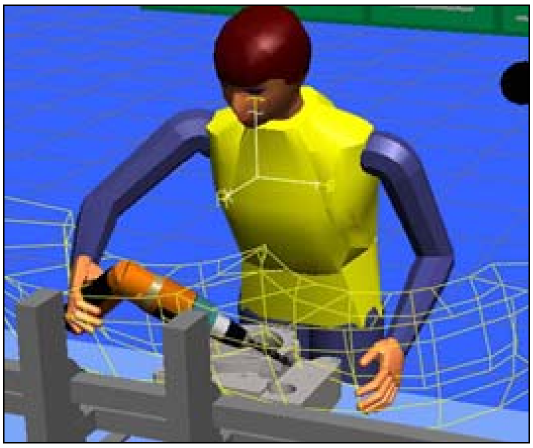


Figure 4.52 - Results of the OWAS analysis

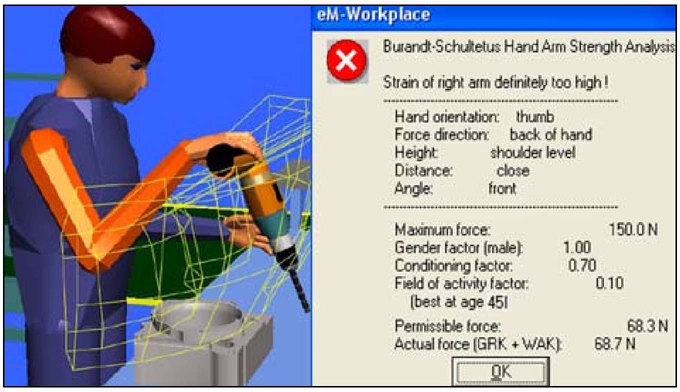
When the OWAS methodology is applied to the Assembly workplace, the program assigns a category 3 to the task of grasping manually the basic mechanical component from a pallet. When the operator uses the working tools (hand drill, hexagonal wrench and hammer) for performing the assembly activities, the software indicates a category 2. Finally, the software reports a category 2 as soon as the worker brings manually the assembled mechanical part, whose weight is 23 kg, to the mechanical arm location.

As the next step, the ergonomic process is studied through the Lift Analysis (Burandt Schultetus, NIOSH 81, NIOSH 91). Let us consider the Burandt-Schultetus methodology. Table 4.28 reports the input parameters inserted into the simulation software for correctly carrying out such analysis.

Worker physical characteristics	
Physical Condition	normal
Age	45
gender	male
Objects being moved **Load weight (Kg)**	
Basic mechanical component	14
flange	9
hand drill	6
hexagonal wrench	0,2
hammer	0,6
Total task duration (25 mechanical parts)	
Time (sec)	6125

Table 4.28 - Burandt Schultetus input parameters

As soon as high stress levels occur, a message window appears reporting the MPF and AF values. Moreover, the most affected body parts appear orange colored (please refer to figure 4.53).



```
Burandt-Schultetus Hand Arm Strength Analysis

Strain of right arm definitely too high !
-------------------------------------------------
  Hand orientation:    thumb
  Force direction:     back of hand
  Height:              shoulder level
  Distance:            close
  Angle:               front
-------------------------------------------------
  Maximum force:                        150.0 N
  Gender factor (male):        1.00
  Conditioning factor:         0.70
  Field of activity factor:         0.10
     (best at age 45)
  Permissible force:                     68.3 N
  Actual force (GRK + WAK):      68.7 N
```

Figure 4.53 - Results of the Burandt Schultetus methodology

When the Burandt Schultetus methodology is applied to the Assembly workplace, the program detects three critical lifting operations: grasping manually the basic mechanical component from a pallet (1), handling the hand drill (2) and bringing the assembled mechanical part to the mechanical arm location (3); in effect, each of them is characterized by a PF value lower than the AC being exerted. Table 4.29 reports for each operation the maximum permissible force and actual force values.

Operation	Maximum permissible force (N)	Actual force (N)
(1)	67,8	68,7
(2)	68,3	68,7
(3)	52,3	112,8

Table 4.29 - Burandt Schultetus returned values

Concerning the operations (1) and (2), the PF values are very close to the AF values; in fact, in both cases, the AF exceeds the PF no more than 1 N. It means that the stress level is almost acceptable and corrective interventions are necessary in the near future. On the other hand, the operation (3) has extremely adverse effects on the muscular system; in fact, a huge gap between the PF and the AF (the gap value is about 60 N) characterizes it so that corrective interventions must be carried out immediately.

NIOSH 81 and NIOSH 91 methodologies complete the Lift analysis. As Burandt Schultetus analysis, such methodologies identified grasping manually the basic mechanical component from a pallet (1), handling the hand drill (2) and bringing the assembled mechanical part to the mechanical arm location (3) as the most critical movements for the operator. Tables 4.30 and 4.31 show, respectively, the NIOSH 81 and NIOSH 91 results for the critical operations.

NIOSH 81			
Operation	MPL (Kg)	AL (Kg)	Object weight (Kg)
(1)	31,45	10,48	14
(2)	26,54	8,96	6
(3)	27,58	9,19	23

Table 4.30 - Results of NIOSH 81 methodology

NIOSH 91				
Operation	RWL (Kg)		Object weight (Kg)	LI
(1)	Origin	8,83	14	1,58
	Destination	11,30	14	1,23
(2)	Origin	6,23	6	0,96
	Destination	6,11	6	0,98
(3)	Origin	7,26	23	3,16
	Destination	6,15	23	3,73

Table 4.31 - Results of NIOSH 91 methodology

Let us present the NIOSH 81 results. The MPL values exceed the object weight for each lifting operation. It means that the lifting operations have no adverse effects on the muscular system and, in turn, no corrective interventions are necessary. However, note that the MPL represents the weight value, which is permissible for only a small part of the workers population. Concerning the AL values, for the operation (2) it is very close to the object weight (the gap is 0.04 kg) so that the stress level is almost acceptable; in this case, corrective interventions are needed in the near future. For the operations (1) and (3), AL is, respectively, lower 3.52 kg and 13.81 kg than the objects weight. In the first case, the stress level is high and corrective interventions are necessary as soon as possible, in the second case the stress level is very high and corrective interventions are immediately required.

Let us present the NIOSH 91 results discussing about the LI values. LI is calculated as a ratio between the object weight and the RWL value. Operations (1) and (3) are characterized by LI values higher than one in both the origin and the destination points of the lifting operations. In the first case, the LI values (1.58 and 1.23) suggest corrective interventions as soon as possible. In the second case, the very high LI values (3.16 and 3.73) require corrective interventions immediately. Considering the operation (2), 0.96 and 0.98 represent acceptable LI values so that no corrective interventions are needed.

Finally, the Garg analysis completes the evaluation process of the ergonomic risk level within the Assembly workplace: the total amount of energy spent during the whole shift is about 1437 kcal.

Let us summarize the most noteworthy results provided by the ergonomic analysis. The ergonomic process has pointed out the high level of ergonomic risks affecting the Assembly workplace. In particular, three operations were identified as the most harmful for the operators' muscular system:

(1) grasping the basic mechanical component from a pallet;
(2) handling the hand drill;
(3) bringing the assembled mechanical part to the mechanical arm location.

The operation (1) hurts the back and the legs of the worker, the operation (2) affects the operator right hand-arm system and the operation (3) causes pain to the worker's back and arms. It can be concluded that the effective design of the workplace is required for preserving the workers health. Note that the effective design should also aim at reducing the total amount of energy spent during the assembly process.

Next section presents the design guidelines for developing an improved workplace configuration in terms of ergonomic risk levels.

Final Workplace Configuration

Let us list the critical operations affecting the workstation and describe for each of them the proposed workplace modifications for solving the ergonomic problems.

- *Grasping the basic mechanical component from a pallet*. It requires to the worker continuous bending owing to the location of the pallet on a hand cart high 20 cm. Operator's back and legs are the most affected body parts. It was decided to substitute the initial hand cart for an adjustable one. This change allows to custom the pallet height according to the operators needs. Figures 4.54 shows, the initial configuration (left side) and the final (right side).

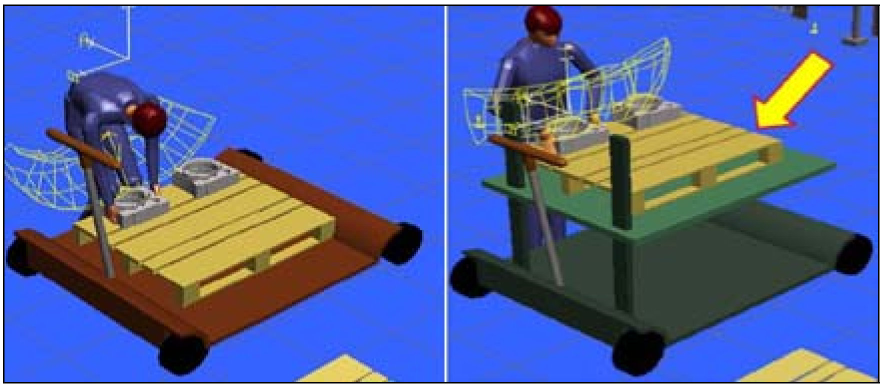


Figure 4.54 - Alternative workplace configuration

- *Handling the hand drill*. It causes pain to the operator right hand-arm system. In a first moment, the authors thought to modify the mechanical component and the hand drill positions for making them easier to manage. Actually, this operation is strongly affected by the hand drill weight (6 kg), so any change regarding the objects position would have been a useless solution. In this regard, the authors advised the company top management to purchase a lighter hand drill. In particular, they proposed a 1.6 kg hand drill characterized by an ergonomic handle.
- *Bringing the assembled mechanical part to the mechanical arm location*. 670 cm must be walked carrying manually the mechanical part, whose weight is about 23 kg. Obviously, the worker's back and arms are the most stressed body parts. It was proposed to adopt the adjustable hand cart for performing such operation. In this way, the worker has to place only the assembled mechanical part on the adjustable hand cart and then push it to the final destination. Figures 4.55 show the initial (left side) and the final (right side) configurations.

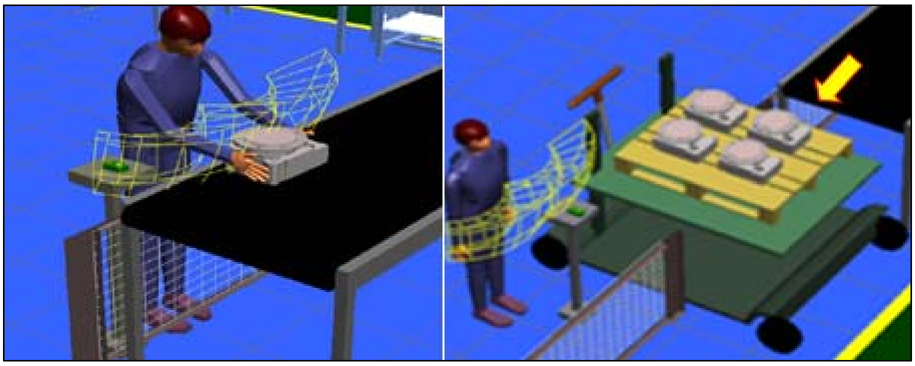


Figure 4.55 - Alternative workplace configuration

Figure 4.56 shows the final workplace configuration. Two red boxes point out the workstation changes with respect to the initial configuration.

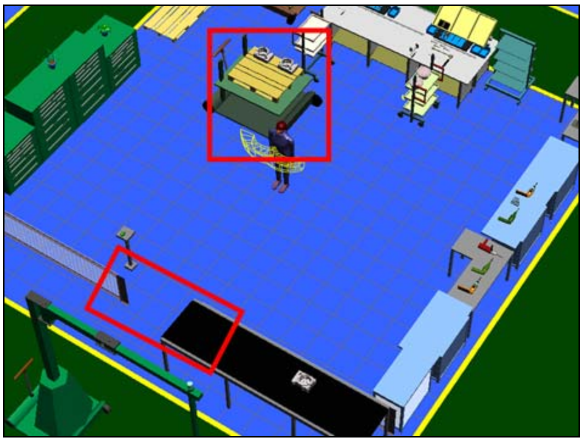


Figure 4.56 - Assembly workplace final configuration

The final workplace configuration has been tested in terms of ergonomic issues by means of the simulation model. The simulation results point out the effective design of the workplace. In particular, the ergonomic issues related to the three critical operations have been solved and no other ergonomic problems have been detected. The OWAS methodology does not reveal any particular posture problem. The stress level related to each body posture is optimum. According to the Lift analysis (Burandt Schultetus, NIOSH 81 and NIOSH 91), no lifting problems affect the workplace. Considering the Garg methodology, the total amount of energy spent during the whole shift is about 1203 kcal. It means that the EE reduction is about 17% with respect to the initial configuration.

STEP 6: Results Presentation and Implementation

A history of the study has been provided by writing progress and final reports. Reporting has occurred at least monthly in order to make the top management directly and deeply involved in the application of the methodology. Moreover an ad hoc oral presentation has been developed giving a chronology of work done, decision made and achieved results.

Conclusions

The PhD thesis focuses on the development of a multi-measure based methodology that can be used by industrial engineers for achieving the effective design of workplaces within industrial environments. The design methodology aims at considering both the interaction of the operators with their working environment (ergonomic issues) and the work methods (time issues). As support tool for applying the design methodology Modeling & Simulation (M&S) and virtual three-dimensional environments are used for recreating, with satisfactory accuracy, the evolution over the time of the real industrial workplaces. In particular the effective design of the workplaces is achieved by using the simulation model for comparing workplaces' alternative configurations (in terms of workplaces layout, tools disposition and operators' work methods). The generation of the alternative configurations comes out from the variation of multiple design parameters that affect multiple performance measures (ergonomic and time performance measures). The evaluation of the effects of the multiple design parameters on the multiple performance measures allows to choose the final configuration of the workplace.

The first step of the research activities was to accurately review the state of the art concerning this research area. The descriptive analysis of the literature has revealed heterogeneity among the scientific approaches proposed by researchers and scientists working in this field. In particular, three main scientific approaches have been identified: the first and the second are based on the use of ergonomic and work measurement methodologies, respectively; while the third one deals with the integration of ergonomic and work measurement methodologies with the most widely used Modeling & Simulation (M&S) tools.

After the literature overview, next step was to bring clarity to the foundational understanding of the methodology placing specific emphasis on its principles and procedures. To this end, the methodology main steps have been deeply discussed and presented. The methodology main steps can be summarized as follows: STEP 1 Problem Formulation and Objectives Definition, STEP 2 Performance Measures and Design Parameters Definition, STEP 3 Data Collection, STEP 4 Simulation Model Development, STEP 5 Effective Workplace Design, STEP 6 Results Presentation and Implementation.

Then, practical examples are provided to understand the use of the methodology for improving ergonomics and productivity within industrial workplaces. All the application examples regard either industrial workplaces where highly manual tasks are performed or industrial workplaces characterized by man machine operations. The first ones belong to an industrial plant producing leather goods such as leather bags, leather planner cases, leather handbags, leather pockets, etc., while the second ones belong to an industrial plant that manufactures high pressure hydraulic hoses.

Finally, the PhD thesis is completed by proposing the application of the design methodology to industrial workplaces still not in existence. In particular an assembly line for heaters production and an industrial plant that manufactures mechanical parts for agricultural machineries engines are considered.

References

[1] Adrion, W. R., Branstad, M. A., and Cherniavsky, J. C., 1982. *Validation, verification and testing of computer software*. Computing Surveys, Vol. 14, N. 2, pp. 159-192.

[2] Aft, L., 1992. *Productivity, Measurement and Improvement.* Prentice-Hall, New Jersey.

[3] Aft, L., 2000. *Work Measurement and Methods Improvement*. John Wiley & Sons, New York.

[4] Aft, L., and Merritt, T., 1984. *Meeting the Requirements of MIL-STD 1567 and Lockheed-Georgia Computerized Standard Data Development System.* Annual International Industrial Engineering Conference Proceedings.

[5] Armstrong, T., 1983. *An Ergonomics Guide to Carpal Tunnel Syndrome.* Akron: American Industrial Hygiene Association.

[6] Armstrong, T., and Chaffin D., 1979. *Carpal Tunnel Syndrome and Selected Personal Attributes*. Journal of Occupational Medicine, 21:481–486.

[7] Armstrong, T., Fine, L., and Silverstein, B., 1985. *Occupational Risk Factors of Cumulative Trauma Disorders of the Hand and Wrist.* Final Report, NIOSH Contract No. 200-82-2507.

[8] Badler, N.I., Phillips, C.B., and Webber, B.L., 1993. *Simulation Humans.* Computer Graphics Animation and Control. Oxford University Press, New York.

[9] Bailey and Presgrave, 1958. *Basic Motion Timestudy*, McGraw-Hill, New York.

[10] Bailey and Presgrave, 1958. *Basic Motion Timestudy*, McGraw-Hill, New York.

[11] Banks, J., 1998. *Handbook of Simulation*. John Wiley and Sons, New York.

[12] Banks. J., 1998. *Principles of Simulation, Handbook of Simulation*. Wiley Interscience, New York.

[13] Barnes, R., 1957. *Work Sampling*. Chapman and Hall, New York.

[14] Barnes, R., 1980. *Motion and Time Study*. Wiley, New York.

[15] Bell, P. C., and O'Keefe, R. M., 1994. *Visual interactive simulation: a methodological perspective*. Annals of Operation Research, Vol. 53, pp. 321-342.

[16] Bonney, M. C., Blunsdon, C., Case, K., and Porter, J. M., 1979. *Man-,machine interaction in work systems.* International Journal of Production Research, 17(6), 619-629.

[17] Bossomaier T., Bruzzone A., Cimino A., Longo F. , Mirabelli G., 2010. *Scientific approaches for the industrial workstations ergonomic design: a review.* Proceedings of European Conference on Modeling & Simulation (ECMS2010), 1-4 June, 2010, Kuala Lumpur, Malaysia.

[18] Bouisset, 1973. *EMG and Muscle Force in Normal Motor Activities in New Developments*. Electromyography and Clinical Neurophysiology, pp. 547–583.

[19] Brain, W., and Wilkinson, 1947. *Spontaneous Compression of Both Median Nerves in Carpal Tunnel*. Lancet, 1:277–282.

[20] Brandenburgh, R. L., 1999. *Getting a digital foot in the door: how virtual human modeling is changing the way human factors influences cockpit design*. Flight Deck International.

[21] Brouha, L., 1960. *Physiology in Industry*, Pergamon, London.

[22] Burandt, U., 1978. *Ergonomie fur Design und Entwicklung.* Verlag Otto Schmidt, Cologne, KG.

[23] Carrasco, C., Coleman, N., Healey, S., 1995. *Packing products for customers, An ergonomics evaluation of three supermarkets checkouts*. Applied Ergonomics, 26, 101-108.

[24] Case, K., Bonney, M. C., Porte, J. M., Freer, M. T., 1990a. *Applications of the SAMMIE CAD System in workplace design.* Taylor & Francis, London.

[25] Case, K., Porter, J. M., and Bonney, M. C., 1990b. *SAMMIE: a man and workplace modeling system.* Computer-Aided Ergonomics: A research's Guide. Taylor & Francis, London, 31-56.

[26] Case, K., Porter, J. M., Bonney, M. C., and Levis, J. A., 1980. *Design of mirror systems for commercial vehicles.* Applied Ergonomics, 11(4), 199-206.

[27] Chaffin, D. B., 1998. *Prediction of population strengths.* Digital Human Modeling for Design and Engineering Conference. Dayton, OH.

[28] Chaffin, D., and Andersson, G., 1984. *Occupational Biomechanics,* New York: John Wiley & Sons.

[29] Chaffin, D., and Andersson, G., 1991. *Occupational Biomechanics*. John Wiley & Sons, Inc, New York.

[30] Chaffin, D., Herrin, G., and Keyserling, W. M., 1978. *Pre-Employment Strength Testing: An Updated Position*. Journal of Occupational Medicine, 20:403–408.

[31] Chang, S.-W., Wang, M.-J. J., 2007. *Digital Human Modeling and Workplace Evaluation: Using an Automobile Assembly Task as an Example*. Human Factors and Ergonomics in Manufacturing, 17, 445-445.

[32] Choobineh, A., Tosian, R., Alhamdi, Z., Davarzanie, M., 2004. *Ergonomic intervention in carpet mending operation*. Applied Ergonomics, 35, 493-496.

[33] Chung, M.K., Kee, D., 2000. *Evaluation of lifting tasks frequently performed during fire brick manufacturing processes using NIOSH lifting equations*. International Journal of Industrial Ergonomics, 25, 423-433.

[34] Cohen, K. J., and Cyert, R. M., 1961. *Computer models in dynamics economics*. Quarterly Journal of Economics, Vol. 75, N. 1, pp. 112-127.

[35] Colombini, D., Grieco, A., Occhipinti, E., 1998. *Occupational musculoskeletal disorders of the upper limbs due to mechanical overload*. Ergonomics, 41, 1347-1356.

[36] Colombini, D., Occhipinti, E., Delleman, N., Fallentin, N., Kilbom, A., Grieco, A., 2001. *Exposure assessment of upper limb repetitive movements: a consensus document*. International Encyclopaedia of Ergonomics and Human Factors, London: Taylor & Francis.

[37] Colombini, D., Occhipinti, E., Grieco, A., 2002. *Risk Assessment and Management of Repetitive Movements and Exertions of Upper Limbs*. Vol. 2 New York: Elsevier.

[38] Corlett, E., Medeley, S., and Manenica, I., 1979. *Posture Targetting: A Technique for Recording Working Postures*. Ergonomics, 22:357–366.

[39] Das, B., Sengupta, A. K., 1996. *Industrial workstation design: a systematic ergonomics approach*. Applied Ergonomics, 27, 157-163.

[40] Davidson, H.O., 1960. *Work Sampling – Eleven Fallacies*. Journal of Industrial Engineering.

[41] Davis, H. L., Faulkner, T. W., and Miller, C. I., 1971. *Evaluating Work Performance*. The American Journal of Clinical Nutrition.

[42] Davis, L., 1991. *Handbook on Genetic Algorithms.* Van Nostrand Reinhold, New York.

[43] Deutsch, M. S., 1982. *Software Verification and Validation: Realistic Project Approaches*. Prentice Hall, Upper Saddle River, USA.

[44] DeVries, H., 1968. *Efficiency of Electrical Activity as a Physiological Measure of a Functional State of Muscle Tissue.* American Journal of Physiological Medicine, 47:10–22.

[45] Dun, R. H., 1987. *The quest for software reliability*. Handbook of Software Quality Assurance. Van Nostrand Reinhold, New York, pp. 342-384.

[46] Emerson, H., and Naehring D. C., 1988. *Origins of Industrial Engineering: The Early Years of a Profession.* Industrial Engineering and Management Press, Institute of Industrial Engineers, Atlanta/Norcross.

[47] eM-Workplace by UGS. Available from: http://www.plm.automation.siemens.com/en_us/products/tecnomatix/assembly_planning/process_simulate_human/index.shtml.

[48] Engström, T., Jonsson, D., and Johansson, B., 1996. *Alternatives to Line Assembly: Some Swedish Examples*. International Journal of Industrial Ergonomics, 17:235–245.

[49] Engström, T., Medbo, P., 1997. *Data collection and analysis of manual work using video recording and personal computer techniques*. International Journal of Industrial Ergonomics, 19, 291-298.

[50] Eynard E., Fubini E., Masali M., Cerrone M., Tarzia A., 2000. *Generation of virtual man models representative of different body proportions and application to ergonomic design of vehicles.* Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Association, Ergonomics for the New Millennium, San Diego, CA, USA.

[51] Feyen R., Liu Y., Chaffin D., Jimmerson G., Joseph B., 2000. *Computer-aided ergonomics: a case study of incorporating ergonomics analyses into workplace design*. Applied Ergonomics, 31, 291- 300.

[52] Forrester, J. W., 1961. *Industrial Dynamics*. MIT Press, Cambridge, Mass.

[53] Forsman, M., Hansson, G.Å., Medbod, L., Asterland, P., Engström, T., 2002. *A method for evaluation of manual work using synchronised video recordings and physiological measurements*. Applied Ergonomics, 33, 533-540.

[54] Garg A., 1976. *A metabolic rate prediction for manual materials handling jobs*. Dissertation, University of Michigan.

[55] Garg, A., Chaffin, D. B., and Herrin, G.D., 1978. *Prediction of Metabolic Rates for Manual Materials Handling Jobs*. Am. Ind. Hyg. Ass. J. 39:661–674.

[56] Gill S.A. and Ruddle R.A., 1998. *Using virtual humans to solve real ergonomic design problems*. International Conference on Simulation, IEEE Conference Publication 457, pp. 223–229.

[57] Gonzáles, B.A., Adenso-Dìaz, B., Torre, P.G., 2003. *Ergonomic performance and quality relationship: an empirical evidence case*. International Journal of Industrial Ergonomics*,* 31, 33-40.

[58] Gordon, C. C., Bradtmiller, B., Churchill, T., Clauser, C. E., McConville, J. T., Tebbetts, I. O., Walker, R. A., 1988. *1988 Anthropometric Survey of U.S. Army Personnel: Methods and Summary Statistics.* Technical Report NATICK/TR-89/004, AD A225 094.

[59] Grant, K.A., Habes, D.J., Bertsche, P.K., 1997. *Lifting hazards at a cabinet manufacturing company: Evaluation and recommended controls*. Applied Occupational and Environmental Hygiene, 12, 253-258.

[60] Grant, K.A., Habes, D.J., Tepper, A.L., 1995. *Work activities and musculoskeletal complaints among preschool workers*. Applied Ergonomics*,* 26, 405-410.

[61] Griffith, G. N., 1970. *MODAPTS A Predetermined Time System That Can Be Memorized.* Assembly Engineering.

[62] Gutowski, P., Bush, T. R., Hubbard, R., and Balzulat, J., 2001. *Influences of automotive seta and package factors on posture and applicability to design models.* SAE Digital Human Modeling Conference, Arlington, VA.

[63] Hammer, A. W., 1935. *Tenosynovitis*. Medical Record, 353–355.

[64] Hanson L., 2000. *Computerized tools for human simulation and ergonomic evaluation of car interiors*. Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Association, Ergonomics for the New Millennium, San Diego, CA, USA.

[65] Hedén, K., and Bjurvald, M., 1995. *Ergonomic Assessment Models for Labour Inspection Personnel*. Proceedings of the Premus 95, Montreal, pp. 320–322.

[66] Heiland, R. E., and Richardson, W. J., 1957. *Work Sampling.* McGraw-Hill, New York.

[67] Hermann, C. F., 1967. *Validation problems in games and simulations with special references to models of international politics*. Behavioral Science, Vol. 12, N., 3, pp. 216-231.

[68] Hermans, C., Hautekiet, M., Spaepen, A., Cobbaut, L., De Clerq, J., 1999. *Influence of material handling devices on the physical load during the end assembly of cars*. International Journal of Industrial Ergonomics*,* 24, 657-664.

[69] Hetzel, W., 1984. *The Complete Guide to Software Testing*. QED Information Sciences, Wellesley, Mass.

[70] Holland, J. H., 1975. *Adaptation in Natural and Artificial Systems*. University of Michigan Press, Ann Arbor.

[71] International Labour Office, 1992. Introduction to Work Study, ILO, Geneva, Switzerland.

[72] Jayaram U., Jayaram S., Shaikh I., Kim Y., Palmer C., 2006. *Introducing quantitative analysis methods into virtual environments for real-time and continuous ergonomic evaluations*. Computers in Industry, 57, 283-296.

[73] Jones, T., Kumar, S., 2007. *Comparison of ergonomic risk assessments in a repetitive high-risk sawmill occupation: Saw-filer*. International Journal of Industrial Ergonomics*,* 37, 744-753.

[74] Jones, T., Strickfaden, M., Kumar, S., 2005. *Physical demands analysis of occupational tasks in neighborhood pubs*. Applied Ergonomics*,* 36, 535-545.

[75] Kadefors, R., Forsman, M., 2000. *Ergonomic evaluation of complex work: a participative approach employing video computer interaction, exemplified in a study of order picking.* International Journal of Industrial Ergonomics*,* 25, 435-445.

[76] Karger, O., and Bayh, F., 1987. *Engineered Work Measurement*. Industrial Press, New York.

[77] Karger, O., and Bayh, F., 1987. *Engineered Work Measurement*. Industrial Press, New York.

[78] Karwowski, W., Genaidy, A. M., and Asfour, S. S., 1990. *Computer Aided Ergonomics*. Taylor & Francis, Bristol, PA.

[79] Kelsey, J. L., and White, A. A., 1980. *Epidemiology and Impact on Low Back Pain*. Spine, 5(2):133–142.

[80] Kelsey, J. L., Pastides, H., and Bisbee, G. E., 1978. *Musclo-Skeletal Disorders*. Prodist, New York.

[81] Keyserling, W. M., Herrin, G. D., Chaffin, D. B., 1980. *Isometric Strength Testing As a Means of Controlling Medical Incidents on Strenuous Jobs.* Journal of Occupational Medicine, 22:332–336.

[82] Kharu, O., Harkonen, R., Sorvali, P., Vepsalainen, P., 1981. *Observing working postures in industry: Examples of OWAS application*. Applied Ergonomics, 12, 13-17.

[83] Krick, E., 1962. *Methods engineering.* Wiley, New York.

[84] Kuorinka, I., and Forcier, L., 1995. *Work Related Musculoskeletal Disorders: A Reference Book for Prevention*. Taylor & Francis, London.

[85] Laring J., Forsman M., Kadefors R., Örtengren R., 2002. *MTM-based ergonomic workload analysis*. International Journal of Industrial Ergonomics, 30, 135-148.

[86] Lin, R.T., Chan, C.-C., 2007. *Effectiveness of workstation design on reducing musculoskeletal risk factors and symptoms among semiconductor fabrication room workers*. International Journal of Industrial Ergonomics*,* 37, 35-42.

[87] Lippold, O., 1952. *The Relation Between Integrated Action Potentials in a Human Muscle and Its Isometric Tension*. Journal of Physiology, 117:492–499.

[88] Makelä, M., Hentilä, H., 2005. *Physical workstrain of dairy farming in loose housing barns*. International Journal of Industrial Ergonomics*,*35, 57-65.

[89] Marcos, P., Seitz, T., Bubb, H., Wichert, A., Feussner, H., 2006. *Computer simulation for ergonomic improvements in laparoscopic surgery*. Applied Ergonomics*,* 37, 251-258.

[90] Marshall, R., Case, K, K., Oliver, R., Gyi, D. E., and Porter, J. M., 2002. *Collection of Design Data from Older and Disabled People.* International Occupational Ergonomics & Safety Conference, Toronto, 1-5.

[91] Massaccesi, M., Pagnotta, A., Soccetti, A., Masali, M., Masiero, C., Greco, F., 2003. *Investigation of work-related disorders in truck drivers using RULA method*. Applied Ergonomics*,* 34, 303-307.

[92] Masud, A., Don M., and Scott S., 1985. *A High Level Predetermined Time Standard System and Short Cycle Tasks.* Annual International Industrial Engineering Conference Proceedings.

[93] Maynard, H. B. and Company, Inc., ErgoMOST System, Pittsburgh, PA.

[94] Maynard, H. B., 1963. *Industrial Engineering Handbook.* McGraw-Hill, New York.

[95] Maynard, H. B., 1963. *Industrial Engineering Handbook.* McGraw-Hill, New York.

[96] Maynard, H. B., Stegemerten, G., and Lowry, S., 1948. *Methods Time Measurement.* McGraw-Hill, New York.

[97] McAtammey, L., and Corlett, E. N., 1993. *RULA:A Survey Method for the Investigation of Work-Related Upper Limb Disorders.* Applied Ergonomics, 24(2): 91–99.

[98] McAtamney, L., Corlett, E.N., 1993. *RULA: a survey method for the investigation of work-related upper limb disorders*. Applied Ergonomics, 24, 91-99.

[99] Miller, D. K., 1975. *Validation of computer simulation in the social sciences*. Annual Conference on Modeling and Simulation, Pittsburgh, pp. 743-746.

[100] Mitchell, M., 1996. *An introduction to Genetic Algorithms*. MIT Press, Cambridge.

[101] MTM Association, 1978.

[102] Myers, G. J., 1978. *A controlled experiment in program testing and code walkthroughs/inspections*. Communication of the ACM, Vol. 21, N. 9, pp.760-768.

[103] Myers, G. J., 1979. *The Art of Software Testing.* Wiley, New York.

[104] Nadler, G., 1992. *The Role and Scope of Industrial Engineering.* The Handbook of Industrial Engineering*,* Wiley, New York.

[105] Nance, R. E., 1994. *The conical methodology and the evolution of simulation model development*. Annals of Operations Research, Vol. 53, pp. 1-46.

[106] NASA, 1978. *Anthropometry Source Book*, *A Handbook of Anthropometric Data*. NASA, Houston, TX.

[107] Neumann, W.P., Wells, R.P., Norman, R.W., Kerr, M.S., Frank, J., Shannon, H.S., OUBPS Working Group, 2001. *Trunk posture: reliability, accuracy, and risk estimates for low back pain from a video based assessment method*. International Journal of Industrial Ergonomics*,* 28, 355-365.

[108] Niosh Technical Report 81-122, 1981. *National Institute for Occupational Safety and Health. Work practices guide for manual lifting*. Center for Disease Control, U.S. Department of health and human services, Cincinnati, OH, USA.

[109] Norman, R. W., McGill, S. M., Lu W., and the Mardon Frazer Department Of Kinesiology, Faculty Of Applied Health Sciences, University Waterloo,Waterloo, Ontario Canada, 1994.

Improvement in Biological Realism in an Industrial Low Back Injury Risk Model: 3DWATBAK. Proceedings of the 12th Congress of the International Ergonomics Association, vol. 2, Toronto, Canada, pp. 299-301.

[110] Occhipinti, E., Colombini, D., 1996. *Alterazioni muscolo-scheletriche degli arti superiori da sovraccarico biomeccanico: metodi e criteri per l'inquadramento dell'esposizione lavorativa*. Medicina del Lavoro, 87, 491-525.

[111] Occhipinti, E., Colombini, D., Cairoli, S., Baracco, A., 2000. *Proposta e validazione preliminare di una checklist per la stima dell'esposizione lavorativa a movimenti e sforzi ripetuti degli arti superiori*. Medicina del Lavoro, 91, 470-485.

[112] Oliver, R., Gyi, D., Porter, J. M., Marshall, R., and case, K., 2001. *A survey of the design needs of older and disabled people.* Contemporary Ergonomics 2001, Ergonomics Society Annual Conference. Taylor & Francis, London.

[113] Phalen, G., 1966. *The Carpal Tunnel Syndrome.* Journal of Bone and Joint Surgery, 48A:211–228.

[114] Pheasant S., 1996. *Bodyspace, Anthropometry, Ergonomics and the Design of Work*. Taylor & Francis, London.

[115] Pope, M., Frymoyer, J., and Andersson, G., 1984. *Occupational Low Back Pain.* New York: Praeger Publishers.

[116] Porter, J. M., Almeida, G. M., Freer, M. T., and Case, K., 1991. *The design of supermarket workstations to reduce the incidence of musculoskeletal discomfort.* Designing for Everyone and Everybody. Taylor & Francis, London.

[117] Porter, J. M., case, K., and Freer, M. T., 1999. *Computer aided design and human models.* The Occupational Ergonomics Handbook. CRC Press, Boca Raton, FL.

[118] Porter, J. M., Case, K., Freer, M. T., and Bonney, M. C., 1993. *Computer-aided ergonomics design of automobiles.* Automotive Ergonomics, Taylor & Francis, London.

[119] Porter, J. M., Case, K., Gyi, D. E., Marshall, R., and Oliver, R. E., 2002. *How can we "design for all" if we do not know who is designed out and why?*. XVI Annual International Occupational Ergonomics & Safety Conference, 1-5.

[120] Porter, J. M., Freer, M. T., Case, K., and Bonney, M. C., 1996. *Computer aided and workspace design.* Evaluation of Human Work: A practical Ergonomics Methodology. Taylor & Francis, London.

[121] Pritsker, A. A. B., 1990. *Papers, Experiences, Perspectives.* Systems Publishing Corp., Lafayette, IN.

[122] Pro-Engineer by PTC. Available from: http://www.ptc.com/products/proengineer

[123] Pruett, C. J., Brown, C. M., and Balzulat, J., 2001. *Development of an Electronic Belt Fit Test Device (eBTD) for Digitally Certifying Seat Belt Fit Compliance.* SAE Digital Human Modeling for Design and Engineering Conference.

[124] Quick, J. H., Duncan, J. H., and Malcolm J. A., 1962. *Work Factor Time Standards.* McGraw-Hill, New York.

[125] Raschke, U., Martin, B. J., and Chaffin, D. B., 1996. *Distributed moment histogram: a neurophysiology based method of agonist and antagonist trunk muscle activity prediction.* Journal of Biomechanics, 29, 1587-1596.

[126] Resnick, M.L., Zanotti, A., 1997. *Using ergonomics to target productivity improvements*. Computer & Industrial Engineering, 33, 185-188.

[127] Rice, R. S., 1977. *Survey of Work Measurement and Wage Incentives.* Industrial Engineering.

[128] Roebuck, J. K., 1995. *Anthropometric Methods: Designing to Fit the Human Body.* Human Factors and Ergonomic Society, santa Monica, CA.

[129] Rohmert, W., 1985. *Ergonomics and Manufacturing Industry*. Ergonomics, 28(8):1115–1134.

[130] Ronald, G., 1996. *The Engineer in Transition to Management.* IIE Solutions, pp. 18-23.

[131] Roy, D. E., 1960. *Banana Time – Job Satisfaction and Informal Interaction.* Human Organization.

[132] Russell S. J., Winnemuller L., Camp J. E., Johnson P. W., 2007. *Comparing the results of five lifting analysis tools*. Applied Ergonomics, 38, 91-97.

[133] Sargent, R. G., 1996. *Verifying and validating simulation models*. Winter Simulation Conference, Piscataway, USA, pp. 55-64.

[134] Schultetus, W., 1980. *Daten, hinweise und beispiele zur ergonomischen arbeitsgestaltung. Montagegestaltung*, Verlag TÜV Rheinland Gmbh, Köln.

[135] Schultz, A., 1970. *The Quiet Revolution: From Scientific Management to Operations Research*. Engineering: Cornell Quarterly, Winter.

[136] Scott, G. B., Lambe, N. R., 1996. *Working practices in a pherchery system, using the OVAKO Working posture analysing System (OWAS)*. Appied Ergonomics, 27, 281-284.

[137] Seidl, A., 1994. *RAMSIS – a newly developed CAD tool for ergonomic analysis vehicle and its 3-dimensional system of analysis of postures and movements.* 12th Triennal Congress of the International Ergonomics Association, Toronto.

[138] Seidl, A., 1997. *RAMSIS – a new CAD tool for ergonomic analysis of vehicle developed for German automotive industry.* International Congress & Exposition, Detroit, MI.

[139] Seidl, A., 2000. *The ergonomic tool ANTHROPOS in virtual reality – requirements, methods and realization.* IEA Congress, San Diego, CA.

[140] Shannon, R. E., 1975. *System Simulation: The Art and Science*. Prentice Hall, Upper Saddle, River, USA.

[141] Shaw, M. J., 1994. *Manufacturing Systems Integration*. McGraw-Hill Yearbook of Science and Technology, McGraw-Hill, New York.

[142] Sheldon, W. H., 1940. *The Varieties of Human Physique.* Harper & Bros, New York.

[143] Shuval, K., Donchin, M., 2005. *Prevalence of upper extremity musculoskeletal symptoms and ergonomic risk factors at a Hi-Tech company in Israel*. International Journal of Industrial Ergonomics,35, 569-581.

[144] Snook, S. H. and Ciriello, V. M., 1991. *The Design of Manual Handling Asks: Revised tables of maximum acceptable weights and forces*. Ergonomics, 34:1197–1213.

[145] Snook, S. H. and Ciriello, V. M., 1991. *The Design of Manual Handling Asks: Revised tables of maximum acceptable weights and forces*. Ergonomics, 34:1197–1213.

[146] Snook, S., and Jensen, R., 1984. *Occupational Low Back Pain*. New York: Praeger Publishers, pp. 115–121.

[147] Snook, S., and Jensen, R., 1984. *Occupational Low Back Pain*. New York: Praeger Publishers, pp. 115–121.

[148] Sundin A., Christmansson M., Ortengren R., 2000. *Methodological differences using a computer manikin in two case studies:Bus and space module design.* Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Association, Ergonomics for the New Millennium, San Diego, CA, USA, pp. 496–498.

[149] Tanzer, R., 1959. *The Carpal Tunnel Syndrome.* Journal of Bone and Joint Surgery, 41A:626–634.

[150] Tecnomatix Technologies GmbH & Co, 2000. *eM-Workplaces Training Manual.*

[151] Temple, R., Adams, T., 2000. *Ergonomic Analysis of a Multi-Task Industrial Lifting Station Using the NIOSH Method*. The Journal of Industrial Technology, 16, 1-6.

[152] University of Michigan Center for Ergonomics, 2D Static Strength Prediction Program, 3D Static Strength Prediction Program.

[153] University of Michigan Center for Ergonomics, Energy Expenditure Prediction Program.

[154] Van Wendel de Joode, B., Burdorf, A., Verspuy, C., 1997. *Physical load in ship maintenance: Hazard evaluation by means of a workplace survey*. Applied Ergonomics, 28, 213-219.

[155] Vedder, J., 1998. *Identifying postural hazards with a video-based occurrence sampling method*. International Journal of Industrial Ergonomics, 22, 373-380.

[156] Vedder, J., Hellweg, 1998. *Identifying postural hazards with a video-based occurrence sampling method*. International Journal of Industrial Ergonomics, 22, 4-5.

[157] Waters, T. R., Putz-Anderson, V., Garg, A., and Fine, L. J., 1993. *Revised NIOSH Equation for the Design and Evaluation of Manual Lifting Tasks.* Ergonomics, 36(7):749–776.

[158] Waters, T. R., Vern, P. A., Garg, A., 1994. *Application Manuals for the Revised NIOSH Lifting Equation*. U.S. Department of health and human services, National Institute for Occupational Safety and Health, Cincinnati, OH, USA.

[159] Waters, T.R., Vern, P.A., Garg, A., 1994. *Application Manuals for the Revised NIOSH Lifting Equation*. U.S. Department of health and human services, National Institute for Occupational Safety and Health, Cincinnati, OH, USA.

[160] Waters, T.R., Vern, P.A., Garg, A., 1994. *Application Manuals for the Revised NIOSH Lifting Equation*. U.S. Department of health and human services, National Institute for Occupational Safety and Health, Cincinnati, OH, USA.

[161] White, H.A., Kirby, R.L., 2003. *Folding and unfolding manual wheelchairs: an ergonomic evaluation of health-care workers*. Applied Ergonomics*,* 34, 571-579.

[162] White, K. P., and J. W. Fowler, 1994. *Manufacturing Technology.* McGraw-Hill Yearbook of Science and Technology, McGraw-Hill, New York.

[163] Whitner, R. B., and Balci, O., 1989. *Guidelines for selecting and using simulation model verification techniques*. Winter Simulation Conference, Piscataway, USA, pp. 559-568.

[164] Wild, R., 1975. *On Selection of Mass Production Systems*. International Journal of Production Research, 13:5.

[165] Wilson J.R., 1997. *Virtual environments and ergonomics: needs and opportunities.* Ergonomics*,* 40, 1057-1077.

[166] Wilson, J. R., and Corlett, E. N., 1990. *Evaluation of Human Work: A Practical Ergonomics Methodology*. Taylor & Francis, Bristol, PA.

[167] Wright, R. D., 1972. *Validating dynamic models: an evaluation of tests of predictive power*. Summer Computer Simulation Conference, San Diego, pp. 1286-1296.

[168] Yourdon, E., (1985). *Structured Walkthroughs*. Yourdon Press, New York.

[169] Yu, T., Roht, L. H., Wise, A. W., Kilian, J., and Weir, F.W., 1984. *Low-Back Pain in Industry: An Old Problem Revisited*. Journal of Occupational Medicine, 26(7):517–524.

[170] Zandin K.B., 2001. *Maynard's Industrial Engineering Handbook*, McGraw-Hill, New York.

[171] Zandin K.B., 2001. Maynard's Industrial Engineering Handbook, McGraw-Hill, New York.

[172] Zandin, K. B., Gardner, D. L., Gill, E. J., and Wilk, J. R., 1996. *ErgoMOST: An Engineer's Tool for Measuring Ergonomic Stress*. Occupational Ergonomics, Marcel Dekker, New York, pp. 417–429.

[173] Zandin, K., 1990. *MOST® Work Measurement Systems*. Marcel Dekker, New York.

[174] Zehner, G.F., Meindl, R. S., and Hudson, J. A., 1993. *A multivariate anthropometric method for crew station design.* Technical Report AL-TR-1992-0164, Wright Patterson Air Force Base, OH.