COMPUTER AIDED DESIGN FOR WORK INJURY ELIMINATION IN PRODUCTION ASSEMBLY SYSTEMS

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ABSTRACT

Work injury is one of the major obstacles in manufacturing industries especially in production assembly systems all over the world. Work injuries reduce production efficiency and threat human health. Among various types of work injuries, repetitive work injuries are the one that can be easily neglected. This thesis is about the application of computing technology to analysis and synthesis of repetitive work injuries in production assembly systems for the purpose of reduction or elimination of these injuries.

A production assembly system consists of the assembly machines, products, tools, humans (workers), and particular environments. Injuries of the worker are basically caused by over stress, strain, and fatigue, which are further related to the worker's posture.

This research proposed a general methodology for constructing a software system for analysis and simulation of a worker's postures in a virtual environment. The implementation of such a computer system was discussed. This research also proposed methods to compute work injury cost. Finally, this research proposed a more systematic method for the synthesis or re-design of worker' postures to reduce or eliminate work injuries. The major contribution of this thesis work is to advance computing to work injury analysis and synthesis in production systems.

This thesis study concludes that the computer technology is matured enough to highly automate the process of work injury analysis and synthesis. It is possible that a complete design of production systems with consideration of work injuries can be done in a much more efficient manner – perhaps reduction of the ramp-up process in the automobile industry from 6 months (typically) to one month in addition to the

removal of wasted materials and potential injuries in the ramp-up process.

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Chapter 1: Introduction

1.1 Work Injury

Due to the increasing cost of work injuries as well as concern of health work place, both governments and industries have taken effort on preventing work injury occurrences. In 2005, the government of Canada paid nearly $6.8 billion dollars in benefits through its Workers' Compensation Boards (WCBs) organization. In 2005, the WCBs paid an average of approximately $19,990 per each new compensated time-loss injury or fatality (Labour Canada, 2007). The cost of WCBs includes the medicine, treatment, pension and funeral expenses (Labour Canada, 2007). An estimated 630,000 Canadians experienced at least one activity-limiting occupational injury, representing 5% and 2% of employed men and women, respectively (Kathryn et al., 2007). Ten percent of Canadian adults had a repetitive strain injury (RSI) critical enough to limit their normal activities in 2000/2001 (Kellie et al., 2006). The expenses for work injury in production during 2002-2007 keep at high level and at the peak as about 8 billion dollars in 2004.

Further, it has been found that most of the non-preventable injuries occur as a result of excessive repetitive motion, over-exertion or poor production assembly design (SWCB, 2004). The percentage of work injuries caused by repetitive work operation in all kinds of work injuries is increasing year over year. A report from National Working Environment Authority shows that from 1993-2003, illness and injury caused by heavy lifting and repetitive work is 24% of all reported work related injuries in 2003, compared to 19% in 1993 (Nation Working Environment Authority, 2004).

Work injuries especially repetitive work injuries have been viewed as a major problem to affect the efficiency and cost of production. The repetitive work injuries are caused by the repetitive work operations during the production especially the assembly production with a high frequency of the repetitive workload. This has been a major issue. However, there is no systematic method as well as tool for analysis of work injuries on the assembly, nor is there one for synthesis of the production system for work injury elimination. Currently, the National Institute of Occupational Safety and Health (NIOSH) has published a guideline which is used to guide the manual lifting task in production. Also, there is a recommended table about what should be good postures for work operations.

1.2 Production System and Work Injury

The current design and management practice in production systems takes the work injury out of the loop in the sense that the work injury is a business of financial and human resource departments. The cost and the work environment deterioration due to work injuries do no constrain the production system. The work injury problem persists also due to the tough competition in manufacturing industries today in terms of a desire to have a production system with low cost, quick lead time and high quality of products, making the human in an ever increasing stress situation.

In the automobile industry, the design of the auto assembly system is especially time consuming due to the lack of effective computer support. Partly, this is due to the difficulty of integrating human operations with machine operations. There are some computer support systems available for assembly planning and scheduling, but they are mostly for the machine system with consideration the human side. There is a software system available to study biomechanics problems, such as Delmia V5©, but it appears not fully integrated with other software systems such as Solidwork© or Pro-Engineering©, that are necessary to specify assembled objects and to calculate their load on both the human and machines. Without a proper integration, capabilities of Delmia 5 are not fully utilized. Furthermore, the cost of the production system does not include the cost incurred due to work injuries. This has made the design and management of the production system incomplete. As the result of these practices, it is well known in the auto manufacture that the design of a new assembly system, called “Ramp-Up” design process, takes extremely long time (about 2-3 months).

1.3 Problem Statement

Computer aid or support is highly needed for analysis and synthesis of the production system for reduction of work injuries and for integration of various existing computer support systems. The following are the research questions summarized from our interaction with the agriculture machinery industry:

(1) What information is required of the production system, human worker and their work environment?
(2) How can the information be understood by the computer and what is the format of data that carries the information?
(3) How can all of the information be integrated to form a coherent system?
(4) How can the cost of the work injury be calculated?
(5) How can the synthesis of the worker’s posture be done systematically?

This research study was primarily to develop answers to the above-mentioned questions.

1.4 Objectives and Scopes

In light of addressing to the above questions, there were three research objectives proposed for this thesis study and they are:

(1) To develop an integrated computer system for systematic analysis of work injuries in the context of production systems.

(2) To develop a general methodology to calculate the cost of work injury in the context of production systems.

(3) To develop a general methodology for systematic synthesis of a worker's postures in the context of production systems to eliminate work injuries.

It may be clear that the first objective addresses questions 1-3, the second objective addresses question 4, and the third objective addresses question 5. In the case of analysis, this study was to look into existing computer programs (e.g., Delmia V5©) and to investigate the effective integration of them into a coherent one to be useful to an application. It is also noted that this thesis study was not concerned with the medical roots of various injuries.

1.5 Organization of the Thesis

Chapter 2 will give a background of the study and critical review of related work to the objectives of the thesis presented above. Chapter 3 presents a practical production system that was used as a case for both facilitating theoretical developments and validating these developments. Chapter 4 will present a general computer system for analysis of work injuries in production systems. Chapter 5 will give a general methodology for computing the cost of work injuries. Chapter 6 will present a computer-based code system for a more systematic way of the synthesis of worker postures in the context of production systems or redesign of a problematical posture in terms of work injuries. Finally, Chapter 7 will give a conclusion of this study and recommendation of future research.

Chapter 2: Background and Literature Review

2.1 Introduction

This chapter will give some necessary background to understand this study and present a critical review of related work in literature. Section 2.2 describes human biomechanics and ergonomics. Section 2.3 discusses previous work on the subject of work injury analysis. Section 2.4 is a conclusion with a further discussion of the proposed objectives for this thesis study described in Chapter 1.

2.2 Human Biomechanics and Ergonomics

2.2.1 Human Body Structure

The human body contains approximately six hundred and thirty nine (639) muscles and two hundred and six (206) skeletons. Muscles are connected with skeletons. The movements and postures of humans are realized with constriction and extension of the muscles and the movements of skeletons. Human body can be made in analogy to machine in such a way that skeletons in human body are links in the machine and muscles in human body are joints in the machine. The movement of skeletons and muscles are controlled by the centre nerve system of the human, the same as the movement of links and joints in the machine is controlled by a machine control system.

Human body is further divided into several groups: head, neck, torso, two arms and two legs. This division is a generic one. Specialized divisions for specific purposes when dealing with human body are existed. For instance, for the purpose of work compensation, human body is divided into one hundred and thirty seven (137) parts which include the abdomen, ankles, arms, back including the spine and spinal cord, balls, body systems, brains, buttocks, chest, cranial region, digestive system, elbow, eyes, face, foot, forehead, kidney, knees, leg, hips, nose, outer ear, pelvic region, neck, cheek, etc. Emodi (2007) argued that human body may be divided into body system, head, lower extremities, multiple body parts, neck-including throat, trunk, and upper extremities from a point of view of impact of injuries to the work time loss, treatment, and total cost of compensation to the persons who are injured.

2.2.2 Human Biomechanics

According to Knapp (2006), the discipline of human biomechanics integrates both the laws of physics and working concepts of engineering to describe the motion of various body segments and forces acting on these segments. In human biomechanics, researchers not only focus on the relationships among all kinds of tissues and organisms when a movement is accelerated but also find out the force applied to each tissue and organism when the tissue and organism interact to each other.

One important application with human biomechanics is to find out root causes for human injuries which are related to human movements. After that, intervention processes can be developed to resolve the root causes. There are many factors that can cause human body be injured. These factors can be classified into two basic groups: internal and external. The internal factors are those coming from the interior of human body, such as emotion, metal workload, and so on. The external factors are those related to the interaction between the human and environment. Examples are the task load, environment temperature and humidity, and so on. It might be clear that the external factor will affect the internal factor. The injury is also dependent on individuals (body & mind conditions of individual). This means that for the same factors, the injury situation differs from one individual to another. Human biomechanics helps to establish the relationships among the external factors, internal factors and body in the aspect of motion and force. Further, since human body can be divided into three levels: organ level, tissue level, and cell level, such relationships will have three levels: organ, tissue and cell. Therefore, one can imagine three kinds of biomechanics: organ biomechanics, tissue biomechanics and cell biomechanics.

2.2.3 Human Ergonomics

Ergonomics is the scientific discipline concerned with designing artifacts to meet human needs in terms of safety, and ease of use or operation, adapted from (IEA, 2000). In the context of production system design, the safety is a main concern, which is further related to designing artifacts for no work injury. The work injury here further refers to repetitive work injury. Fig 2.1 shows a flow chart for ergonomics design in light of no repetitive work injuries. In this figure, the left column shows a flow of design which takes ergonomics consideration, and the right column shows inputs from ergonomics consideration.

Ergonomics is based upon biomechanics in the sense that ergonomics is to study how to change the external factors using the rules created by biomechanics. These external factors are further associated with individual artificial design problems – for example in the production assembly system, the problem of designing parts and /or tools the human worker holds and manipulates and managing the flow of the parts/tools.

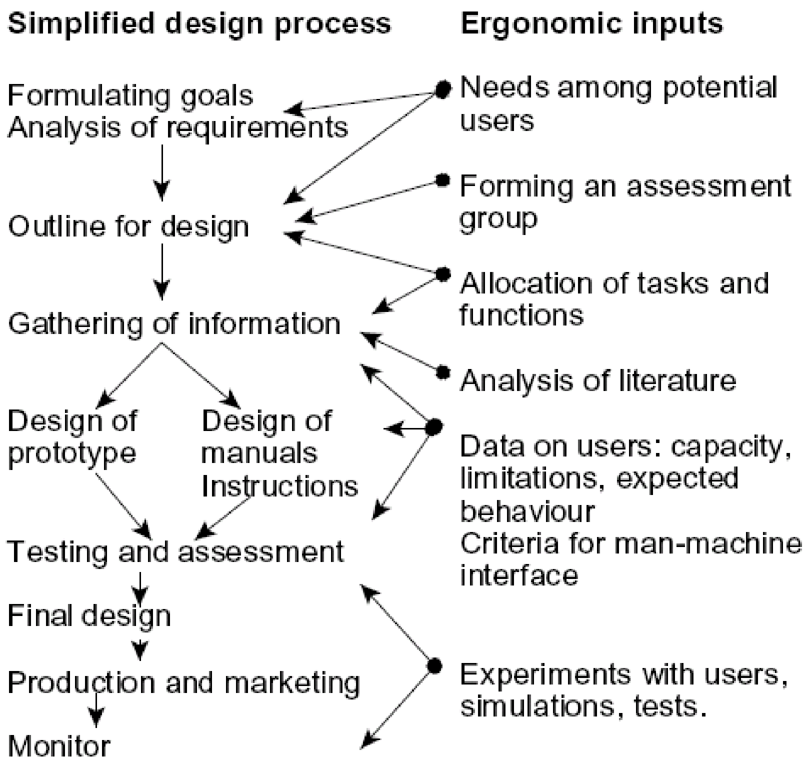


FIG 2.1 THE COMPARISON OF TRADITIONAL DESIGN AND THE DESIGN WITH ERGONOMICS DESIGN (SINGLETON, 1974 AND WILSON, 1990)

2.3 Related Previous Work

The main issues for ergonomics design are: analysis of human physical state and injury analysis, design guidelines or rules for the assembly system without (repetitive) work injury, and cost analysis for work injury. In the following, the existing work on these issues is presented.

2.3.1 Design Guidelines

The design guideline includes the rules address that two problems: (i) to determine the maximum workload the human worker can bear without work injury given a posture trajectory and (ii) to determine the posture trajectory given a workload. For (i), there are two approaches: analytical approach and experimental approach.

Analytical Approach to Determine Workload:

It is assumed that a worker posture trajectory is given at the start of the operation and the end of the operation. National Institute of Occupational Safety and Health (NIOSH) published a practical guide for lifting task or operation (NIOSH, 1981; 1991). In this guide, Recommended Weight Limit (RWL) and Limit Index (LI) for the lifting task under the condition that the back pain injury and the forearm injury are avoided are given. In particular, RWL is given by the following equation:

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM \tag{2.1}$$

where LC represents the Load Constant;

HM represents the Horizontal Multiplier;

VM represents the Vertical Multiplier;

DM represents the Distance Multiplier;

AM represents the Asymmetric Multiplier;

FM represents the Frequency Multiplier; and

CM represents the Coupling Multiplier.

The parameters above are all called multipliers. Table 2.1 gives the values of these multipliers, some of which are constant and others are computed by formulas which are included. Further, the first letter of two letters of the multipliers describes the task feature; see Table 2.2. Fig 2.2 illustrates these features further.

TABLE 2.1 VARIOUS MULTIPLIERS AND THEIR VALUES (Waters et al., 1994)

		Metric	U.S.
Load Constant	LC	23kg	51lb
Horizontal Multiplier	HM	(25/H)	(10/H)
Vertical Multiplier	VM	1-(.003[V-75])	1-(.0075 [V-30])
Distance Multiplier	DM	.82 + (4.5/D)	.82 + (1.8/D)
Asymmetric Multiplier	AM	1-(.0032A)	1-(.0032A)

Frequency Multiplier	FM	From NIOSH tables	From NIOSH tables
Coupling Multiplier	CM	From NIOSH tables	From NIOSH tables

TABLE 2.2: TASK VARIABLES IN NIOSH EQUATION (Waters et al., 1994)

Task variable	Meaning
H	horizontal component
V	Vertical location
D	distance component
A	asymmetric component
F	lifting frequency
C	coupling component

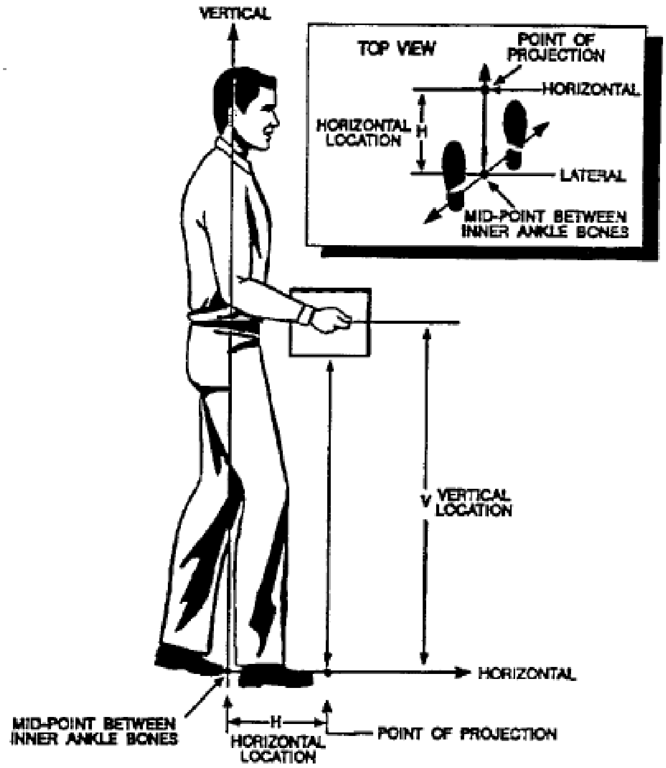
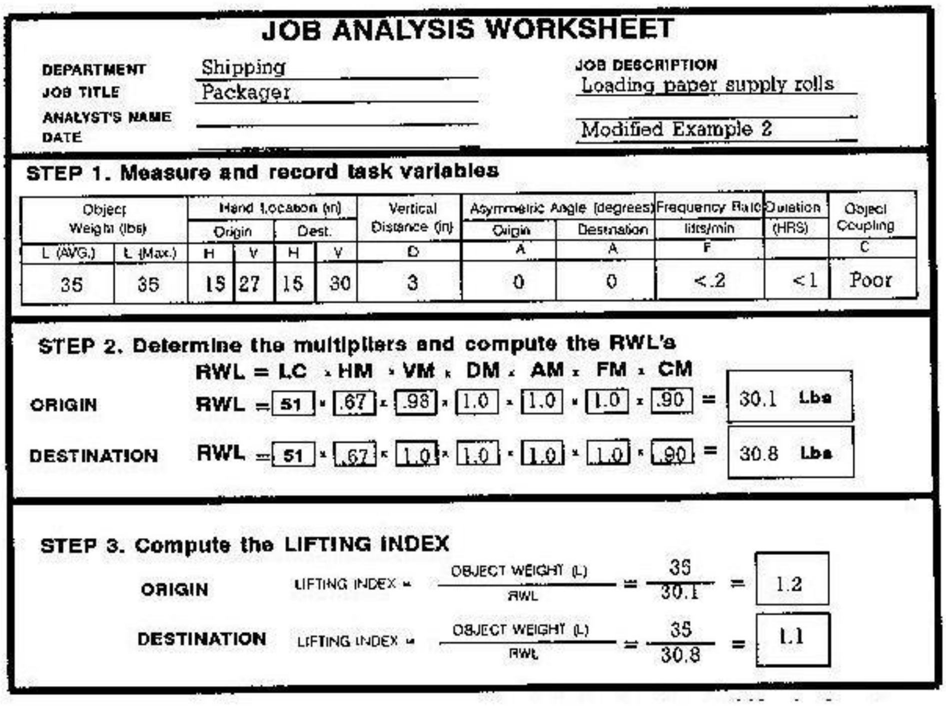


FIG 2.2 GRAPHIC REPRESENTATION OF HAND LOCATION (WATERS ET AL., 1994)

The LI is calculated with the following equation (Waters et al., 1994):

$$LI = \frac{Load\ Weight}{\mathrm{Re}commended\ \ Weight\ \ Limit} = \frac{L}{RWL} \tag{2.2}$$

It is clear that if LI>1, there would be potentially some injuries. Fig 2.3 shows a form used in practice for ergonomics design based on RWL and LI which follows the NIOSH standard.



JOB ANALYSIS WORKSHEET

DEPARTMENT Shipping
JOB TITLE Packager
ANALYST'S NAME
DATE

JOB DESCRIPTION
Loading paper supply rolls
Modified Example 2

STEP 1. Measure and record task variables

Object Weight (lbs)		Hand Location (in)				Vertical Distance (in)	Asymmetric Angle (degrees)		Frequency Rate lifts/min	Duration (HRS)	Object Coupling
		Origin		Dest.			Origin	Destination			
L (AVG.)	L (Max.)	H	V	H	V	D	A	A	F		C
35	35	15	27	15	30	3	0	0	<.2	<1	Poor

STEP 2. Determine the multipliers and compute the RWL's

RWL = LC × HM × VM × DM × AM × FM × CM

ORIGIN RWL = 51 × .67 × .98 × 1.0 × 1.0 × 1.0 × .90 = 30.1 Lbs

DESTINATION RWL = 51 × .67 × 1.0 × 1.0 × 1.0 × 1.0 × .90 = 30.8 Lbs

STEP 3. Compute the LIFTING INDEX

ORIGIN LIFTING INDEX = OBJECT WEIGHT (L) / RWL = 35 / 30.1 = 1.2

DESTINATION LIFTING INDEX = OBJECT WEIGHT (L) / RWL = 35 / 30.8 = 1.1

FIG 2.3 NIOSH EQUATION IN WORK INJURY ANALYSIS (Waters et al., 1994)

Equations (2.1) and (2.2) have not considered the factors such as the gender, age, population, and psychophysical status. Hildalgo et al. (1997) proposed a modified equation for the NIOSH equation as follows:

$$LC = WB \times H \times V \times D \times F \times TD \times T \times C \times HS \times AG \times BW \tag{2.3}$$

where LC represents lifting capacity;

WB represents base weight;

H represents horizontal distance;

V represents starting height;

D represents vertical distance of lift;

F represents frequency /min;

TD represents task duration;

T represents twisting angle factor (degrees);

C represents coupling factor;

HS represents heat stress factor;

AG represents age factor; and

BW represents body weight factor.

More factors can be found and incorporated into the above equations. In general, the analytical approach has its limitation in that it is a linear form function; however, it is simple and easy to be applied.

Experiment Approach to Determine Workload:

The basic idea of the experimental approach is to have a group of human subjects (or participants). They are equipped with sensors which can measure their psychophysical signal while they are performing tasks. These psychophysical signals are further used to infer their mental and physical states which are related to work injuries. As such, the relationship between the task performing and the worker injury is established.

Krawczyk et al. (1993) carried out some experiments to analyze upper extremity cumulative trauma disorder with repetitive task operation in the assembly system. The purpose was to examine a different combination of workloads of repetitive upper extremity work to determine design recommendations. One of these experiments was to perform combinative task of transferring a product from the storage bin to another place and then screw-driving it onto the place by using a pistol shaped pneumatic. Twenty-four (24) experienced workers were recruited for this. The participants were all “right-hand’. Five combinations of tasks, 100% transfer, 75% transfer and 25% screw driver, 50% transfer and 50% screw driver, 25% transfer and 75% screw driver, and 100% screw driver, were performed in this experiment, and each task was performed for an hour. 10 cm visual analog scale (VAS) with verbal descriptions at the end points was used to measure exertions due to transporting and screw-driving.

The left side corresponds to “Easiest imaginable work” at 0 cm, and the right side corresponds to “Hardest imaginable work” at 10 cm, respectively. The perceived exertion (VAS) rating was provided by the participants based on the participant’s perception of pain or discomfort in each combination task. The mean overall VAS ratings were 5.3, 4.3, 3.5, 4.4, and 5.3 for the five combination tasks, respectively. It was found that exertions would be higher for the work that needs more than one upper extremity, and upper extremity tasks should be designed as varied as possible and by utilizing as many body parts as possible. However, the VAS rating provided by the participants could vary with respect to the participant’s perception of pain or discomfort.

Another experiment was carried out for determining the shoulder flexion torque strength in young men and women (Koski et al., 1994). The objective of the experiment was to understand the effect of the exterior force on shoulder. In this experiment, 26 young male and 25 young female subjects were recruited. A computer controlled dynamometer (KIM-COM) was used to measure the shoulder angle and shoulder flexion torsional strength. The shoulder flexion torques were collected at 50 °/s angular velocity from 0 ° to the limit at which each participate felt comfortable, and the peak static shoulder torsional strengths were collected at 0 ° and 45 ° shoulder angles, respectively. The results of this experiment show that male subjects had two times the strength of the female subjects. The age factor was not considered in this experiment. It was also observed that the experiment can only be used for a younger population about the mean age of 22 years (Koski et al., 1994). In the real assembly production, the average age of workers may fall beyond this limit.

The mean and standard deviation of strengths across various joints were studied (Chaffin et al., 1991). They were able to discover a large variation in the strength as joint angle increases from 0 ° to 90 °. A set of equations known as mean joint moment strength prediction equations were derived for the calculation of strength at various angular positions of the body segments by taking the factors such as gender, percentile, posture, and mass of segments (Chaffin et al., 1991).

An experiment was carried out for strength analysis with consideration of the age factor (Lannersten et al., 1993). The result of this experiment showed that there was no significant influence on the age of female women on the flexors, abductors, and external rotators, especially the age between 19 to 65, yet there was a significant difference in the shoulder flexion strength between the old male workers and the young male workers; in particular the old male worker's strength is far lower than the young male worker's strength. The most valuable information obtained from this experiment is that there is no significant difference in the muscular strength of the workers between the ages of 19 to 44 in any of the groups (Lannersten et al., 1993). However, this result does not mean that the age factor can be ignored from worker injury analysis, because the range of the ages of workers on the assembly system is larger than the range from 19 to 44.

The experimental approach has a limited use because they are not controlled in a standard manner; moreover, the exterior factors such as lighting, noise and so on were not considered. One big challenge with this approach is perhaps the intrusiveness to the human. A large scale of data collection implies the need of a large amount of human resources, which can be problematic especially with the strong presence of intrusiveness of experiments. Other databases which were obtained from the previous experiments exist in the current literature; and they are the Snook and Ciriello tables, Rapid Upper Limb Assessment (RULA) database, and Rapid Entire Body Assessment (REBA).

The Snook and Ciriello table is used quite often in industry. The Snook and Ciriello table allows the user to find the maximum acceptable weight for a particular task with consideration of the factors such as frequency, population, and time. This database was generated based on the experiment that lasts over a period of 30 years (Snook and Ciriello, 1991). Participants were asked to manipulate objects with adjustable weights for a proper feel of the exertion. The maximum weight is an acceptable weight that the participants do not feel exertion to manipulate. The participants were also asked to lift the object with adjustable weights to test the maximum weight for various lifting tasks.

There are still some limitations associated with the Snook and Ciriello table: (1) The experiments were carried out based on the feel of participants, thus the reliability of the result is doubtable, (2) The maximum weight from the Snook and Ciriello table is higher than the recommended weight from the NIOSH guideline calculation, (3) the Snook and Ciriello table has not considered the factors such as the coupling/gripping characteristics, duration of a task, the load asymmetry, load placement clearance, thermal stress, and limited headroom (Snook and Ciriello, 1991).

Design Guideline for Work Posture:

Ultimately, the concern is how to design an assembly system free of work injuries. There is a clear need of design guidelines to assist in the conceptual design of an assembly system. The detailed design of an assembly system may be assisted with tools for worker injury analysis. Emodi (2007) presented a table which includes several design rules – see Table 2.3. In this table, the first column is a list of assembly processes, the second column is a list of the features of the postures that are observed and inadequate from an ergonomics point of view, and the third column is a list of recommendations of correct postures as well as their corresponding processes.

TABLE 2.3 DESIGN RECOMMENDATIONS

PROCESS	**OBSERVATION**	**RECOMMENDATION**
1	Eye level far above or far below the view location.	Alternate between standing and the use of adjustable stools to ensure a near horizontal eye level
2	Hand above shoulder level	Place tools, parts, and equipments in locations where they can be easily be accessible without having to raise the hands above the should level

		Paint line hangers for example should be reduced in height to eliminate this condition
3	Body twisting	Place tool on shelves in front of the workers to avoid twisting while obtaining them
4	Load weight	Do not lift loads greater than 20kg or the recommended weight limits obtained from CAD analysis. Do not lift long (>5 feet) and slender (< 2 inch thick) loads
5	Power tools	The use of power tools for various operations should be alternated between individuals on a daily basis to reduce risk of carpal tunnel.
6	Lunch/ coffee breaks	Coffee breaks, lunch breaks, and momentary rests should be ensured to reduce high work frequency and also introduce rest periods
7	Carry	Avoid carry operations as much as possible unless carrying a very small weight less than 10kg. Carry over short distances or use a trolley to carry for longer distances
8	Push-pull	The maximum initial and sustained forces of push or pull should not exceed any results obtained from the push-pull analysis using any generic ergonomics software Push all the time if possible and avoid pulling as much as possible
9	Lifting	Bend at the knee level and not at the waist while lifting or lowering Lift from a platform and not from ground level Lower loads from platforms about chest level Keep back straight while lifting or lowering Ensure that object size being lifted do not have a larger width than the body width.
10	Standing/Seating	Alternate standing and seating. Do not stand for more than 45 minutes at a stretch. Do not seat for long periods on a high stool

		(above knee level) to avoid build up of blood on the legs. For computer use in the plant, use of seats without arm rests should be avoided

2.3.2 Human State and Work Injury Analysis

Both analytical and experimental approaches to work injury analysis are at the qualitative level or imperial. An obvious direction of research is to model human body more comprehensively. Research along this direction is also under the heading of “computer manikin modeling (CMM)”. The general idea of CMM here is to view human body as a mechanical system or robot with joints and links which correspond to human muscles and bones. In this way, a computer modeling of humans can be established, and the software such as Delmia V5© to facilitate the establishment of such a model is available. With such software, the parameters such as the height, weight, population and gender are specified by the user, and the model is automatically generated by this software.

Currently, in the context of manufacturing assembly systems, this software system further allows for the analysis of the movement of workers based on the manikin model along with the capability of simulating the robotic assembly. Therefore, it is possible that with this software system, the assembly details such as fit, clearance, reach, and line of sight can be simulated. This is quite useful to determine the problematic areas of an assembly system, which have harmful impact to human body and or fail to reach a particular assembly task. The use of computer manikins is faster and easier than experimental methods (Dukic et al., 2002).

The Delmia V5© software has an activity simulation and an ergonomic analysis module that can simulate the human worker activities and analyze the work injury identification. The Delmia V5© software generates the human manikin models with a wide range of input variables which represent individuals such as age, gender, population, and the anthropometry. The ergonomics option in the Delmia V5© software could accept the input data which are obtained from the activity simulation of human manikins, and provided information of work injuries. This information includes such as L4-L5 moment, L4-L5 compression, body load, compression, axial twist compression, flexion/extension compression, L4-L5 joint shear, abdominal force, abdominal pressure, ground reaction, maximum acceptable sustained force, and maximum acceptable initial force. This information is automatically compared with the standard data such as the data from the NIOSH and the database from the previous experiments. The result of work injury and the recommendation will be generated based on the comparisons. The Delmia V5© software is also able to generate the result into different formats of data representation to facilitate the user for information collection and information transportation.

A number of other software systems for work injury analysis are: UGS' Jack Software; ErgoIntelligence©; Envision Ergo©; ErgoEASER©; and SafeWork©. They are found not as powerful as Delmia software.

2.3.3 Cost Analysis

Cost of work injuries includes the direct cost and indirect cost (Currie et al., 2000). The direct cost contains the expense on the resources of preventing, detecting and treatment. The indirect cost relates to the loss of production output in economics. According to Currie et al. (2000), the measurement of work injuries which may occur in production is the obstacle of cost analysis. The cost estimation of work injuries is limited by the uncertain measurement of them. Unfortunately, there was no method for cost analysis with an acceptable estimation of work injuries until 2007 when Emodi (2007) developed a method for cost estimation for work injuries on the production system. The method was based on the exploration of a large volume of historical data (i.e., the cost for an injured worker in the past). The specific approach to "discover" the knowledge of work injury cost (i.e., the relationship between the worker's injury and cost) is to be further desired, as his approach takes a simple average for each case, ignoring many individual differences which can produce errors in cost estimation.

2.4 Conclusion

It can be concluded that in general, the current state of knowledge in production systems design and management has less considered the work injury problem, in particular work injury analysis, production system design or synthesis with consideration of work injury, and cost estimation of work injuries. Though work injury analysis software systems seem to be readily available, they do not seem to be well integrated in the production system design and management. This situation has hindered a wide application of work injury analysis software in industry.

The uniqueness of the proposed work for objective 1 as defined in Chapter 1 lies in a much better integration system for work injury analysis – i.e. the focus of this thesis study is to develop a general approach to integrate all relevant software systems. The uniqueness of the proposed work for objective 2 lies in the consideration of more individual features or characteristics in developing a work injury cost estimate equation. The uniqueness of the proposed work for objective 3 lies in a more systematic and computer-aided approach to production systems synthesis, especially for conceptual design, towards a work injury free production system.

Chapter 3 Case Assembly System

3.1 Background of the Example Assembly System

This study was closely collaborative with a local company called ABC. ABC is a farm equipment and machine manufacturer. One of their production tasks is to assemble components into a system (i.e., assembly). The company has several assembly systems, one of which is called “Corn Combine Header” (CCH) assembly system. The CCH deals with the assembly of “combine header” for corn harvesting. The “combine header” system consists of such a number of components such as “row bars”, “row units” and so on. The reason to choose the CCH for this study is, somewhat, an ad hoc choice yet with some consideration of the size and complexity of the system appropriate for this thesis study. Furthermore, only a part of the CCH was considered especially those that cause most repetitive work injuries. In the remainder of this chapter, Section 3.2 describes the combine header system. Section 3.3 discussed the measurement technique employed for CCH. Section 3.4 describes two particular assembly tasks in the CCH assembly, which were studied in detail throughout this thesis.

3.2 Combine Header Assembly System

The business of ABC is very dynamitic, and their assembly system seasonally changes due to the seasonal products for the market. In particular, the combine header assembly system was developed from April to October every year. Fig 3.1 shows the combine header with rows. The combine header can be attached to the tractor, and separates the grain from the chaff, while the tractor is running on the farm. The combine header in this assembly system is mainly for corn harvesting, therefore it is also called corn combine header. Depending on different types of grains, the rows can be changed to generate different ranges of combine headers. The size of combine headers could be ranged from 6, 8 to 12 rows. Different types of rows are further assembled in different cells, and they are combined to the row bar which further corresponds to different types of "combine headers".

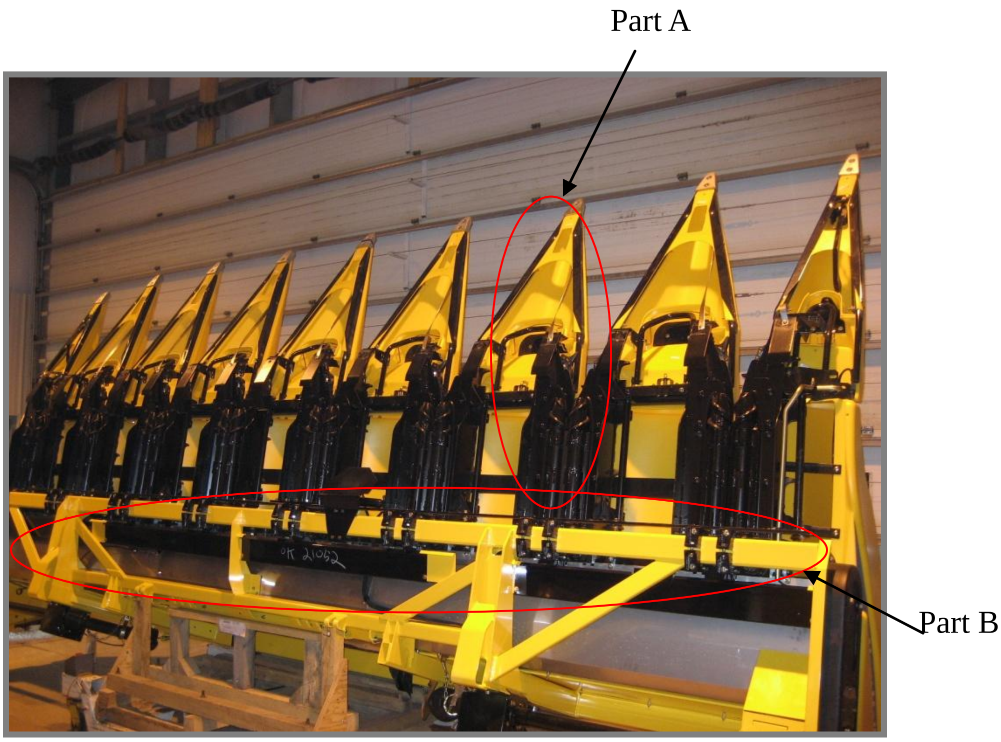


FIG 3.1 THE ENTIRE CORN COMBINE HEADER (PART A: ROW UNIT; PART B: ROW BAR)

The current assembly system contains fourteen work cells or work stations. Fig 3.2 shows a general layout of the entire assembly system. In Fig 3.2, symbol P is used to represent the work cell, and symbol A and M are used to represent the work stations. Different tasks are carried out on each cell, such as painting, wielding and installing. The machines, tools and product components are arranged for each cell. Some cells contain robots and machines to assembly parts automatically, such as painting. Most of the tasks on the assembly system were operated by workers with the power tools or machines are repetitive in nature, which could cause work injuries.

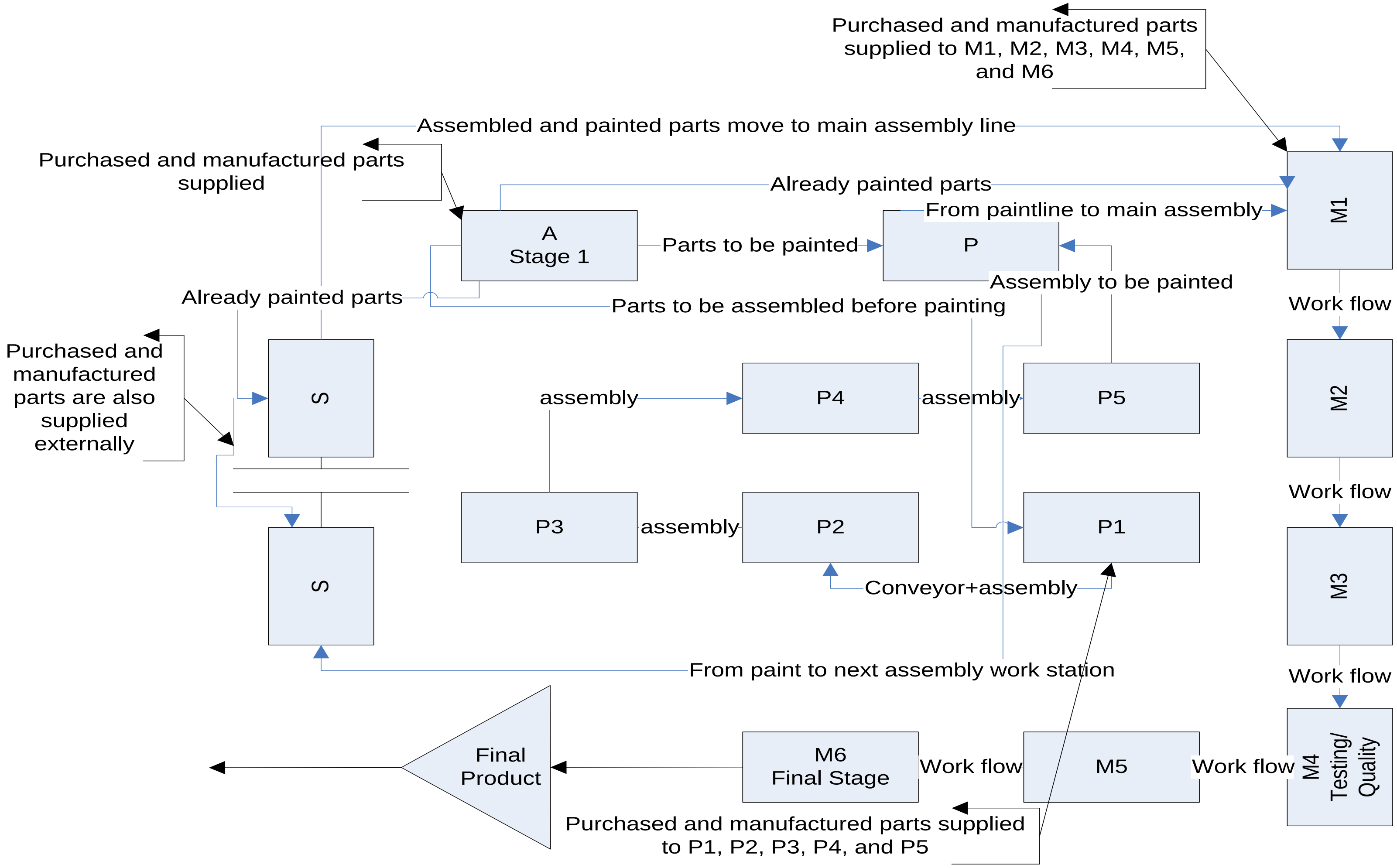


FIG 3.2 THE GENERAL LAYOUT OF ENTIRE ASSEMBLY SYSTEM (EMODI, 2007)

In this research, only work cells P4 and P5 were analyzed as they are the cells that carry out the assembly of the row units. As can be seen in Fig 3.2, production starts from A. Some parts for this assembly work station were manufactured in this plant, and others were purchased from suppliers. All of these parts were gathered in Station A and moved to Cell P and Cell P1 depending on the painting needs of parts. If parts need to be assembling before painting, they are moved to Cell P1. Otherwise, parts will be moved to Cell P for painting directly. Each part is assembled on Cell P1 and P5. In Cell P5, the semi-manufactured products (row bar with row units, say R) were completed and will be delivered to Cell P for the final painting. The painted assembly parts and semi-manufactured products R were transported to work station S. In this station, all the parts and semi-manufactured products R were tested before the final assembly. The final assembly of corn combine header was commenced at work station M1. Different assembly parts and semi-manufactured products R were transported to different work station M1 to M3 depending where the exact assembly was needed. The assembly flow from M1 to M3 is shown in Fig 3.2. In work station M4, the product will be tested to ensure the quality and moved to the work stations M4 and M5. The final product which is corn combine header was assembled with the plastic cover and packed in work station M5, and then the product was moved to the warehouse.

3.3 Measurement of Human Worker's Operation

Video tapes were used to record worker's parameters which describe movements and postures on the whole combine header assembly system. These parameters include (1) the frequency of task, (2) the duration of task, (3) the break time of task, and (4) generic operation posture. Further, there are parameters that describe the work object, including (a) the weight of the object, (b) the geometry of the object, (c) the material of the objects, and (d) the mass distribution of the object. Some parameters such as the geometry of the object and the material of the object can be obtained by using the software system such as Solidworks©. The break time and frequency of task are observed from the video tape and the real production.

Finally the interaction of the worker with the object is described by (1) their contact detail, and (2) trajectory of the worker's movement in contact with the object. The measurement of trajectory was made by the software system Delmia V5©. In software Delmia V5©, the movement of worker with objects can be simulated in the virtual environment. These movements include the lifting movement, walking movement, and so on. Software Delmia V5© will record the parameters of movements automatically, such as the distance of the movements, the duration of the movements, and the posture of movement.   Then, a report will be generated for gathering all this parameters. The detailed data will be shown in the following section with the different work cells. Fig 3.3 shows an example of the worker and object and their interaction.

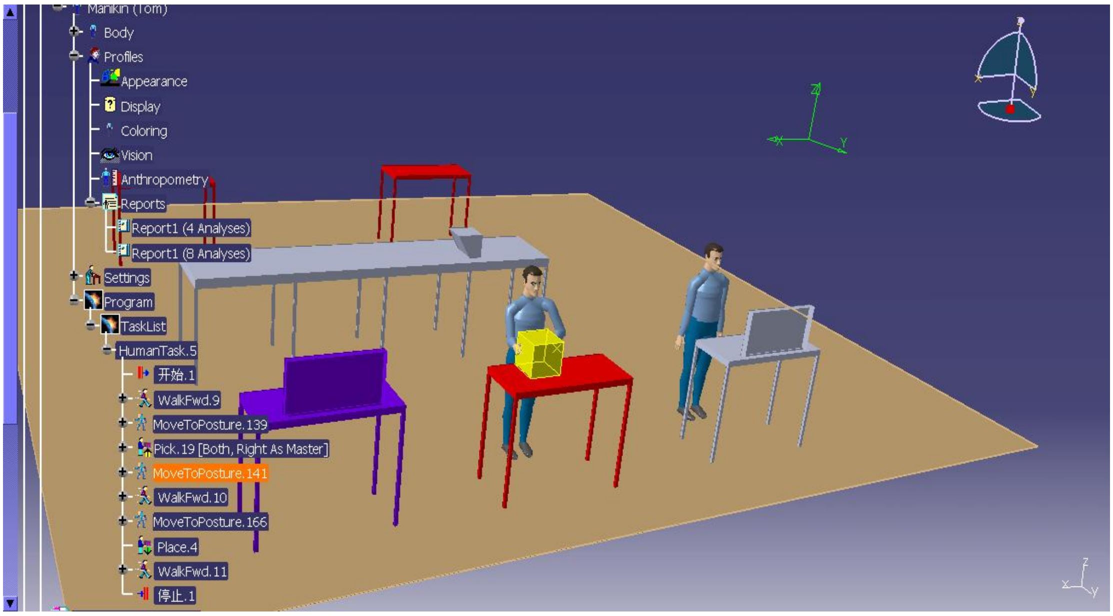


FIG 3.3 THE INTERACTION OF WORKER AND OBJECT

3.4 Assembly Cells Used in This Research

Some cells were identified as having potential risk and thus they need for the injury analysis in this research. In this connection, Cell P4 and Cell P5 which contain the most repetitive work tasks were picked up.

From Fig 3.2, Cell P4 takes the components transported by the hoisting machine from Cell P3. The major task on Cell P4 is tightening the hook component on the row bar. The hook was used to hold row units on row bar. Most of activities on Cell P4 were operated by workers with the hand tool and power tool. In this cell, the row bar was raised up by the hoisting machine. The workers took the hook components from the work table, lifted it up and held it, and then tighten it on the row bar. The corresponding postures of the worker were observed and measured in this study. Table 3.1 shows the recorded postures data in Cell P4

TABLE 3.1 THE PARAMETERS FOR ANALYSIS ON CELL P4

	Duration (sec)	Repeat Frequency (min)	Distance (cm)	Weight (kg)
Carry Component	72.0	> 9	30[b] (Vertical)	5
Move Component	12.23	> 9	1300[c] (Horizontal)	5
Install by Hand	40.17	> 9	60[d] (Vertical)	5
Tighten by Hand	14.39	> 9	60[e] (Vertical)	4

[a] The repeat frequency represents the duration between two postures such as carry posture to next carry posture. [b] The distance is from the hand to the table. [c] The distance is from table to the row bar. [d] The distance is from the hand to the chest. [e] The distance is from the hand to the chest.

Cell P5 follows Cell P4 (see Fig 3.2) and Cell P5 is the final install operation on this part of assembly. The major task on Cell P5 was installing the small row units on the row bar by workers with the hand tool and the power tool. Workers took the small row units from the work tables, lifted them up, and then installed them on the row bar. Due to the weight of the row units, the workers took twisted and bended postures for the holding and installing. These postures were picked for injury analysis. Table 3.2 shows the recorded postures data in Cell P5.

TABLE 3.2 THE PARAMETERS FOR ANALYSIS ON CELL P5

	Duration (sec)	Repeat Frequency (min)	Distance (cm)	Weight (kg)
Carry Component	72.0	> 9	30[b] (Vertical)	10
Move Component	16.23	> 9	1500[c] (Horizontal)	10
Install by Hand	7.17	> 9	60[d] (Vertical)	10
Tighten by Hand	19.39	> 9	60[e] (Vertical)	5

[a] The repeat frequency represents the duration between two postures such as carry posture to next carry posture. [b] The distance is from the hand to the table. [c] The distance is from then table to the row bar. [d] The distance is from the hand to the chest. [e] The distance is from the hand to the chest

CHAPTER 4: Computer Aided Analysis of Work Injury

4.1 Introduction

This chapter presents a software system for computer aided design of production assembly systems for work injury elimination (CADASWIE). Section 4.2 presents the architecture of this system, including major system components and their relations. These components include: Module 1: specification of the information of worker, task, workload; Module 2: work injury analysis and evaluation; Module 3: calculation of work injury cost; and Module 4: synthesis of worker's postures to eliminate work injuries. The implementation of this architecture based on advanced biomechanics and computing technology will also be discussed.

Section 4.3 discusses Module 1 and Section 4.4 discussed Module 2. Module 3 and Module 4 will be discussed in later chapters of this thesis. Section 4.5 presents the application of CADASWIE to the example system of Chapter 3 to show the effectiveness and efficiency of CADASWIE. Section 4.6 gives a conclusion of this chapter.

4.2 Architecture of CADASWIE

The nature of the assembly system is a human-machine system as shown in Fig 4.1. Human workers collaborate with machines to fulfill a task or tasks. Human workers can be generally divided into supervisors and operators. The operator directly operates on parts and machines, while the supervisor monitors the automatic machine to perform the task. The machine can be viewed as an assistant to the human, and this is true as ultimately it is the human who is interested in and benefits from the accomplishment of the task. From Fig 4.1, it can also be seen that to both the machine and human, there is a workload on them, and the execution of the task is subject to this load. The task could directly affect the human worker especially the worker's health and could also indirectly affect the human worker by the operation of the machine. These effects are not only detrimental to the human hut also increase the cost of production. Due to the significant costs from work injuries, design of the assembly system should seriously consider the factor of work injuries.

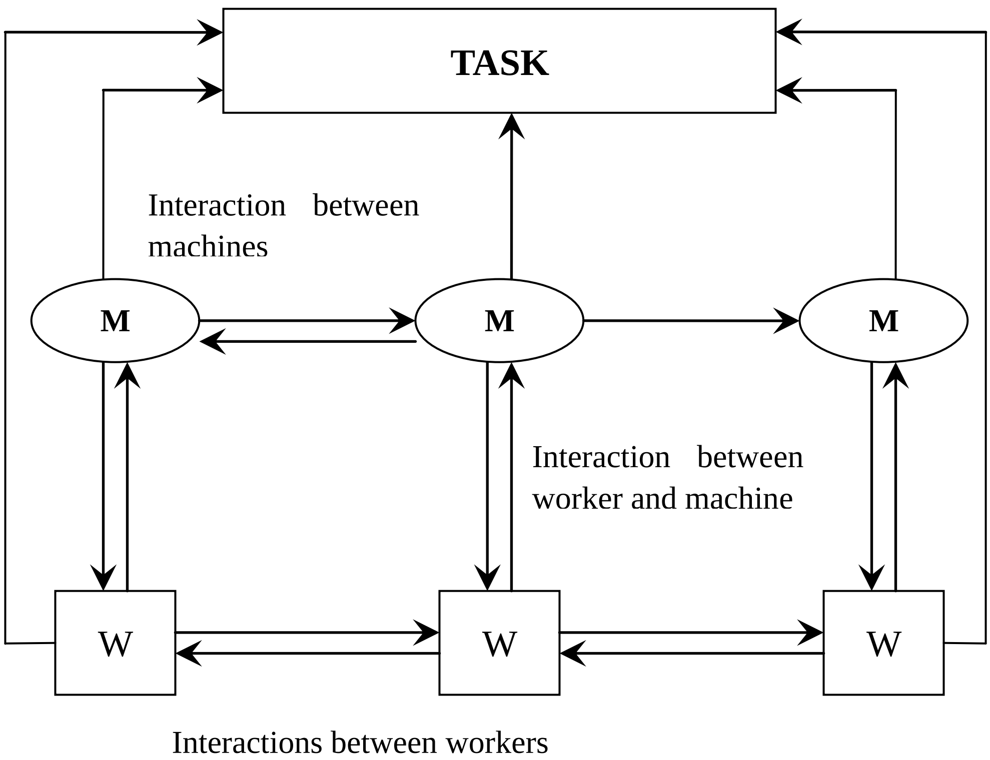


FIG 4.1 THE INTERACTIONS IN ASSEMBLY SYSTEM (W: WORKER; M: MACHINE)

However, both production system design and work injury analysis are complex. There is a high need to apply the computing technology for these design and analysis activities. As a result of this thinking, the software system called "computer aided design of assembly system for work injury elimination" (CADASWIE) was developed in this thesis work. However, in the context of this thesis, CADASWIE will focus on work injury analysis. The requirement of CADASWIE includes: extendibility in terms of functionality, computing device dependency, and interrogating or interfacing capability. As always, the first thing of developing a system is to define its architecture. The architecture of CADASWIE is presented in Fig 4.2. This figure shows that CADASWIE should have the following computer program modules: (1) module for specification of the information of worker, tool, task; (2) module for work injury analysis; and (3) module for synthesis which determines assembly operations – especially worker's postures and movements; (4) module for cost estimation. In the following sections, the first and second modules will be discussed in detail, while, the third module will be discussed in Chapter 5 and the fourth module will be discussed in Chapter 6.

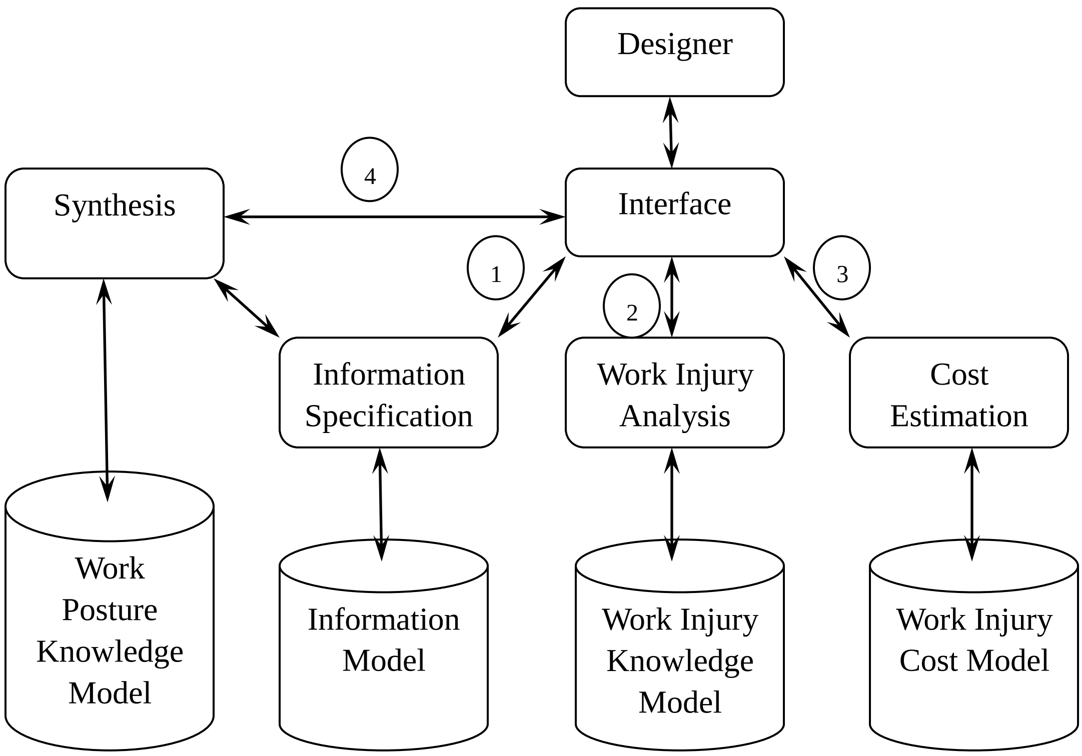


FIG 4.2 ARCHITECTURE OF CADASWIE (NUMBER 1-4 REPRESENTS EACH MODEL)

4.3 Information Model of Worker, Task, and Workload

4.3.1 Conceptual Data Model

The purpose of an information model is to structure information and represent it in a formal way. The formal way means that the model of information is established by following a data or database model (Zhang, 1994). The scope of information in the context of CADASWIE is the information needed for a complete analysis of work injures for a production assembly system. Fig 4.3 is a conceptual data model which captures the semantics of the information needed for CADASWIE.

In any production assembly system, there are machines (e.g., conveyer), loads, humans, and parts, and they are related to each other, as shown in Fig 4.3a. Fig 4.3a describes the assembly system from a point of view of 'part-whole' relationship which is denoted by 'has-a' data abstraction. However, in Fig 4.3a, there is also a description of the generalization (i.e., one entity may be more generalized than other entities); for example, a cell is a kind of machine. The generalization relationship is represented by 'is-a' data abstraction.

Occurrences of the data model of Fig 4.3a are shown below:

In 'Assembly'

< A #1, C#1, WS#2, WK#100, P#2, T#5>

< A #3, C#2, WS#5, WK#102, P#4, T#7>

……

In 'Cell'

<C#1, 'Combine', … , >

<C#1, 'Head', … , >

In 'Worker'

<WK100, 'Forrest', …,>

In the above, 'A#1' stands for the assembly system ID; this applies to 'C#1', 'WS#2' and so on. Each entity in the data or database model gets a unique ID. Fig 4.3b represents the 'interaction' or 'association' or 'connection' among the entities of the assembly system (i.e., part, cell, work station, worker, and tool). The word ‘relationship’ is used for interaction, association, and connection in order to embody all different types of relationships. It is particularly noticed that ‘part’ is a central player in the assembly system, which further implies a scenario where the machine, worker, and tool serve as “infrastructure”, and the part “flows” over the infrastructure.

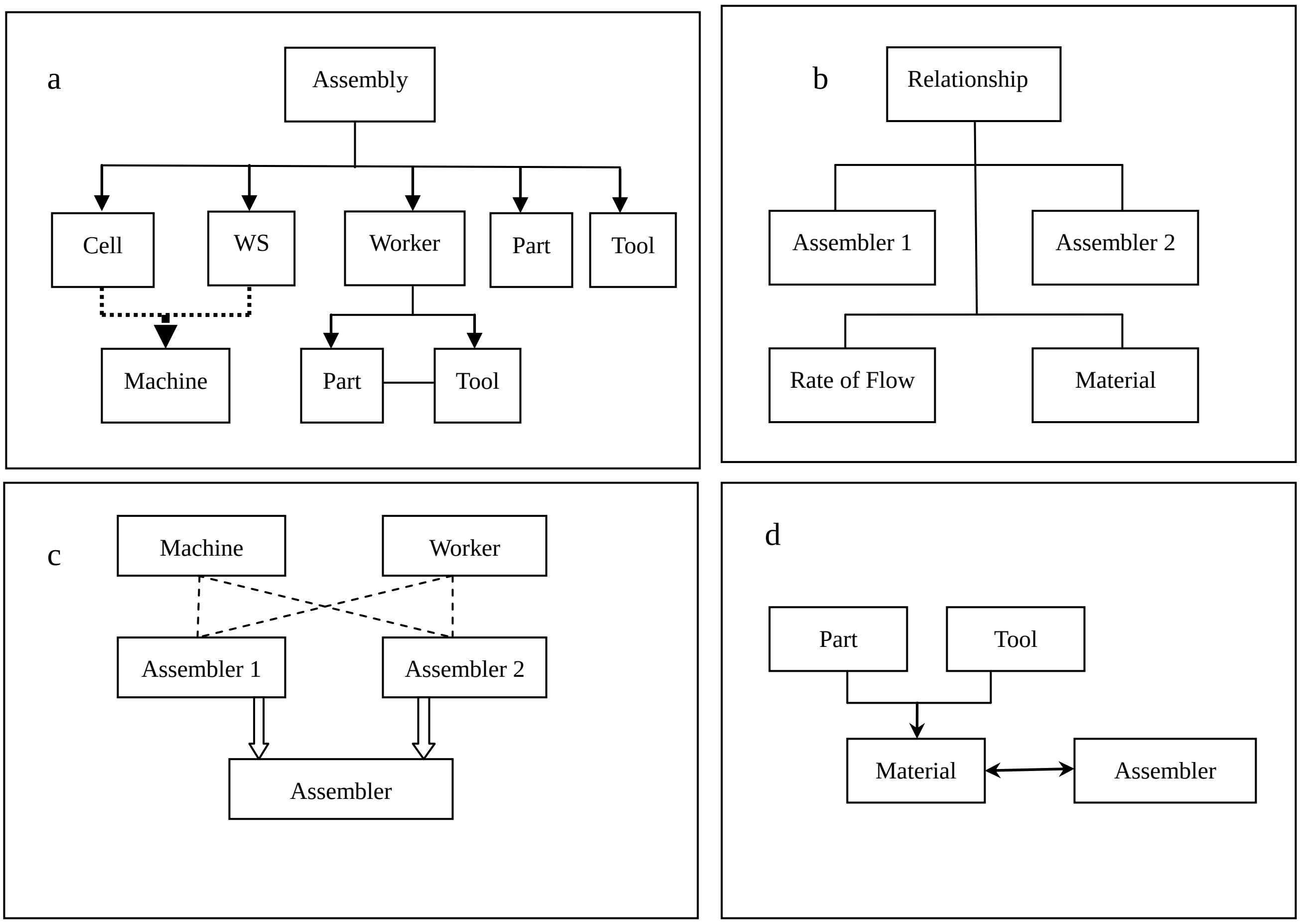
Occurrences of the data mode of Fig 4.3b are shown below:

< R#1, A#1, A#2, M#3, ‘100s’ >

< R#2, A#2, A#3, M#3, ‘200s’ >

……

In the above, ‘s’ in ‘100s’ or ‘200s’ stands for second. The two occurrences depict that three assemblers (#1, #2, #3) are connected in series. Assemblies can be connected, with respect to a particular material, into a network topology, and this can be represented by writing the occurrences of the data model properly. Fig. 4.3c further describes that the assembler can be either the machine or worker. Fig 4.3d expresses that material can be either part or tool.



↔ 'MANY TO MANY ASSOCIATION'; → 'IS-A'; ⇢ 'HAS-A'; ⇨ 'HAS-TYPE-OF'

FIG 4.3 CONCEPTUAL DATA MODEL

With the above data model, along with the personal database that is available to any manufacturing organization, a complete computer model of the assembly system can be established. This model is essential to the application of the computing and information technology to the assembly system design construction, and management with consideration of human factors.

4.3.2 Implementation

The implementation of the conceptual information model is described as follows. The software system called Solidworks© was used to construct components or subsystems to be assembled and tools to be used by the human worker. Solidworks© is a powerful Computer Aided Design (CAD) software system. The component constructed with

Solidworks© needs to be stored in the IGES format in order to be interrogated by other program systems such as the Delmia V5© software which fulfills biomechanics analysis and work injury analysis. It is noted that currently there is a problem of inconsistency between Solidworks© and Delmia V5© in the definition of the reference coordinate system. In particular, the reference coordinate system in Solidworks© is to take the left-upper corner as the origin, while Delmia V5© takes the left-lower corner as the origin. To resolve this inconsistency, modeling with Solidworks© should follow the coordinate system of Delmia V5©, because eventually, the part created in Solidworks© needs to be imported into Delmia V5©.

Fig 4.4 shows an example modeled with Solidworks©.

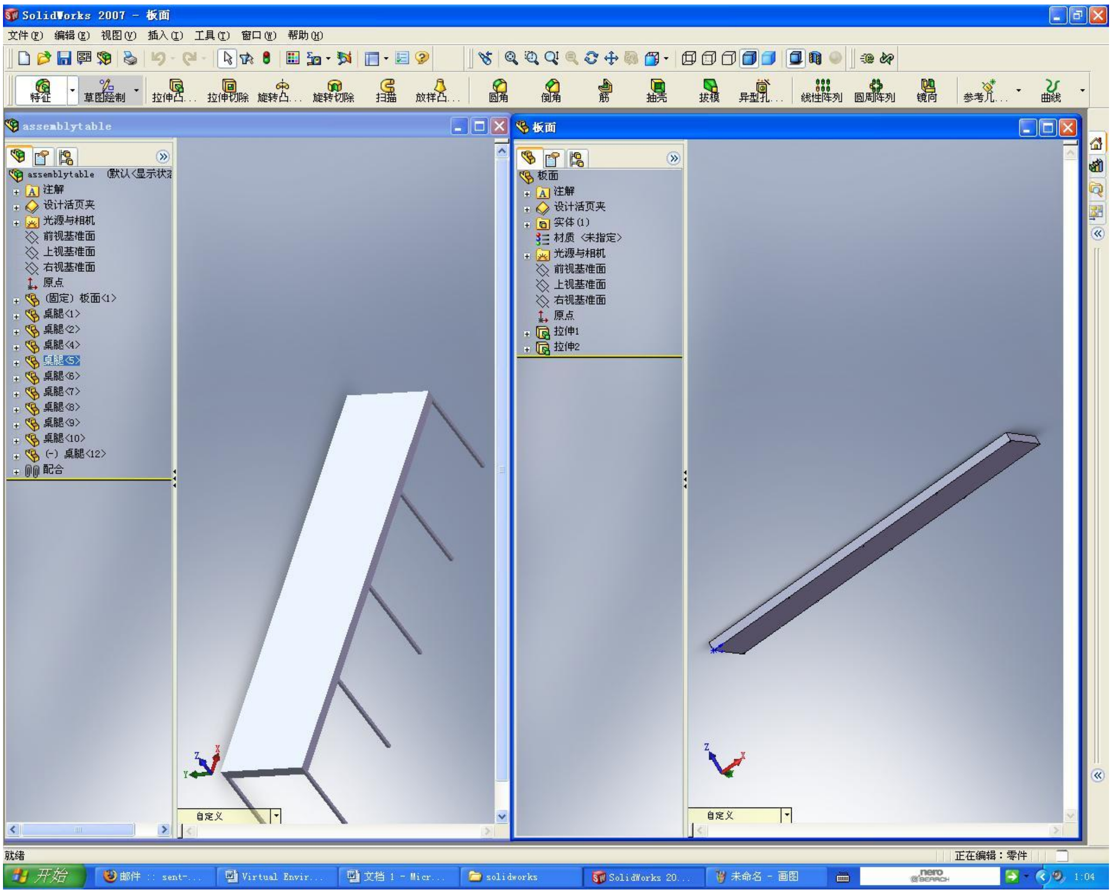
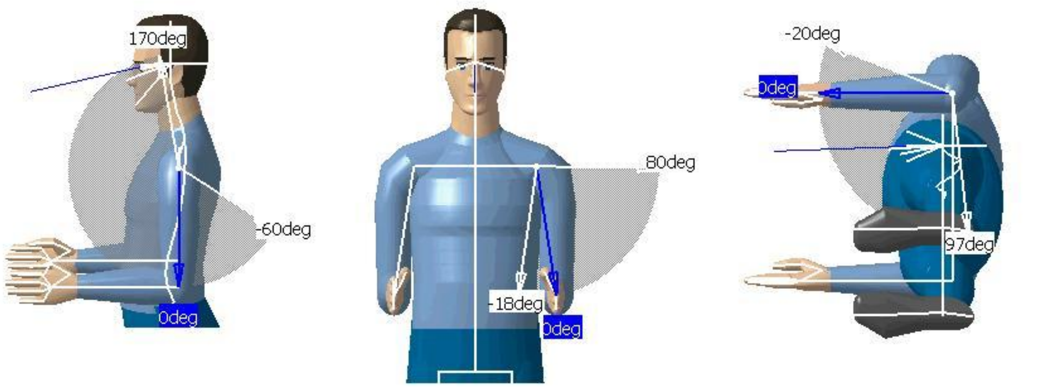


FIG 4.4 AN EXAMPLE MODELED WITH SOLIDWORKS©

The human biomechanics model was implemented by Delmia V5©, in particular the so-called ‘manikins’ model. The Delmia V5© software contained the human model with as many as 99 independent links, segments, and ellipses. The module or tool for building the human model in Delmia V5© was called ‘Human Builder’. The human builder (HB) module needs the parameters from the user, such as name, gender, population and percentile of the range of strength. In most occasions, the anthropometric value of 50^{th} percentile for men or 75^{th} percentile for female was used to ensure that a large population is accommodated in the analysis (Emodi, 2007). Also, the detailed worker anthropometry data such as the length of leg, length of arm and so on could be calculated by the human builder module. Nevertheless, the human builder module could generate the manikin shape automatically according to the percentile and gender chosen by user. The human builder module offered a tool for kinematics of a human worker.

Kinematics is a scientific method used in manipulating segments attached to joints. Human body can be viewed as a robot with various segments connected with various joints. In Delmia V5©, segments or joints are attached with two or three possible Degrees of Freedom (DOF). Three kinds of DOF were represented in the Delmia V5© software: (1) Flexion/Extension; (2) Elevation/Depression; (3) Dorsiflexion/Plantar Flexion which are shown in Fig 4.5, respectively. Kinematics movements should be restricted to the limits of three DOFs of each segment.

The human builder module offers the function to allow the user to drag on the appropriate body segment to the interface window to obtain the desired posture. Also it allows the user to change the angular position of the segment by directly giving values.



Flexion/Extension Elevation/Depression Dorsiflexion/Plantar Flexion

FIG 4.5 THREE KINDS OF DEGREES OF FREEDOM IN DELMIA V5©

However, the human builder module offered by the Delmia V5© had the following limitations: (1) the age of worker was not included, and (2) the way of specifying the DOF was not quite user-friendly.

4.3.3 Information Integration

The integration of the information of worker, parts, and tools was implemented by Delmia V5© – in particular Environment Lay-Out module. This module can accept the data formats such as (1) STEP AP203/AP214 format, (2) IGES format- IGES Interface (IG1) product, (3) V5 - IGES Interface (IG1) that helps users working in a heterogeneous CAD/CAM environment to exchange data through a neutral format, (4) DXF/DWG format- Generative Drafting Products, (5) CGM format- Object Manager Products, (6) STL format- Object Manager Products. STL concerns stereolithography document (.STL), and (7) STRIM/STYLER.

The Initial Graphic Exchange Specification (IGES) format was the most popular format to transfer data between heterogeneous CAD systems. Users can perform bi-directional data exchange between dissimilar systems with the direct and automated access to IGES files (Delmia V5©). When Solidworks© create an IGES file, it is first modified by Delmia V5© to a file called 'CATPart'. Further, in the

Environment Lay-Out module, all objects (workers, parts, and tools) can be further edited for their relationships.

4.4 Work Injury Analysis Module

4.4.1 Assembly System Simulation

Delmia V5© had an activity simulation module which allowed simulating all the human activities on the assembly system. These activities are: (1) Walking; (2) Moving to posture; (3) Picking; (4) Placing and (5) Climbing. These activities can be combined to generate a complex assembly task. Also, the activity simulation included the tool models and product models. Each activity was designed separately, and then all of them were integrated. More detailed information for each activity design is discussed further in the following.

For the walk activity design, the user can drags the human manikin to the initial position or specifies the initial position by directly giving values. Then, the user needed to specify the activity plane which was defined as the walking floor. The trajectory of the worker can be specified either graphically or directly giving values. The path of the walking activity can be designed by dragging the human manikin to the desired position or specifying the coordinates of the trajectory value. It is facilitated to design a trajectory of forward and backward or reciprocating movement. The strokes of movements were the same for the forward and backward motions in default. A round trajectory can be designed. For the pick and place activity design, the user can specify the position and orientation of the manikin either by directly dragging the manikin or specifying values.

The simulation results in (1) the movement history and (2) the time of the movement. It is possible to have two ways to gather this information from the simulation and they are described below: (1) capture the motion during the simulation and (2) analyze the posture during the simulation. For both methods, data can be directly read and used by the injury analysis tool. The data can be easily traced by the user as well. The other convenient option of Delmia V5© was that all the designed activity simulation can be compressed in a video format (ACC) and stored in the tool library for reusing or analyzing later.

Currently, the limitation of the Delmia V5© is such that there are some difficulties in specifying the assembly activities that demand the basic operations such as setting and holding.

Fig 4.6 gives a general procedure to simulate the worker's movement activity.

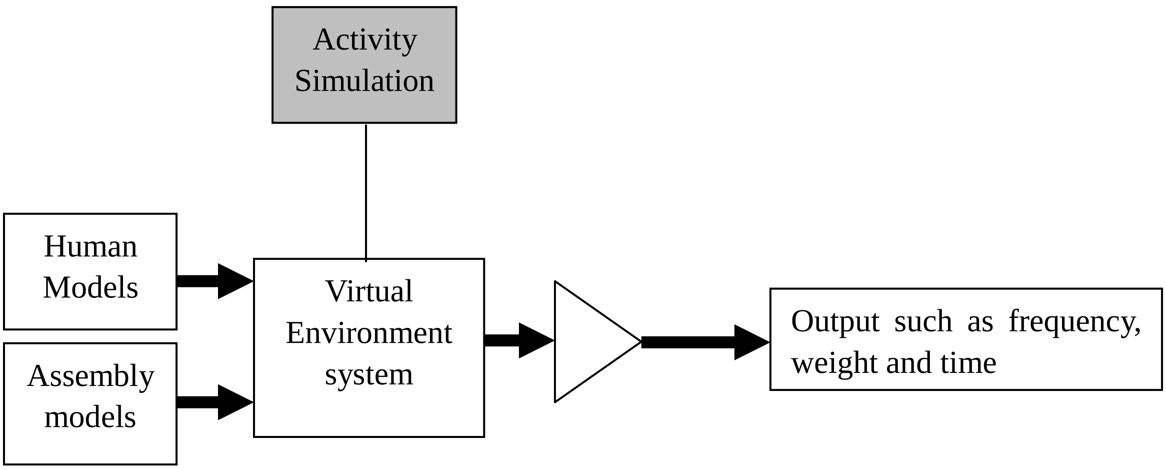


FIG 4.6 THE GENERAL PROCEDURE OF INFORMATION MODEL

4.4.2 Work Injury Classification

The work injury classification will be fulfilled by algorithms or procedures that may make use of the work injury knowledge model. It may be more convenient for the following discussion to put the knowledge model and the algorithms together with a name "knowledge-based system" for work injury analysis or classification. Fig. 4.7 gives an input-output perspective of this knowledge-based system in which the biomedical model may need some attention. The biomedical model represents an approach to classify work injuries based on a more rigorous analysis of the physical and/or chemical state of the human, and it will be discussed later in Section 4.4.2.2.

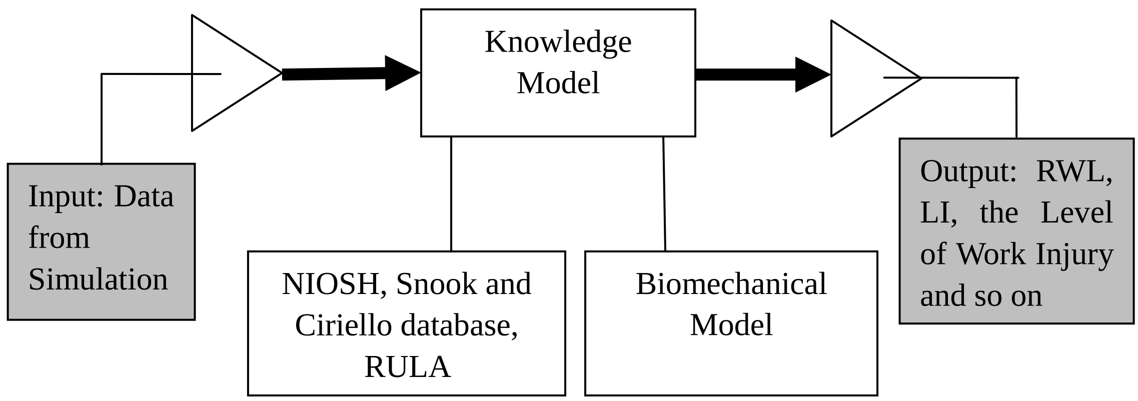


FIG 4.7 KNOWLEDGE-BASED SYSTEM

4.4.2.1 Work Injury Analysis Based on Empirical Databases

The RULA module takes the parameters such as gender, population and posture as input and comes out the level of work injuries. The RULA assigns a score to each level of a particular injury, ranging from 1 to 7 (1: lowest; 7: highest).

The lift activity analysis module was to analyze the lifting task, which is guided by the NIOSH equation (NIOSH 1981 and NIOSH 1991) and Snook and Ciriello database. The NIOSH equation (i.e., Equation 2.7) is used to calculate the Recommendation Weight Limit (RWL) and Limit Index (LI). If the calculated LI is greater than 1, the current lifting task is deemed to be unsafe. The detailed steps of lift activity analysis are as follows: (1) Identify the lifting task and obtain the current work load, (2) Gather the input parameters such as the horizontal component (H), vertical location (V), distance component (D), coupling component (C), and asymmetric component (A) from the activity simulation; see also the discussion in Section 2.3.1, (3) Obtain RWL for the particular lifting task under study, (4) Compare the current workload and the RWL. If the calculated LI is greater than 1.0, the concerned activity is unsafe.

The carry activity analysis module was for the carrying task. This is done with the help of the Snook and Ciriello database. The input parameters of this module are the frequency and distance of carrying. The output of this module is the recommended maximum acceptable weight for the worker who is performing the particular carrying task.

The push and pull analysis module was to analyze the pushing and pulling task. This is done with the help of the Snook and Ciriello database. The input parameters for this module are: the distance and frequency of the pushing or pulling task. The output is the recommended maximum acceptable initial force and the maximum acceptable sustained force in a particular pushing or pulling task.

The aforementioned analyses of work injuries in terms of various types of tasks have not been able to point to a particular body area of injuries and not considered individual profiles of workers such as age. The biomechanics oriented analysis may overcome these limitations; see the next section.

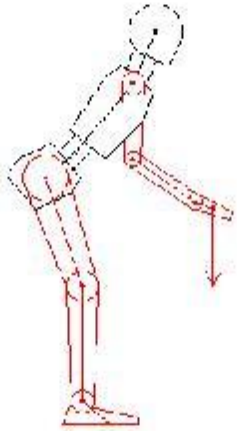
4.4.2.2 Work Injury Analysis Based on Biomechanical Analysis

The biomechanical single action (BSA) module was for a more detailed analysis of work injuries; in particular the analysis of individual organs under a workload. Parameters of the BSA module are: weight, gender, percentile, population and anthropometry data of a captured posture from the activity simulation module. The outputs of the BSA module are the information such as the lumbar spinal loads (abdominal force, abdominal pressure, and body displacements), and forces and moments on joints (Delmia V5©, 2007). This information was further presented in association with the L4-L5 Moment, L4-L5 Compression, and L4-L5 Joint Shear (see Fig 4.8).

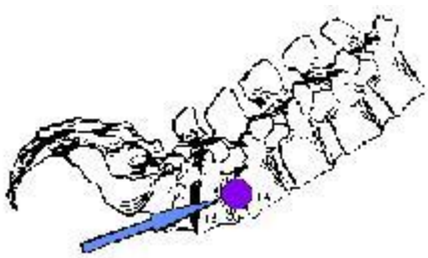
L4-L5 Moment describes the moment created at L4-L5 (point) of human body due to the mass of body and the workload force which acts upon the hand of the worker (UW Ergonomics, 2001). To maintain stability, or static equilibrium, the worker must actively resist the load moment created by these forces by activating his/her trunk muscles (UW Ergonomics, 2001). Fig 4.8 displays the L4-L5 Moment. The extensor moment of L4-L5 is expressed as a positive and the flexor moment of L4-L5 is expressed as a negative.

L4-L5 Compression represents the compressive force on L4 and L5 vertebrae. The force acting upon the hands and trunk muscles or ligaments is used to generate the support moment (UW Ergonomics, 2001). Fig 4.8 shows the compressive force acting upon L4-L5 intervertebral joint.

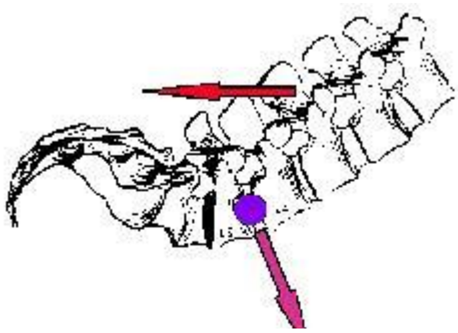
L4-L5 Joint Shear represents the shear force in the area of L4-L5 joint. This shear force affects the capability of the muscle (or ligament) to resist the shearing (UW Ergonomics, 2001). Fig 4.8 shows the shear force on L4-L5 disc.



L4-L5 Moment



L4-L5 Compression



L4-L5 Joint Shear

FIG 4.8 MOMENT, COMPRESSION AND JOINT SHEAR (UW ERGONOMICS, 2001)

The steps of the BSA analysis are presented as follows: (1) Identify the required posture for a BSA analysis, acquire the input parameters from the activity simulation, and enter them into the BSA module, (2) Perform the BSA analysis to that specified posture, (3) Identify the hazards in the worker’s body and give recommendations in conjunction with the RULA analysis.

One of the important applications with the BSA analysis is to identify the back pain and injury which were quite common in many repetitive work situations. Currently, the BSA analysis did not consider the age factor.

4.5 Case Study

The example system described in Chapter 3 is used here to demonstrate how CADASWIE works. Not a complete assembly system of example system was covered here, while a complete analysis of the example system is found in Appendix B. In the following, first, a summary of the steps for work injury analysis with CADASWIE is revisited, and then selected assembly activities are analyzed with CADASWIE to examine their work injury.

4.5.1 Summary of the Work Injury Analysis with CADASWIE

Step 1: Data collection

In this step, data of the assembly system or part of it are collected, which include the characteristic of human workers, such as the gender, population, anthropometry, workload of the task such as the frequency of the operation, weights of parts and tools, trajectory of the operation, break time between every two operations.

Step 2: Assembly system model creation

In the current version of CADASWIE, the Solidworks© CAD software was used to create each assembly model, product model, and tool model. All these models were stored in the 'IGES' format.

Step 3: Human worker model creation

In the current version of CADASWIE, Delmia V5© was used, in particular its module Human Builder. Input information in this step includes: the age, gender, population and percentile (75th percentile for male and 50th percentile for female), and output information of this step is the initial posture of the worker.

Step 4: Models integration

In the current version of CADASWIE, the Environment Lay-Out option of Delmia V5© was used to bring together the assembly model, component model, tool model and basic environment model.

Step 5: Simulation of the worker's activity

In the current version of CADASWIE, the activity simulation module in Delmia V5© was used to generate the manikin' activity in the virtual environment. The activities include walk, pick and place, and climb.

Step 6: Work Injury analysis result data collection

During the activity simulation in Step 5, the concerned postures of the worker are captured. All information associated with these postures was stored for the subsequent work injury analysis.

Step 7: Work injury analysis

This step includes the following four steps.

Step 7.1: Use the activity analysis module in Delmia V5© and the NIOSH guideline to determine the Recommendation Weight Limit (RWL) and the Limit Index (LI). If LI is over 1.0, the actual workload is unsafe for the concerned human worker.

Step 7.2: Use the activity analysis module in Delmia V5© and the Snook and Ciriello database to perform the push and pull analysis, carry analysis, and lift and lower analysis with the input parameters such as frequency, distance of operation, and duration of operation. The output of this analysis will be the recommended weight or force for the push, pull, carry, lift and lower tasks.

Step 7.3: Use the posture analysis module of the RULA in Delmia V5© to obtain the scores for both the posture and individual body group. The scores represent the level of work injuries for each segment of body, as well for the individual body groups.

Step 7.4: Use the biomechanical single action analysis module of Delmia V5© to obtain the internal forces, external forces, and moments acting on the worker while carrying out the various assembly activities.

4.5.2 Analysis of Selected Assembly Components

CADASWIE was applied to the assembly system which was described in Chapter 3. The following begins with the generation of information model and ends with the result of work injury analysis for the example system.

Fig 4.9 shows a component called ‘assembly table’ of the example system, and Fig 4.10 shows a tool called ‘power screw driver head’ of the example system. The two models are stored in the IGES format.

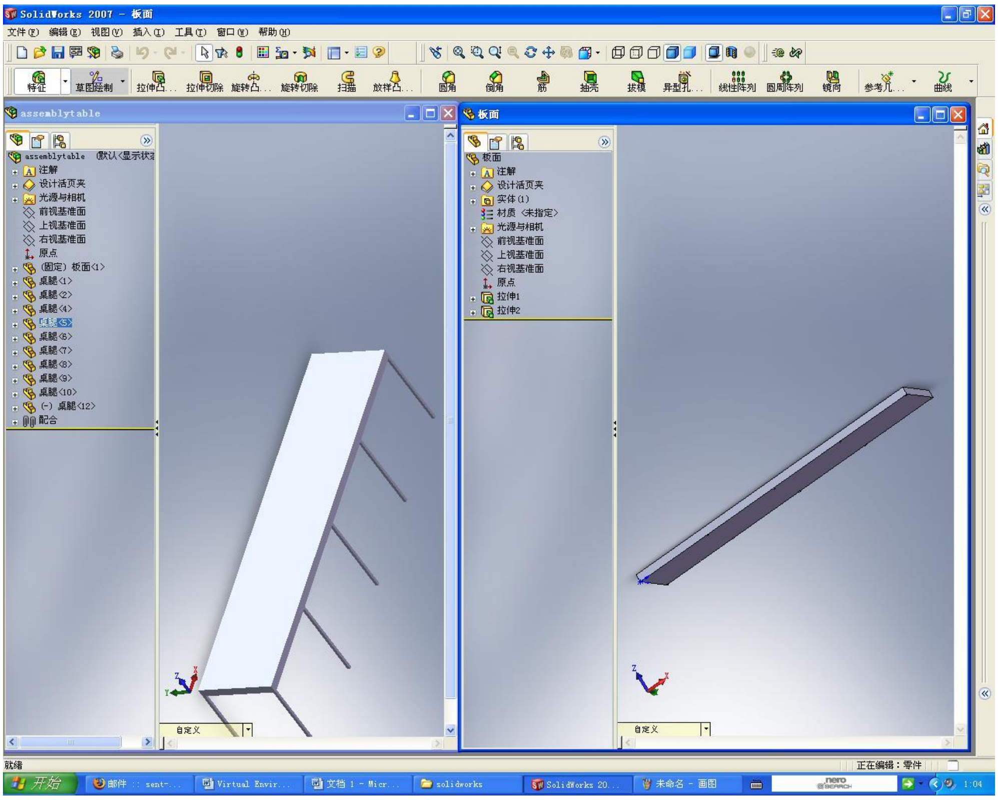


FIG 4.9 MODELING OF ASSEMBLY TABLE IN SOLIDWORKS©

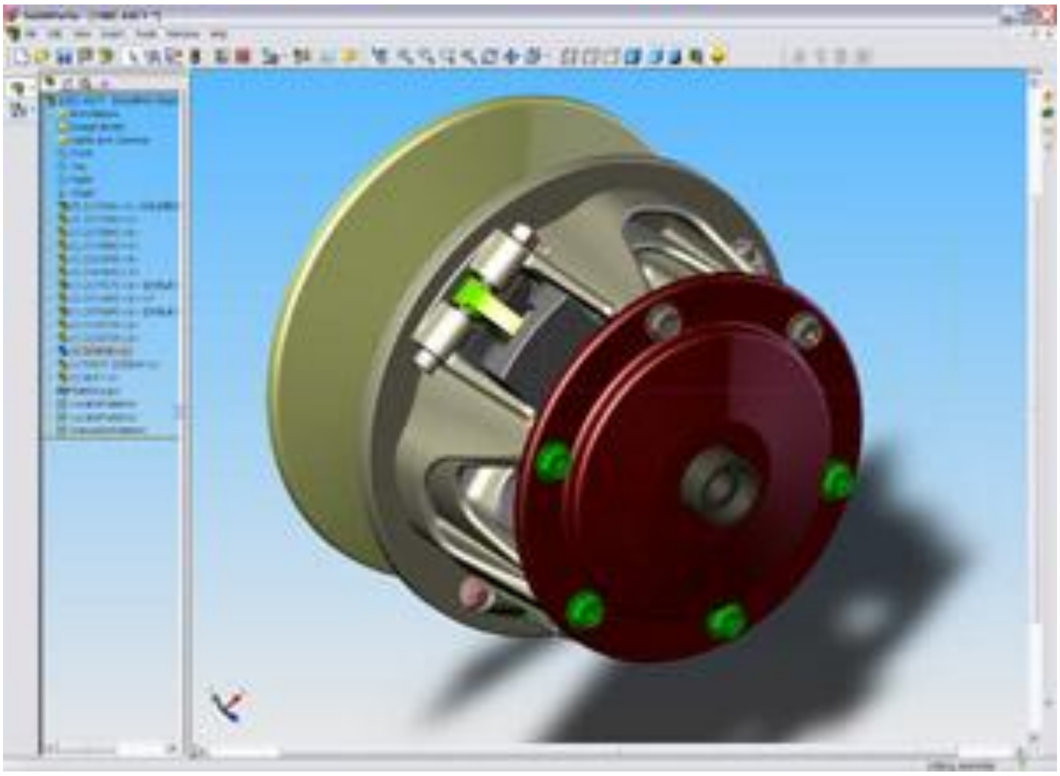


FIG 4.10 POWER TOOL MODELING IN SOLIDWORKS©

The worker information will be described by the human builder module. With the input parameters such as age, gender, population and percentile, the worker model is created. The anthropometry data was given to CADASWIE to generate the manikin with the detailed anthropometry measurement. According to the assembly requirement, the initial posture for the activity can be created by the kinematics method. Table 4.1 gives the parameters of the workers for the creation of the human worker model. Three people were considered.

TABLE 4.1 INPUT PARAMETERS FOR MANIKIN CREATION

Name	Gender	Population	Percentile
Forrest	Male	Canada	75%
Tom	Male	Canada	75%
Tracy	Female	Canada	50%

The assembly models, product components models, and tool models were imported into Delmia V5© and automatically converted to the format of 'IGES' to 'CATPart'. The assembly models and worker models were integrated into a simulated assembly system. Fig 4.11 shows a part of the virtual environment where the human worker models, components models and tool models are brought together.

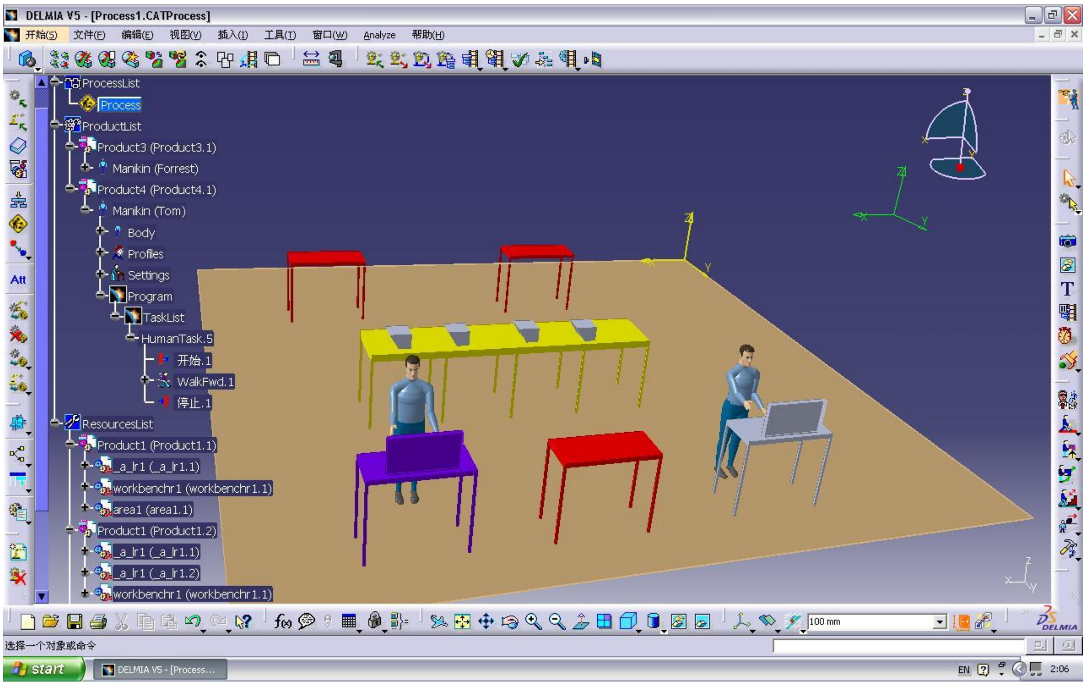


FIG 4.11 PART OF VIRTUAL ENVIRONMENT SYSTEM

In this example system, there are six activities required for work injury analysis, and they are: installing and tightening the rows on the combine header bar, moving the exterior component to the work station, installing three kinds of components on rows. The task of installing and tightening the rows into the combine header bar can further be divided into the tasks of walking to the row components storage table, picking up the row components, walking to the tool station, picking up the tools, walking to the work station, installing and tightening the row components, and walking back to the row components storage table.

The simulation was performed by specifying a time increment or continuously. The simulation result was saved in the ‘ACC’ file. The simulation result can be played back on other media system (e.g. video).

4.5.3 Work Injury Analysis

The work injury analysis for the selected activity is presented below.

(1) RULA Injury Analysis

The RULA analysis was applied to twelve postures. The information of these postures has been available through the aforementioned steps. The output of the RULA analysis gives the level of work injury. The level is given by number: ‘1-7’. The number ‘1’ represents the lowest level of work injury which is associated with ‘green’ color, while the number ‘7’ represents the highest level of work injury which is associated with ‘red’ color. In Delmia V5©, the ranges of levels of work injuries are not the same for segments of the human body, and they depend on different tolerances for each segment of the human body. The tolerance is from the previous injury experiments research (Delmia V5©, 2007). Table 4.2 and Table 4.3 show the classification of levels of work injuries for each segment of the human body.

TABLE 4.2 CLASSIFICATION OF LEVELS OF WORK INJURY

Segment	Upper Arm	Forearm	Wrist	Muscle	Wrist/ Arm	Neck	Trunk	Leg	Neck/ Trunk/ Leg
Level	1-6	1-3	1-4	1-2	1-7	1-6	1-6	1-7	1-7

TABLE 4.3 CLASSIFICATION OF COLOR

RED	change immediately	7
ORANGE	change soon	5, 6
YELLOW	investigate further:	3, 4
GREEN	Acceptable	1, 2

Table 4.4 shows the input parameters to and the result of the RULA analysis module. From this table it can be seen that one of these postures (Cell P4) is required to change immediately. Table 4.5 shows details of the results of the RULA analysis on

this risk posture.

Table 4.4: RULA ANALYSES INPUT AND RESULTS

Name	Posture	Repeat freq.	Arm supported/ person leaning	Arms working across midline	Load (kg)	Score	Description
Forrest 1	Intermittent	<4Times/min	_	_	0	2	Acceptable
Forrest 2	Static	>4Times/min	Yes		1	5	Investigate further and change soon
Tom 1	Repeated	>4Times/min	Yes	_	5	5	Investigate further and change soon
Tom 2	Static	<4Times/min	_	yes	5	7	**Investigate further and change immediately**
Tracy 1	Static	>4Times/min	Yes	yes	5	5	Investigate further and change soon
Tracy 2	Intermittent	<4Times/min	Yes	yes	5	5	Investigate further and change soon

TABLE 4.5 SCORES FOR EACH SEGMENT OF BODY

Component of Body	Scores	Classification Color
Upper Arm	2	
Forearm	1	
Wrist Twist	3	
Posture A	2	
Muscle	1	
Force/Load	2	
Wrist and Arm	3	

Component of Body	Scores	Classification Color
Neck	4	
Trunk	5	
Leg	1	
Posture B	1	
Neck, Trunk and Leg	3	
Final Scores	7	

(2) Lifting and Lower Analysis

Table 4.6 presents the input parameters for the lifting and lower analysis, and Table 4.7 gives the result of the analysis.

It can be observed from the result of this analysis that the recommended weight limit of Lifting and Lower Analysis is 4.506kg, while the actual weight of the component operated by the human worker is 5kg. So the LI comes out with 1.11, which means that this lifting operation is unsafe for the concerned human worker.

TABLE 4.6: LIFTING AND LOWER ANALYSES INPUT

Guideline**:** NIOSH 1991	
Mass of component	5kg
1 lift every	180secs
Duration of Lift	1hr or less
Coupling condition	Good

TABLE 4.7 OUTPUT OF LIFTING AND LOWER ANALYSIS

Tom2	Lift Time	Duration	Object Weight	population	Action Limit	Maximum Limit	RWL	LI	MAW
NIOSH1981	5	<1hour	N/A	N/A	4.263kg	12.778kg	N/A	N/A	N/A
NIOSH1991	5	<1hour	5kg	N/A	N/A	N/A	4.506kg	1.11	N/A
SNOOK	5	<1hour	N/A	75%	N/A	N/A	N/A	N/A	131.98N

(3) Push and Pull Analysis

Table 4.8 presents the input parameters for the Push and Pull Analysis, and the result from the analysis.

From Table 4.8, the maximum initial force and the maximum sustained force are 269.07N and 135.208N, respectively. This gives a limit for the human worker to access this push and pull operation. However, the force limit used as scale to determine the work injury was unsuitable, because (1) the measurement of initial force and sustained force by means of the spring scales was difficult to apply to the worker; (2) the worker was hard to control their push or pull force as required. Therefore, the maximum weight was applied in this project. By considering the friction between the components and floor, the maximum forces were further converted into the weights. The friction index was assumed as 0.5 in this case. The formula to calculate the weight is given below:

$$F = M \times g \times \mu \tag{4.1}$$

Where F represents the push or pull force;

M represents the weight of object;

g represents the acceleration of gravity; and

μ represents the friction index.

According to Equation 4.1, the expected weight of components for maximum initial force is no more than 54kg, and the expected weight of components for maximum sustained force is no more than 27kg.

TABLE 4.8 INPUT AND OUTPUT PARAMETERS OF THE PUSH AND PULL ANALYSIS

Forrest 1	Push Duration	Distance of Push	Distance of Pull	Population	Maximum Initial Force	Maximum Sustained Force	Maximum Initial Weight	Maximum Sustained Weight
SNOOK	3600s	2133.6mm	206mm	75%	Push 269.07N Pull N/A	Push 135.208N Pull N/A	54 Kg	27

(4) Biomechanical Single Action Analysis

The result of biomechanical single action analysis is shown in Table 4.9 to Table 4.13.

From Table 4.7a, the L4-L5 Moment is 67 (N-m) which is calculated from the BSA module. From the carry analysis, LI is greater than 1 means that the workload is over the recommended weight. Using the recommended weight (4.506kg, form Table 4.14), the L4-L5 moment can be obtained which is 47 (N-m) by the BSA module. Therefore, the worker took higher resistive moment on the worker's trunk.

The L4-L5 Compression in Table 4.7a is 1535 (N) which is the larger force between the L4-L5 disc. From Table 4.14, with the recommended weight applied to hand, the L4-L5 Compression is 1204 (N) (see Table 4.14). Therefore, the force 1535 (N) indicates that the worker has to generate a large support force on trunk due to the heavy work load attached on the hands of the worker.

Also in Table 4.7a, it shows that the Joint Shear is 51 (N) which affects the muscles on worker. Using the recommend weight (4.506kg, form Table 4.14), the joint shear force can be obtained which is 51 (N) (see Table 4.14). According to the RULA analysis, the level of work injury on the muscle is green (see Table 4.5), which implies no work injury there. This conclusion is also supported by the small difference between 50 (N) and 51 (N) in Table 4.14.

TABLE 4.9 L4-L5 INFORMATION IN BIOMECHANICAL SINGLE ACTION ANALYSIS

Analysis	Value
L4-L5 Moment (N-m)	67
L4-L5 Compression (N)	1535
Body Load Compression (N)	430
Axial Twist Compression (N)	0
Flex/Ext Compression (N)	87
L4-L5 Joint Shear (N)	51 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N-m2)	0

TABLE 4.10 GROUND REACTION (N) IN BIOMECHANICAL SINGLE ACTION ANALYSIS

Total (X)	0
Total (Y)	0
Total (Z)	803
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	194
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	609

TABLE 4.11 SPINE LIMIT DATA TAB IN BIOMECHANICAL SINGLE ACTION ANALYSIS

Forces	Value (N)
Compression Limits	535
Joint Shear Limits	31 Anterior

TABLE 4.12 JOINT MOMENT STRENGTH DATA TAB IN BIOMECHANICAL SINGLE ACTION ANALYSIS

Joint	DOF	Moment (N-m)	% Pop.	Not Capable	Mean (N-m)	Reference
Right Elbow	Flexion-Extension	3 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	7	2	Askew, An, Morrey and Chao (1987)
Left	Flexion-Extension	3 Flexion	0.0	71	15	Askew, An,

Elbow						Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	4 Extension	0.0	90	20	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Abduction-Adduction	0	0	72	28	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	0	0.0	27	9	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Left Shoulder	Flexion-Extension	6 Extension	0.0	69	14	Koski and McGill (1994)
	Abduction-Adduction	0	DNA	DNA	DNA	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Lumbar (L4-L5)	Flexion-Extension	5Extension	0.0	369	69	Troup and Chapman (1969)
	Right-left lateral bend	1 Right Lateral Bend	0.0	143	40	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	0	0.0	72	20	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

TABLE 4.13 SEGMENT POSITION TAB IN BIOMECHANICAL SINGLE ACTION ANALYSIS

Segment	Proximal Coordinated (mm)	Distal Coordinates (mm)	XY plane angle	YZ plane angle	Length

Right Foot	11228.398,8351.727,-800.999	11233.827, 8475.502, -848.890	-22.9	-43.7	132.829
Right Leg	11202.978, 8374.100, -386.780	11228.398, 8351.727, -800.999	-94.2	-87.9	415.600
Right Thigh	11176.202, 8397.668, 49.555	11202.978,8374.100, -386.780	-94.2	-87.9	437.791
Left Foot	10982.570, 8321.818, -803.299	10935.262, 8438.459, -845.728	-18.6	-92.0	132.829
Left Leg	10996.293, 8327.193, -387.961	10982.570, 8321.818, -803.299	-90.0	-92.0	415.600
Lift Thigh	11010.749, 8332.856, 499.555	10966.293, 8327.193, -387.961	-90.0	-90.0	437.791
Right Hand	1151.659, 8701.524, 227.043	11122.333, 8796.776, 236.369	5.4	51.4	100.100
Right Forearm	11222.309, 8456.298, 227.020	11151.659, 8701.524, 227.043	0.0	0.1	255.200
Right Arm	11227.804, 8403.109, 525.204	11222.309, 8456.298, 227.020	-80.2	-87.3	302.904
Left Hand	10849.552, 8635.662, 236.346	10825.234, 8730.795, 216.898	-11.3	-58.2	100.100
Left Forearm	10832.692, 8381.660, 254.397	10849.552m, 8635.662, 236.346	-4.5	-9.5	255.200
Left Arm	10964.152, 8349.208, 518.830	10832.692, 8381.660, 254.397	-67.3	-110.3	302.940

TABLE 4.14 BIOMECHANICAL SINGLE ACTION ANALYSIS WITH RECOMMENDED WEIGHT

Weight of Workload	L4-L5 Moment (N-M)	L4-L5 Compression (N)	Joint Shear (N)
5Kg	67	1535	51
4.506Kg	47	1204	50

4.6 Summary and Conclusion

In this chapter, a computer software system that allows for the analysis of work injuries in the context of a whole assembly system was presented. This system is called CADASWIE. In particular, this system provided a facility for the assembly system designers to create a complete assembly system in a virtual environment and to simulate various assembly activities. The system subsequently allowed the designers to specify a particular worker on a particular assembly cell for work injury analysis. The system provided a diagnosis report for various work injuries on various parts of the body and their levels of seriousness. A case study was provided to illustrate how CADASWIE works. A more complete analysis of an existing assembly system of the ABC company was done, providing useful information about work injuries to the ABC company.

There are a couple of conclusions that can be drawn from the study presented in this chapter: (1) it is possible to create an open and flexible computer aided design and management system for production assembly systems with the current computing technology in biomechanics, (2) Delmia V5© is a very good software system, and together with Solid Work it can well achieve the goal stated in the first conclusion, and (3) Delmia V5© has a few places that need to be improved, including the provision of more types of primary activities of human workers and of more user-friendly interfaces for communicating with other computer software systems.

Chapter 5 Work Injury Cost Analysis

5.1 Introduction

This chapter will present two methods for estimating the cost of work injuries on the assembly system. The first method is based on artificial neural network (ANN) that is widely used to develop a function which is highly non-linear and uncertain. The second method is based on a linear regression (LR) procedure that can only deal with a linear function but in a manner that the structure of a function is simpler. This chapter is organized in the following. In Section 5.2, a conceptual model of work injury cost calculation is presented. Section 5.3 presents the ANN method for work injury cost calculation, and Section 5.4 presents the LR method for work injury cost calculation. In Section 5.5, a case study is given to illustrate how the two methods work and compare them. The chapter will be summarized in the final section.

5.2 Conceptual Model of the Cost of Work Injuries

The cost for work injuries has a very complex structure as it involves many factors. When a human worker gets injured, he or she goes through several steps toward a final settlement of compensation. During these steps, the person cannot work as usual, therefore, there will be the cost for work time loss. The cost also covers such activities as the examination and treatment of the injured worker. There may also be a situation that the person is arranged for a “reduced” workload. Further, the cost differs from one individual to another even though they work on the same task and in the same working environment. This is because humans are inherently different, and there are always some factors about human bodies that have not been captured in any model but they influence the treatment of injuries workers. There is also some uncertainty in determining the cause of a particular work injury. This demands expert judgment, which costs. For such a complex process of work injury cost calculation of estimation, this thesis work takes the direction of work injury cost estimation by a “black-box” modeling approach. By black-box, it is meant that the complex process is “hidden” but the input and output information of the process is collected and analyzed for “guessing” the structure of a model, work injury cost (WIC) model in this case. Based on a preliminary observation, this study considered the age and gender factors together with injury information such as the level of a work injury and number of days for compensation. In any black-box model development, there is a need of training data that are the historical known data (word ‘training’ is used particularly with ANN model but used for the LR method in this thesis hereafter). The training data in this study was obtained from the Saskatchewan Workers’ Compensation Board (S-WCB).

The S-WCB database contains about 20000 injury claims from different companies in Saskatchewan from 2001-2007. Each claim has the information: age, gender, compensation days, part of body that is injured, and cost for compensation. It is noted that all these claims are related to the workers who worked on the assembly system and performed repetitive tasks.

Fig 5.1 shows a conceptual WIC model with inputs and outputs. The output of the model is ‘work injury cost’ of a particular worker. The input of the model includes a couple of things about the worker: age, gender, body injury part, and other related injury information that can be added. Two methods were developed for the WIC model and will be presented in the subsequent sections in detail.

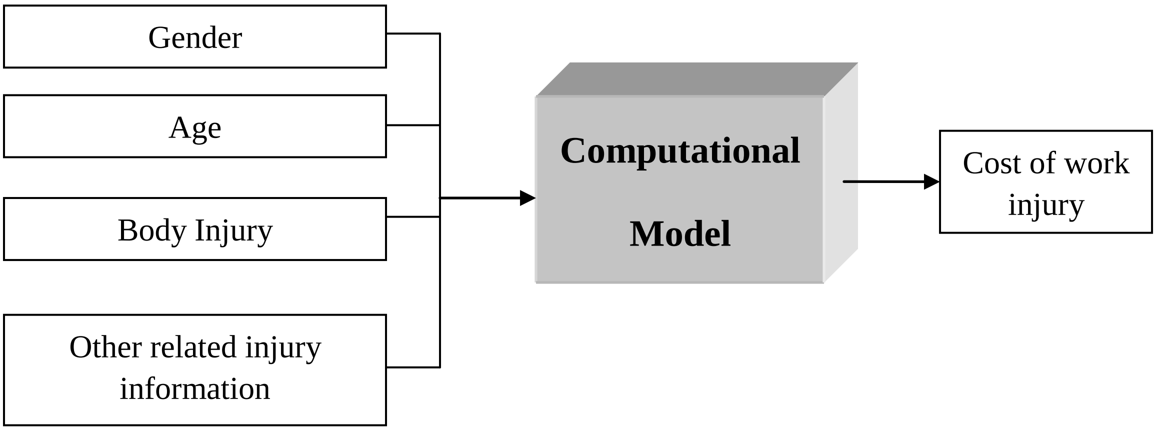


FIG 5.1 GENERAL MODEL OF COST OF WORK INJURY CALCULATION

5.3 Artificial Neural Network for WIC Model

5.3.1 Artificial Neural Network

The Artificial Neural Network (ANN) is a mathematical model based on the biological neural system, and it thus has some properties of the biological neural network. ANN consists of an interconnected group of artificial neurons. Fig 5.2 shows the general model of ANN. Each neuron contains a predefined function and is connected by other neurons with the constant called weight on the edge (see Fig 5.3). According to Fig 5.3, the following mathematical expression holds:

$$y = f(\sum_{i=1}^{m} w_i x_i) \tag{5.1}$$

Where f represents the activated function of an artificial neuron,

y represents the output of ANN,

x represents the input of ANN, and

w represents the weight connecting each neuron from other neurons.

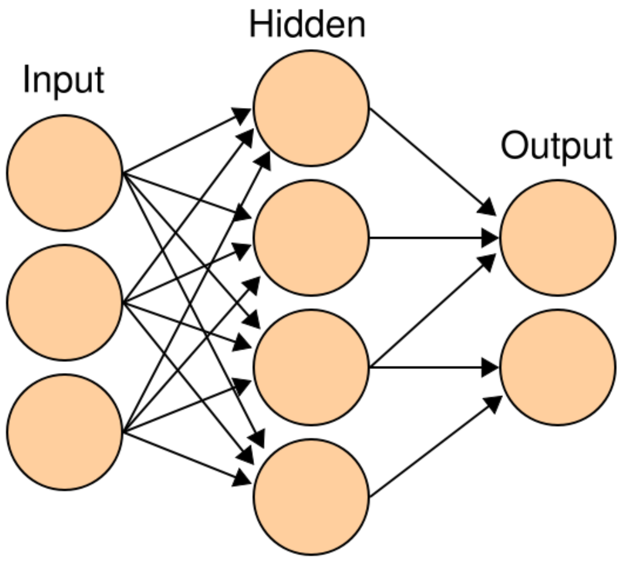


FIG 5.2 GENERAL MODEL OF ARTIFICIAL NEURAL NETWORK (ANN, 2007)

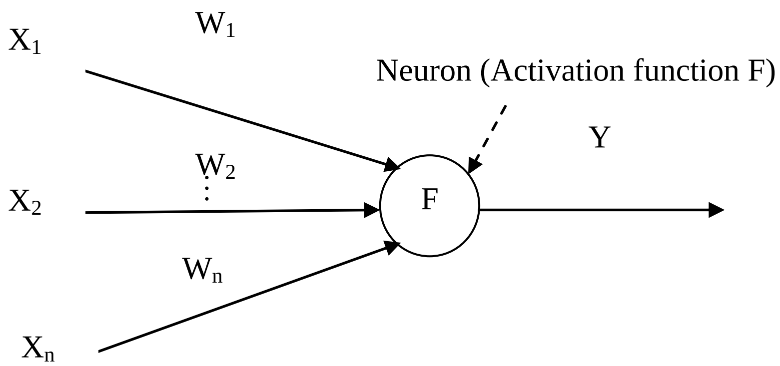


FIG 5.3 MODEL OF A SINGLE ARTIFICIAL NEURON

The learning is a process to determine the weight. In Fig 5.3, input information is always transformed forward output information and this transformation path is a directed acyclic graph. Such a model is called feedforward ANN. There are limitations with the feedforward ANN model: (1) the error between the actual and target outputs are not utilized to guide the learning process, and (2) it takes a long time to find the weight for the multi-layer network (i.e., learning takes long time). The back propagation method was proposed for learning by Williams et al. (1986). This method allows the error between the actual and target outputs to be used for the learning process, so the method is more effective. Such a model is called Back

Propagation Feedforward Artificial Neural network (BP- ANN).

The BP- ANN process consists of the following steps: (1) Given the actual information and the target information, (2) Compare the actual output with the target information and obtain the error between the actual value and target value, (3) Feed the error back to the network, and determine the modification of the weight to match the target information, (4) Modify the weight among each neuron, and (5) Repeat the above steps until the error is acceptable.

Further, in the BP-ANN learning process, the way to determine the modification of the weight follows the so called Delta Rule which is a gradient descent algorithm for updating the weights of artificial neurons. The Delta Rule has the following scheme (Rojas, 1996): For a neuron j with its activation function $g(x)$, the delta rule for j's the ith weight w_{ji} is given by

$$\Delta w_{ji} = \alpha(t_j - y_j)g'(h_j)x_i \tag{5.2}$$

Where α is a small constant called learning rate, $g(x)$ is the neuron's activation function, t_j is the target output, y_j is the actual output, and x_i is the ith input. Further, there is the following equation:

$$h_j = \sum x_i w_{ji} \text{ and } y_j = g(h_j). \tag{5.3}$$

The Delta Rule is commonly stated in a simplified form for a neuron with a linear activation function as

$$\Delta w_{ji} = \alpha(t_j - y_j)x_i \tag{5.4}$$

This thesis work employed the BP-ANN learning method for constructing an ANN model for work injury cost calculation, called ANN-WIC for short.

5.3.2 ANN Model for Work Injury Cost Calculation

5.3.2.1 Definition of the ANN Model

The general scheme of the ANN-WIC model is shown in Fig 5.4. From Fig 5.4, the information such as gender, age, injury part, compensation days and type of business is taken to be associated with the input neuron and the work injury cost is associated with the output neuron. The training data were obtained from S-WCB. However, the data in S-WCB database was not completely consistent with the data generated by the work injury analysis system (i.e. CADASWIE; see Chapter 4). Such a situation creates a problem of integration of work injury analysis and cost estimation, which is desired, the designer can get cost feedback when he or she designs a production assembly system. Therefore, there was a need to make both data consistent.

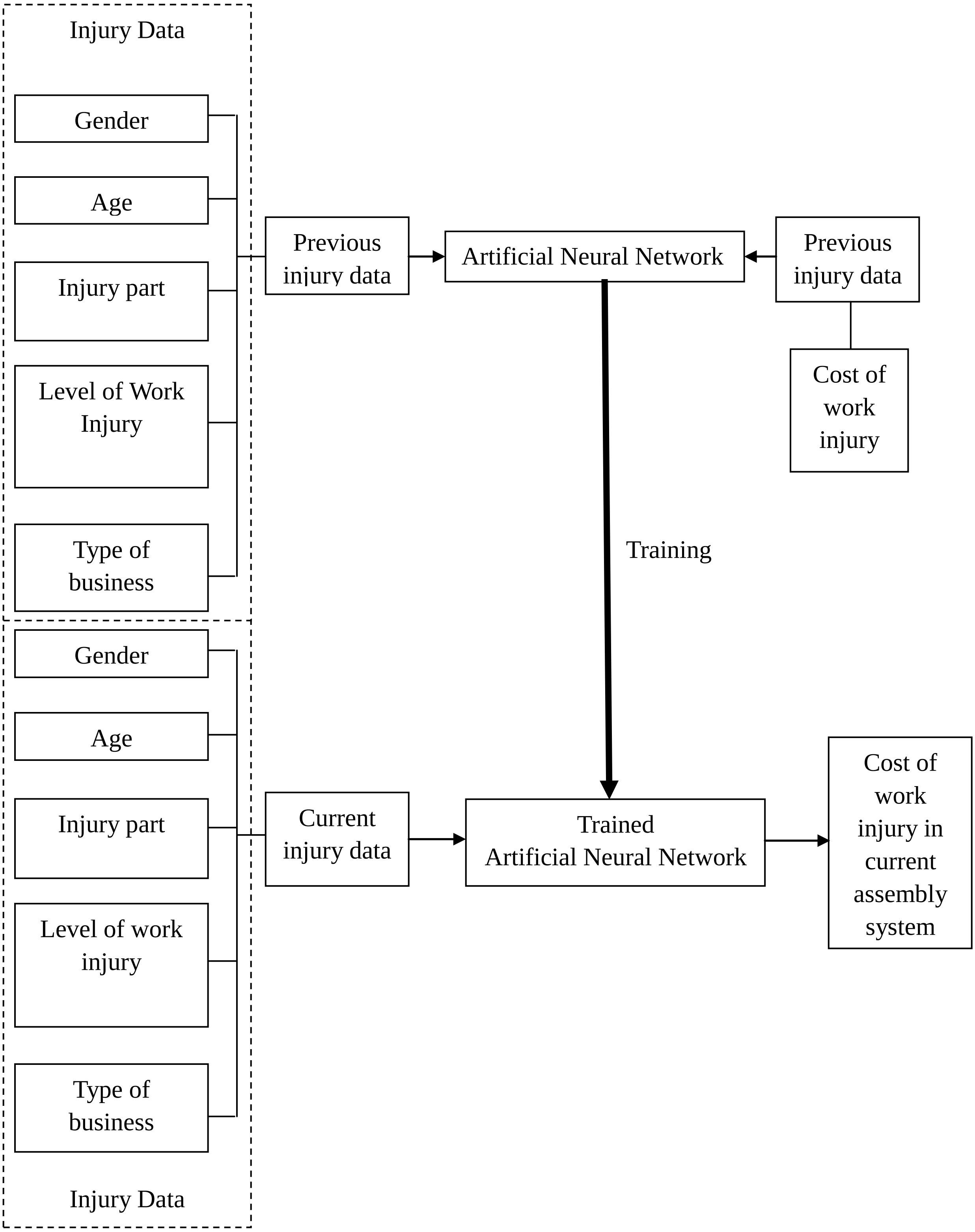


FIG 5.4 GENERAL MODEL OF METHOD BY USING ARTIFICIAL NEURAL NETWORK

It is noted that the CADASWIE (RULA module and biomechanics analysis module) discussed in Chapter 4 will generate the analysis results of the current assembly system, including age, gender, and the level of work injury. These data are categorized into different groups with the different injured body parts, such as the forearm, upper arm, wrist, neck, and leg. However, the S-WCB database has its own description regarding specific body locations that may have injuries. In particular, in CADASWIE, the injury classification is related to the upper arm, forearm, wrist, neck, trunk and leg; while the S-WCB database has more subtle classification along with the classification taken by CADASWIE. A mapping between these two classifications is given in Table 5.1

TABLE 5.1 CLASSIFICATION OF DELMIA AND S-WCB

Delmia V5	**S-WCB**		
	Part of Body	Part of body Group	Part of Body Sub-Group
Upper Arm	Upper Arm	Upper extremities	Upper arm(s)
Forearm	Forearm	Upper extremities	Finger(s), fingernail(s); Hand(s), except finger(s); Forearm(s)
Wrist	Wrist	Upper extremities	Wrist(s)
Neck	Neck	Neck including throat	Neck, except internal location of diseases or disorders
Trunk	Trunk	Trunk	Back, including spine, spinal cord; Trunk; Shoulder, including clavicle, scapula and trapezius muscle if shoulder is mentioned
Leg	Leg	Lower extremities	Ankle(s); Leg(s); Foot (feet), except toe(s); Multiple lower extremities; Toe(s), toenail(s)

Currently, the S-WCB database has no information regarding the level of work injuries but it has the information about compensation days. From the output information of the analysis system (i.e., CADASWIE), 'level of work injury' is the one close to 'compensation day' in S-WCB database. Therefore, in this study, the information of compensation day in the S-WCB database was mapped to the level of work injury in the context of CADASWIE, and details about this mapping are given below.

From CADASWIE (or Delmia V5©), the levels of work injuries were defined with respect to different parts of bodies; see Table 5.2. For instance, for the upper arm, the level of the work injury is from 1 to 6; however, for the leg, the level of work injury is from 1-7. The idea to correspond the compensation days in the S-WCB database to the level of work injury in the context of CADASWIE is to group the compensation days in light of the proposition – that is, more compensation days imply more serious the work injury and thus the higher levels of work injury.

TABLE 5.2 LEVEL CLASSIFICATION IN DELMIA V5©

Part of Body	Upper Arm	Forearm	Wrist	Neck	Trunk	Leg
Level	1-6	1-3	1-4	1-6	1-6	1-7

The TwoStep Cluster method was particularly employed for the classification of compensation days. First, compensation day were treated as continuous numbers and are ranged from small to large. Second, the numbers were then divided into groups with the number of groups being the same as the number of levels as defined in Table 5.2. The grouping at this point is rather subjective, though the profile of the data was taken as an input to make the grouping decision. Third, the average of the compensation days for each group was calculated, and the significant test was performed. If the significance test is not passed, the regrouping process will be triggered; that is to say, the whole process is then back to the first step. This progress went on until the significant test is passed. Table 5.3 shows the result of the classification of compensations days. Fig 5.5 shows a snapshot of the TwoStep Classification Module in SPSS statistical software used to perform this grouping process.

TABLE 5.3 LEVEL CLASSIFICATION WITH THE RANGE OF COMPENSATION DAYS

Part of Body	Level of work injury	Range of Compensation days (day)						
		1	2	3	4	5	6	7
Upper Arm	1-6	0-12	13-49.29	56-138	146.97-269	303.17-465	616.97-1251.85	
Forearm	1-3	0-19.29	20-97	100.86-1087				
Wrist	1-4	0-39	39-100.24	101-562	563-812.21			
Neck	1-6	0-11	12-24.25	27-71	82-123.52	186-215	1035	
Trunk	1-6	0-20.66	20.69-81.23	82-204.41	207-517.19	518.53-981	990-2280	
Leg	1-7	0-31	32-117	117.24-247	259-424	456-606	734.18-1117	1246.94-1547.48

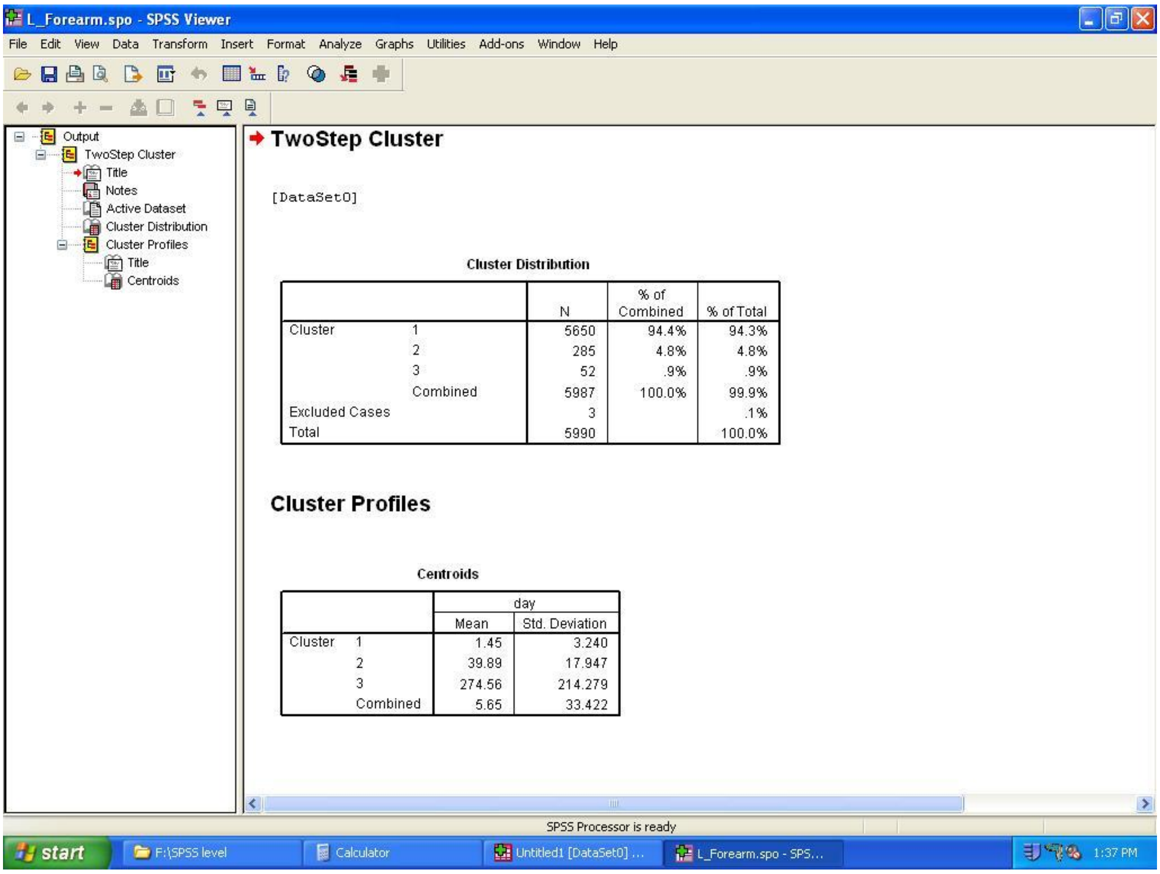


FIG 5.5 THE CLASSIFICATION OF WORK INJURY WITH COMPENSATION DAYS

Manufacturing companies in the database of S-WCB were divided into several groups and coded with a number; see Table 5.4. The reason for this classification was because different types of business were found quite different in work injury compensation from our observation of the S-WCB database. This classification was, however, experience-based and subjective.

TABLE 5.4 BUSINESS TYPES WITH CODES

Code	Type of Business
M62	Mills, Semi-medium Manufacturing
M81	Metal Foundries and Mills
M91	Agricultural Equipment
M92	Machine Shops, Manufacturing
M94	Iron and Steel Fabrication

Due to the effect of the inflation, the real value of the compensation cost of each year should be adjusted according to the rate of inflation. If the inspection of the cost is made for a particular year, for example 2007, that particular year is called base year. This adjustment was done based on the concept of Consumer Price Index (CPI). Table 5.5 shows the CPI on December each year from 2001 to 2007. The conversion formula to eliminate the inflation factor is given below:

TABLE 5.5 CPI FROM 2001 TO 2007 (BANK OF CANADA, 2008)

Year	Total CPI	Core CPI[a]
2007	112.0	110.0
2006	109.4	108.4
2005	107.6	106.2
2004	105.4	104.6
2003	103.2	102.8
2002	101.1	100.7
2001	97.4	98.0

a: The CPI includes the whole basket of goods and services, while the Core CPI excludes more volatile items like food and energy,

$$\text{Real Cost} = \text{Nominal Cost}\frac{\text{BCPI}}{\text{PCPI}} \tag{5.5}$$

Where

Nominal Cost represents the absolute price of a good which is unadjusted for inflation (Robert et al., 2001);

Real Cost represents the price to an aggregate measure of prices which is adjusted for inflation (Robert et al., 2001);

BCPI represents the base year CPI; and

PCPI represents the past year CPI.

In this study, the base year was 2007. The nominal cost of work injury for the past years from 2001 to 2006 were adjusted into the real cost of work injury based on the year of 2007.

For a better convergence in the learning process of ANN, the range of continuous variables such as age and cost were mapped to the range of [-1, 1], and the category variables such as gender and business type were defined as a number (i.e., number 0 and 1). Therefore, the data in the original S-WCB database were needed to re-define or normalize. Table 5.6 shows that the level of work injury is represented by number from 0.1 to 0.7; Table 5.7 shows that the gender is represented by number 0 and 1; and Table 5.8 shows that the business type is represented by number from 0.1 to 0.5.

TABLE 5.6LEVEL OF WORK INJURY WITH NUMBER

Level	1	2	3	4	5	6	7
Number	0.1	0.2	0.3	0.4	0.5	0.6	0.7

TABLE 5.7 GENDERS ASSOCIATED WITH NUMBER

Gender	Female	Male
Number	1	0

TABLE 5.8 VARIOUS BUSINESS TYPES WITH NUMBER

Code	Type of Business	Number
M62	Mills, Semi-medium Manufacturing	0.1
M81	Metal Foundries and Mills	0.2
M91	Agricultural Equipment	0.3
M92	Machine Shops, Manufacturing	0.4
M94	Iron and Steel Fabrication	0.5

To normalize the age and compensation cost in the range of [-1, 1], the following normalization equation was applied:

$$Y = \frac{X - MinValue}{MaxValue - MinValue} \qquad (5.6)$$

Where

MinValue represents Minimum value from data;

MaxValue represents Maximum value from data;

X represents real value before normalization;

Y represents the value after normalization.

5.3.2.2 ANN Model Generation

Normally, there are three layers in BP-ANN model. One layer is an input layer which contains several neurons depending on the number of input variables, the middle layer is hidden layer, and the last layer is the output layer. Fig 5.6 shows the specific BP-ANN model used for this study. Due to the huge data (about 20000 groups of data) that are used for training the network, the BP-ANN model in this case consists of four layers. The input layer has four neurons which are corresponded to the four variables of input (gender, age, level of work injury and type of business); the two hidden layer has 10 neurons each; and the output layer has 1 neuron which is corresponded to one output (cost of work injury). It is further noted that, the types of body injury (see in Fig 5.1) is not included in the input neuron (first layer). In fact, the treatment of the injury was done by having separate ANN-WIC models over the injured body types. In other words, there were six ANN-WIC models; corresponding to six body injury types: upper arm injury, forearm injury, wrist injury, neck injury, trunk injury, leg injury (see Table 5.2).

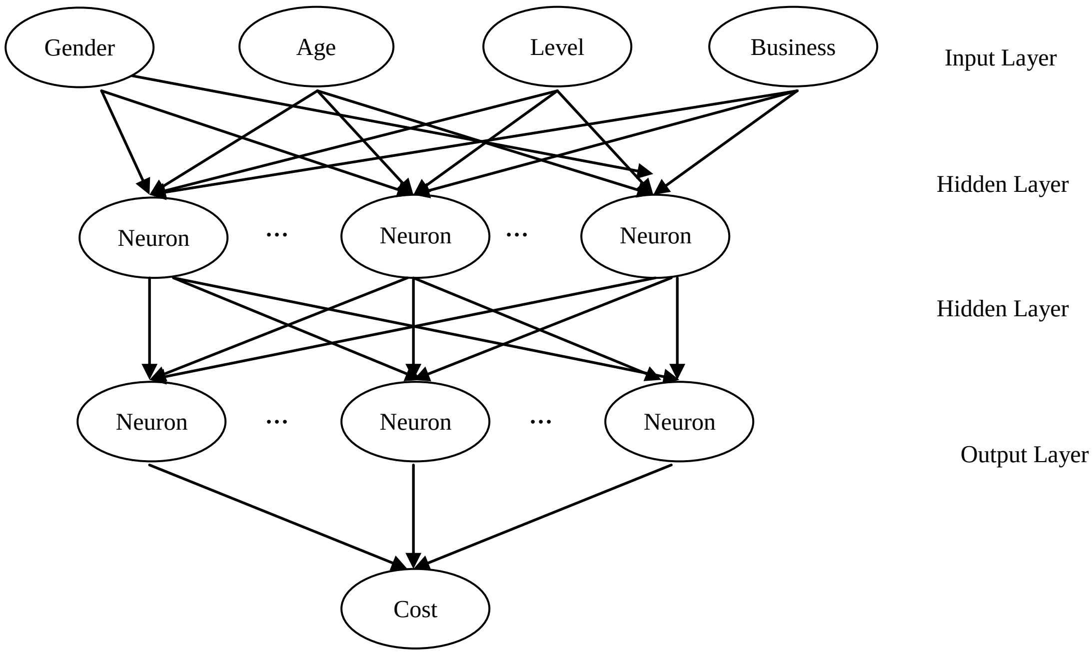


FIG 5.6 THE SPECIFIC BP-ANN MODEL

The generation of an ANN model consists of two steps: Step 1: Training, Step2: Testing. In the following sections, some common descriptions are given, and then specialized descriptions are presented for each of six models. For six models, the neck part model was picked up for determining various neuron network parameters for training. Then, the other five models applied these parameters rewrite. Finally, the testing procedure was performed for testing the accuracy of BP-ANN model.

Matlab 7.0© is the software program employed for this study. It offers a powerful ANN module. The input values (such as age, gender, level of work injury and type of business) and target value (actual cost) were import into Matlab 7.0©. Fig 5.7 shows input data in Matlab7.0©, and Fig 5.8 shows the target data.

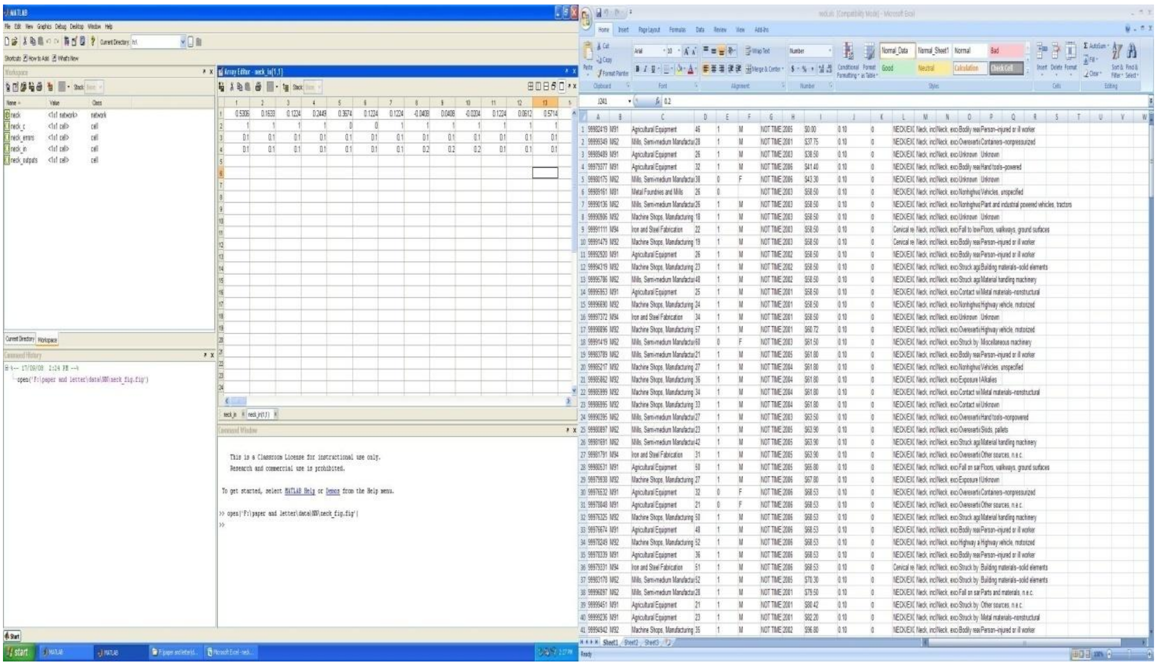


FIG 5.7 INPUT DATA IN MATLAB©

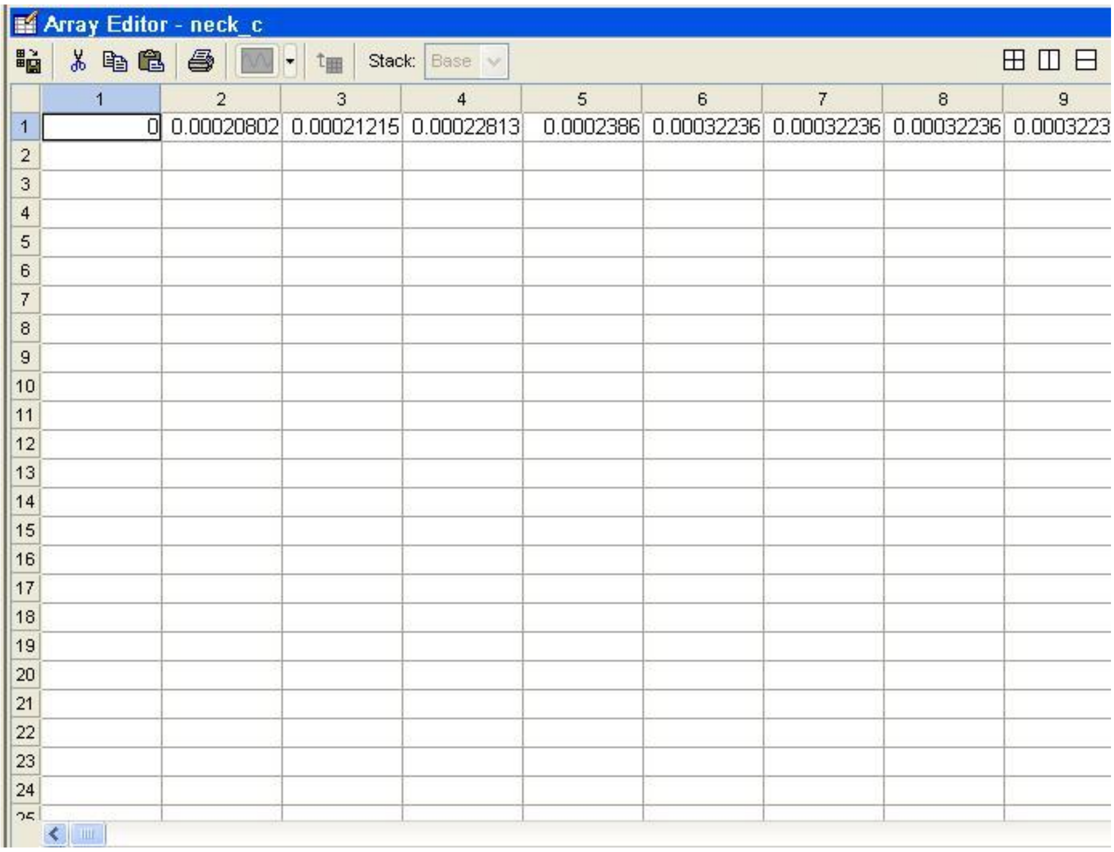


FIG 5.8 OUTPUT DATA IN MATLAB©

Fig 5.9 shows a window with which certain parameters to conduct the training process are specified.

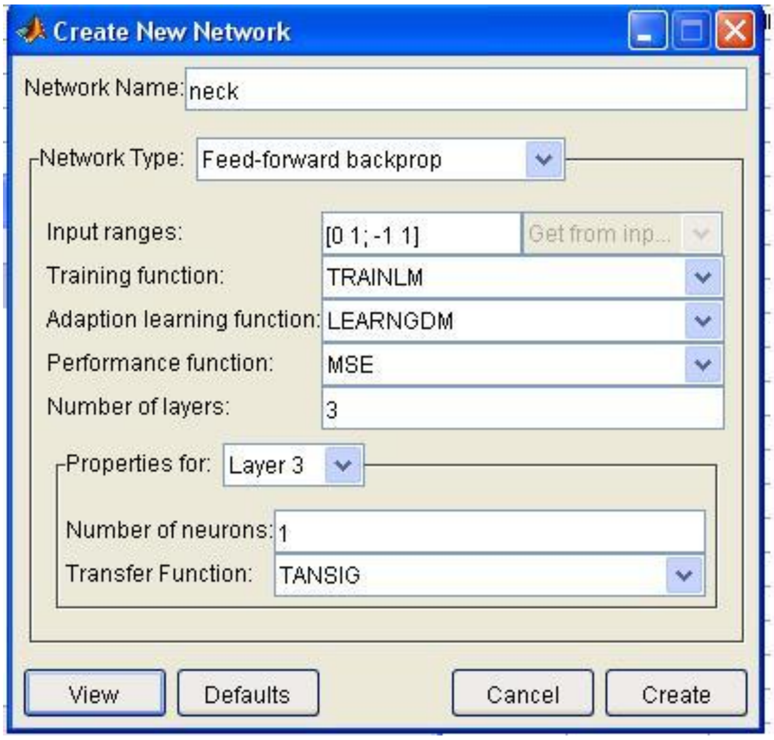


FIG 5.9 NEURAL NETWORK TOOLBOX

In particular, the following parameters are set up with this window: (1) the number of layers, (2) the number of neurons, (3) transfer function, and (4) training function. The number of layers was initially 4, and the number of neurons for each hidden layer was initially 10. There are three kinds of activated functions (called transfer functions in Matlab©): (1) TANSIG function, (2) PURELIN function, and (3) LOGSIG function. They are all applicable to the problem here. Some tests were done, discovering that their performances are close (TANSIG function was chosen). There are three major training functions and they are (1) Levenberg-Marquardt, (2) Gradient descent, and (3) Gradient descent with momentum and adaptive learning rate. Their corresponding names in the Matlab© were called, respectively, (1) TRAINLM, (2) TRAINGD and (3) TRAINGDX. To decide which training function is the best for the problem here, they were all tried for the problem. The results of the training using all these training functions are presented in the following.

The ANN module offered by Matlab 7.0© takes the input values and output values. Fig 5.10 shows the data in Neural Network that 'neck_in' is the input values and 'neck_c' is the output values.

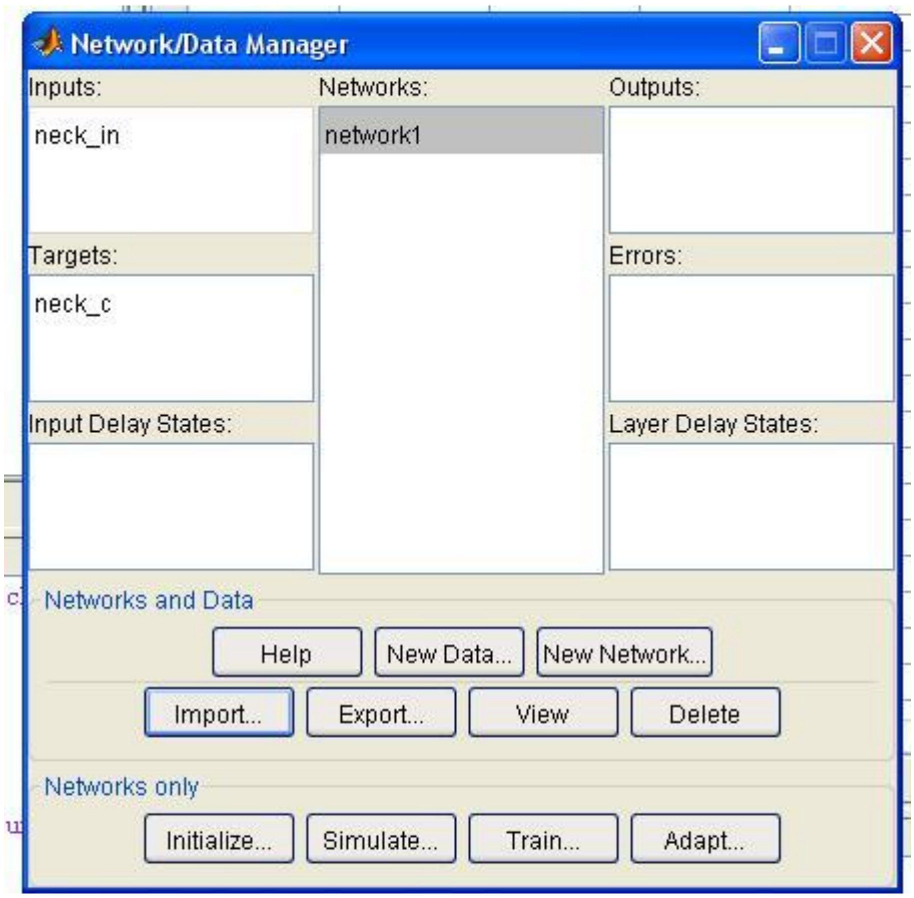


FIG 5.10 DATA IN NEURAL NETWORK

Then, the ANN module offered by Matlab 7.0© generated the BP-ANN model by training with three different training functions. The results corresponded to three training function are shown below.

A. TRAINLM Function

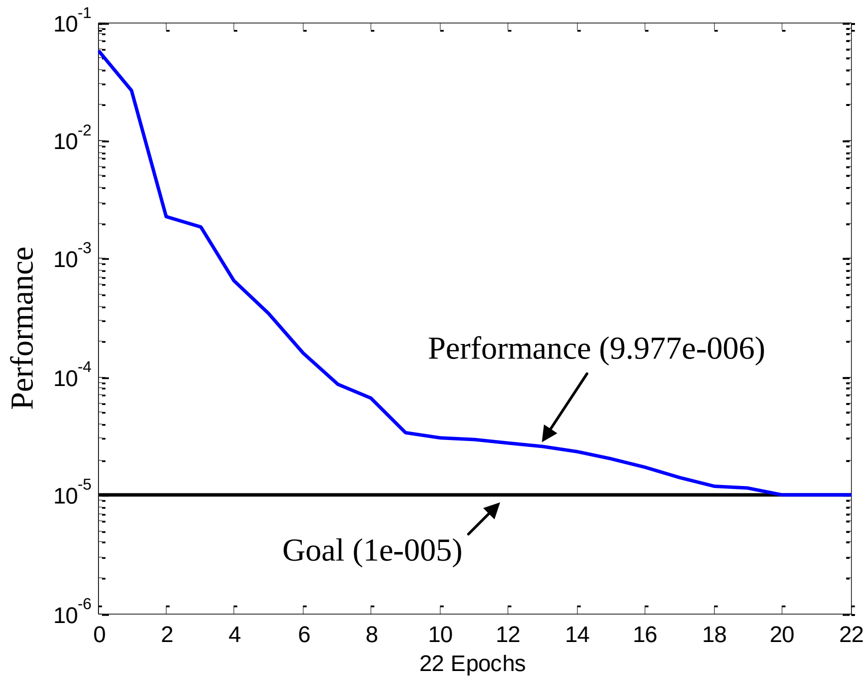


FIG 5.11 THE PERFORMANCE OF NEURAL NETWORK WITH TRAINLM FUNCTION

B. TRAINGD Function

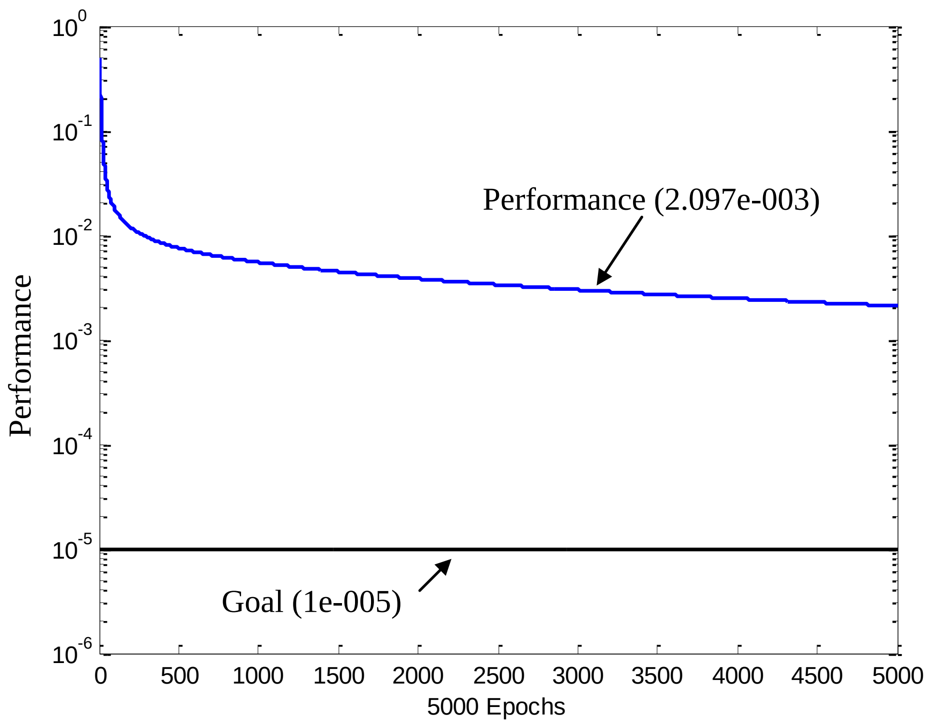


FIG 5.12 THE PERFORMANCE OF NEURAL NETWORK WITH TRAINGD FUNCTION

C. TRAINGDX Function

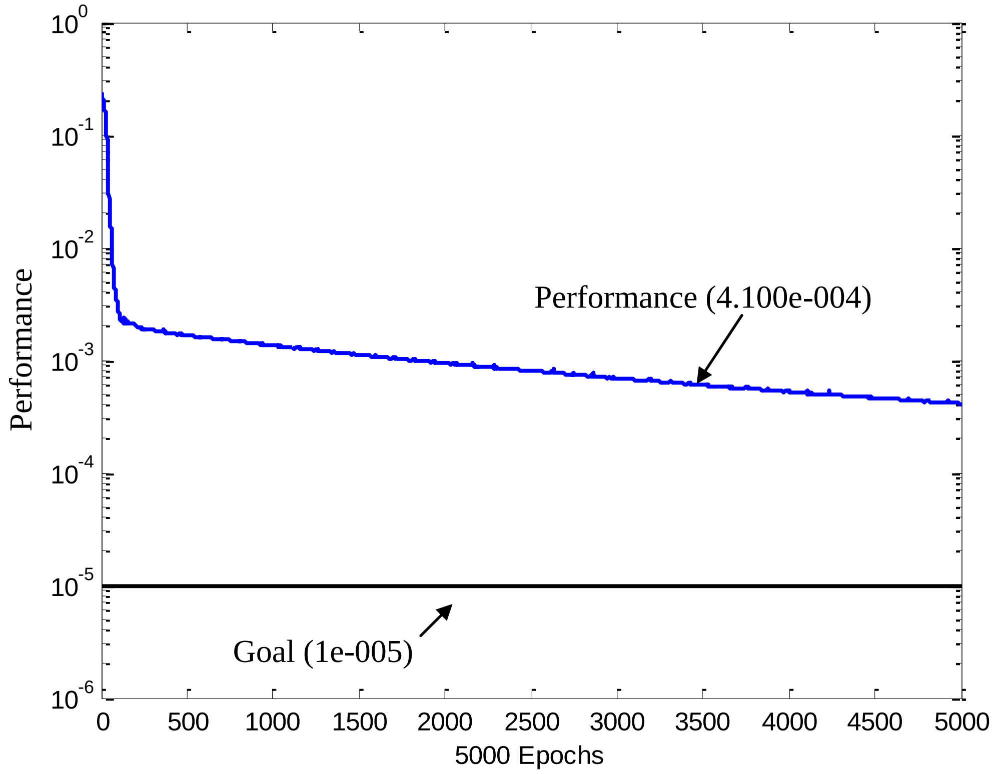


FIG 5.13 THE PERFORMANCE OF NEURAL NETWORK WITH TRAINGDX FUNCTION

Table 5.9 shows the training goal and epochs of training procedures by three training functions in terms of performance.

TABLE 5.9 RESULTS OF THREE KINDS OF TRAINING FUNCTION

Training Function	Training Goal	Epochs
LM	0.000010000	22
GD	0.00209662	5000
GDX	0.000410027	5000

From Table 5.9, with TRAINLM training function, the ANN model only took 22 epochs to reach the training goal of 0.00001; while with TRAINGD training and TRAINGDX training, the ANN model took 20000 epochs to reach the training goals of 0.00209662 and 0.000410027, respectively. TRAINLM training function takes fewer epochs but reaches the highest training goal. Therefore, TRAINLM training function was chosen for a final ANN cost model.

Further, the three layers BP-ANN model and the four layers BP-ANN model were compared based on the TRAINLM training function. The results are shown in Fig 5.14, and Fig 5.15, respectively.

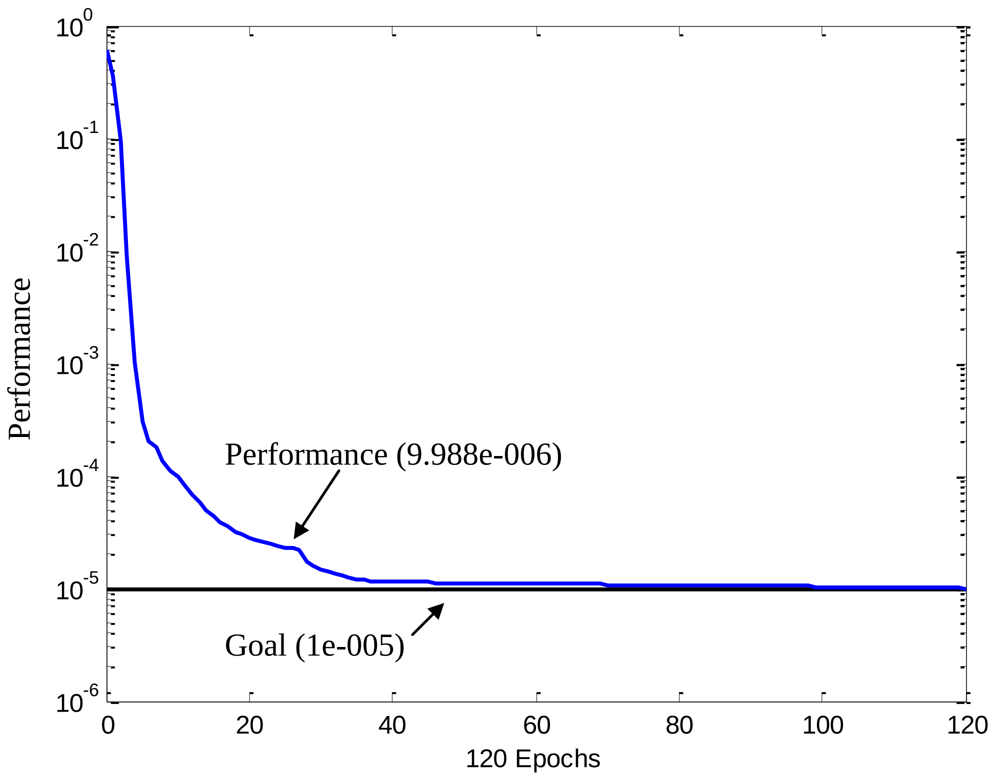


FIG 5.14 THE PERFORMANCE OF THREE LAYERS NEURAL NETWORK MODEL

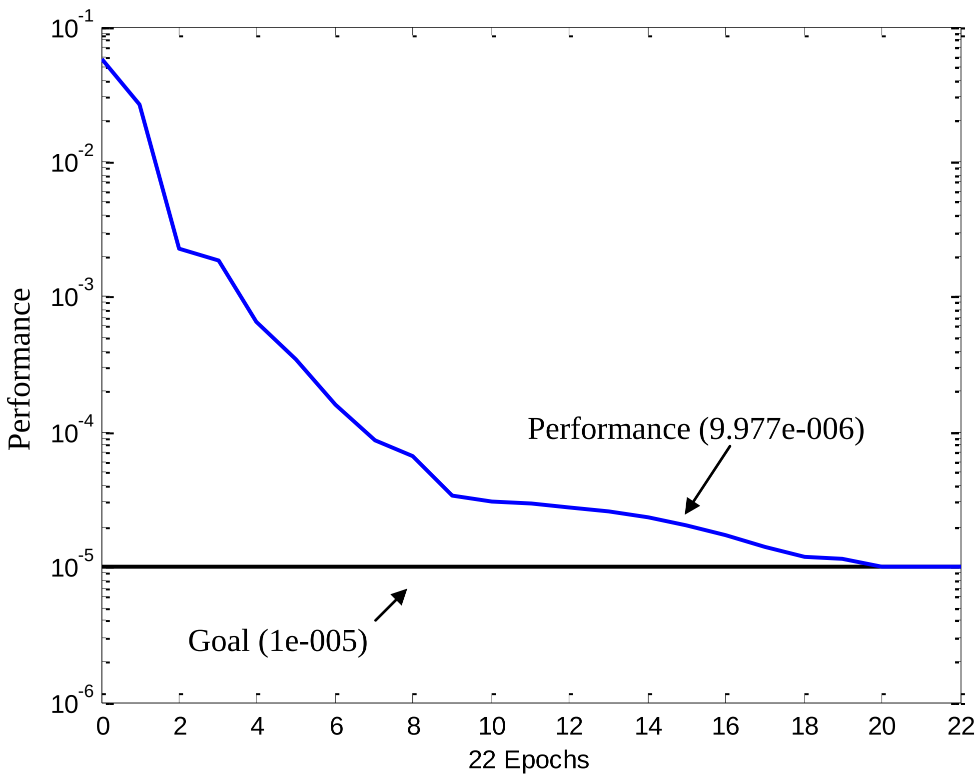


FIG 5.15 THE PERFORMANCE OF FOUR LAYERS NEURAL NETWORK MODEL

Table 5.10 shows the training goal and epochs by performance of these two models.

TABLE 5.10 THE EPOCHS OF TWO DIFFERENT STRUCTURE NEURAL NETWORK

Model	Training Goal	Epochs
Three layers	0.00001	120
Four layers	0.00001	22

From Table 5.10, the four layer model takes less epochs to reach the same training goal as the three layer model. In summary, for this study, the BP-ANN model took the TRAINLM function for training and took four layers of neurons to build the structure of model.

After the training of the ANN model, the accuracy of the trained BP-ANN model was examined. Five test data were randomly picked from S-WCB database and used to exam. Table 5.11 shows the results of the testing. From Table 5.11, the errors between the estimated value and actual value is less than 4%, thus, the trained BP-ANN model is acceptable.

TABLE 5.11 THE RESULT OF TEST

Number	Business Type	Age	Gender	Level	Error
1	M91	22	Male	2	0.001
2	M93	32	Male	1	0.029
3	M81	45	Female	3	0.007
4	M62	28	Female	2	0.012
5	M91	36	Female	2	0.032

Based on above description, the other five BP-ANN models which are upper arm model, forearm model, wrist model, leg model and trunk model are represented below:

Upper Arm BP-ANN Model Training:

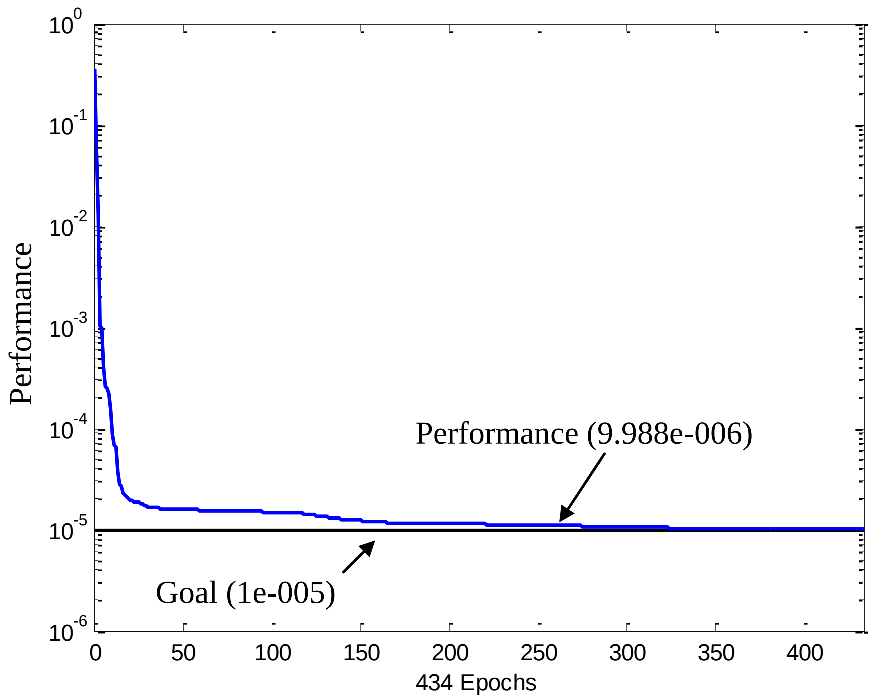


FIG 5.16 THE PERFORMANCE OF UPPER ARM BP-ANN MODEL

Leg BP-ANN Model Training:

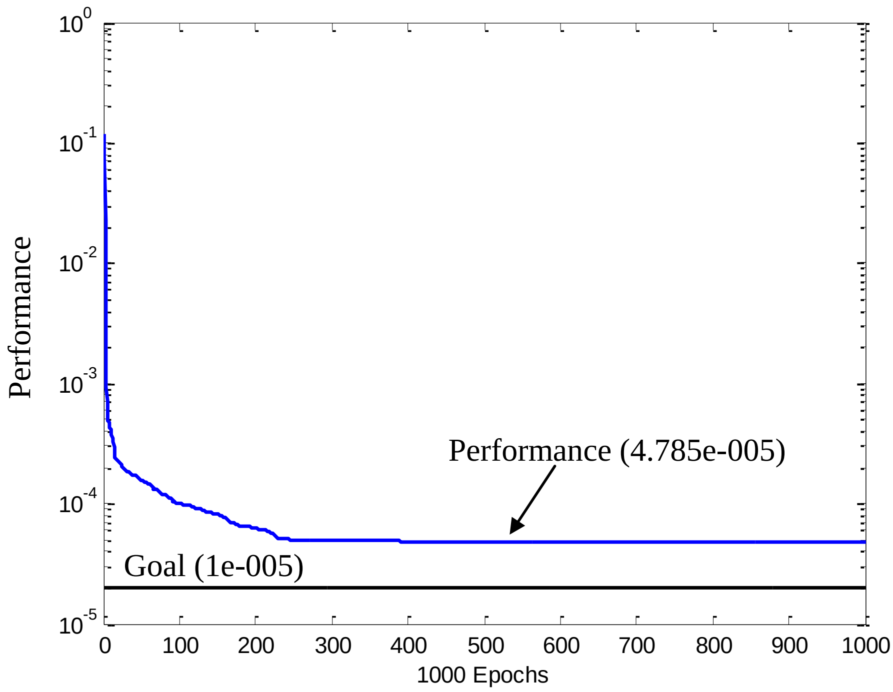


FIG 5.17 THE PERFORMANCE OF LEG BP-ANN MODEL

Forearm BP-ANN Model Training:

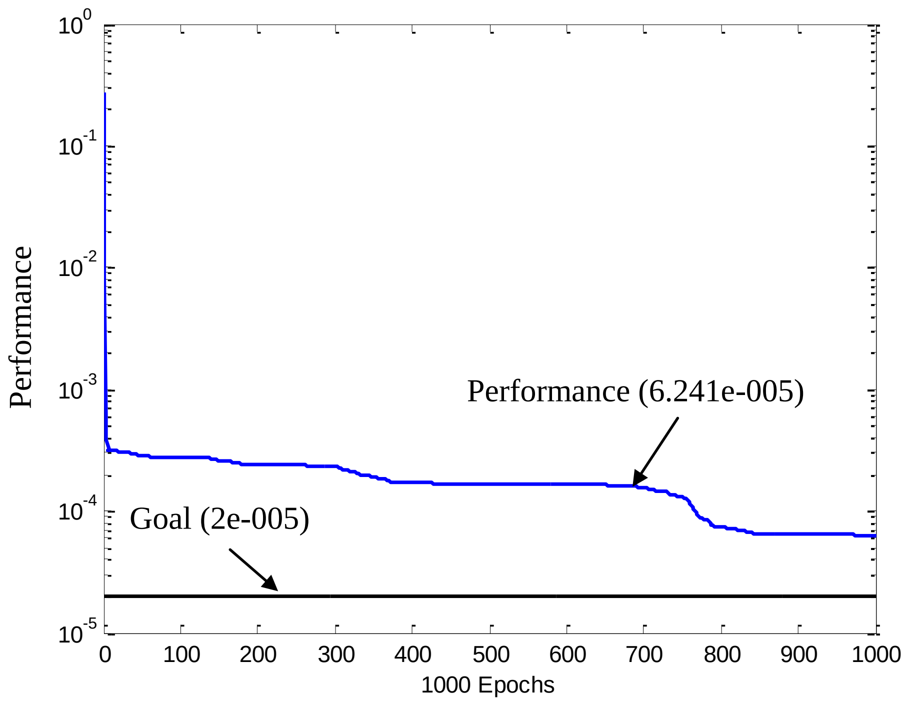


FIG 5.18 THE PERFORMANCE OF FOREARM BP-ANN MODEL

Wrist BP-ANN Model Training:

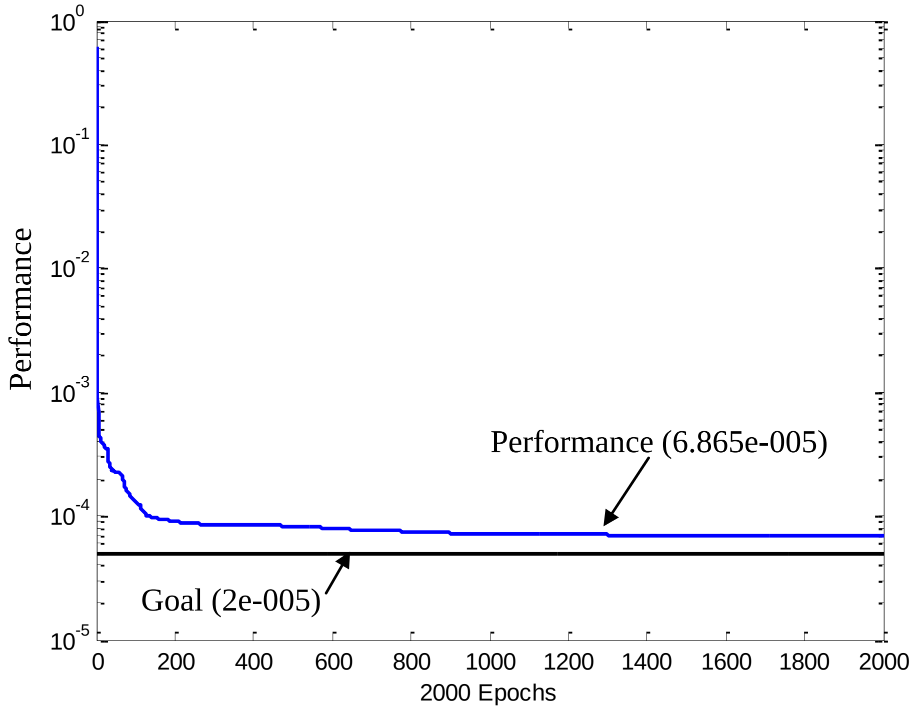


FIG 5.19 THE PERFORMANCE OF WRIST BP-ANN MODEL

Trunk BP-ANN Model Training:

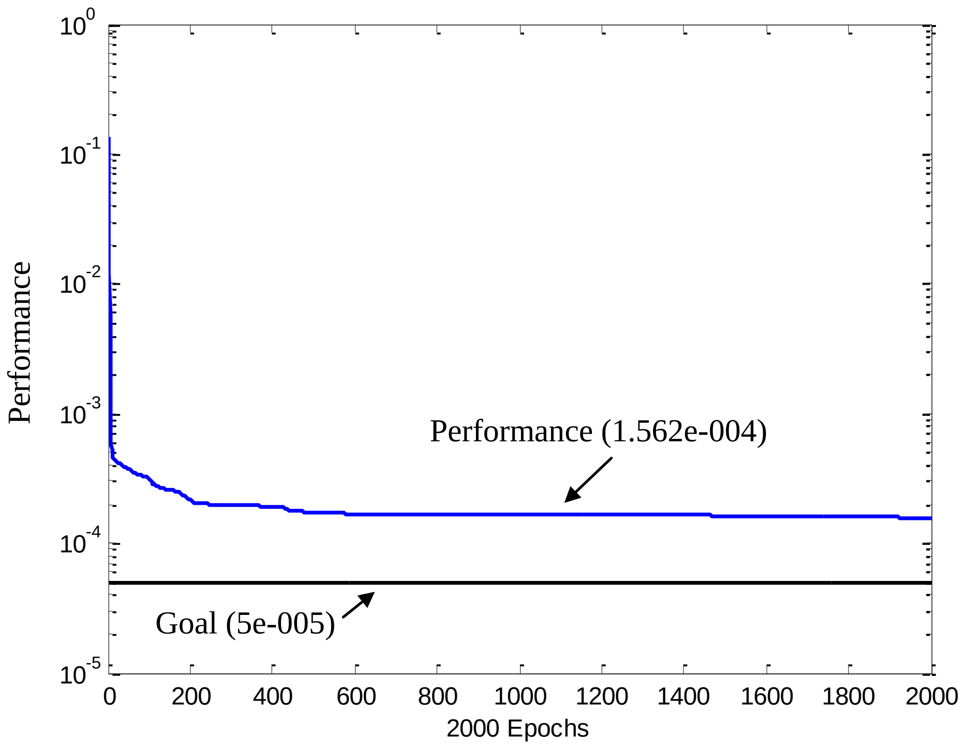


FIG 5.20 THE PERFORMANCE OF TRUNK BP-ANN MODEL

Table 5.12 gives the training results of all BP-ANN models corresponded to various body injuries.

TABLE 5.12 THE RESULTS OF ALL BP-ANN MODELS

Parts of Body	Epochs	Training Results
Upper Arm	434	0.0000099827
Forearm	1000	0.0000624131
Wrist	2000	0.0000680407
Neck	22	0.0000099817
Trunk	2000	0.00015624
Leg	1000	0.0000478507

5.4 Linear Regression Model for WIC Model

The linear regression (LR) method takes the same input and output variables as the BP-ANN method to build a linear relationship between them. The general equation of the LR method is shown in the following:

$$C = \alpha + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_4 x_4 + \alpha_5 x_5 + \alpha_6 x_6 + \alpha_7 x_7 + \varepsilon \qquad (5.5)$$

Where:

C represents the cost of work injury;

α_n represents the coefficient of each multiplier;

x_1 represents the type of business M61;

x_2 represents the type of business M81;

x_3 represents the type of business M91;

x_4 represents the type of business M92;

x_5 represents age;

x_6 represents gender;

x_7 represents the level of work injury; and

ε represents the error term.

The LR model involves a procedure to determine α_n and their significant differences in the model (Goodman, 1999). The significant difference means statistical evidence that there is a difference between the target valve and 0. The process is in a similar nature as the learning process in the BP-ANN method. Therefore, the same training data as used in the ANN was used for the LR method. Similarly, there are six LR models corresponded to six body injury. The LR model of neck injury was picked to demonstrate how the parameters in this section are determined, and LR models for other body parts can be developed in a similar manner.

The software SPSS© was employed in this study, as it offered the linear regression module which can generate the equation with multipliers and do significance test to each multiplier. The modified or re-defined input data such as age, gender, the level of work injury, the type of business and the historical cost of work injury were specified as input to the SPSS©. The coefficient of each multiplier X_n (see Equation 5.5) will be calculated associated with the significance of each coefficient. Some line figures also will be generated by SPSS©. These line figures show the linear characteristic of equation, and the relationship between the tolerances and variables.

The variables for LR model include the age, gender, level of work injuries, the type of business and the historical cost of work injuries. The definitions of each variable are given below:

(1) The values of variables such as age, level of work injury and cost of work injury are the same as in ANN model.
(2) The type of business and gender are re-defined by number “1” and “0”. (see in Table 5.13)

TABLE 5.13 THE DEFINITIONS OF SOME VARIABLES

Variable	Code	Definition
M62	X_1	1, if it is Mills and Semi-medium Manufacturing; 0, otherwise.
M81	X_2	1, if it is Metal Foundries and Mills; 0, otherwise.
M91	X_3	1, if it is Agricultural Equipment; 0, otherwise
M92	X_4	1, if it is Machine Shops, Manufacturing; 0, otherwise.
Gender	X_6	1, if it is male; 0, otherwise

Fig 5.21 shows the snapshot of neck injury LR model procedure in SPSS software.

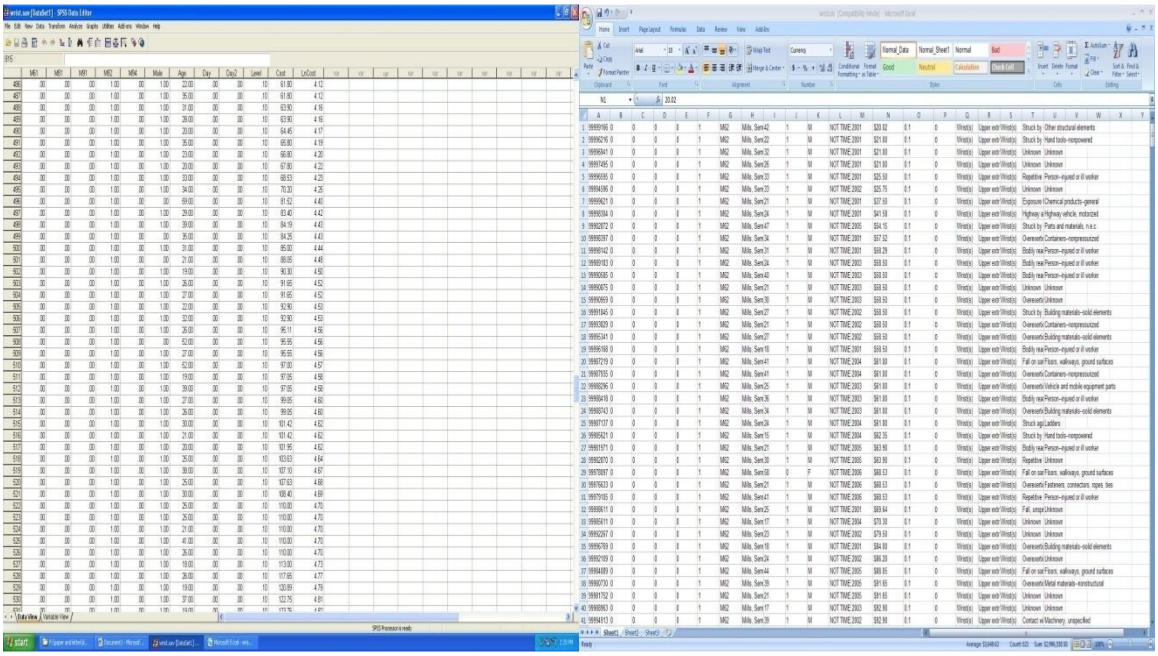


FIG 5.21 THE INPUT DATA OF LINEAR REGRESSION MODEL

Fig 5.22 shows the Normal P-P Plot and Fig 5.23 shows the scatter plot about the relationship between predicted values and actual values, while Table 5.14 gives the coefficient of each multiplier and significance of each multiplier. Both of table and figure were for the neck injury.

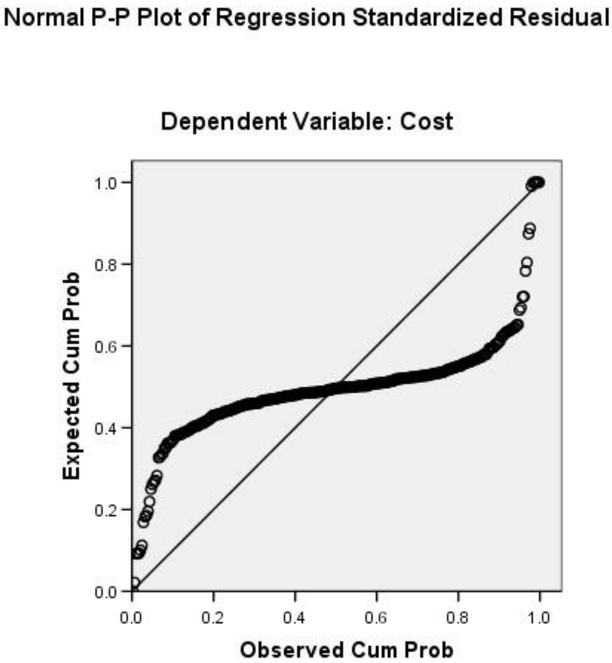


FIG 5.22 NORMAL P-P PLOT OF REGRESSION STANDARDIZED RESIDUAL

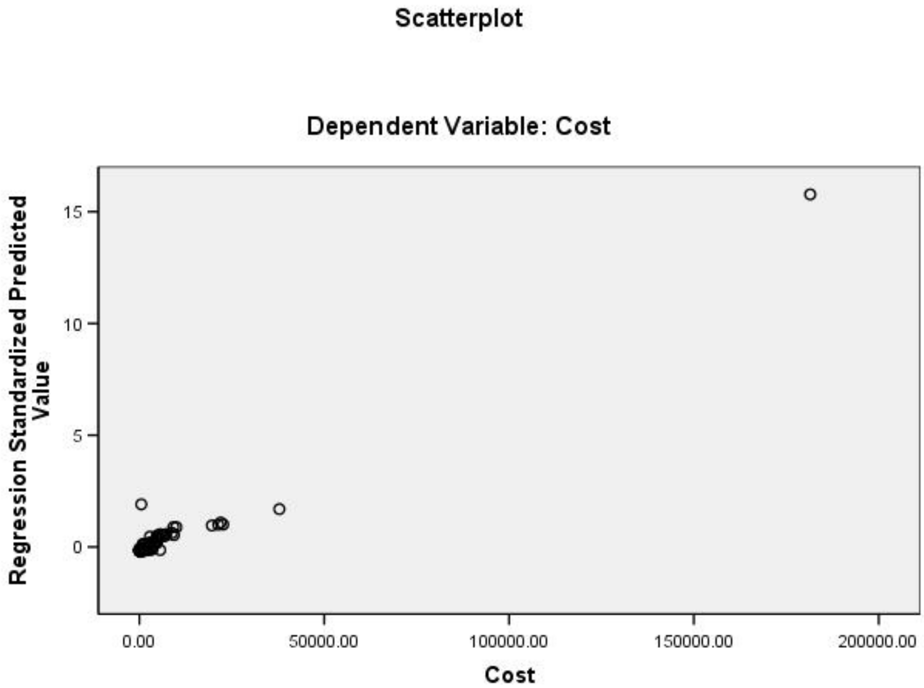


FIG 5.23 THE SCATTER PLOT BETWEEN THE REGRESSIONS STANDARDIZED RESIDUAL AND THE DEPENDENT VARIABLE

TABLE 5.14 THE COEFFICIENTS OF EACH MULTIPLIER

Model		Coefficients	Std. Error	t	Sig.
1	(Constant)	-11066.293	3119.785	-3.547	.000
	M62	61.232	1887.308	.032	.974
	M81	778.481	3075.557	.253	.800
	M91	2284.873	1914.407	1.194	.234
	M92	-75.412	1774.668	-.042	.966
	Age	21.274	52.197	.408	.684
	Gender	447.202	2097.171	.213	.831
	Level	9078.555	751.036	12.088	.000

a Dependent Variable: Cost

Fig 5.22 represents the relationship between the estimated value and the actual value. The error between the estimated value and the target value does not follow the normal distribution that means there is a huge error between each expected value and actual value. In other words, there are still some non-linear relationships between the estimated cost and the input parameter. Based on the observation, the value of actual cost is much larger than the value of other parameters. Therefore, value modification of actual cost should be applied to eliminate this limitation. Power transformation is employed in this model to modify the value of actual cost. The power transformation is defined as a continuously varying function, with respect to the power parameter λ, in a piece-wise function form that makes it continuous at the point of singularity (λ = 0) (George, 1964). The equation for power transformation is presented below:

$$y^{(\lambda)} = \begin{cases} (y^{\lambda} - 1)/\lambda, & \text{if } \lambda \neq 0 \\ \log y, & \text{if } \lambda = 0 \end{cases} \qquad (5.6)$$

The Box and Cox transformation is the major transformation of power transformation. The equation is shown below:

$$\tau(Y;\lambda,\alpha) = \begin{cases} [(Y+\alpha)^{\lambda}-1]/\lambda & \text{if } \lambda \neq 0, \\ = \ln(Y+\alpha) & \text{if } \lambda = 0. \end{cases} \tag{5.7}$$

Here, if $\tau(Y, \lambda, \alpha)$ follows a normal distribution, then Y is said to follow a Box-Cox distribution (George, 1964). In this project, the Box and Cox transformation was chosen for the modification of the dependent variable (i.e., work injury cost). The parameter α was assumed as 0, the parameter Y was the current injury cost, and λ was chosen to be the number 0.25,0 and -0.25 in this case. Fig 5.24 shows the result of each transformation with different λ.

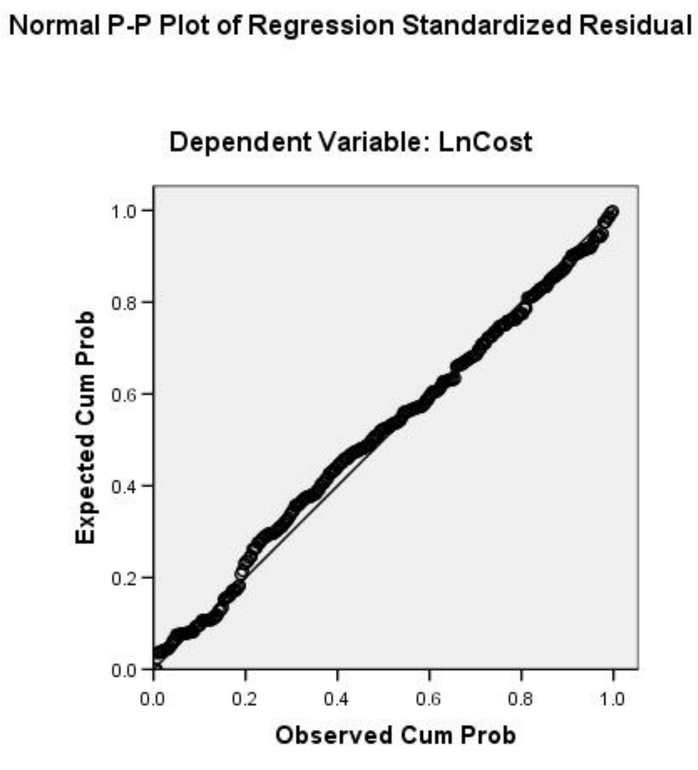


FIG 5.24A THE RESULT OF TRANSFORMATION WITH Λ=0

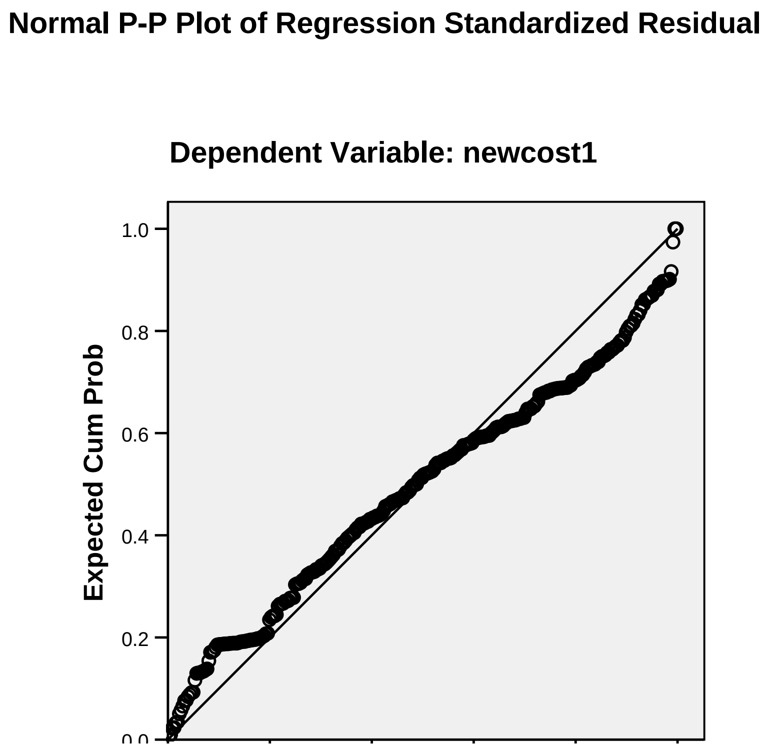


FIG 5.24B THE RESULT OF TRANSFORMATION WITH Λ=-0.25

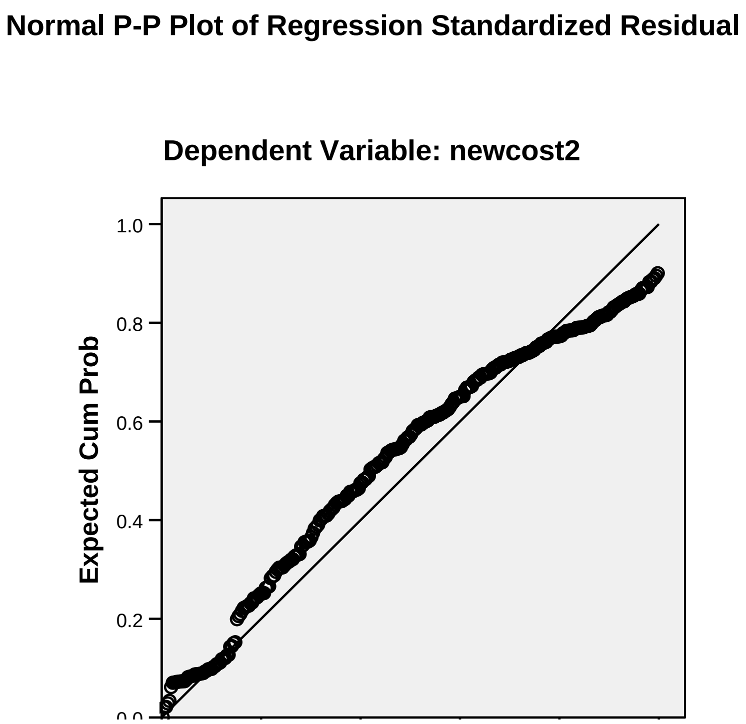


FIG 5.24C THE RESULT OF TRANSFORMATION WITH Λ=0.25

From these figures, the relationship between the estimated value and the actual value are close to the normal distribution. When λ=0, the distribution is better than other two distributions with λ=0.25 and -0.25. So the transformation τ =ln*Y* was picked in this case. Table 5.16 shows the result of the coefficient of each multiplier.

TABLE 5.15 THE COEFFICIENT OF NECK EQUATION

Model		Coefficients	Std. Error	t	Sig.
1	(Constant)	4.584	.344	13.325	.000
	M62	-.460	.208	-2.211	.028
	M81	-.195	.339	-.576	.565
	M91	-.546	.211	-2.585	.010
	M92	-.341	.196	-1.742	.083
	Age	.004	.006	.641	.522
	Gender	-.116	.231	-.504	.615
	Level	1.343	.083	16.220	.000

a Dependent Variable: LnCost

The final estimated equation for the cost of neck injury is that:

$$Log\,\text{Cost}_{\text{(neck)}} = 4.584 + (-0.460)\,X_1 + (-0.195)\,X_2 + (-0.546)\,X_3 + (-0.341)X_4 + 0.004X_5 + (-0.116)X_6 + 1.343X_7 \quad (5.8)$$

Where: X_n represent each variable. (See in Equation 5.5)

The estimated equations for other body injuries are presented below. The coefficients and significance of each multiplier also are shown in Table 5.16.

TABLE 5.16A THE COEFFICIENT FOR LEG EQUATION

Model		Coefficients	Std. Error	t	Sig.
1	(Constant)	3.428	.127	27.077	.000
	M62	.017	.073	.231	.817
	M81	-.108	.104	-1.032	.302
	M91	-.106	.075	-1.409	.159
	M92	.027	.071	.387	.699
	Age	.008	.002	4.081	.000
	Gender	.202	.086	2.353	.019
	Level	1.841	.039	47.632	.000

a Dependent Variable: LnCost

The estimated equation is shown as follows:

$$LogCost_{(leg)} = 3.428 + 0.017 X_1 + (-0.108) X_2 + (-0.106) X_3 + 0.027 X_4 + 0.008 X_5 + 0.202 X_6 + 1.841 X_7 \quad (5.9)$$

TABLE 5.16B THE COEFFICIENT FOR TRUNK EQUATION

Model		Coefficients	Std. Error	t	Sig.
1	(Constant)	3.909	.093	42.183	.000
	M61	-.138	.054	-2.539	.011
	M81	-.257	.085	-3.020	.003
	M91	-.207	.056	-3.712	.000
	M92	-.259	.054	-4.821	.000
	Age	.008	.001	5.999	.000
	Gender	.004	.063	.060	.952
	Level	1.840	.021	88.286	.000

a Dependent Variable: LnCost

The estimated equation is shown as follows:

$$LogCost_{(Trunk)} = 3.909 + (-0.138) X_1 + (-0.257) X_2 + (-0.207) X_3 + (-0.259) + 0.008 X_5 + 0.004 X_6 + 1.840 X_7 \quad (5.10)$$

TABLE 5.16C THE COEFFICIENT FOR FOREARM EQUATION

Model		Coefficients	Std. Error	t	Sig.
1	(Constant)	2.487	.082	30.518	.000
	M62	-.144	.046	-3.136	.002
	M81	-.147	.068	-2.172	.030
	M91	-.067	.047	-1.433	.152
	M92	-.073	.044	-1.671	.095
	Age	.004	.001	3.988	.000
	Gender	-.027	.045	-.590	.555
	Level	2.820	.043	66.083	.000

a Dependent Variable: LnCost

The estimated equation is shown as follows:

$$Log\,\text{Cost}_{\text{(Forearm)}} = 2.478 + (-0.144)X_1 + (-0.144)X_2 + (-0.147)X_3 + (-0.067)X_4 + 0.004X_5 + (-0.027)X_6 + 2.820X_7 \quad (5.11)$$

TABLE 5.16D THE COEFFICIENT FOR UPPER ARM EQUATION

Model		Coefficients	Std. Error	t	Sig.
1	(Constant)	3.471	.179	19.380	.000
	M61	.063	.107	.588	.556
	M81	.086	.154	.563	.574
	M91	.060	.112	.531	.595
	M92	.048	.105	.457	.648
	Age	.006	.003	2.147	.032
	Gender	-.022	.118	-.187	.851
	Level	1.723	.042	41.140	.000

a Dependent Variable: LnCost

The estimated equation is shown as follows:

$$Log\,\text{Cost}_{\text{(upper arm)}} = 3.471 + 0.063X_1 + 0.086X_2 + 0.060X_3 + 0.048X_4 + 0.006X_5 + (-0.022)X_6 + 1.723X_7 \quad (5.12)$$

TABLE 5.16E THE COEFFICIENT FOR WRIST EQUATION

Model		Coefficients	Std. Error	t	Sig.
1	(Constant)	3.961	.240	16.516	.000
	M62	-.360	.164	-2.194	.029
	M81	-.005	.257	-.018	.985
	M91	-.267	.169	-1.573	.116
	M92	-.339	.161	-2.099	.036
	Age	.016	.004	4.062	.000
	Gender	-.048	.130	-.367	.714
	Level	1.558	.050	31.175	.000

a Dependent Variable: LnCost

The equation is shown as follows:

$Log\mathrm{Cost}_{\text{(Wrist)}} = 3.961 + (-0.360)X_1 + (-0.005)X_2 + (-0.267)X_3 + (-0.339)X_4 + 0.016X_5 +$

$(-0.048)X_6 + 1.558X_7$ (5.13)

5.5 Case Study

Both the ANN and LR methods were applied to the example system which is described in Chapter 3 to calculate the cost of work injury, and the results of this case study are described in the following.

5.5.1 Sample Task and the Result from CADASWIE Revisit

The sample task is the installing and tightening task on Cell P4 in the assembly system. Table 5.17 shows the level of work injuries obtained from CADASWIE.

TABLE 5.17 THE LEVEL OF WORK INJURY OF MANIKIN TOM

Part of Body	Level
Upper Arm	2
Forearm	1
Wrist	2
Neck	4
Trunk	5
Leg	1

5.5.2 Results of Artificial Neural Network Model

The ANN-WIC will take the injury information of the current assembly system from the injury analysis as input parameters, and output the cost of the work injury. The input parameters will be given in Table 5.17. Table 5.18 shows the result of estimation of the cost of work injury. The sum represents the cost for the whole work injuries. This means when the worker gets this kind of injury, he needs to be paid $15742.30 for treatment and compensation.

TABLE 5.18 THE COST OF WORK INJURY

Part of Body	Level	Age	Gender	Business Type	Cost
Upper Arm	2	28	Male	M92	$292.69
Forearm	1	28	Male	M92	$74.17
Wrist	2	28	Male	M92	$197.00
Neck	4	28	Male	M92	$2521.36
Trunk	5	28	Male	M92	$12543.25
Leg	1	28	Male	M92	$113.83
Sum					$15742.30

5.5.3 Results of Linear Regression Model

The input parameters are the same as the input parameters of BP-ANN model which is shown in Table 5.17. The equations for calculating the cost were shown in Section 5.4. Each equation takes the input parameters to calculate the cost of the injury at a specific body part. For instance, Equation 5.8 calculates the cost for neck injury. The results with the LR model are shown in Table 5.19.

TABLE 5.19 INPUT PARAMETERS AND RESULT FOR LR MODEL

Part of Body	Level	Age	Gender	Business Type	Cost
Upper Arm	2	28	Male	M92	$223.47
Forearm	1	28	Male	M92	$68.33
Wrist	2	28	Male	M92	$155.34
Neck	4	28	Male	M92	$2433.12
Trunk	5	28	Male	M92	$6186.47
Leg	1	28	Male	M92	$115.23
Sum					$9181.96

5.6 Discussion and Conclusion

The BP-ANN model is for predicting a non-linear relation directly for multiple input and multiple output variables. The LR model is inherently for predicting a linear relation but can be enhanced by careful designing terms to cope with non-linear relations.

Several individuals were picked up from the S-WCB database for comparing the BP-ANN model and the LR model. The actual costs for these individuals have already been available in the S-WCB database, so they were treated as a control. The input parameters are age, gender, level of work injury and type of business. The data of these individuals are put in Table 5.20. The results predicted by both ANN and LR are shown in Table 5.21 and they show that for some individuals LR is better than ANN in terms of prediction accuracy, while for other individuals, ANN is better. Therefore, at this time, which one is better between, ANN or LR, is not possibly determined. In theory, LR can be viewed as a special case of ANN (i.e., there are only input and output layers without any hidden layer), but for some individual cases that may show a highly linear relation, LR could be better due to the computation overhead with ANN for these cases.

TABLE 5.20 THE INFORMATION OF NECK INJURY FROM THE S-WCB DATABASE

Number	Business Type	Age	Gender	Injury Level
1	M91	48	M	1
2	M62	26	M	1
3	M91	24	M	2
4	M81	55	M	2
5	M92	56	M	3
6	M92	31	M	3
7	M94	62	M	4
8	M92	28	F	4

TABLE 5.21 THE RESULTS OF THE ANN METHOD AND THE LR METHOD

Neck Injury	ANN Estimated Value	LR Estimated Value	Actual Value	ANN Error (%)	LR Error (%)
1	$71.98	$69.97	$68.53	1.31	2.10
2	$69.42	$233.92	$58.5	18.57	290.87
3	$1235.72	$1237.14	$1214.44	1.75	1.86
4	$4124.55	$1311.59	$4720.58	12.62	72.21
5	$6146.64	$4359.00	$5629.92	3.14	22.57
6	$5911.72	$3944.19	$5959.52	0.80	33.81
7	$21411.06	$28175.21	$19612.59	2.17	43.66
8	$19542.44	$23576.36	$22621.60	13.61	4.22

Chapter 6 Methodology for Synthesis

6.1 Introduction

In this chapter, a methodology for synthesis of assembly systems with consideration of both the efficiency of assembly production and work injury reduction is presented. Section 6.2 presents this methodology. Section 6.3 gives a detailed procedure of this methodology. A case study is given in Section 6.4. The chapter is summarized in Section 6.5.

6.2 General Methodology of Synthesis

Synthesis is a process to find out solutions and pick up the best one among them to meet the required condition of a problem. Synthesis can be viewed as a constraint satisfaction problem. The constraint here refers to three general sources: the limitation of the system, the rule which bounds system operations, and the limitation of an environment where the system interacts. While synthesis is primarily for a new design, it should be also available for re-design, as both new design and re-design share the core meaning of the synthesis (i.e., there is a set of constraints to be satisfied). In the context of the present study, re-design was concerned.

For synthesis of an assembly system for work injury elimination, our general idea was to develop a knowledge base which describes the worker’s task and the worker’s posture. The task is the condition, and the posture is the result of synthesis to fulfill the condition. For a given worker’s task, correct postures can be obtained by searching this knowledge base. Table 6.1 gives a knowledge base which contains the “task-posture” knowledge elements that are verified to meet the safety requirements in many industries by NIOSH. This table was first developed by Emodi (2007).

To facilitate the use of Table 6.1 with a computer, a coding scheme was developed in the present thesis. Table 6.2 shows the coding scheme for the tasks. Table 6.3 lists the task code and the recommended "correct" postures. In fact, Table 6.3 results by combining Table 6.1 and Table 6.2.

Table 6.1: DESIGN KNOWLEDGE BASE (EMODI, 2007)

PROCESS	OBSERVATION	RECOMMENDATION
1	Eye level far above or far below the view location.	Alternate between standing and the use of adjustable stools to ensure a near horizontal eye level
2	Hand above shoulder level	Place tools, parts, and equipments in locations where they can be easily be accessible without having to raise the hands above the should level Paint line hangers for example should be reduced in height to eliminate this condition
3	Body twisting	Place tool on shelves in front of the workers to avoid twisting while obtaining them
4	Load weight	Do not lift loads greater than 20kg or the recommended weight limits obtained from CAD analysis. Do not lift long (>5 feet) and slender (< 2 inch thick) loads
5	Power tools	The use of power tools for various operations should be alternated between individuals on a daily basis to reduce risk of carpal tunnel.
6	Lunch/ coffee breaks	Coffee breaks, lunch breaks, and momentary rests should be ensured to reduce high work frequency and also introduce rest periods

7	Carry	Avoid carry operations as much as possible unless carrying a very small weight les than 10kg. Carry over short distances or use a trolley to carry for longer distances
8	Push-pull	The maximum initial and sustained forces of push or pull should not exceed any results obtained from the push-pull analysis using any generic ergonomics software Push all the time if possible and avoid pulling as much as possible
9	Lifting	Bend at the knee level and not at the waist while lifting or lowering Lift from a platform and not from ground level Lower loads from platforms about chest level Keep back straight while lifting or lowering Ensure that object size being lifted do not have a larger width than the body width.
10	Standing/Seating	Alternate standing and seating. Do not stand for more than 45 minutes at a stretch. Do not seat for long periods on a high stool (above knee level) to avoid build up of blood on the legs. For computer use in the plant, use of seats without arm rests should be avoided

TABLE 6.2A THE LIFTING TASK CODE

Code	Classification of Task	Code	Type of Task
L	Lifting	L1	Lift from Ground Level
		L2	Lift from Platform Level
		L3	Lift over the Chest Level
		L4	Lift below the Chest Level

TABLE 6.2B THE CARRY TASK CODE

Code	Classification of Task	Code	Type of Task
C	Carry	C1	Holding components
		C2	Carry for distance
		C3	Carry for repeat
		C4	Carry for over height

TABLE 6.2C THE PUSH AND PULL TASK CODE

Code	Classification of Task	Code	Type of Task
P	Push and Pull	P1	Push/Pull on the Ground Level
		P2	Push/Pull on the Platform Level
		P3	Push/Pull with over height component
		P4	Push/Pull with overweight component

TABLE 6.2D THE INSTALLING TASK CODE

Code	Classification of Task	Code	Type of Task
I	Installing	I1	Installing at bottom of component
		I2	Installing at the Eye Level
		I3	Installing at the Chest Level
		I4	Installing with tools

TABLE 6.2E THE VIEWING TASK CODE

Code	Classification of Task	Code	Type of Task
V	Viewing	V1	Eye Level above the view location
		V2	Eye Level below the view location

TABLE 6.3A SOLUTIONS FOR TASK L CODE

Type of Task	Code	Solutions for Task
L1	L1S1	Weight should under the lift limit
	L1S2	Both hand symmetry on component
	L1S3	Two workers for overweight components
	L1S4	Use tools to lift the over-weight components
	L2S5	Bend at knee level not at the waist level

L2	L2S1	Weight should under the lift limit
	L2S2	Both hand symmetry on components
	L2S3	Keep back straight
	L2S4	Use tools to help lift for over-weight components
L3	L3S1	Weight should under the 10kg
	L3S2	Duration of Lift should over 5 min
	L3S3	The time of Lift should under 1 min
	L3S4	Use tools for over time lift or over weight components
L4	L4S1	Weight should under the lift lime
	L4S2	Keep the back and neck straight
	L4S3	Better keep the arm straight
	L4S4	Do not bend at waist level

TABLE 6.3B SOLUTIONS FOR TASK C CODE

Type of Task	Code	Solutions for Task
C1	C1S1	The weight should be under 5kg
	C1S2	The time for holding should below 3 min
	C1S3	The time for twist at the wrist level should below 30 sec
C2	C2S1	The weight should be under 10kg
	C2S2	The duration of carry should over 5 min
	C2S3	The distance should under the limit
	C2S3	Both hand symmetry on components
	C2S4	Use tool for long distance carry
C3	C3S1	The frequency should at low level
	C3S2	The weight should under 5kg
	C3S3	Use tool for high frequency carry
C4	C4S1	Use tools for overweight carry
	C4S2	More than one workers for low frequency carry load

TABLE 6.3C SOLUTION FOR TASK P CODE

Type of Task	Code	Solutions for Task
P1	P1S1	The weight should under the push/pull limit
	P1S2	Push posture is better than pull posture
	P1S3	Keep the upper body straight
	P1S4	Do not bend at waist level
P2	P2S1	The weight should under the push/pull limit
	P2S2	Both two hands symmetry on the components
	P2S3	One hand on the middle of the components
	P2S4	The components should close to edge of table
P3	P3S1	Low down the over-height components
	P3S2	Use tools to push/pull components
	P3S3	Pull posture is better than push posture

	P3S4	Do not twist the upper body at waist level over 20 Degrees
P4	P4S1	Use tool or conveyor to move the component
	P4S2	Take long break during the push/pull

TABLE 6.3D SOLUTION FOR TASK I CODE

Type of Task	Code	Solutions for Task
I1	I1S1	Hoist up the components to see the bottom
	I1S2	Take seated posture to see the bottom
	I1S3	Turn over the components to see the bottom
	I1S4	Do not bend at the waist level and keep back straight
I2	I2S1	The tools or components should under 5kg
	I2S2	Do not wrist or bend the body
	I2S3	Do not keep arm straight
	I2S4	Duration of install should over 4 min
	I2S4	Use hoist machine for over-weight components
I3	I3S1	The tools or components should under 10kg
	I3S2	The duration should over 5 min
	I3S3	Keep the upper body straight
	I3S4	Take seated posture is better
I4	I4S1	The weight of tool should under 5kg
	I4S2	The tool should be placed close to the operator
	I4S2	The power of power tool should be far from operator

TABLE 6.3E SOLUTION OF TASK V CODE

Type of Task	Code	Solution for Task
V1	V1S1	Raise up the components to eye level
	V1S2	Take the seated posture
	V1S3	Alternate between standing and posture on knee
V2	V2S1	Low down the component to see the bottom
	V2S2	Take the standing posture
	V2S3	Raise up the platform under the operator

6.3 Producer of Synthesis for Re-design

Re-design is to improve poor designs of the current assembly system for a certain objective – worker injury removal in our case. In this study, the re-design of the assembly system was guided by the new design knowledge base developed before (i.e., Table 6.3).

To identify the poor work condition of an assembly system is the first step in synthesis. This can be fulfilled by the work injury analysis - i.e., by the CADASWIE system. Suppose a particular assembly task by a particular human worker is deemed to create some work injuries. This task is compared with the task and solution principle knowledge base, and new designs maybe generated. The new designs are further analyzed with CADASWIE to determine whether the identified work injury is eliminated or reduced to a satisfied level.

6.4 Case Study

In Chapter 4, it is mentioned that a task in the example assembly system needs to be a re-designed to reduce level of the work injuries. In this section, the methodology for synthesis is applied to re-design these activities to eliminate the work injuries.

6.4.1 Injury Situation of Initial and Modified Assembly System

Initial Design of the Assembly System:

The initial design is a task that involves a worker who carries a product component and installs it onto another product. The worker's posture at which to perform this task is 45 degree at the neck. Fig 6.1 shows the initial posture of the worker on Cell P4. The work injury analysis with CADASWIE has shown that the worker may get the back injury in this posture that the level of trunk injury is 5 (See previous discussion in Chapter 4, Table 4.5).

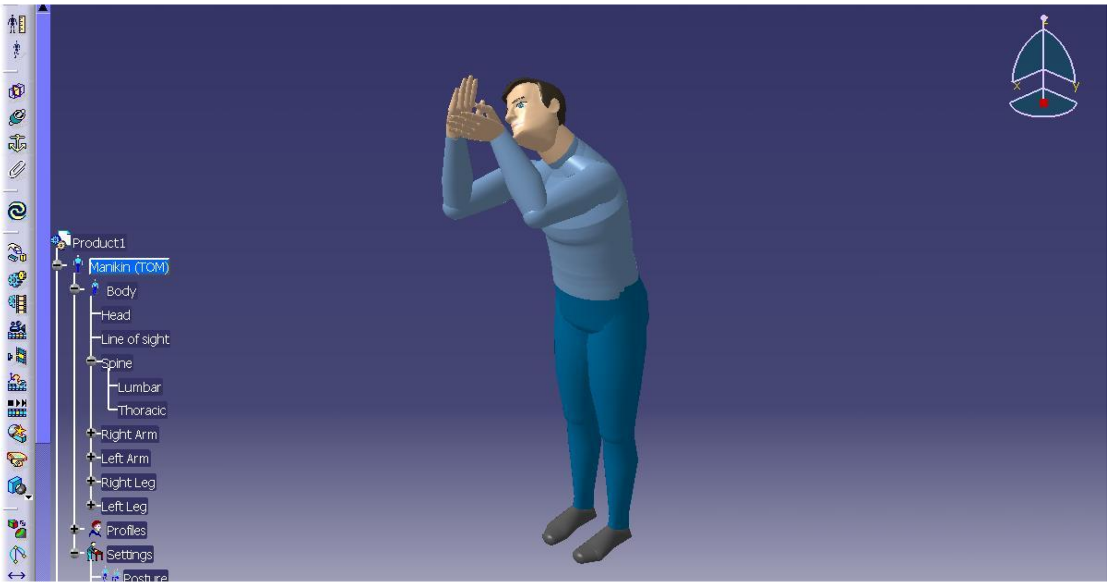


FIG 6.1 INITIAL POSTURE

Design Process:

The improved solution to poor designed task was not found in particular directly from the task table (i.e., Table 6.2). Therefore, the task was divided into several smaller tasks; this task is divided into the carrying, installing and viewing. The codes for these smaller tasks are C1, I1 and V1, respectively. According to Table 6.3, the solution principle can be found. There are a few solutions in this case and they are C1S1, C1S3, I1S2, I1S3 and V1S2. They are further evaluated with CADASWIE.

Final Design:

The final design is to have a seat on which the worker should sit (see Fig 6.2). This new posture could eliminate the bending or twisting of human body, compared with the previous posture (Fig 6.1). The seat was designed to be adjustable to the range of the workers' anthropometric. Also, whole seat can be hoisted to a certain distance, which depends on the height of the worker. The power tools the worker holds were placed close to the work station, which is conducive to reduce the workload of the worker.

FIG 6.2 FINIAL POSTURE

Table 6.4 shows the RULA analysis of both the new design and the previous design. The level of the work injury for the re-designed assembly system is numbered as ‘2’ which is lower than the current assembly system.

TABLE 6.4: RULA ANALYSIS RESULT BOTH INITIAL AND FINAL DESIGN

Body part	INITIAL		MODIFIED	
	Tom 2		Tom 2	
Upper arm	2		1	
Fore arm	1		2	
Wrist	3		1	
Muscle	1		1	
Wrist and arm	3		2	
Neck	4		2	
Trunk	5		2	
Leg	1		1	
Neck, trunk, & leg	3		2	
Final score	7		2	

6.4.2 Cost Analysis of the Initial and Modified Assembly System

Suppose that the total cost includes the wage of workers, cost of work injury, material cost, and other expense. Based on our observation from the ABC company, we obtained: (1) the wage of two workers of 8 hours is $15×8×2=$240, (2) the material cost is $10000, and (3) the other expense is $500

The cost of the work injury of the current assembly system is $15742.3 that is obtained from the ANN method (see Chapter 5). Therefore, the total cost of assembly system is $240+$10000+$500+$15742.3=$26482.3.

The cost of work injury for the re-designed system is $841.2 that is calculated with the ANN method. The other expense of the new design includes the cost of the adjustable seat, which is estimated to be $500. Therefore, the total cost of the new design is $240+$10000+$500+$500+$841.2=$12081.2. The new design saves 54.38% in cost, which is quite significant.

6.5 Conclusion

The knowledge base for work injury synthesis is a very useful tool. By coding the tasks and corrected posture solutions, both re-design and new design of work postures can be carried out in a more systematic manner.

Chapter 7: Summary, Conclusions, and Future Work

7.1 Overview

This thesis work was motivated by an observation that the work injury analysis was not integrated or not well integrated into the existing approach to production assembly systems design. This can cause the problem of poor assembly systems design in terms of both human work injury and cost. This problem was first addressed by Emodi (2007) at the Advanced Engineering Design Laboratory (AEDL) of the University of Saskatchewan in 2007. The present thesis was intended to improve the work of Emodi (2007).

Based a preliminary study of the work of Emodi (2007) as well as the related literature, the following were objectives defined for this thesis work:

(1) To develop an integrated computer system for assembly system design with consideration of work injuries. The integrated computer system should allow to specifying a complete assembly system in the digital format so that design of assembly systems with elimination of work injury can be performed automatically.

(2) To develop a methodology for calculating work injury cost more accurately than the one developed by Emodi (2007).

(3) To develop a methodology for synthesis, especially for re-design of assembly system for the purpose of work injury reduction or elimination.

This thesis began with a further literature review to justify the need of the defined objectives for this thesis study. After that, an example system provided by the sponsor company was presented; such is always important for this kind of research – i.e., grounding to one particular application to facilitate the concepts development and illustration. With these two background introductions detailed studies with respect to the three objectives were presented.

With respect to Objective 1, an integrated computer system for work injury analysis was developed. The system was called CADASWIE (Computer Aided Design of Assembly System with Consideration of Work Injury Elimination). The CADASWIE system has achieved the extendibility, flexibility and interrogating capability. The CADASWIE was implemented with the Delmia and Solidwork software systems, both of which are commercially available. The example assembly system was used to explain this computer system.

With respect to Objective 2, a general model for calculating the cost of work injuries was developed. Based on the general model, two implantation methods were developed: (1) the method based on Artificial Neural Network (ANN) that can deal with a highly non-linear function; and (2) the method based on Linear Regression (LR) that can deal with the linear function yet generate the structure of the function explicitly.

With respect to Objective 3, a methodology for synthesis was developed. Based on the previous experimental and analytical approaches, a set of new knowledge bases was developed which involves recommended solutions regarding various types of tasks on the assembly system. With the new knowledge base and the work injury analysis, problematic assembly systems were re-designed with a significant reduction of work injury.

7.2 Conclusions

The following are the conclusions drawn from this research:

(1) The software Delmia V5© and Solidworks© systems are suitable for an integrated computer program for modeling, simulation and analysis of an assembly system especially work injury analysis. The two software systems are readily available to industry.

(2) Both methods (ANN method and LR method) for calculating work injury cost are effective. The ANN method is known for its capability of modeling non-linear functions and its being of high fault tolerance. The S-WCB database provided valid information for the development of these two models; however, it has some large mismatch with the respect to the data generated from CADASWIE. A careful conversion between these two is extremely important.

(3) The new knowledge base that was generated for synthesis gives an efficient way to re-design a problematic assembly system for eliminating work injuries.

7.3 Contributions

The following are the major contributions made through this study:

(1) Proposed an integrated computer system for work injury analysis and system design and verified the feasibility of the implementation of this integrated system using the commercially available software systems.

(2) Proposed two new work injury cost calculation methods with one (i.e., ANN model) being more accurate and the other (i.e., LR model) being simpler.

(3) Proposed a knowledge base which contains the different tasks on the assembly system and the solution principles of posture for each of the tasks. The knowledge base allows a quick and systematic generation of correct postures over problematic postures.

7.4 Limitation and Future Work

Data for cost analysis were collected from the S-WCB database. These data contained enough details for analysis in this research. However, the data from the S-WCB may contain some injury claims from accident injuries, and these accident injuries were not indicated in S-WCB. The cost analysis could be affected by these non-repetitive work injury data. For more accurate computing of the cost of repetitive work injuries, the data source could be collected further, and the non-repetitive work injury data should be removed.

The Delmia V5© offered the powerful option of simulating the activity. However, the basic activities and postures offered by Delmia V5© are not enough to simulate all possible activities on an assembly system. For some special activities or postures, the designer can only use the kinematic method offered by Delmia V5© to design the postures by manually specifying the required parameters such as the degree of angles. Motion tracking systems could be developed to address this problem. The cameras of the motion tracking systems could capture the postures and activities. The captured activities and postures can be generated in the computer as 3-Dimension models. These models can be sent to the Delmia V5© software for simulation and analysis. However, due to a high cost of the motion tracking system, practicability of this idea needs to be examined.

The cost of the work injury is still difficult to be calculated due to the mismatch in data between the workers' compensation board community and work injury analysis community. In this study, the Saskatchewan Work Compensation Board provided the data; however, it is not sure whether the data model used by S-WCB is genetic. Further studies are needed for a general understanding of the data model used by various different workers' compensation boards and for understanding of how sensitive these different data models would be to the work injury cost calculation. Closely related to the work injury cost issue, the issue of polices for work injury compensation needs to be studied in order to make manufacturing companies more alerted about the work injury problem in lien of cost increase and thus be more willing to develop a safe, health and cost effective work place.

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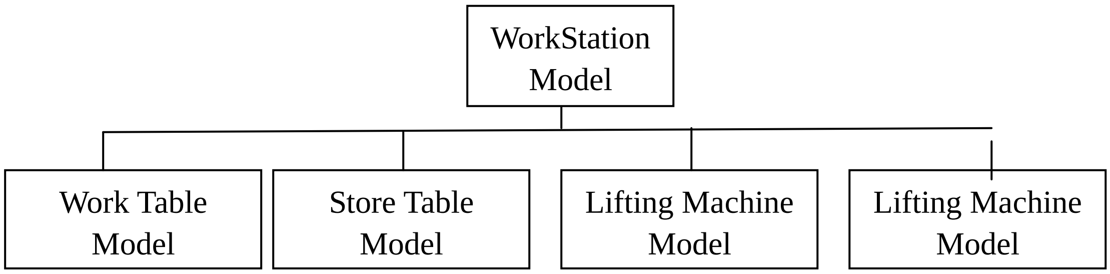
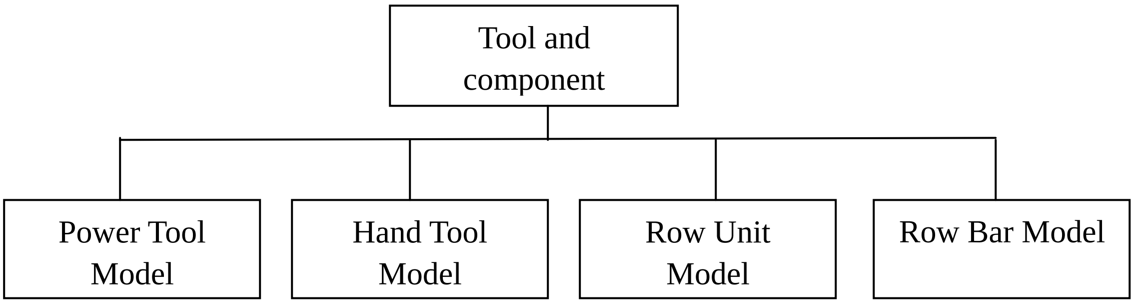
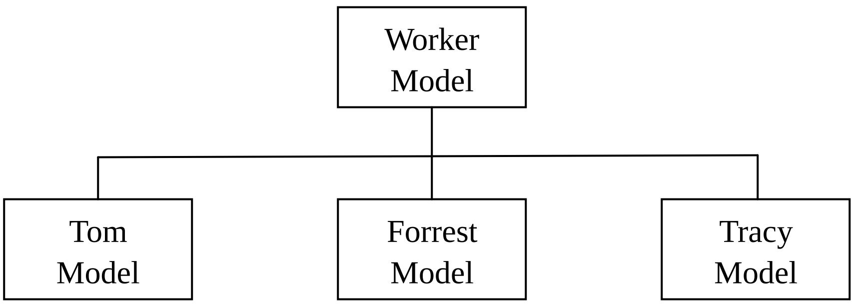
APPENDIX A: Detailed Component and Tool Model List







APPENDIX B: Detailed Results on Biomechanical Single Action Analyses

TOM 1

SUMMARY DATA TAB

Analysis	Value
L4-L5 Moment (N-m)	67
L4-L5 Compression (N)	1535
Body Load Compression (N)	430
Axial Twist Compression (N)	0
Flex/Ext Compression (N)	87
L4-L5 Joint Shear (N)	51 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N-m2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	803
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	194
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	609

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	535
Joint Shear Limits	31 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N-m)	% Pop.	Not Capable	Mean (N-m)	Reference
Right Elbow	Flexion-Extension	3 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)

	Supination-pronation	0	0.0	7	2	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	3 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	4 Extension	0.0	90	20	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Abduction-Adduction	0	0	72	28	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	0	0.0	27	9	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Left Shoulder	Flexion-Extension	6 Extension	0.0	69	14	Koski and McGill (1994)
	Abduction-Adduction	0	DNA	DNA	DNA	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Lumbar (L4-L5)	Flexion-Extension	5Extension	0.0	369	69	Troup and Chapman (1969)
	Right-left lateral bend	1 Right Lateral Bend	0.0	143	40	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	0	0.0	72	20	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

SEGMENT POSITIONS TAB

Segment	Proximal Coordinated (mm)	Distal Coordinates (mm)	XY plane angle	YZ plane angle	Length
Right Foot	11228.398,8351.727,-800.999	11233.827, 8475.502, -848.890	-22.9	-43.7	132.829
Right Leg	11202.978, 8374.100, -386.780	11228.398, 8351.727, -800.999	-94.2	-87.9	415.600
Right Thigh	11176.202, 8397.668, 49.555	11202.978,8374.100, -386.780	-94.2	-87.9	437.791
Left Foot	10982.570, 8321.818, -803.299	10935.262, 8438.459, -845.728	-18.6	-92.0	132.829
Left Leg	10996.293, 8327.193, -387.961	10982.570, 8321.818, -803.299	-90.0	-92.0	415.600
Lift Thigh	11010.749, 8332.856, 499.555	10966.293, 8327.193, -387.961	-90.0	-90.0	437.791
Right Hand	1151.659, 8701.524, 227.043	11122.333, 8796.776, 236.369	5.4	51.4	100.100
Right Forearm	11222.309, 8456.298, 227.020	11151.659, 8701.524, 227.043	0.0	0.1	255.200
Right Arm	11227.804, 8403.109, 525.204	11222.309, 8456.298, 227.020	-80.2	-87.3	302.904
Left Hand	10849.552, 8635.662, 236.346	10825.234, 8730.795, 216.898	-11.3	-58.2	100.100
Left Forearm	10832.692, 8381.660, 254.397	10849.552m, 8635.662, 236.346	-4.5	-9.5	255.200
Left Arm	10964.152, 8349.208, 518.830	10832.692, 8381.660, 254.397	-67.3	-110.3	302.940

TOM 2

SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	20
L4-L5 Compression (N)	1623
Body Load Compression (N)	134
Axial Twist Compression (N)	48
Flex/Ext Compression (N)	131
L4-L5 Joint Shear (N)	3 Posterior
Abdominal Force (N)	0
Abdominal Pressure (N_m2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	657
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	432
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	211

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	1760
Joint Shear Limits	2 Posterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N-m)	% Pop.	Not Capable	Mean (N-m)	Reference
Right Elbow	Flexion-Extension	3 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	7	2	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	3 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	4 Extension	0.0	90	20	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Abduction-Adduction	0	0	72	28	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	0	0.0	27	9	Lannersten, Harms-Ringdahl,

						Schuldt and Ekholm (1993)
Left Shoulder	Flexion-Extension	6 Extension	0.0	69	14	Koski and McGill (1994)
	Abduction-Adduction	0	DNA	DNA	DNA	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Lumbar (L4-L5)	Flexion-Extension	5Extension	0.0	369	69	Troup and Chapman (1969)
	Right-left lateral bend	1 Right Lateral Bend	0.0	143	40	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	0	0.0	72	20	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

FORREST 1

SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	7
L4-L5 Compression (N)	450
Body Load Compression (N)	231
Axial Twist Compression (N)	11
Flex/Ext Compression (N)	59
L4-L5 Joint Shear (N)	4 Posterior
Abdominal Force (N)	0
Abdominal Pressure (N_m2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0

Total (Z)	453
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	678
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	86

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	684
Joint Shear Limits	2 Posterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	2 Flexion	0.0	42	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	2 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	1 Extension	0.0	45	20	Koski and McGill (1994)
	Abduction-Adduction	6 Abduction	DNA	DNA	DNA	DNA
	Internal-external rotation	2 Ext. Rotation	DNA	DNA	DNA	DNA
Left Shoulder	Flexion-Extension	1 Extension	0.0	65	20	Koski and McGill (1994)
	Abduction-Adduction	4 Adduction	0.8	23	28	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)

	Internal-external rotation	1 Ext. Rotation	0.0	27	9	DNA
Lumbar (L4-L5)	Flexion-Extension	11 Extension	0.0	500	93	Troup and Chapman (1969)
	Right-left lateral bend	30 Left Lateral Bend	0.0	12	40	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	2 Left Twist	0.0	74	23	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

FORREST 2

SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	28
L4-L5 Compression (N)	1390
Body Load Compression (N)	480
Axial Twist Compression (N)	12
Flex/Ext Compression (N)	453
L4-L5 Joint Shear (N)	43 Anterior
Abdominal Force (N)	2
Abdominal Pressure (N_m2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	719
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	296
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	324

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	1324
Joint Shear Limits	34 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	2 Flexion	0.0	42	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	2 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	9	2	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	1 Extension	0.0	45	20	Koski and McGill (1994)
	Abduction-Adduction	6 Abduction	DNA	DNA	DNA	DNA
	Internal-external rotation	2 Ext. Rotation	DNA	DNA	DNA	DNA
Left Shoulder	Flexion-Extension	1 Extension	0.0	65	20	Koski and McGill (1994)
	Abduction-Adduction	4 Adduction	0.8	23	28	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	1 Ext. Rotation	0.0	27	9	DNA
Lumbar (L4-L5)	Flexion-Extension	11 Extension	0.0	500	93	Troup and Chapman (1969)
	Right-left lateral bend	30 Left Lateral Bend	0.0	12	40	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	2 Left Twist	0.0	74	23	Gomez, P.T., Beach, G., Cooke, C.,

						Hrudey, W., and Goyert, P (1991)

Tracy 1

SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	33
L4-L5 Compression (N)	1345
Body Load Compression (N)	326
Axial Twist Compression (N)	15
Flex/Ext Compression (N)	966
L4-L5 Joint Shear (N)	65 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N_m2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	432
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	431
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	200

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	1432
Joint Shear Limits	67 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference

Right Elbow	Flexion-Extension	2 Flexion	0.0	42	11	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	2	9	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	2 Flexion	0.0	71	15	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	4	8	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	4 Flexion	0.0	64	12	Koski and McGill (1994)
	Abduction-Adduction	1Abduction	DNA	DNA	DNA	DNA
	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	DNA
Left Shoulder	Flexion-Extension	3 Flexion	0.0	63	16	Koski and McGill (1994)
	Abduction-Adduction	3 Abduction	0.8	58	22	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Internal-external rotation	0	DNA	DNA	DNA	DNA
Lumbar (L4-L5)	Flexion-Extension	Flexion-Extension	60 Extension	0.0	431	Troup and Chapman (1969)
	Right-left lateral bend	4 Left Lateral Bend	0.0	122	35	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	1 Right Twist	0.0	13	23	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

TRACY 2

SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	14
L4-L5 Compression (N)	689
Body Load Compression (N)	234
Axial Twist Compression (N)	22
Flex/Ext Compression (N)	23
L4-L5 Joint Shear (N)	145 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N_m2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	432
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	431
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	200

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	3211
Joint Shear Limits	110 Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	2Flexion	0.0	67	14	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	7	1	Askew, An, Morrey and Chao (1987)
Left	Flexion-Extension	0	0.0	57	13	Askew, An,

Elbow						Morrey and Chao (1987)
	Supination-pronation	0	0.0	7	1	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	0	0.0	78	14	Koski and McGill (1994)
	Abduction-Adduction	4 Abduction	DNA	DNA	DNA	DNA
	Internal-external rotation	0	0.0	20	6	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Left Shoulder	Flexion-Extension	8 Flexion	0.0	34	7	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Abduction-Adduction	1 Abduction	DNA	DNA	DNA	DNA
	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	DNA
Lumbar (L4-L5)	Flexion-Extension	72 Extension	0.0	450	78	Troup and Chapman (1969)
	Right-left lateral bend	35 Left Lateral Bend	0.0	112	23	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	2 Right Twist	0.0	767	21	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

TRACY 3

SUMMARY DATA TAB

Analyses	Value
L4-L5 Moment (N_m)	23
L4-L5 Compression (N)	143
Body Load Compression (N)	309
Axial Twist Compression (N)	42

Flex/Ext Compression (N)	323
L4-L5 Joint Shear (N)	24 Anterior
Abdominal Force (N)	0
Abdominal Pressure (N_m2)	0

GROUND REACTION (N)

Total (X)	0
Total (Y)	0
Total (Z)	432
Left Foot (X)	0
Left Foot (Y)	0
Left Foot (Z)	431
Right Foot (X)	0
Right Foot (Y)	0
Right Foot (Z)	200

SPINE LIMIT DATA TAB

Forces	Value (N)
Compression Limits	1600
Joint Shear Limits	29Anterior

JOINT MOMENT STRENGTH DATA TAB

Joint	DOF	Moment (N_m)	% Pop.	Not Capable	Mean (N_m)	Reference
Right Elbow	Flexion-Extension	2Flexion	0.0	67	14	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	7	1	Askew, An, Morrey and Chao (1987)
Left Elbow	Flexion-Extension	0	0.0	57	13	Askew, An, Morrey and Chao (1987)
	Supination-pronation	0	0.0	7	1	Askew, An, Morrey and Chao (1987)
Right Shoulder	Flexion-Extension	0	0.0	78	14	Koski and McGill (1994)
	Abduction-Adduction	4 Abduction	DNA	DNA	DNA	DNA

	Internal-external rotation	0	0.0	20	6	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
Left Shoulder	Flexion-Extension	8 Flexion	0.0	34	7	Lannersten, Harms-Ringdahl, Schuldt and Ekholm (1993)
	Abduction-Adduction	1 Abduction	DNA	DNA	DNA	DNA
	Internal-external rotation	1 Ext. Rotation	DNA	DNA	DNA	DNA
Lumbar (L4-L5)	Flexion-Extension	72 Extension	0.0	450	78	Troup and Chapman (1969)
	Right-left lateral bend	35 Left Lateral Bend	0.0	112	23	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)
	Right-left twist	2 Right Twist	0.0	767	21	Gomez, P.T., Beach, G., Cooke, C., Hrudey, W., and Goyert, P (1991)

APPENDIX C: RULA and Some DELMIA V5 Body Part Range

C1 RULA WORK SHEET (Delmia V5© manual, 2005)

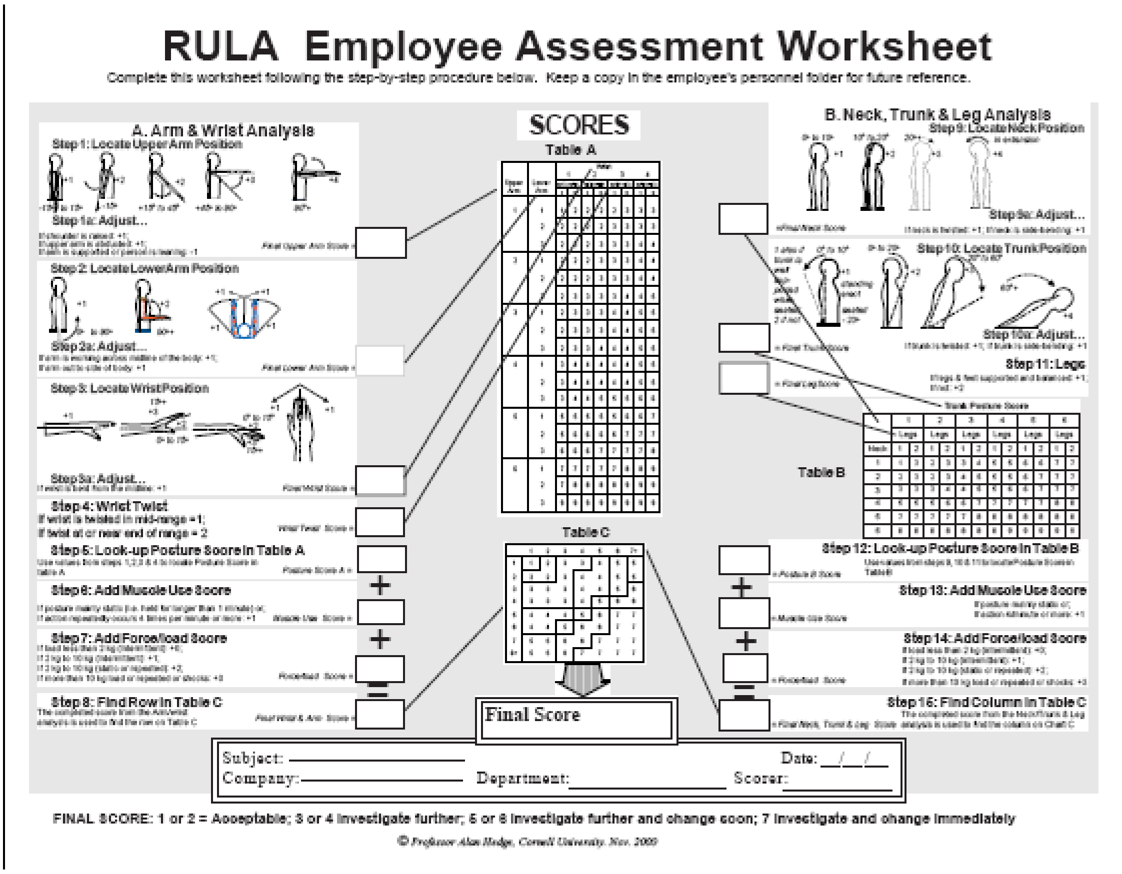


FIG C1: RULA ASSESSMENT WORK SHEET

C2 Color Associated To Various Scores In Delmia V5©

Table C2 Color Associations To Scores (Delmia V5© manual, 2005)

Segment	Score Range	Color associated to the scores					
		1	2	3	4	5	6
Upper arm	**1 to 6**						
Forearm	**1 to 3**						
Wrist	**1 to 4**						
Wrist twist	**1 to 2**						
Neck	**1 to 6**						
Trunk	**1 to 6**						

C3 Extended classification For Body Parts In Delmia V5©

Table C3 Extended classification For Body Parts In Delmia V5©

Segment	Score Range	Color associated to the score						
		1	2	3	4	5	6	7
Upper arm	**1 to 6**							
Forearm	**1 to 3**							
Wrist	**1 to 4**							
Wrist twist	**1 to 2**							
Posture A	**1 to 7**							
Muscle	**0 to 1**							
Force/Load	**1 to 7**							
Wrist/ Arm	**1 to 7**							
Neck	**1 to 6**							
Trunk	**1 to 6**							
Leg	**1 to 4**							
Posture B	**1 to 7**							

Neck, **Trunk Leg**	**1 to 7**							

Note: The grey colored regions represent blank regions that are out of range

APPENDIX D: Data Stored in Disc

In this project, all data and information related to the safety analysis and cost estimation were stored in a disc. The following table is a list of data stored in disc.

TABLE D DATA LIST IN DISC

Data and information Description	File in Disc
Assembly system CAD models (parts, workers, tool and load)	File in Documentation 'Assembly Model'
Input data for activity simulation and analysis (i.e., Table 3.1)	File in Documentation 'Data for Simulation'
All of activities simulation (6 activities)	File in Documentation 'Activity Simulation'
All of analysis result (6 postures)	File in Documentation 'Result of Analysis'
Original S-WCB claim report	File in Documentation 'S-WCB Original'
Data for ANN method (original data, data after modification, model of each body parts and results of ANN method)	File in Documentation 'ANN method'
Data for Linear Regression method (original data, data after modification and result of linear regression method)	File in Documentation 'Linear Regression method'