EFFECTS OF WORK INJURY COST TO OVERALL PRODUCTION COST

WITH LINEAR PROGRAMMING APPROACH

A Thesis

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Canada

By

He Xu

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ABSTRACT

Production planning is an important activity in manufacturing industries. The main goal of production planning is to minimize the cost under the condition that the customer requirement in terms of quality, quantity, and time is satisfied. An important player (human) is with little attention in traditional production planning. This thesis studied production planning with consideration of human factor, especially human work injuries as a result of performing a repetitive operation for a certain period of time in production systems. Production planning in this thesis only takes the minimization of total production cost as its goal.

A linear programming technique was employed to incorporate the cost of work injury into the total production cost model. The LINDO$^{\text{TM}}$ software was used to solve the linear production planning model and to analyze the solution. Finally, the benefits of the production planning, which considers work injury, were discussed.

Several conclusions can be drawn from this study: (1) the traditional production planning model, which only takes the material costs and labor costs into account, cannot deal with the cost related to work injury; (2) the work injury cost could be significant in those manual-intensive assembly systems, especially with high production rates; (3) the careful design of the worker's postures can significantly reduce the work injury cost and thus the total cost of production.

The significant contributions of this thesis are: (1) the development of a mathematical model for the total production cost including the work injury cost and (2) the finding that the work injury

cost may be a significant portion in the total cost of production in the assembly system that has intensive manual works.

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DEDICATION

To my wife:

Wei Wang

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ANN   : Artificial Neural Network

CPLEX   : IBM ILOG CPLEX Optimization Studio, an optimization software package

GA   : Genetic Algorithms

GLPK   : GNU Linear Programming Kit, a software package intended for solving large-scale LP, MIP and other related problems

MIP   : Mixed integer programming

MILP   : Mixed integer linear programming

LINDO   : Linear interactive and discrete optimizer

LP   : Linear programming

LR   : Linear regression

WI   : Work injury

WIC   : Work injury cost

PPC   : Production planning cost

SCOP   : Chain operations planning

WI   : Production planning cost considering work injury cost

WIM   : Production planning cost considering work injury cost with modified postures

CHAPTER 1 INTRODUCTION

1.1 Research Background and Motivation

Traditionally, production planning is primarily about materials resource planning. The materials include both the material for parts and the machine tools for production of the parts (Krajewski et al., 2005). Many techniques have been developed to improve the effectiveness of production planning, namely to make a plan which meets the customer demand in terms of the quality, quantity, lead time, and cost with additional features such as robustness, sustainability and resilience. The concept of resilience is referred to Zhang and Lin (2010).

Advancement of computing technology (both in hardware and software) allows us to model production situations in a more realistic manner. For instance, the set-up cost of a machine was considered in the production planning model (Atmani, 1995) to allocate a variety of parts to different machines with a minimum production cost. A hierarchical production distribution planning approach (Ozdamar and Yazgac, 1999) was proposed to achieve the total cost minimization, considering multi-time periods and penalty costs. There have been also studies on the production planning for multi-objects that are in conflict (Gramani et al., 2011).

It is worth mentioning that workers are an important participant in production especially for manual-intensive assembly systems. In other words, the production system almost always involves human factors such as human decision-making, qualification of employees,

stakeholders' interests, as well as work injuries. However, these aforementioned human factors, especially work injury, have not been considered in the design of a production system and in production planning (Wiendahl et al., 2005).

The report from Human Resources and Skills Development Canada shows that over the period from 1996 to 2008, the compensation payments to injured workers, after adjusting for inflation, have generally shown an increasing trend; the total cost of occupational injuries to the Canadian economy is estimated to be more than $19 billion annually (Labour Canada, 2011). It is being realized that the cost incurred by work injuries contributes a large portion to the total production cost, and strategies are urgently required to tackle the problem of work injury.

1.2 Research Questions and Related studies

A new technique is needed for incorporating work injury into production planning especially establishing a total production cost model which includes work injury cost. With this understanding, the following research questions were proposed in the context of manual intensive assembly line production scenario (e.g., CNH Saskatoon):

Question 1: how significant is the work injury cost in the total production cost?
Question 2: how significant is the cost effect of assembly system design with the minimization of work injury on the total production cost?

There have been studies concerning the aforementioned research questions in the existing literatures. Jensen (2002) put forward the point of view that human factors and ergonomics should be considered in production planning and drew the organizational attention to it. The

study performed an overview on the existing approaches for integrating ergonomics (working environment) into production planning. Some ergonomic assessment tools and design processes were reviewed; however no manufacturing case was illustrated to demonstrate the effect of human factors or ergonomics in the production planning process. Othman et al. (2012) developed a new approach to integrate human factors (worker's difference) with workforce planning. Human factors in the study referred to as skills, training as well as workers' personalities and motivation. A multi-objective model was built, which could assist a manufacturing planner to determine the required work levels for each position, the number of trained workers as well as overtime hours.

To conclude, neither of the aforementioned approaches has included the impact of work injury. Therefore, it is in urgent need of a new technique for production planning that includes work injury factor and to study the effect of work injury cost on the total production cost.

1.3 Research Objective and Scope

To address the above questions, there were two research objectives proposed for this thesis study and they are:

- o **Objective 1**. Develop a production planning model to incorporate work injury cost into the total production planning cost model.
- o **Objective 2**. Study the significance of the work injury factor to the production planning in terms of production cost.

It is noted that for the first objective, a linear model was tailored for use, as the purpose of this thesis was not in the pursuit of accuracy of the model but the sufficiency to study the effect of work injury on the cost of production planning. Besides, a linear production planning model has been widely used in both academia and practice. The linear production planning model has an excellent solver, which can thus facilitate the analysis of the model. In particular, LINDO^{TM} software (which is a solver to linear programming model) was applied in this thesis for its wide availability of the software.

For the second objective, different designs of worker postures were tried for finding their work injury level and cost incurred. The work injury analysis was performed by a software system called Delmia, and the work injury cost was calculated by a program developed in our research group in the past (Lin, 2008).

1.4 Organization of the Thesis

This thesis consists of five chapters. The remaining four chapters are outlined as follows:

Chapter 2 presents a literature review to summarize the significance of the existing literature work and the need of the proposed research objectives in Chapter 1. The literature review covered both material and human factors in production planning and methods to evaluate them. Further, in this chapter, the computer system that will be applied to analyze work injury and calculate the cost of work injury will also be described to give a background for the total production model, including the work injury cost in the next chapter.

Chapter 3 describes the mathematical models of production planning in three different scenarios. First, the traditional production planning model was written in a linear programming model with the demand, labor and inventory constraints. The model was based on an assembly line production where repetitive manual assembly operations are intensive. Second, the foregoing model was extended by incorporating the working injury cost into the model, and at this point, the work injury level was pretty high. Third, the design of the worker posture was modified such that the work injury level was pretty low, and accordingly a new production planning model was implied. Further, four cases of assembly line production (including worker posture) are described, drawn from the literature, for further analysis of them.

Chapter 4 performs an analysis of the four assembly lines based on the production planning models (three model scenarios: traditional production planning, production planning of the assembly system with high level of work injury, production planning of the assembly system with low level of work injury).

Chapter 5 draws the conclusions from this thesis study and discusses the research contributions of the study and future work.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter provides a literature review that is expected to help to further understand the motivation and proposed research objectives of this study. The review was also expected to give a further background for the remaining parts of the thesis. Section 2.2 reviews typical production planning methods and cost models, including their applications, advantages and disadvantages. Section 2.3 introduces the basic idea of work injury as well as the measurements and mathematical models. Section 2.4 discusses the linear programming technique. Section 2.5 revisits the proposed research objectives of the thesis in light of their necessity and urgency.

2.2 Production Planning

2.2.1 Production planning concept

Production planning does not act alone, rather it usually comes with other production activities, such as aggregate production planning, production scheduling and production control (Laperrière et al., 2014). The relationship among these various activities is shown in Fig. 2.1.

According to Vallmann et al. (1997), "Production planning and control system (PPC) is usually introduced first in order to shape an explicit understanding of core operations inside an industry

organization. Production planning and control is the hub that ties up with product design and manufacturing engineering. It addresses the process that translates business plans into reality."

In the production planning and control system, the production activities are carried out through a series of decisions. The process can be described in a hierarchical way according to Pinedo (2005). The aggregate production planning covers the first stage, which determines the quantity of each product for a long-term planning period. It is based on the demand of customer, considering the work force level, production rate and inventory status, and it is the start of the detailed plans. The second stage considers the sequence of production for planned products on weekly or daily basis, which is the objective of production scheduling. In the next stage, production control monitors the real-time information in production processes such as the inventory and work force level to make decisions for adjustment.

Since the focus of this thesis is production planning, not production scheduling, it is worth to clarify the difference between them. First, the main function of production planning is to determine the quantities and product mix, while production scheduling is to sort out the priorities of the products to be finished. Second, they can be distinguished from the amount of decisions and value involved (Mönch et al., 2013).

The term 'production planning' in this thesis is referred to as an aggregate production planning. It is concerned with "determination of production, inventory and work force level to meet the demands over a planning horizon that ranges from six months to one year" (Gallego, 2001). Production planning is a management tool in determining the quantity of products, allocating material, manpower, machine and financial resources. The production activities are conducted based on the pre-determined demand and within a certain period of time.

Resource Planning → Production Planning ↔ Demand Management

Final Assembly Scheduling ← Master Production Scheduling ↔ Rough Cut Capacity Planning

Material Requirements Planning → Capacity Requirements Planning

Purchasing   Shop Floor Control
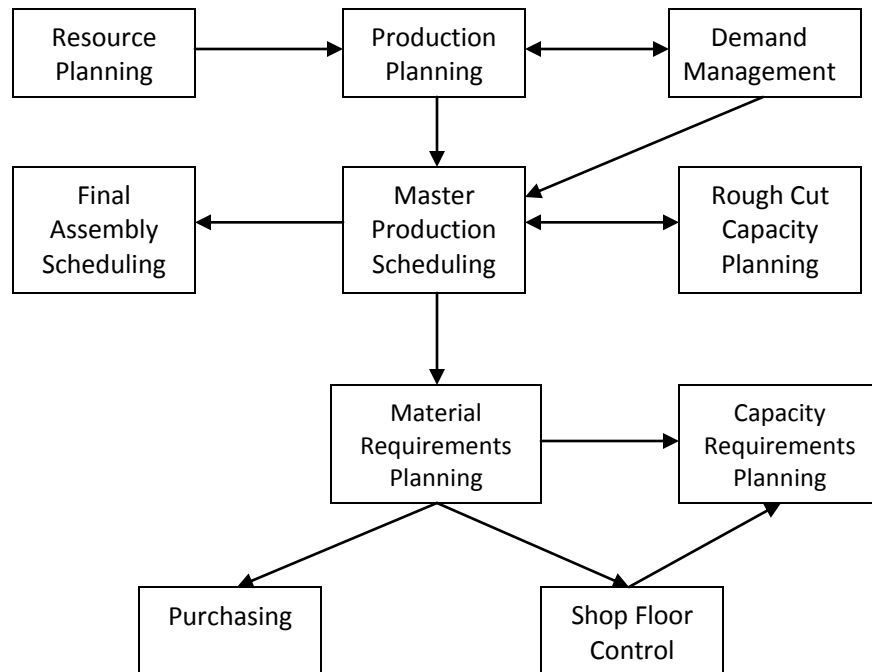
Figure 2.1 Production planning and control framework

(Vallmann et al., 1997)

2.2.2 State of arts of production planning

In the real world manufacturing scenario, the various production planning settings such as product mix, inventory status and work force level are so complex that the optimization technique is usually employed to tackle the complexity in determining these settings. There are two categories of effective techniques according to the current literature: they are the analytical techniques (Jordan et al., 2002; Chinneck, 2004) and genetic algorithm (GA) or evolutionary algorithm (Park et al., 2007, Chan et al., 2005 and Elahipanah et al., 2008).

The analytical techniques include linear programming (LP) and mixed integer programming (MIP), and they are relatively matured. Most of them have proved that optimal or near optimal

solutions can be achieved for certain types of problems (Lair, 2008). Haq et al. (1991) discussed the MIP method in dealing with the planning problem of multiple plants over multiple time-periods, considering the inventory costs and penalty costs. A mixed integer linear programming (MILP) coded method was developed by Hamedi et al. (2009) to solve the similar production planning model but without inventory costs included, and LINGO is a software system to solve the linear optimization model. Additionally, these two studies (Haq et al., 1991; Hamedi et al., 2009) limit the manufacturing to the production of a single product. Dhaenens-Flipo and Finke (2001) created a MILP formulation which is solved with CPLEX to cope with the production planning model of multiple product types and plants over multiple time-periods without penalty costs.

Chen and Wang (1997) applied the linear programming technique to solve the production planning model including different product types, multiple plants and time-periods. Kanyalkar and Adil (2008) presented a similar planning model along with inventory and penalty costs via a linear mathematical formulation and had it solved using GLPK solver.

However, there are the challenges for the analytical techniques when solving complex realistic planning problems (Fahimnia et al., 2013). First, the increasing number of variables and constraints intensifies the complexities in building the mathematical models (Jordan et al., 2002). Consequently, the analytical techniques are only applicable to small or medium size planning problems according to Lair (2008) and Fahimnia et al. (2013). Second, even though the complex problems were interpreted into linear models, simplification of the model is inevitable and may incur oversimplification. On the other hand, Dantzig (2002) concluded that the significant increase of the complexity in the model will require a highly configured computer and long computing time to derive the solutions.

9

More efficient tools are urgently required to solve complex manufacturing problems. GA (or evolutionary algorithm) is such a useful technique that can be employed in the production planning optimization (Park et al., 2007). The basic idea of GA is to develop computer codes to mimic the evolution of natural systems in solving combinatorial optimization problems (Klein et al., 2015).

A multi-objective GA was proposed by Chen et al. (2005), which was used to solve the production planning problem, minimizing the total flow time, machine workload unbalance, greatest machine workload and total tool cost. This approach obtained a set of solutions in a single run. Chakrabortty et al. (2013) employed a similar multi-objective GA approach to deal with the multi-period aggregate production planning. The objective was to minimize the total cost considering the inventory, labor, overtime, subcontracting and back-ordering levels, and the proposed method achieved a compromise solution to the planning problem. Yimer and Demirli (2010) proposed a GA based solution procedure in the planning problem of multiple product styles, multiple production distributions with penalty costs. It also provided a comparison with analytical techniques. Although GA techniques have the advantage in solving planning problems with a large number of variables, one challenge of the GAs in the optimization procedure is that it may be difficult to set up the constraints due to the large number of variables according to Fahimnia et al. (2012) and Klein (2015).

Some hybrid methods have been proposed, which foster the merits of both the analytical techniques and GAs. Chan et al. (2005) developed a combined linear programming approach and a genetic algorithm and analytical hierarchy process to solve the multiple plants and multiple end-users planning model. The results indicated the hybrid algorithm is robust and reliable. Ganesh et al. (2005) proposed a hybrid genetic algorithm and simulated annealing (GA-SA) for

continuous time-based production planning problems. The results of GA-SA appeared to be the best compared to GA or SA. Such a combined algorithm is powerful in both the global search and local search.

2.2.3 Human factors in production planning

The concept of human factors refers to the role of humans in technical systems. Humans are always involved in any technical system at different levels. Humans are highly individualized, and therefore, there is certainly an issue of whether a human fits a technical system. The unfitness of humans to technical systems may even cause injuries in the humans, which is the main concern of human factors in this thesis.

McKay et al. (2006) reviewed the positive and negative aspects of human factors in planning and scheduling, as well as the consequences when these aspects were ignored or overlooked. The concepts for better decision support mechanisms were proposed incorporating the individual and organizational aspects of planning and scheduling. The review was based on four elements: autonomy, transparency, level of support and presentation of information.

A new approach was proposed by Othman et al. (2012) to integrate workers' differences with workforce planning in the aspects of skills, training as well as workers' personalities and motivation. A multi-objective optimization model was built and solved to determine the required work levels for each position, the number of trained workers and overtime hours. The results showed this approach could be employed in a manufacturing system to assist in decision-making.

2.2.4 Cost in production planning

According to the comment of Phruksaphanrat et al. (2006), minimization of the production cost is one of the most important concerns in production planning. The costs in production planning are generally divided into three kinds according to Gallego (2001): (1) basic production costs, typically including the material cost, labor cost and overhead cost; note that the overhead cost is incurred indirectly in making the product, which includes the costs required in the areas such as electricity, gas, insurance of the facilities and so on (Swamidass, 2000); (2) costs associated with the production rate, including the costs of hiring and lay-off, training as well as overtime costs; (3) inventory related costs.

Rasmussen (2013) concluded two principles for cost calculation: opportunity cost principle (implicit cost) and accounting principle (explicit cost). Opportunity costs are equal to the earnings lost and are the key basis for all economic planning. The accounting principle is used in the calculation of a financial profit and is, and as such, directed towards the past ("history writing"). The accounting principle and its alternative versions are further discussed in (Rasmussen, 2013; P. 277-286). Note that the cost in production planning considered in this thesis includes the raw material costs, labor costs and inventory costs, which will be discussed in detail in Section 3.2.1. One of the new elements in this thesis is work injury cost, which will be discussed in detail in Section 3.4.1.

2.3 Work Injury

2.3.1 Motivation of work injury concern in production planning

Taking an insight into the recent report "Occupational Injuries and Diseases in Canada 1996-2008" (Labour Canada, 2010), several highlights might draw attention to the public. The incidence rate of time-loss injuries per 100 workers across all jurisdictions in Canada has steadily declined in all years since 1996 (with the exception of 2000 only).

Yet, over the 2000 to 2012 period, compensation payments to injured workers, after adjusting for inflation, have shown a generally increasing trend (Fig. 2.2.). By factoring into direct and indirect costs, the total costs of occupational injuries to the Canadian economy can now be estimated to be more than $19 billion annually.

In addition, up to ten percent Canadian adults had a repetitive strain injury (RSI) critical enough to limit their normal activities, reported in 2000/2001 (Cole et al., 2005). It has been found that most of the injuries resulting from excessive repetitive motion, over-exertion or improper production assembly design. Unfortunately, no work injury cost has yet to be incorporated in production planning and scheduling in literature, and as such, no knowledge available about whether the work injury cost may be a significant factor in the total production cost. Most studies on work injury have been focused on how to evaluate work injury given a product and assembly posture of a worker on the product. There are also studies on how to improve a workplace in a safe and healthy condition.

Current year benefit costs incurred by work injury 2000-2012

Figure showing a bar chart titled "Current year benefit costs incurred by work injury 2000-2012". The y-axis is labeled "Payments (CAD)   Billions" ranging from 0 to 6. The x-axis is labeled "Year" with values from 2000 to 2012. The bars increase from about 4 billion in 2000 to about 5.6 billion in 2012.
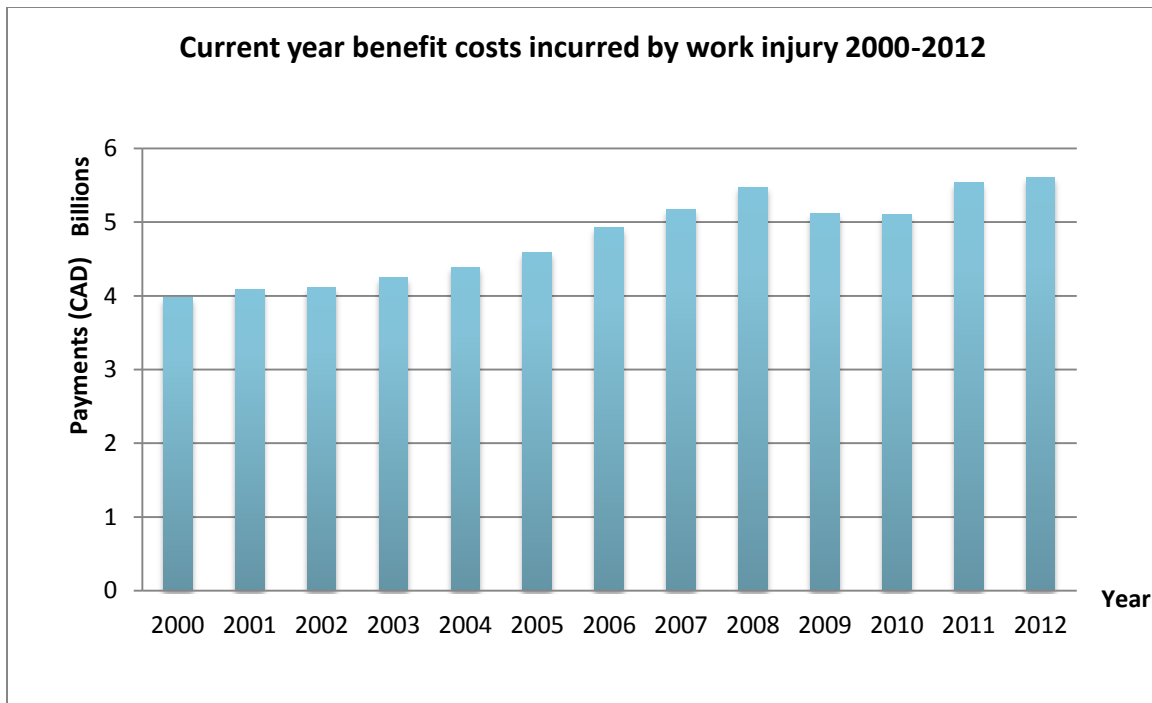
Figure 2.2 Current year benefit costs incurred by work injury

O'Sullivan and Gallwey (2005) proposed an assessment tool for the workplace injury and the potential risk for the electronic assembly work. This method provided a framework for both expert ergonomists and non-expert employers. Emodi (2007) proposed a general computer-based methodology for analysis of work injuries given an assembly line where human workers perform repetitive operations. The proposed methodology for analysis and synthesis was implemented in a real assembly line to understand the effects of different work activities on the human body. A new method for simulating manual work activities was introduced by Fritzsche et al. (2012), which was an assessment system to avoid the risk factor of the aging workforce. This simulation technique enabled modeling of worker's movements with consideration of the required skills and knowledge of the worker. Moreover, the technique could also help production planners analyze the ergonomic conditions of workers to avoid potential overloads. Hernandez et al. (2012) reviewed the current situation of work-related musculoskeletal disorders (WRMDs) in Handbook

14

of Occupational Health and Wellness. They provided a review of common work injuries, including those resulting from exposures in the work environment. For example, when assembling the products, workers are required to use hand tools along with vibrations for hours a day. Researchers found that the frequency and duration of these exertions increase the upper limb disorders (van Rijin et al., 2010). The review also indicated that further investigation and intervention are necessary to limit the work-related disorders and increased costs.

2.3.2 Measurement of work injury

National Institute of Occupational Safety and Health (NIOSH) published a practical guide for lifting task or operation (NIOSH, 1981; 1991). The recommended weight limit and limit index for lifting task were given to avoid back and forearm injury. Waters et al. (2011) evaluated the revised NIOSH lifting equation (RNLE) for the assessment of low back pain (LBP). The results indicated that the risk of LBP increases as the limit index grows. The Snook and Ciriello table was used quite often to find the maximum acceptable weight for a particular task (Snook and Ciriello, 1991). Rapid Upper Limb Assessment (RULA) database (McAtamney, 1993) is the experimental approach to evaluate the work injury level of upper limb.

Computer-aided approaches to analyzing work injury have been proposed in the recent past years. In order to realize the approaches, a computer manikin modeling system (Lin, 2008) was employed. In this way, a set of parameters featuring a human's characters such as population, height, weight and gender are captured in the model. Alzuheri et al. (2010) reviewed the common ergonomics measuring techniques of manual assembly postures and pointed out the limitations of single ergonomic measure implementation. The paper further proposed a framework that combines individual measurements into a single objective function (e.g.,

desirability function (Derringer et al., 1980), which simultaneously optimized several response variables). Then, a gradient search technique such as Response Surface Methodology (RSM) or GA was suggested to solve the function. As a result, the conflicting conclusions from individual measures might be avoided.

Kinect (by Microsoft) is recently implemented in ergonomic assessment (Dutta, 2012) and pose estimation (Obdrzálek et al., 2012). The precision and accuracy of the Kinect system were determined by Bonnechère et al. (2014). Spector et al. (2014) proposed an error-correction Kinect-based tool to estimate the NIOSH lifting equation parameters automatically. The system combined the Kinect skeleton with an error-correction regression model to improve the accuracy of estimation. The results indicated the possibility to automate the calculation of task postures and task frequency. Additional force assessments were prompted to support the findings.

2.3.3 Work injury cost

The cost of work injury in this thesis is referred to as one incurred by repetitive motions in assembly operations, which is mentioned in Section 1.3. It is the indirect cost to the loss of production output (Currie et al., 2000). Thus, estimation of work injury cost is the prerequisite to evaluate the impact of work injury in a production system.

Emodi (2007) developed a method for estimating the cost of work injury in an assembly line. The method was based on a large volume of historical data of the cost of worker's injury; particularly the database contains 20,000 injury claims and was owned by Saskatchewan Workers' Compensation Board (SWCB). However, his method only took a simple average of

16

individual cases, which could lead to large errors in the cost estimation in this particular application.

Lin (2008) improved the method of Emodi (2007) and proposed with two methods to estimate the repetitive work injury cost. Lin's methods considered the age, gender and work injury levels as input. The first method of Line (2008) was based on the artificial neural network (ANN) technique which was a non-linear model. The second method was a linear function by linear regression (LR) technique. It is noted that this thesis employed the LR method for the cost estimation for repetitive work injury for the sake of simplicity but without loss of generality, as the methodology for incorporating the work injury cost is equally applied to any non-linear regression model. Details of the LR method will be presented in Chapter 3.

2.4 Linear Programming and Its Application in Production Planning

Linear programming is one of the optimization techniques widely used for production planning, particularly useful for optimal allocating of resources among competing demands. It possesses the following characteristics and assumptions: objective function, decision variables, constraints, feasible region, linearity, proportionality and additivity, non-negativity (Eiselt and Sandblom, 2012). Linear here refers to the fact that both the objective and constraint have a linear relation with the decision variable. Applying linear programming to production planning is for example the work of planning a product family (Krajewski, 2005) and the work in planning mixed products (Onwubolu, 2002), respectively.

Linear programming can also be used to solve the management problems such as distribution, inventory, scheduling, and so on. Spitter et al. (2005) developed the models for capacity

constrained Supply Chain Operations Planning (SCOP) with arbitrary supply chain structures. The SCOP problem was solved with linear programming (LP) and two LP approaches were discussed. A special case of the capacitated lot sizing problem (CLSP) was studied by Akbalik and Penz (2009). The aim was to achieve optimal production planning without backlogging. Three MILP formulations were given in the study to simplify the CLSP. Rasmussen (2013) provided a case of the application of LP to an agricultural operation planning. A combination of several methods was employed to develop a model for the total planning of an agricultural operation.

Considering the above advantages, LP was selected to model production planning in this thesis. A further consideration of choosing LP was also that the focus of the thesis is to incorporate a new production cost (i.e., work injury cost) into the existing production planning model which is a LP model and to examine the effect of this new cost to the total cost. Therefore, accuracy of the model was considered as comparable with the accuracy of the model without including the work injury cost.

LINDO^{TM} software is usually employed to solve the linear production planning model due to its wide use in industry as well as of efficiency in solving the model. In this software, the algorithm is Simplex method (LINDO System, Inc., 2003). Simplex method (algorithm) was proposed by George B. Dantzig and is an efficient algorithm for LP problem (Pan, 2014). As per Gass et al. (2013), "The method starts with a known basic feasible solution or an artificial basic solution, and finds a sequence of basic feasible solutions (extreme-point solutions) such that the value of the objective function improves or does not degrade". In other words, the algorithm is the process that the starting vertex moves to the adjacent vertex until the maximum or minimum of the objective function is reached (Pan, 2014).

2.5 Conclusion

A literature review on the problem of production planning and linear programming techniques to solve this problem was presented in this chapter. The review reveals that the work injury cost is not included in the cost for production planning, though there were few studies on other issues of human factors in the context of production planning, such as work force planning. As discussed before in Chapter 1, the work injury cost in Canada seems to be a considerable amount and work injury itself is not unpopular among Canadian adults. Therefore, the proposed research objectives as presented before in Chapter 1 are worthy of study, and the outcome of the study is expected to give a clear picture of how significant the work injury cost would be in the total production cost.

CHAPTER 3 PRODUCTION COST MODEL

3.1 Introduction

This chapter describes a mathematical model of production planning in terms of cost with consideration of work injury. Section 3.2 presents the model for production planning in terms of cost (not yet including the work injury cost), i.e., the specification of the objective function and constraints in the context of optimization model. In Section 3.3, four different production planning cases, drawn from the literature, are illustrated, and they serve as a test-bed for the study. Then, how the work injury cost is incorporated into the total production cost model is discussed, and an integrated production cost model (i.e., the model explicitly including the work injury cost and implicitly including the worker's posture for assembly of products) is presented in Section 3.4. There is a summary in the final section.

3.2 Linear Production Planning Model

Production planning model is an optimization model, which takes the total production cost as an objective function with constraints on the decision variable or variable to be determined in light of the optimum of the objective function subject to the constraint. The decision variable refers to production quantity, inventory quantity and outsourcing quantity. In many cases, costs and production quantities have a linear relation, and that is why linear model is called (also see the

discussion before in Chapter 2). The development of the model thus refers to the specification of the objective function and constraint function.

3.2.1 Objective function

The total production cost in traditional production planning consists of material costs, labor costs and inventory costs. Let C represent various costs. The model of production planning can be described by

$$C_{production} = C_{material} + C_{labor} + C_{inventory} \tag{3.1}$$

where,

$C_{production}$: the total production costs;

$C_{material}$: the material costs;

C_{labor} : the labor cost;

$C_{inventory}$: the inventory cost.

There were the following assumptions in the foregoing costs:

- Material costs: the raw material costs that directly contribute to the finished products and the overhead costs that support the production process such as managerial cost and utility cost.

- Labor cost: the worker salary and pension.

- Inventory cost: the holding cost of products left over in stock.

Further considerations in the model are: (1) production planning is for single product, (2) the planning horizon is up to 12 months, and (3) the work force level is stable (i.e., no hiring or lay-off during the production period). The objective function of the model is as follows:

$$\text{minimize} \quad C_{\text{material}} + C_{\text{labor}} + C_{\text{inventory}} \tag{3.2}$$

and it can be further written into

$$\text{minimize} \quad \sum_{t=1}^{n} C_M(P_t + O_t) + \sum_{t=1}^{n}(C_R H_t + C_E E_t) + \sum_{t=1}^{n} C_I I_t \tag{3.3}$$

where,

t : the time period ($t=1, 2, 3, ..., n$, represents *January, February, March, ..., December*);

C_M : the unit production cost of product;

P_t : the units of product fabricated (assembled) during the regular working time in period t;

O_t : the units of product fabricated (assembled) during the overtime in period t;

C_R : the unit labor cost during the regular working time;

H_t : the regular working time labor hours required in period t;

C_E : the unit labor cost during overtime;

E_t : the overtime labor hours required in period t;

C_I : the unit inventory cost;

I_t : the units of product to be left over as an inventory during period t.

The first part in the model, i.e. Equation 3.2, is the material cost over the planning period; the second part is the overall labor cost, including the regular working hour cost and overtime cost over the planning period; the third part is the inventory cost for over-produced products over the planning period. Further, the decision variables in the model are: P_t, O_t, I_t.

3.2.2 Constraints

There were four constraints on the decision variables, and they are described below:

- Demand satisfaction constraint:

The units produced in the current production, including both the regular time and overtime production volume together with the previous period inventory, should be greater than or equal to the demand in the current period with or without leftover units ($I_t=0$). This constraint can be expressed as:

$$I_{t-1} + P_t + O_t \geq D_t + I_t \tag{3.4}$$

where,

I_{t-1} : the units of left over products in the previous period of t;

D_t : the units of product demands in time period t.

- Labor hour limit constraint:

Regular working hours in period t should be less than 8 hours per day, monthly working days as well as employee numbers. Overtime working hours should not exceed the maximum allowable hours per month by law. This constraint can be expressed as:

$$0 \leq H_t \leq 8d_tW, \ 0 \leq E_t \leq \overline{E} \tag{3.5}$$

where,

d_t : the number of working days in period t;

W : the number of employees;

$\overline{E}$: the maximum allowable overtime hours in period t.

- production rate constraint:

Assume that the unit time is one hour, and the relation between the produced units and labor hour can be expressed as:

$$P_t - R_H H_t = 0, \ O_t - R_E E_t = 0 \tag{3.6}$$

R_H : the production rate during regular working time;

R_E : the production rate during overtime

- non-negative constraint:

The number of planned products, the number of demands and the number of left-over products are non-negative, respectively, that is:

$$P_t \geq 0, \; O_t \geq 0, \; D_t \geq 0, \; I_t \geq 0 \tag{3.7}$$

3.3 Four Cases

To facilitate the study, four particular cases of single product production are established to serve as a test-bed. These cases are drawn from the literature and the author's own experience in industry.

Case study 1:

In the first case, the data are taken from Chopra et al. (2007). The company in the example is called "Red Tomato Tool" which is a manufacturer of multi-purpose gardening tools. The production plan of this company is over a six-month horizon, which is given in Table 3.1.

Table 3.1 Product demand for Case 1

Period (t)	January	February	March	April	May	June
Demand (D_t)	1600	3000	3200	3800	2200	2200

Table 3.2 Cost data for Case 1

Item	Cost
Material cost - C_M	\$10 / unit
Inventory cost - C_I	\$2 / unit / month
Regular time labor cost - C_R	\$4 / hr
Overtime labor cost - C_E	\$6 / hr

In addition to the data given in Table 3.2, other initial settings and constraints are also considered. The company has a staring inventory of 1000 units, a workforce of 80 employees. There are 20 working days in each month. The regular working time is eight hours a day and the overtime for each employee is limited to 10 hours monthly. A minimum of 500 units is required by the end of planning period (June). The production rate is 4 hours per unit.

Table 3.3 Constraints data for Case 1

Item	Value
Initial inventory – I_0	1000 unit
Period end inventory – I_6	500 unit (minimum)
Regular time labor hours - H_t	≤12800 hr
Overtime labor hours - E_t	≤800 hr
Production rate	0.25 unit / hr

Case study 2:

In the second case, the practical data of Daya Technologies Corporation is used (Wang et al., 2005). The company is a producer of precision machinery and transmission components. The production planning is regarding a standard ballscrew over a four month planning horizon. Table 3.4 gives the monthly demand of product from May to August.

Table 3.4 Product demand for Case 2

Period (t)	May	June	July	August
Demand (D_t)	1000	3000	5000	2000

As shown in Table 3.5, the production cost includes the material cost and the labor cost to assemble one ballscrew. Additionally, the initial inventory in period 1 (May) is 400 units and the end inventory in period 4 (August) is 300 units. The initial labor level is 158 hours and the production rate is 0.05 hour per unit. All constraint parameters are listed in Table 3.6.

25

Table 3.5 Cost data for Case 2

Item	Cost
Regular time production cost – C_R	$20 / unit
Overtime production cost – C_E	$30 / unit
Inventory cost – C_I	$0.3 / unit / month

Table 3.6 Constraints data for Case 2

Item	Value
Initial inventory – I_0	400 unit
Period end inventory – I_4	300 unit
labor hours – $H_t + E_t$	≤ 158 hr
Production rate	20 unit / hr

Case study 3:

The data of the third case is adapted from the study by Filho et al. (2007). The data in this production planning example are summarized in Table 3.7 – 3.9. The planning horizon is 12 months and the demands are listed in Table 3.7.

Table 3.7 Product demand for Case 3

Period (t)	Jan	Feb	Mar	Apr	May	Jun
Demand (D_t)	1200	1500	1250	1800	1350	2200
Period (t)	Jul	Aug	Sep	Oct	Nov	Dec
Demand (D_t)	2100	2300	1580	1470	1350	1100

Table 3.8 Cost data for Case 3

Item	Cost
Regular time production cost – C_R	$129 / unit
Overtime production cost – C_E	$180 / unit
Outsourcing cost – C_S	$219 / unit
Inventory cost – C_I	$15.5 / unit / month

There is no initial inventory at the starting period (January), while the units in stock for each period should be kept under 1500. The capacity for each month is 900 units during regular time production and 300 units during overtime production. In this case, the outsourcing production is considered to complement the in-house production capacity. For each month, the outsourcing units should not exceed 600. The labor level is limited to 10 employees each month. Case 3 has different production rates during regular time and overtime (Table 3.9), while the production rates of the other cases in regular time and overtime are the same.

Table 3.9 Constraint data for Case 3

Item	Value
Initial inventory – I_0	N/A
Inventory – I_t	1500 unit (maximum)
Outsourcing limit – S_t	≤ 600 unit
labor hours – H_t	≤ 1600 hr
Regular time production rate	0.5625 unit / hr
Overtime production rate	0.1875 unit / hr

Case study 4:

The fourth case is based on the CNH Company's presentation of operations management overview (CNH, 2013) and the master thesis of Lin (2008). This company is a manufacturer of farm equipment and machinery, such as planters and harvesters. The production planning is for the component called "row bar", which is a subassembly of the corn header system. There are two employees involved in this assembly station every day for 8 hours. Neither overtime nor inventory is considered in this example. All the data settings can be found in Table 3.10 – 3.12.

Table 3.10 Product demand for Case 4

Period (t)	Jan	Feb	Mar	Apr	May	Jun
Demand (D_t)	104	95	87	40	48	40
Work days (W_t)	23	19	19	20	24	20

Table 3.11 Cost data for Case 4

Item	Cost
Material cost – C_R	$3,125 / unit
Regular time labor cost – C_R	$15 / hr

Table 3.12 Constraints data for Case 4

Item	Value
labor hours – H_t	$\leq (W_t$ x 8x 2) hr
Regular time production rate	0.2 unit / hr

3.4 Work Injury Cost Model

3.4.1 Introduction

A linear work injury cost model (Lin, 2008) was employed in this thesis to compute the cost for repetitive work injuries. The model (Lin, 2008) is re-visited here, which is:

$$CWI = \alpha + \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + \alpha_4 X_4 + \alpha_5 X_5 + \alpha_6 X_6 + \alpha_7 X_7 + \varepsilon \qquad (3.8)$$

where,

CWI   : the cost of work injuries;

α_n : the coefficient of multiplier associated with each variable X_1 to X_7;

X_1 : the type of business M61; 1: Mills and Semi-medium Manufacturing;

   0: otherwise;

X_2 : the type of business M81; 1: Metal Foundries and Mills; 0: otherwise;

X_3 : the type of business M91; 1: Agricultural Equipment; 0: otherwise;

X_4 : the type of business M92; 1: if it is Machine Shops, Manufacturing;

   0: otherwise;

X_5 : worker's age;

X_6 : gender; 1: if it is male; 0: otherwise;

X_7 : the level of work injury;

ε : the error term.

The work injury levels of different body parts are defined in Table 3.5 (Lin, 2008).

Table 3.13 Work injury level range

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

In order to determine the coefficient of each independent variable in Equation 3.8, the statistics software SPSS® was employed (Lin, 2008). At the very beginning of this process, all the historical data such as age, gender, level of work injury were redefined or normalized for a better convergence in linear regression. After that, an observation was performed to investigate the

relevancy between the independent and dependent variables. However, there was still a non-linear relationship between them. Therefore, the dependent variable, namely work injury cost, was modified by power transformation and it was redefined as *Ln*Cost. Finally, the modified data of the input and output were solved by SPSS®; as such, the work injury cost model is expressed from the following equations:

$$Ln\text{Cost}_{(neck)} = 4.584+ (-0.460)X_1+(-0.195)X_2+(-0.546)X_3+(-0.341)X_4+0.004X_5+(-0.116)X_6$$
$$+1.343X_7 \tag{3.9}$$

$$Ln\text{Cost}_{(leg)} = 3.428+ 0.017X_1+ (-0.108)X_2+ (-0.106)X_3+ 0.027X_4+ 0.008X_5+ 0.202X_6+1.841X_7 \tag{3.10}$$

$$Ln\text{Cost}_{(Trunk)}=3.909+(-0.138)X_1+(-0.257)X_2+(-0.207)X_3+(-0.259)X_4+0.008X_5+0.004X_6+1.840X_7 \tag{3.11}$$

$$Ln\text{Cost}_{(Forearm)}=2.478+(-0.144)X_1+(-0.144)X_2+(-0.147)X_3+(-0.067)X_4+0.004X_5+(-0.027)X_6$$
$$+2.820X_7 \tag{3.12}$$

$$Ln\text{Cost}_{(upper\ arm)} =3.471+ 0.063X_1+ 0.086X_2+ 0.060X_3+ 0.048X_4+ 0.006X_5+ (-0.022)X_6 +1.723X_7 \tag{3.13}$$

$$Ln\text{Cost}_{(Wrist)} = 3.961+ (-0.360)X_1+ (-0.005)X_2+ (-0.267)X_3+ (-0.339)X_4+ 0.016X_5+ (-0.048)X_6$$
$$+1.558X_7 \tag{3.14}$$

In order to simplify the calculation of the work injury cost, Equation 3.9 to Equation 3.14 were further modified as per the following parameter settings. The type of business here was manufacturing, and thus $X_1=X_2=X_3=0$, $X_4=1$. The coefficients of variable 'Age' and 'Gender' were small enough to be neglected, which means that the main contribution to the work injury cost was the work injury level of each body segment. The modified equations for work injury cost were described below:

$$LnCost_{(neck)} = 4.243 + 1.343X_7 \tag{3.15}$$

$$LnCost_{(leg)} = 3.455 + 1.841X_7 \tag{3.16}$$

$$LnCost_{(Trunk)} = 4.168 + 1.840X_7 \tag{3.17}$$

$$LnCost_{(Forearm)} = 2.545 + 2.820X_7 \tag{3.18}$$

$$LnCost_{(upper\ arm)} = 3.519 + 1.723X_7 \tag{3.19}$$

$$LnCost_{(Wrist)} = 3.622 + 1.558X_7 \tag{3.20}$$

3.4.2 Assumption of the work injury level for the cases

From the above discussion, it is clear that the key step to calculate the work injury cost was to get the work injury level for a particular assembly posture. The work injury cases varied among the four production cases as collected before, since they had different production processes. In another word, in order to get the cost of work injury, specified assembly postures of workers were required for each of the production cases.

To derive the value of work injury level, the following steps were performed via a digital manufacturing and production software, DELMIA$^{\circledR}$ V5. First, the "Human Builder" module was implemented to build a manikin model to visualize the assembly postures. Second, the postures of the involved body segments were elaborated by the "Posture Editor" window to simulate the postures of assembly production. Finally, the build-in ergonomics analysis module, namely RULA (Hedge, 2001), was employed to obtain the work injury level of the evaluated assembly posture. The assembly postures for the four production cases were set up, as shown in Fig. 3.1 to Fig. 3.3. The RULA assessment results were discussed in the next chapter.

Figure 3.1 Posture in Case 1

For Case 1, the product assembled was a gardening tool. The worker was standing to install the components that were placed on a work table. The legs were balanced but not supported during the assembly process. The worker used a screw driver to tighten the parts, which meant that the worker's trunk was tilted forward a little bit and the neck was tilted down to focus on the components. The neck may bend to get a better view of installation if necessary. The upper arms were raised and adjusted together with forearms to the height of the work table. Rotation was required to align the center of the parts (Fig. 3.1).

Figure 3.2 Posture in Case 2

For Case 2, the assembly process was completed with a seating posture. The worker was sitting on a stool to assemble the ballscrew components, which means that the legs could be regarded as supported and balanced. The postures of other body parts were similar to the scenario of Case 1. The main difference is that the components in this assembly process were much smaller than those in Case 1, and thus the wrist did not require any bending motion (Fig. 3.2).

For Case 3, the product type in this scenario was not given; therefore the assembly postures of worker were not possibly specified. The worker postures in Case 1 (Fig. 3.1) and Case 2 (Fig. 3.2) were assumed for Case 3, respectively, for the purpose that a relatively large range of products

33

can be covered. Note that the gardening tool in Case 1 was relatively large in size, while the ballscrew in Case 2 was relatively small.

Figure 3.3 Posture in Case 4

In Case 4, the design of the assembly process is a standing posture. The worker has to lift the component to a height at eye level and install it onto the base product. The worker has to look up 45 degrees in this process. As shown in Fig. 3.3, the worker may get back injury in this assembly posture.

3.4.3 Integrated linear programming model

Let C_{WI} denote a total work injury cost caused by repetitive assembly production over an entire production period. The cost of production planning in Equation 3.1 can be rewritten as follows:

$$C'_{production} = C_{material} + C_{labor} + C_{inventory} + C_{WI} \qquad (3.21)$$

In the above equation, $C'_{production}$ denotes the total cost considering work injury. Note that work injury in this thesis refers to the injury from long-term repetitive motions. The relevant cost is calculated on a yearly basis as per the study by Lin (2008), and the work days each month are assumed to be 21.74 on average. In addition, the work injury cost is calculated based on the assumption of an 8 hour period (which is the daily regular working time). Finally, the effective work injury cost in all four cases over time period t is,

$$C_{WI} = \frac{1}{12} \times \frac{1}{21.74} \times \frac{1}{8} \times CWI(H_t + E_t) = \frac{1}{2087.04} CWI(H_t + E_t) \qquad (3.22)$$

Substituting Equation 3.22 into Equation 3.3 leads to:

$$\text{minimize } \sum_{t=1}^{n} C_M(P_t + O_t) + \sum_{t=1}^{n}(C_R H_t + C_E E_t) + \sum_{t=1}^{n} C_I I_t + \frac{1}{2087.04} CWI(H_t + E_t) \quad (3.23)$$

CWI denotes the work injury cost of specific assembly production in each case over one year period, which is calculated by Equation 3.15 to Equation 3.20. The cost of the work injury in each case can be estimated by multiplying the actual work hours in their production planning periods. All the other variables and constraints are exactly the same as those in Equation 3.3.

The first part of Equation 3.23 is the overall material cost over the production period; the second part is the overall labor cost (worker's salary) and the third part is the overall inventory cost for over-produced products in the production period; the fourth part is the work injury cost incurred

in the planning period. It is noted that the foregoing model, i.e., Equation 3.23, implicitly include the worker's assembly posture, (which can be generalized to the design of an assembly system), because the work injury level and cost must be upon the known worker's posture. For this reason, the proposed model is also called integrated production planning model with consideration of work injury cost.

3.5 Summary

The cost model of production planning with consideration of work injury was developed and presented in this chapter, which is applicable to assembly lines in general. The assumptions and constraints were adapted from Chopra et al. (2007), Wang et al. (2005), Filho et al. (2007) and CNH (2013) to establish four cases (i.e., specific assembly lines). The mathematical model of repetitive work injury (Lin, 2008) was employed to calculate the work injury cost. Consequently, Objective 1 described in Section 1.3 has been achieved by the proposed model. More details regarding the effect of the work injury cost on the total production cost will be studied in the next chapter.

CHAPTER 4 RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the study of the effect of the work injury cost on the total production cost through the integrated production planning model as developed in Chapter 3. The first step is to solve the model with the help of LINDO^{TM} software. Section 4.2 presents screen-shots of the LINDO^{TM} interface. Section 4.3 describes the execution of the LINDO program for three scenarios: (1) a general production planning model (PPC), (2) production planning with high level of work injury (PPCWI), (3) production planning with low level of work injury (PPCWIM). It is noted that the so called high level and low level of work injury refer to the following situations: the high level of work injury corresponds to the worker's assembly postures as described before in Chapter 3 for all the four cases, while the low level of work injury corresponds to the worker's assembly posture for Case 4 (this study was restricted to this case only due to the availability of the information) – particularly the modified worker's posture (to be discussed later). Section 4.4 presents an analysis of the results produced from the preceding section. A summary is given in Section 4.5.

4.2 LINDO^{TM} program

To run the LINDO program, one needs to specify the program through LINDO interface. In this thesis, LINDO^{TM} 6.1 Educational version was employed. The interface of the software for output is explained in Fig. 4.1, which is drawn from Lindo User's Manual (LINDO System, Inc., 2003). A couple of parameters need to be specified through the interface in order to run the LINDO program, and they are given below.
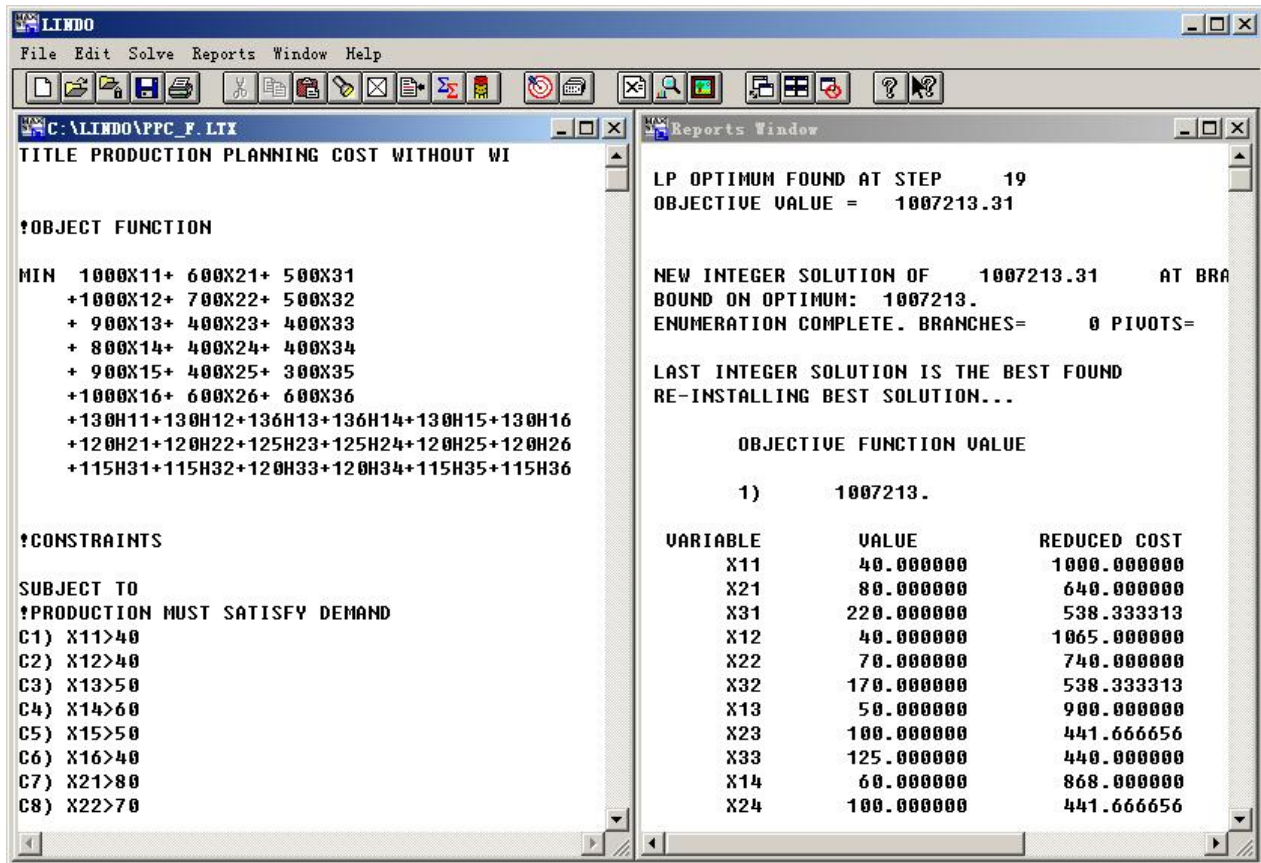

Figure 4.1 Lindo^{TM} software interface

(1) Slack or Surplus

The information of slack and surplus describes the behavior of solutions relative to the constraint. Particularly, slack refers to the ($\leq$) constraint, while the surplus refers to the ($\geq$) constraint. If a constraint is exactly satisfied as equality, both Slack and Surplus values will be zero.

(2) Dual price

It is the amount that the objective function would be improved when given a unit of increase in the right-hand side of the constraint. In a minimization optimization problem (which is the case in this study), if the dual price is negative, this implies that the increase of the right-hand side of this constraint by one unit would cause the objective function increase by that amount.

(3) Reduced cost

The reduced cost refers to the amount of penalty one would have to pay by increasing one unit of decision variable. From Figure 4.1, the reduced cost of product B in February ($X21$) is 640, and this means that the production cost of product B will increase by that amount when one more unit of B is produced in February.

4.3 Simulation-based Analysis

The following scenarios are considered to generate knowledge on how significant the effect of the work injury cost would be on the total production cost.

Scenario 1: Production planning without consideration of work injury;

Scenario 2: Production planning with high level of work injury;

Scenario 3: Production planning with low level of work injury.

Note that validity of the model is out of question; as a linear production model is widely used in production practice. Validation of the model for the work injury cost is assumed to be accurate enough, which is supported by the validation testing in (Lin, 2008) (though the model used in this thesis only took a linear part of the model in (Lin, 2008)). On a general note, inaccuracy of the work injury cost model due to neglecting non-linear components may be tolerable, just as the situation that non-linear components in the traditional production planning model are neglected.

4.3.1 Traditional production planning cost model

The traditional production planning cost model refers to the model without consideration of work injury. In this section, the result of solving the traditional production planning cost model is discussed. For details of the command scripts, refer to Appendix B.

Step 1: Specify the mathematical model (Equation 3.3) as a LINDO^{TM} model.
This LINDO^{TM} model is named as PPC and saved as LTX file. The objective function here describes a minimization problem.

Step 2: Include all constraints (Table 3.3, 3.6 & 3.9).
Use "SUBJECT TO" or "ST" to write the constraints, including the product demand, work force limit, production rate, and non-negative constraint.

Step 3: Define types of the variables.
The volume of products and inventory should be an integer. "GIN" command can be used to specify decision variables as integer.

Step 4: Solve the model and record results.

Click on the "SOLVE" button to run the LINDO^{TM} program. The values of all variables are easy to be read from the "Report" window. In addition, the potential improvement of the objective function and constraint boundary are also recorded in the calculation result of the program output.

In the following, the results of PPC for the four cases as introduced before in Chapter 3 are presented.
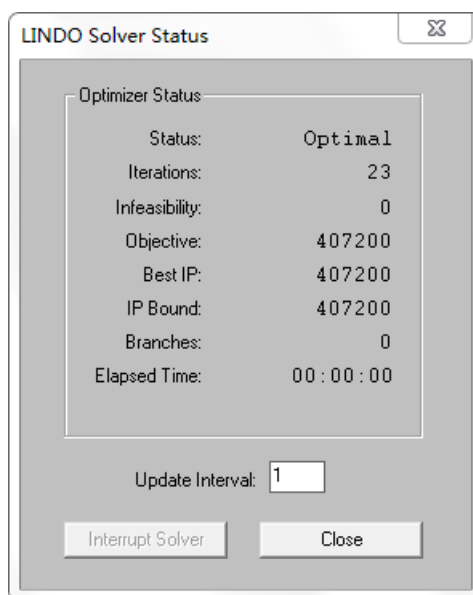
PPC model for Case 1:

Figure 4.2 Solver status window of C1_PPC.ltx

Table 4.1 Output of model C1_PPC.ltx

Period	Jan	Feb	Mar	Apr	May	Jun
P_t (unit)	1000	3200	3200	3200	2200	2700
O_t (unit)	0	0	0	0	0	0
H_t (hr)	4000	12800	12800	12800	8800	10800
E_t (hr)	0	0	0	0	0	0
I_t (unit)	400	600	600	0	0	500

As per Figure 4.2, the running time for solving model is less than a second. After 23 iterations, the overall production planning cost is $407,200 CAD (Appendix C (a)). From the data in Table 4.1 and Table 3.1 & 3.2, it can be found that the raw material cost adds up to $155,000 CAD, taking 38.06 % of the overall production cost. The labor cost is $248,000 CAD, which takes 60.90 % of the overall production cost. The inventory cost is $4,200 CAD, taking only 1.03 % of the overall production cost. The result is close to that of the literature (Chopra et al., 2007). This also provided a proof of the accuracy of the proposed model in Chapter 3. For the integrated production planning model, the accuracy of the model may also be implied, though the added work injury cost may cause some change.

PPC model for Case 2:

As shown in Figure 4.3, after 7 iterations, the overall production planning cost is $219,146 CAD, which is also available from the status window or from the output summarization (Appendix C (b)). Combining the data from Table 4.2 and Table 3.4 & 3.5, the production cost amounts to $218,000 CAD, including the raw material cost and labor cost. There is no overtime labor hour, so the overtime cost is zero. The inventory cost comes to $1,146 CAD, taking 0.52 % of the overall production planning cost. The result is close to that in the work of Wang et al. (2005).
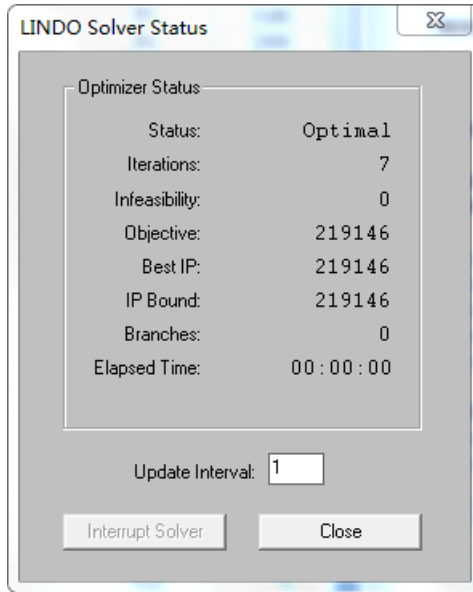
Figure 4.3 Solver status window of C2_PPC.ltx

Table 4.2 Output of model C2_PPC.ltx

Period	May	Jun	Jul	Aug
P_t (unit)	2280	3160	3160	2300
O_t (unit)	0	0	0	0
H_t (hr)	114	158	158	100
E_t (hr)	0	0	0	0
I_t (unit)	1680	1840	0	300

PPC model for Case 3:

As per the report window Figure 4.4, the result (i.e., the minimal objective function) is $3,161,400 CAD after 51 iterations. The running time is nearly zero. Gathering the data from Table 4.3 and Table 3.7 & 3.8, the production cost, including material cost and labor cost, adds up to $3,096,300 CAD, which accounts for 97.94 % of the total production planning cost. This includes the regular time labor cost $1,393,200 CAD, the overtime labor cost $630,000 CAD and

outsourcing cost $1,073,100 CAD. The inventory cost is $65,100 CAD, taking 2.06 % of the overall production planning cost. The result reported is close to that in the study of Filho et al. (2007).
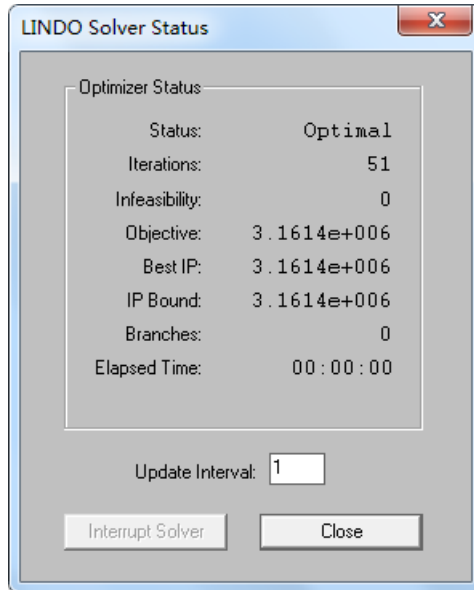
Figure 4.4 Solver status window of C3_PPC.ltx

Table 4.3 Output of model C3_PPC.ltx

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P_t (unit)	900	900	900	900	900	900	900	900	900	900	900	900
O_t (unit)	300	300	300	300	300	300	300	300	300	300	300	300
S_t (unit)	500	600	600	600	600	600	600	600	380	270	150	0
H_t (hr)	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440	1440
E_t (hr)	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1600	1067

PPC model for Case 4:

Figure 4.5 shows that the process terminated after 13 iterations. The overall production planning cost in Case 4 comes to $1,572,200 CAD. It is noted that overtime labor hour and inventory were

not considered in this case. The material cost comes to $1,534,375 CAD (97.66 %) by referring to Table 4.4 and Table 3.10 & 3.11. The labor cost ($36,825 CAD) accounts to 2.4 % of the overall production planning cost. The result is close to that of CNH's presentation (CNH, 2013).
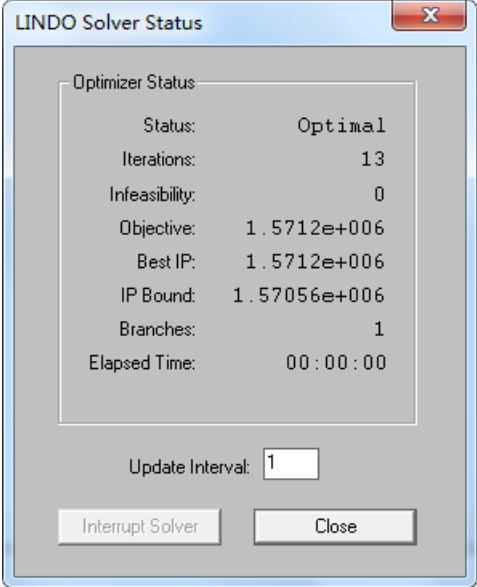

Figure 4.5 Solver status window of C4_PPC.ltx

Table 4.4 Output of model C4_PPC.ltx

Period	Jan	Feb	Mar	Apr	May	Jun
P_t (unit)	104	95	87	64	77	64
H_t (hr)	520	475	435	320	385	320

4.3.2 Production planning cost model with high level of work injury

The three assembly postures (Fig. 3.1 to Fig. 3.3), as discussed in Chapter 3, were analyzed, and their respective work injury levels are given in Table 4.5 as per RULA worksheet (Appendix A).

Table 4.5 Work injury levels for different assembly products

Body Part	Case 1 (C1_WI)	Case 2 (C2_WI)	Case 4 (C4_WI)
Neck	2	3	4
Leg	2	1	1
Trunk	1	2	2
Forearm	1	2	1
Upper Arm	2	2	2
Wrist	2	1	3

Table 4.6 Work injury cost for each case

Work injury cost	Case 1 (C1_WI)	Case 2 (C2_WI)	Case 3 (C3_WI)		Case 4 (C4_WI)
dollar / yr	$4,610	$10,010	$4,610	$10,010	$21,966
dollar / hr	2.2	4.8	2.2	4.8	10.5

Note that the work injury cost, calculated before in Section 3.3.1, Equations 3.15 to Equation 3.20 in particular, is in the context that the length of production is one year. There is a need to convert it to the equivalent hourly cost. From Equation 3.22, the yearly work injury costs and equivalent hourly costs are derived (Table 4.6). After that, production planning cost model with high level of work injury can be derived from Equation 3.23. The model of this scenario can be applied to the four cases in the same procedure in Section 4.3.1, and the corresponding LINDO^{TM} command scripts can be found in Appendix B (e) - (i). The program files are named as 'PPCWI for work injury integrated model'.

It is noted that the results for the decision variables (P_t, Q_t, I_t) for the two scenarios, i.e., PPC and PPCWI, are the same (Appendix C (e) – (i)). From Equation 3.22, the work injury cost in each case can be concluded as follows: (1) for Case 1, the work injury cost accounts to 25.09 % of the overall production planning cost, that is $136,400 CAD during 6 month period; (2) for Case 2,

the work injury cost is $2,616 CAD taking 1.18 % of the overall planning cost; (3) for Case 3, the working postures are adapted from Case 1 and Case 2, therefore the work injury costs result in $79,083 CAD (2.44 %) and $172,544 CAD (5.18 %); (4) the work injury cost in Case 4 takes 1.61 % of the overall production planning cost, that is $25,778 CAD. The work injury costs in four cases can be found in Table 4.7.

Table 4.7 Costs of production planning with high level work injury

Cost	Case 1	Case 2	Case 3		Case 4
Material	$155,000	$218,000	$3,096,300		$1,534,375
Labor	$248,000				$36,825
Inventory	$4,200	$1,146	$65,100		n/a
Work injury	$136,400	$2,616	$79,083	$172,544	$25,778
Total	$543,600	$221,762	$3,240,483	$3,333,944	$1,596,978

4.3.3 Production planning cost model with low level of work injury

Take Case 4 as example (i.e., CNH case). The posture of the worker was shown in Fig. 3.3, which has high level of work injury. The modified posture is shown in Fig. 4.6, which has low level of work injury. In the modified posture, the workers are now sitting on a stool, and the object to be assembled is accordingly lowered down so that the worker does not need to look up. The upperarms are lowered down as well. The work injury levels of modified posture are listed in Table 4.8. The cost of the low level work injury (i.e., modified posture) can be calculated from Equation 3.15 to Equation 3.20, and the result is shown in Table 4.10. It is worth to note that the costs were still calculated based on the situation of every eight hour.

47

Table 4.8 Work injury levels of optimized assembly postures

Body Part	Case 4
Neck	2
Leg	1
Trunk	2
Forearm	2
Upper Arm	1
Wrist	1

Figure 4.6 Modified posture for Case 4

Table 4.9 Work injury cost for the modified posture for Case 4

Work injury cost	Case 4
dollar / yr	$6,250
dollar / hr	3

Next, the similar procedure in Section 4.3.2 can be followed for this modified posture. The results can be generated by running the LINDO program. The output can be found in Appendix B (j).

According to the program report, the structure of the production plan is the same as the output of the production planning with high level work injury (Appendix C (j)). From Equation 3.22, the costs of the low level work injury production planning are derived, and the result is shown in Table 4.10. As shown, the work injury cost of the modified posture has been reduced by 71.43 %, compared with high level of work injury. The work injury cost of the modified posture merely takes 0.47 % of the overall production planning cost, which is $7,365 CAD.

Table 4.10 Costs of reduced work injury production planning for Case 4

Cost	Case 4
Material	$1,534,375
Labor	$36,825
Inventory	n/a
Work injury	$7,365
Total	$1,578,565

4.4 Discussions

4.4.1 Production planning cost analysis

In the PPC model, the material cost occupied the majority of the overall production cost, as high as 99.48 % in Case 2 (Fig. 4.7). The PPC model only considered the material cost, labor cost and inventory cost over a period up to 12 month. However, in the real world, work injury is a hidden

cost existing in manufacturing industries especially to those job positions requiring repetitive movements and postures, such as installing parts and tighten movements on assembly line.

The potential compensation cost of work injury is a very important factor that cannot be avoided as per Lin's research work (2008). In the second production planning model with high level of work injury, the overall cost has an obvious increase in all cases. Comparing the results in Table 4.7 with that of Section 4.3.1, the overall production planning costs are raised by 33.50 %, 1.19 %, 5.26 % (2.37 %) and 1.64 %, respectively. It can be easily found that work injury is the main cause of the higher production expenses. The portion of the work injury cost in production planning varies from 1.18 % to 25.09 % (Fig. 4.8). It might be negligible when the cost of work injury takes 1 % or less against the overall production cost, while it might be noticeable when it goes up to 25 % or more. From the employer's interests, actions must be taken to eliminate or relieve the unwanted cost in production planning.
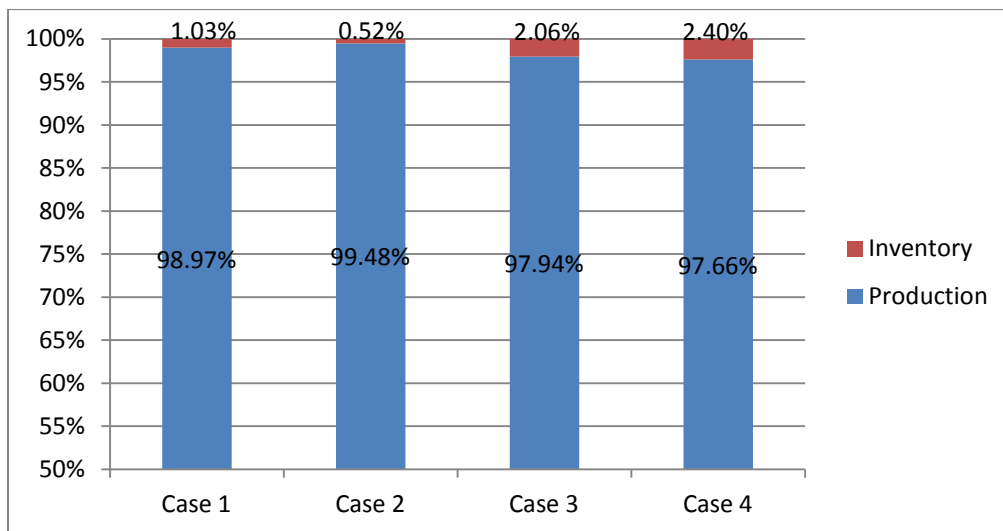
Figure 4.7 Cost distributions of traditional production planning

Fortunately, a methodology was developed recently to optimize the work injury cost according to the assembly requirement of products. A Design Knowledge base (Emodi, 2007) and linear

regression cost model (Lin, 2008) were implemented in this methodology. The work injury integrated production planning model in CNH case was further optimized by employing this methodology. As a result, the work injury cost was significantly decreased to less than one-third of that in the initial model (C4_WI), which yielded a 1.15 % less than the overall production cost (Table 4.11).
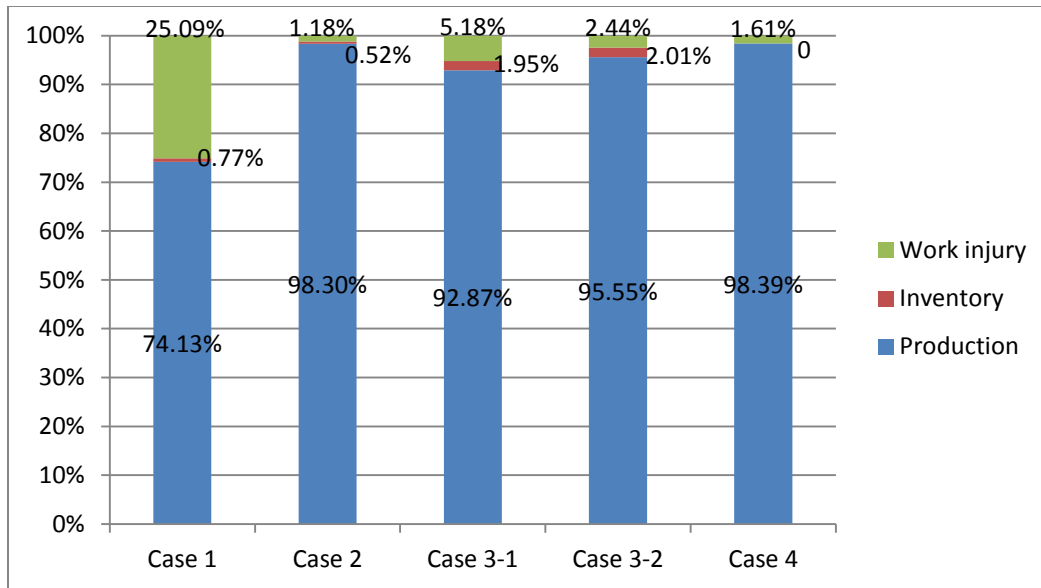
Figure 4.8 Cost distributions of work injury integrated production planning

Table 4.11 Cost distributions of Case 4

Case 4	C4_PPC	C4_WI	C4_WIM
Material	$1,534,375 (97.88%)	$1,534,375 (96.08%)	$1,534,375 (97.20%)
Labor	$37,785 (2.34%)	$36,825 (2.31%)	$36,825 (2.33%)
Work injury	n/a	$25,778 (1.61%)	$7,365 (0.47%)
Total	$1,571,200	$1,596,978	$1,578,565

4.4.2 Effect of work injury cost

The effect of work injury on the total production cost varies depending on (1) production rate, (2) working hours, and (3) work force. Revisiting the results in Table 4.6, the equivalent hourly work injury cost of Case 1 is less than half of that in Case 2. However, the total work injury cost of Case 1 accounts for 25 % of the overall cost, while the percentage in Case 2 only takes 1.18 %. One reason for this situation is that the production rates in these two cases are quite different, which were determined by the manufacturing process of the products. 20 units of product were done per hour in Case 2, while 4 hours were required to produce one unit in Case 1. Another reason is that the necessary working labor levels are different and the work injury cost is closely relevant to the working hours as mention in Lin's work (2008). Therefore, the greater the labor hour it lasts, the higher the work injury cost.

The methodology to redesign the working postures might be a solution to lower the production planning cost. As listed in Table 4.11, the work injury cost decreased more than 70 % when the redesign of the worker's assembly posture for reducing work injury was applied, which is about $18,000's saving in the overall cost. Extra expenses must be charged to implement the solution, such as the costs of special fixtures and ergonomic stools.

There might be another option to improve the situation, that is, to employ more workers in order to downgrade the work injury level on each worker. However, this will cause the increase of hiring cost.

4.5 Summary

In this chapter, LINDO^{TM} software was employed to solve the production planning models developed in Chapter 3. The three production cost models are: (1) traditional planning model, (2) the production planning model considering work injury cost and (3) the model with improved design of the worker postures. The models were written into LINDO^{TM} command scripts and their outputs were worked out by the built-in solver. The results were discussed in terms of the production cost distribution amongst the three models. The percentage range of the work injury cost against overall the production cost was calculated for the four cases or test-beds. The simulation-based analysis was also performed for the modified worker's posture for Case 4, which shows that the modified posture with low level of work injury is significant to make the work injury cost nearly negligible in the total production planning in terms of cost.

CHAPTER 5 CONCLUSIONS AND FUTURE WORK

5.1 Overview

This thesis was focused on the study of production planning with consideration of repetitive work injury. The work injury cost has been largely ignored in literature when production planning is considered. This thesis has the following objectives (re-visited):

Objective 1. To develop a production planning cost model by considering work injury cost.

Objective 2. To study the effect of work injury on production planning in terms of cost.

These objectives have been achieved by this study. An overview of the work conducted in this study is given as follows.

A literature review was conducted on different approaches of building production planning models, which include linear programming, mixed integer programming and genetic algorithm, in Chapter 2. Chapter 2 also includes a state of art review of human in production planning in recent years (Hernandez, 2012). A finding was made that though a number of techniques have been developed to measure the level of work injuries, the effect of repetitive work injury on the cost in production planning has not been known. This thus justified the need of the research conducted in this thesis study.

In Chapter 3, a linear production planning model was developed to estimate the general production cost for an assembly line. The model was extended to include the work injury cost in the total model. Both models are a linear programming model to facilitate the model solving process, which is conducive to the application of the model and analysis of the model. Four cases of production planning were drawn from the literature for further examining the effect of work injury on production planning. In fact, these cases served as the test-bed for this thesis study, as the real time measurement of the production practices with consideration of work injury seems to be difficult.

In Chapter 4, the four cases of production planning were run on the model as developed in the LINDO^{TM} software environment. Basically, three scenarios were compared, which are: (1) production planning without work injury considered, (2) production planning with high level of work injury, and (3) production planning with low level of work injury (which was achieved by redesign of the worker posture). The result shows that the work injury can increase the total production cost from 0.47 % to 25 %.

5.2 Conclusions

The following conclusions can be drawn from this, with respect to the research objectives of the thesis:

(1) A linear programming model for production planning with consideration of work injury cost can be built with a tolerable inaccuracy. This model can be used in practice to improve the accuracy of production planning in terms of cost.

(2) The repetitive work injury may affect the production cost significantly, which could be up to 25 % increase of the production cost without consideration of work injury.

5.3 Contributions

The contributions of this thesis to the field of production engineering are:

(1) Providing the new knowledge that the cost of work injury may be quite significant in the total production cost, particularly the work injury cost may imply about 25 % increase of the production cost as opposed to the cost without consideration of work injury. The importance of this knowledge is that design of a work injury production system is necessary not only for improvement of human worker health and well being but also production cost reduction.

(2) Advancing the modeling technology for production planning, enabling to model the work injury cost in production planning in terms of cost. This is helpful to project management in terms of cost and budget control.

5.4 Future Work

There are some works worthy of future effort. First, the production planning model in this thesis was limited to inclusion of the human work injury cost only. Other human factors such as work rotation and variable work force are worthy to be studied in future together with the work injury problem.

Second, the cost considered in this thesis has not included back order cost, penalty cost and other relevant costs. It is worthy of study of a more complete model for production planning by including them together with the work injury cost.

Third, work injury may affect the product delivery time, and this factor needs to be studied in production planning in future.

Finally, the mathematical model used in this study is a linear programming model, which leaves the model to be desired for more accuracy. A non-linear model may be worthy of study and a genetic algorithm could be applied to solving the non-linear model.

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RULA ASSESSMENT WORK SHEET

Retrieved from http://ergo.human.cornell.edu/Pub/AHquest/RULAworksheet.pdf

APPENDIX B

COMMAND SCRIPTS OF PRODUCTION PLANNING MODEL

(a) Production planning model without work injury considered (Case 1)

(b) Production planning model without work injury considered (Case 2)

(c) Production planning model without work injury considered (Case 3)

(d) Production planning model without work injury considered (Case 4)

(e) Production planning model with high level of work injury (Case 1)

(f) Production planning model with high level of work injury (Case 2)

(g) Production planning model with high level of work injury (Case 3 -1)

(h) Production planning model with high level of work injury (Case 3 -2)

(i) Production planning model with high level of work injury (Case 4)

(j) Production planning model with low level of work injury (Case 4)

Refer to the following link for details:

https://owncloud.usask.ca/public.php?service=files&t=2f02d4c1223a56f50fbd3319ff54974d

APPENDIX C

LINDO^{TM} PROGRAM REPORTS OF PRODUCTION PLANNING MODELS

(a) Production planning model without work injury considered (Case 1)

(b) Production planning model without work injury considered (Case 2)

(c) Production planning model without work injury considered (Case 3)

(d) Production planning model without work injury considered (Case 4)

(e) Production planning model with high level of work injury (Case 1)

(f) Production planning model with high level of work injury (Case 2)

(g) Production planning model with high level of work injury (Case 3 -1)

(h) Production planning model with high level of work injury (Case 3 -2)

(i) Production planning model with high level of work injury (Case 4)

(j) Production planning model with low level of work injury (Case 4)

Refer to the following link for details:

https://owncloud.usask.ca/public.php?service=files&t=1c61019ee0382df856543c83ef990b3d