Application of a Virtual Reality and an Ergonomics Framework for Production Time Optimization: Case study in pen production

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ABSTRACT

The goal of an efficient workstation design is to minimize the stress on the users by eliminating the risk of fatigue and injury, and consequently improve the production time. The primary goal of this research is to study and establish a relation between Ergonomics, Time Study, and Virtual Reality techniques for developing an integrated approach for designing and evaluating of assembly workstations. This proposed integrated approach is applied to improve the design of common storage bins which are being used in workstations for storage in repetitive manual assembly processes, in order to decrease the production time, reduce the fatigue on worker, mitigate the risk of Work-related Musculoskeletal Disorders, and consequently improve the productivity. The objective of this research is to improve the design of a common storage bin used to hold the four parts in the assembly process of pen production. However, these days most of pen production assembly lines are automated, but in small and medium size enterprises this assembly process is still performed manually. Since this assembly task is simple and can be generalized to any other assembly task, therefore it is chosen as a case study. The participants in this experimental study are 10 people, 5 men and 5 women. The average age, body weight, and stature of the participants is 32.6 years, 181.4 cm, and 79.7 for males; and 32.8 years, 166.6 cm, 69.6 kg for females. Their age is between 24 to 43 years. A digital camera is used to record the real time experiments. Proplanner Software is used for Time study and observing experiments. DELMIA Human Activity Analysis is used to study the fatigue in virtual environment. The comparison of the real time and simulation experimental results show that the proposed storage bin could improve the time for pick-up of 30 parts by about 11.5 seconds and decreases the fatigue by 42.5%. It is demonstrated that the redesign of a common storage bin based on proposed technique improves the productivity and efficiency of the workstation.

Keywords: Small and medium size enterprise, Ergonomics, Time study, Virtual reality, DELMIA, Fatigue, storage bin.

ÖZ

verimli bir iş istasyonu tasarımı amacı yorgunluk ve yaralanma riskini ortadan kaldırarak kullanıcılar stresi en aza indirmek ve dolayısıyla üretim süresini arttırmaktır. Bu araştırmanın temel amacı, çalışma ve tasarım ve montaj iş istasyonları değerlendirmek için entegre bir yaklaşım geliştirmek için Ergonomi, Zaman Etüdü ve Sanal Gerçeklik teknikleri arasında bir ilişki kurmaktır. Önerilen bu entegre yaklaşım İşle ilgili musculoskeletal riskini azaltmak, işçi üzerindeki yorgunluğu azaltmak, üretim süresini azaltmak için, tekrarlanan el montaj süreçlerinde depolama için iş istasyonlarında kullanılmakta olan ortak depolama kutuları tasarımını geliştirmek için uygulanan Bozukluklar, ve sonuç olarak verimliliğini artırır. Bu araştırmanın amacı, kalem üretimi montaj sürecinde dört bölümden tutmak için kullanılan ortak bir depolama kutusu tasarımını geliştirmektir. Ancak, en çok kalem üretim montaj hatları bu gün otomatik, ancak küçük ve orta ölçekli işletmelerde bu montaj işlemi hala elle yapılır. Bu montaj, basit bir iştir ve diğer montaj görev jeneralize olabilir beri, bu nedenle bir vaka çalışması olarak seçilmiştir. Bu deneysel çalışmada katılımcılar 10 kişi, 5 erkek ve 5 kadın vardır. Katılımcıların ortalama yaşı, vücut ağırlığı ve boy 32.6 yıl, 181.4 cm, erkeklerde 79.7 olduğu; ve 32.8 yıl, 166.6 cm, kadınlarda 69.6 kg. Yaşları 24 ila 43 yıl arasındadır. Bir dijital fotoğraf makinesi gerçek zamanlı deneyler kaydetmek için kullanılır. Proplanner Yazılım Zaman çalışma ve gözlem deneyleri için kullanılır. DELMIA İnsan Etkinlik Analizi sanal ortamda yorgunluk incelemek için kullanılır. Gerçek zamanlı ve simülasyon deney sonuçlarının karşılaştırılması önerilen depolama kutusu yaklaşık 11.5 saniye 30 parça pick-up için zaman geliştirmek ve% 42,5 ile yorgunluğu azalttığı olamayacağını göstermektedir. Teklif tekniğine dayalı ortak bir

depolama kutusu yeniden tasarlanması iş istasyonunun verimliliğini ve etkinliğini artırdığı gösterilmiştir.

Anahtar kelimeler: Küçük ve orta ölçekli işletme, Ergonomi, Zaman etüdü, Sanal gerçeklik, DELMIA, Yorgunluk, depolama kutusu.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

RULA	Rapid Upper Limb Assessment
VR	Virtual Reality
VM	Virtual Manufacturing
VE	Virtual Environment
WMSD	Work-related Musculoskeletal Disorders
MSD	Musculoskeletal Disorders
APAS	Ariel Performance Analysis System
PTSS	Predetermined Time Standard System
3-D	3-Dimension
CAD	Computer-Aided Design
OWAS	Ovako Working posture Analysis System
3DSSPP	3-Dimensional Static Strength Prediction Program
REBA	Rapid Entire Body Assessment
PSB	Plastic Storage Bin

LIST OF SYMBOLS

T	Time for choosing and picking up a part
k_f	The part that is chosen and picked up
k_n	Part number
A_n	Area number of the segment in bottom of bin

Chapter 1

INTRODUCTION

Nowadays the small and medium size enterprises are playing an important role in most of the countries. Many products those are produced automatically in high-tech enterprises are still made manually by human workforce in small and medium size enterprises. Therefore, if the workers do not have good condition in workstation, it effect on decrease the production and quality, and increase the time production. So that, if the small and medium size enterprises could not solve this problem, they will lose out the competition with other company.

The main concern in designing a work system is improvement of machines and tools and enhancing efficiency to achieve more benefits for enterprises [1]. Therefore, after the managers and owners of companies have tried all common methods to improve the company's benefits (e.g. Cost reduction, quality increase, etc.), ergonomic principles will be considered to improve the poor designed [2, 3]. When an operator works in a workplace with deficient ergonomics for a long time, it can cause physical and emotional stress, inefficiency and pain and consequently low productivity and poor quality of work [4, 5]. Therefore, the workstation should be designed in the way that the worker does operations with better motions and expend less energy and thus reduce and mitigate the risk of injury.

In the past, workplace ergonomic considerations have often been reactive, time-consuming, incomplete, sporadic, and difficult. human interactions have been evaluated in relatively delayed stages of the process using physical scale models [6], thus, ergonomic experts who were consulted after problems occurred in the workplace examined data from injuries that had been observed and reported. There are now emerging technologies supporting simulation-based engineering to address this in a proactive manner. These allow the workplaces and the tasks to be simulated even before the facilities are physically in place [7].

The ergonomic design methodology using Digital human models (DHM) makes the iterative process of design evaluation, diagnosis and revision more rapid and economical. (DHM) simulation systems such as DELMIA contribute to the efficiency of product design process. These systems have been utilized as an effective design tool to visualize the interaction of a human and workstation system (such as passenger car interior, fighter cockpit, and factory workplace) and to evaluate the human–workstation interaction from ergonomic aspects (such as reach, visibility and comfort), and The use of human modeling tools makes fast tests possible, allowing to verify the first designs and accelerate this initial design phase as well as provide the development of a standardized evaluation methodology [8, 9].

The evaluation in the real workplace and Human factor integration are so time consuming and costly [10]. A possible solution in manufacturing systems is the use of virtual modeling, which allows for the visualization of the products and an analysis of the diverse aspects of the product-person interaction at any stage of the product-process [9, 11].

Finally, if the new ergonomic design does not reach the goal, the whole design and evaluation should be repeated again. Therefore, the ergonomic method needs to equip with several tools. Evaluation time and design cost can be decreased by utilizing Virtual reality and Time Study methods. The first goal of this research is to study and make a relation between Ergonomics, Time Study, and Virtual Reality methods for creating an integrated method for design and evaluation of assembly workstations. Second one is to redesign the common storage bin that is being used in a workstation for repetitive assembly and apply the proposed integrated method to evaluate how this proposed storage bin could improve the productivity and decrease the fatigue and WMSDs risk.

Chapter 2

BACKGROUND

2.1 Definition of Ergonomics

Work design is a new field of science that has the objective of outlining an arrangement in the workplace to fit it better to the human administrators in order to boost the organization productivity. In the United States, it is commonly known as human factors, while internationally it is called ergonomics, which is gotten from the Greek words for work (erg) and laws (nomos) [12].

Ergonomics is more than providing a new chair for people. Public awareness of what "ergonomics" means is limited; but during recent years, public understanding of the "ergonomics" has increased. Most people think that ergonomics is about "chair" or about "doing things in a healthy and safe way". Ergonomics is a field of study that aims to find different ways to keep people safe, efficient, comfortable, and productive while they do their tasks [13, 14].

There are many different definitions in the scientific literature such as below definition from Ergo Web Inc.:

Ergonomics removes barriers to quality, productivity, and safe human performance in human-machine systems by fitting products, equipment, tools, systems, tasks, jobs, and environments to people. [15]

There are many definitions like above citation; that mention the basic principle in ergonomics is to “design the task and tools to fit the person, rather than making the person to adjust himself to the task or tools” [13, 14, 16].

Therefore, the final aim of ergonomics is to optimize the performance, safety, efficiency, health, and comfort of labor within the machine-human environment system.

As is shown in Figure 1, the Internal Ergonomics Association divides into three parts, which are Cognitive Ergonomics, Organization Ergonomics and Physical Ergonomics [17, 18].

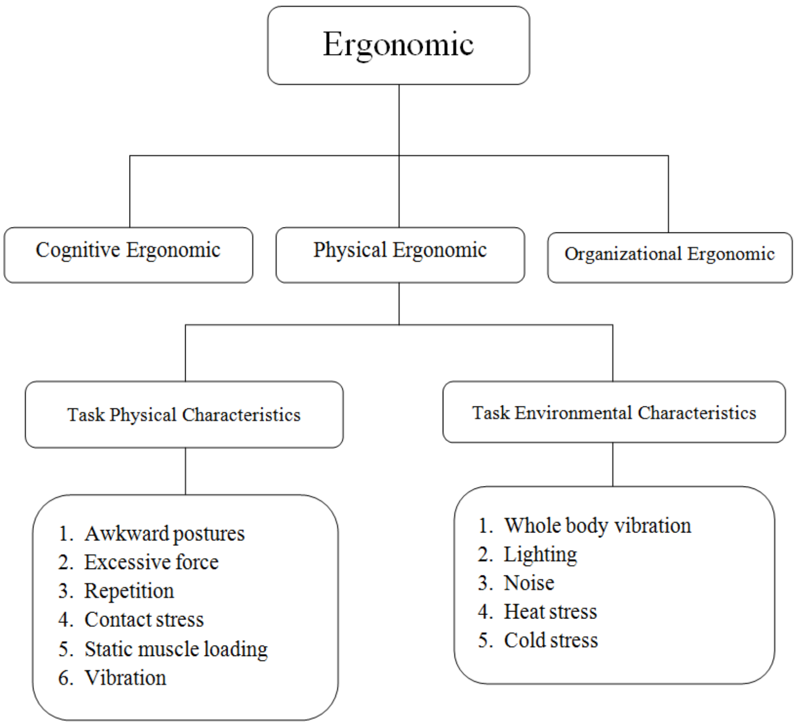


Figure 1. The division of internal ergonomics association

2.1.1 Cognitive Ergonomics

Cognitive ergonomics is a branch of ergonomics that studies the mental processes such as memory, perception, motor response, and reasoning as they affect the humans and other parts of a system and their interaction among each other. The topics that are relevant to cognitive ergonomics are human reliability, decision-making, mental workload, human-computer interaction, work stress, skilled performance and training as these may relate to human-system design [17, 18]. For instance, design a software interface with the user center focus or redesign the management to increase the human reliability and cognitive workload.

2.1.2 Organizational Ergonomics

Organizational ergonomics is a branch of ergonomics that is concerned with the optimization of systems. The subjects that are studied in organizational ergonomics includes: communication, teamwork, work design, telework, virtual organization, cooperative work, community ergonomics and quality management [17, 18].

2.1.3 Physical Ergonomics:

Physical ergonomics studies the physical and physiological stresses and the response of the human body to them. It needs several characteristics of the human like physiology, anatomy, biomechanics and all other fields that are related to physical activities. When the ergonomic principles are ignored in the shop floor, it is certain that musculoskeletal disorders (MSD) are a potential outcome; and it is not an appropriate event for the enterprise. So ergonomic principles are required in the systems [17, 18].

Physical ergonomics is used in manufacturing system with many different objectives, which one of them is the reduction of MSD-risk or decrease in worker’s compensation cost. The other benefits of physical ergonomics are increased productivity, reduced turnover and absenteeism, improved quality, improved efficiency, improved employee morale and reduced downtime [17].

2.1.3.1 Advantage of Physical Ergonomics

2.1.3.1.1 Increased Productivity

Usually, productivity could be increased 10-15 percent of the ergonomic improvement. Studies have shown that the outcome at a computer workstation could be increased 25 percent by using ergonomic furniture that also causes an improvement in employee's wellbeing [17, 19].

2.1.3.1.2 Reduced turnover and absenteeism

When people feel comfortable in their work, they have less motivation to take time off from work and leave their work for discomfort [17].

2.1.3.1.3 Improved quality

Improve quality has direct connection with decrease errors and product defects When comfort increase [19].

2.1.3.1.4 Improved efficiency

Improved efficiency happens by bringing the items closer to the workplace or doing a task with fewer motions, so the task can take less time and cause less muscular fatigue and injury [20].

2.1.3.1.5 Improved employee morale

Ergonomics allows the businesses spread the message that "we value your health and we care about you" across all levels of enterprise, from shop floor to the employees in the office [19, 21].

2.1.3.1.6 Reduced downtime

Reduced downtime means solving and reduction of unplanned events like shortage of operators, unscheduled maintenance, or equipment failure that cause manufacturing process to stop. For example, maintenance tasks can be optimized by improving access points during changeover tasks that results in faster task time [17].

An ergonomist studies the different tasks in the workplace and analyzes the effects of them on increasing the risk of MSDs. The risk factors can be classified into task physical characteristics and Environmental Characteristics [17].

2.1.3.2 Task Physical Characteristics

2.1.3.2.1 Awkward postures

Awkward posture is a position of body that in it the joints and limbs that connecting to them deviates from the neutral posture and the muscles are not in stability. Therefore, it is associated with an increased risk for injury. Examples of awkward posture are reaching behind the body, kneeling, forward or backward bending, twisting, squatting, and working overhead (Figure 2). When the people are in the awkward and uncomfortable postures they cannot do their jobs right in the first time and mistakes are more common [3, 4, 22, 23].

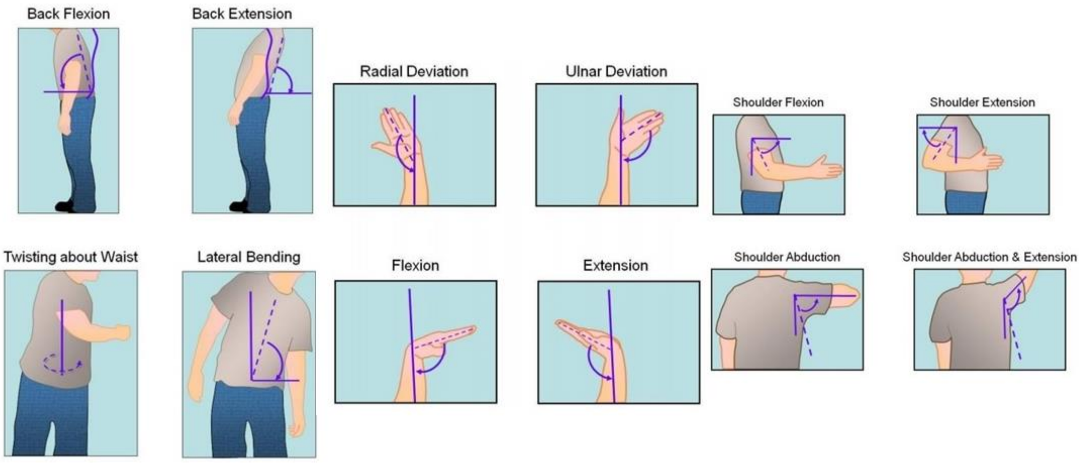


Figure 2. Different awkward posture [23]

2.1.3.2.2 Excessive force

Excessive force is one of the primary ergonomic risk factors. When the labor applies high force in workstation for doing some tasks, it might occur WMSDs on the shoulder/neck, forearm/wrist/hand. In response to high force requirement, muscle effort increases that causes increase in fatigue and risk of MSDs. In general, “the greater the force, the greater the degree of risk”. For example, lifting, lowering, pushing, pulling, pinching, and using the hand as a hammer are several positions that make excessive force. So eliminating the excessive force will reduce the worker fatigue and the risk of MSDs. For example, using mechanical assists, powered equipment, adjustable height lift tables and workstations, counter balance systems, and ergonomic tools reduce effort for doing a task and muscle exertions [23, 24].

2.1.3.2.3 Repetition

Repetition means when a task is done over and over again with little variation also includes repeating multiple tasks with very similar motions that involve the same muscles and tissues. When motions are repeated frequently for long periods of time (several hours continuously) and repeated period is 30 seconds or less, fatigue and strain occur in the muscles and tendons, because they do not have enough time for recovery [17, 25].

2.1.3.2.4 Contact stress

When any part of the body is pressed by an external object, contact stress happens. Contact stress can occur in two forms: internally and externally. Internal contact stress happens when a nerve, tendon, or blood vessel is stretched or bent around a bone or tendon. The external contact stress occurs when a part of body is pressed by a component of workstation for a long time, such as using a mouse for a prolonged period, or rubbing against a part of workplace, such as the chair seat pan or edge of the desk (Figure 3). These things might cause irritation of nerves or constriction of blood vessels [26, 27].

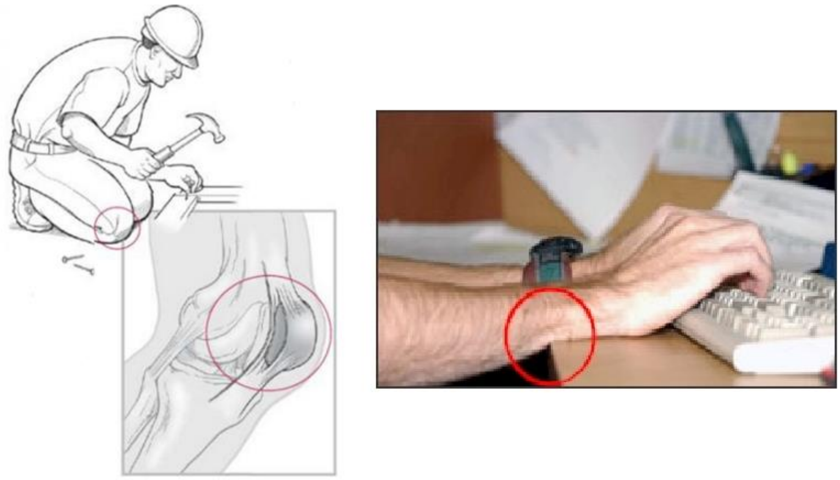


Figure 3. Contact stress on wrist and knee [28]

2.1.3.2.5 Static muscle loading

Static muscle loading happens when a worker remains in one posture for a long time, such as standing, sitting, or otherwise posture for a long time that can increase risk of MSDs. So when force, posture, and duration combine with each other cause contract the muscles and reduce blood flow to them, so create a condition that leads muscles to fatigue and injury [5, 15].

2.1.3.2.6 Vibration

Excessive force is one of the primary ergonomic risk factors. When the labor applies high force in workstation for doing some tasks, it might occur WMSDs on the shoulder/neck, forearm/wrist/hand. In response to high force requirement, muscle effort increases that causes increase in fatigue and risk of MSDs. In general, “the greater the force, the greater the degree of risk”. For example, lifting, lowering, pushing, pulling, pinching, and using the hand as a hammer are several positions that make excessive force. So eliminating the excessive force will reduce the worker fatigue and the risk of MSDs. For example, using mechanical assists, powered equipment, adjustable height lift tables and workstations, counter balance systems, and ergonomic tools reduce effort for doing a task and muscle exertions [23, 24].

2.1.3.3 Task Environmental characteristics

2.1.3.3.1 Whole Body Vibration

This kind of vibration exposure to the human body usually occurs through the seat, platform, or feet/buttocks when riding in a vehicle [17].

2.1.3.3.2 Lighting

When the light in the workplace is set improperly, it may cause inefficiency. For example, lighting with levels above 1000 Lux in a workstation causes glare and eye symptoms. So the important factors about the lighting in a workstation are intensity and color [29-31].

2.1.3.3.3 Noise

Noise is defined as a kind of sound that is unwanted and can cause pain in the ears or may be nuisance sound. The noise can be annoying, distracting and disruptive that can cause inefficiency [32, 33].

2.1.3.3.4 Heat stress

Heat stress is all the external and internal heat factors that make body fatigue and distress. External factors that can cause heat stress are such as air velocity and humidity, ambient air temperature, and radiant heat. Internal factors include acclimatization, natural heat tolerance, core body temperature, and metabolic heat generated by the workload. So extremely hot environment causes a decrease in productivity while increases the rate of the risk workers disorders [34-36].

2.1.3.3.5 Cold stress

Cold stress means low temperature that causes shivering, clouded consciousness, extremity pain, dilated pupils, ventricular fibrillation, frostbite, hypothermia or muscle strain when core body temperature drops from normal body temperature because of winter weather, high altitudes, or cryogenic equipment [37-39].

2.2 Measurement ergonomic methods

One of the most appropriate methods that can be used to estimate MSDs is the Scoring technique. Before applying the scoring technique, first the required duties and sub-duties must be identified, and each of them must be individually examined.

Currently, there are four methods available for applying the scoring technique in order to evaluate musculoskeletal disorders that are shown in (Figure 4). These techniques are Pen-paper based observational methods, Observational Methods Based on Computer or Video Tape, Direct/Instrumental Methods, Self-Reporting Method [34, 35, 40, 41].

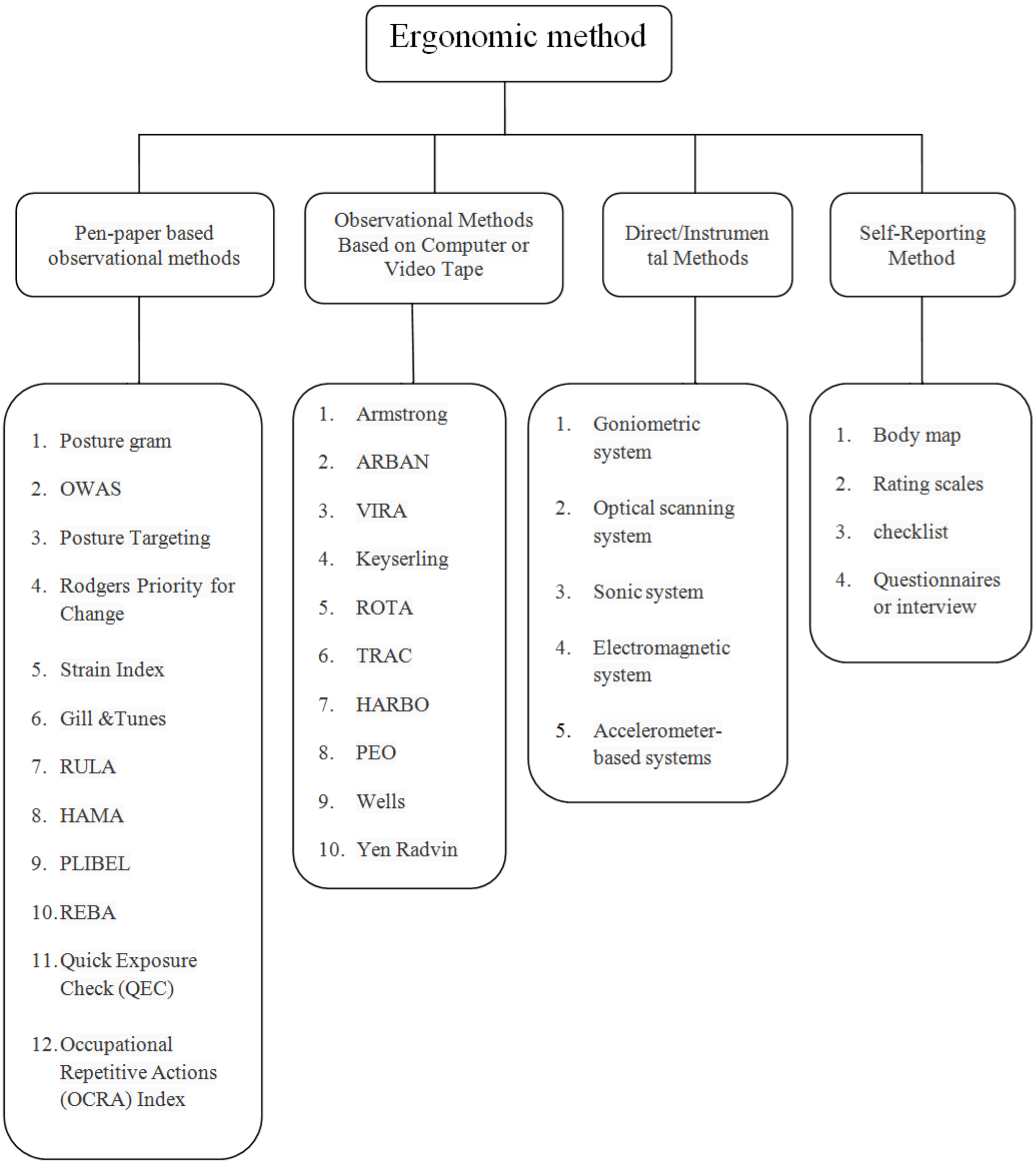


Figure 4. Different kinds of measurement ergonomic methods

The following paragraphs will explain the aforementioned ergonomic methods from Figure 4.

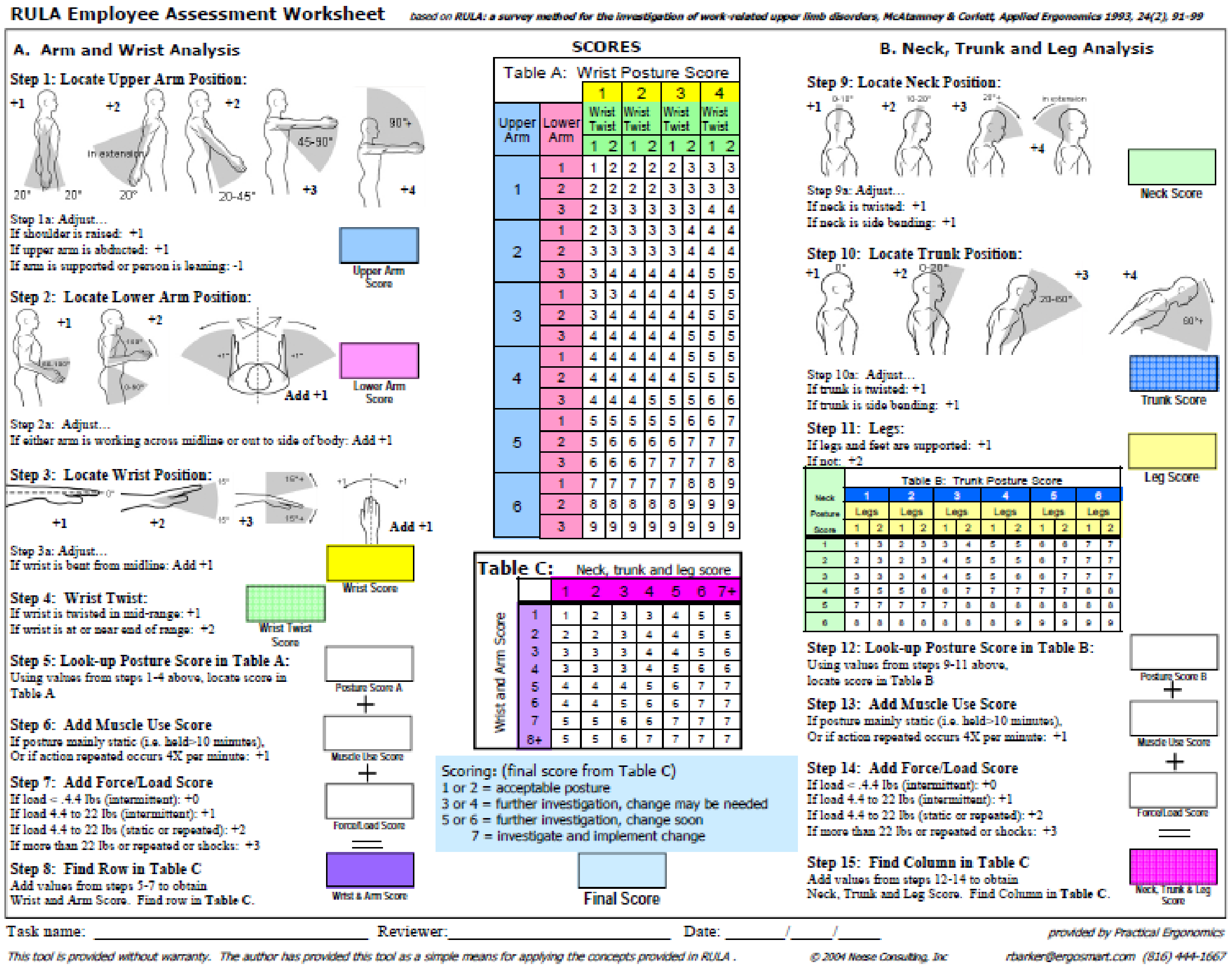
2.2.1 Pen-paper based observational methods

Although, there were always some methods for recording the postures of the human body, before the Priel's method was developed in the early 17^{th} century, the posture was recorded with drawings and photographs. It was after the 17^{th} century that new methods for recording the posture were developed based on pen-paper [34, 42, 43].

Now several important and common Pen-papers based methods will be categorized and shown in Table 1.

2.2.1.1 RULA Method

This method was developed in 1993 by Dr. Lynn McAtamney and prof. E. Nigel corlett. RULA is a postural method for the estimation of the risks that happen to the upper limb body. It gives a systematic and a quick assessment of the postural risks to a worker. This technique uses a scoring system to record different positions of the body to assess every position with numerical scores (Figure 5) [35, 44, 45].



RULA Employee Assessment Worksheet *based on RULA: a survey method for the investigation of work-related upper limb disorders, McAtamney & Corlett, Applied Ergonomics 1993, 24(2), 91-99*

A. Arm and Wrist Analysis

Step 1: Locate Upper Arm Position:

+1 20° 20° +2 in extension 20° +2 20-45° 45-90° +3 90°+ +4

Step 1a: Adjust…
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score

Step 2: Locate Lower Arm Position:

+1 +2 Add +1

Lower Arm Score

Step 2a: Adjust…
If either arm is working across midline or out to side of body: Add +1

Step 3: Locate Wrist Position:

+1 +2 +3 Add +1

Step 3a: Adjust…
If wrist is bent from midline: Add +1

Wrist Score

Step 4: Wrist Twist:
If wrist is twisted in mid-range: +1
If wrist is at or near end of range: +2

Wrist Twist Score

Step 5: Look-up Posture Score in Table A:
Using values from steps 1-4 above, locate score in Table A

Posture Score A

+

Step 6: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

Muscle Use Score

+

Step 7: Add Force/Load Score
If load < 4.4 lbs (intermittent): +0
If load 4.4 to 22 lbs (intermittent): +1
If load 4.4 to 22 lbs (static or repeated): +2
If more than 22 lbs or repeated or shocks: +3

Force/Load Score

=

Step 8: Find Row in Table C
Add values from steps 5-7 to obtain Wrist and Arm Score. Find row in Table C.

Wrist & Arm Score

SCORES

Table A: Wrist Posture Score

Upper Arm	Lower Arm	1: Wrist Twist 1	1: Wrist Twist 2	2: Wrist Twist 1	2: Wrist Twist 2	3: Wrist Twist 1	3: Wrist Twist 2	4: Wrist Twist 1	4: Wrist Twist 2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	7	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

Table C: Neck, trunk and leg score

Wrist and Arm Score	1	2	3	4	5	6	7+
1	1	2	3	3	4	5	5
2	2	2	3	4	4	5	5
3	3	3	3	4	4	5	6
4	3	3	3	4	5	6	6
5	4	4	4	5	6	7	7
6	4	4	5	6	6	7	7
7	5	5	6	6	7	7	7
8+	5	5	6	7	7	7	7

Scoring: (final score from Table C)
1 or 2 = acceptable posture
3 or 4 = further investigation, change may be needed
5 or 6 = further investigation, change soon
7 = investigate and implement change

Final Score

B. Neck, Trunk and Leg Analysis

Step 9: Locate Neck Position:

+1 0-10° +2 10-20° +3 20°+ +4 in extension

Neck Score

Step 9a: Adjust…
If neck is twisted: +1
If neck is side bending: +1

Step 10: Locate Trunk Position:

+1 0° +2 0-20° +3 20-60° +4 60°+

Step 10a: Adjust…
If trunk is twisted: +1
If trunk is side bending: +1

Trunk Score

Step 11: Legs:
If legs and feet are supported: +1
If not: +2

Leg Score

Table B: Trunk Posture Score

Neck Posture Score	1: Legs 1	1: Legs 2	2: Legs 1	2: Legs 2	3: Legs 1	3: Legs 2	4: Legs 1	4: Legs 2	5: Legs 1	5: Legs 2	6: Legs 1	6: Legs 2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	7	7	7	7	8	8
5	7	7	7	7	7	8	8	8	8	8	8	8
6	8	8	8	8	8	8	8	9	9	9	9	9

Step 12: Look-up Posture Score in Table B:
Using values from steps 9-11 above, locate score in Table B

Posture Score B

+

Step 13: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

Muscle Use Score

+

Step 14: Add Force/Load Score
If load < 4.4 lbs (intermittent): +0
If load 4.4 to 22 lbs (intermittent): +1
If load 4.4 to 22 lbs (static or repeated): +2
If more than 22 lbs or repeated or shocks: +3

Force/Load Score

=

Step 15: Find Column in Table C
Add values from steps 12-14 to obtain Neck, Trunk and Leg Score. Find Column in Table C.

Neck, Trunk & Leg Score

Task name: ______________________ Reviewer: ____________________ Date: ____/____/____

provided by Practical Ergonomics

Figure 5. RULA Employee Assessment Worksheet [1]

Table 1. Different pen-and-paper-based observational techniques

Techniques	Creators	Basic features	Field of applications
Posturegram [46]	Priel (1974)	Body postures are recorded and categorized as digital numbers by time sampling.	Evaluation of the whole body posture for static tasks
OWAS [47]	Karhu et al. (1977)	Categorizes body position with digital numbers	Analysis of the whole body posture
Posture Targeting [46]	Corlett et al. (1979)	Body postures are identified by angles and directions together by time sampling	Evaluation of the whole body posture for static tasks
Rodgers Priority for Change [48]	Suzanne Rodgers (1988)	Categorizes body posture risk by evaluation in three factor levels	Evaluation of the whole body posture for static and dynamic tasks
Gill & Tunes [35, 46]	(1989)	Categorizes body posture with angles and frequency of occurrence.	Evaluation of the whole body posture for seated tasks
RULA [35, 44, 45, 49]	McAtamney and Corlett (1993)	Categorizes body posture with numbers that are computed for force and muscle activities.	Upper limb assessment
HAMA [35]	Christmansson (1994)	Records the kinds of motion, load handled, hand position and grasps; the data and work activities are linked to each other.	Upper limb assessment
PLIBEL [35]	Kemmlert and Kilbom (1987), Kemmlert (1995)	Checklist with several questions about different body posture.	Classification of risk factors
Strain index [50]	J. Steven Moore Arun Garg (1995)	Evaluate body posture with strain index that estimates several factors like force, time, body position and etc.	Evaluation of the upper limb MSDs for repetitive activities
REBA [35, 51]	McAtamney and Hignett (1995)	Scores the body position and load according to action levels.	Evaluation of the whole body for the risk assessment in 'non-sedentary' tasks

QEC [35]	Li and Buckle (1998)	Evaluates the body posture and assigns a score to the repetition activities and force/load from a special score table.	Evaluation of the body posture for static and dynamic tasks
OCRA [52]	E. Occhipinti (1998)	Analyzes and evaluates risk factors, force/load, body posture and time sample	Evaluation of the upper limb for static or dynamic Repetitive activities

2.2.2 Observational Methods Based on Computer or Video Tape

This method records the postures, workstation positions, and tasks by computer or video recordings, and analyzes them with computers. In these methods, the observation is based on time sampling and real-time simulation. Table 2 shows categorizing of this method [34].

Table 2. Different computer-aided and videotaping observational methods

Techniques	Creators	Basic features	Field of applications
Armstrong [35]	Armstrong et al. (1982), Armstrong (1986)	Computerized data and time sampling video for posture and force; indicated hand position as several kinds of pinch or grasp; contact area with finger or hand as coded numbers.	Upper limb assessment
ARBAN [35]	Holzmann (1982)	Computerized analysis; Code load situations and postures by time-sampling; used Borg's scale for estimation of the muscle stress, posture effort and vibration.	Assess physical stress in whole body
VIRA [35]	Persson and Kilbom (1983), Kilbom et al. (1986)	Computerized real-time analysis for duration and frequency of postures and motion.	Upper limb assessment
Keyserling [35]	Keyserling (1986)	Computerized real-time analysis for duration and frequency of body position in predefined body position categories.	Evaluation of the repetitive and non-sedentary tasks

ROTA [53]	Ridd et al. (1989)	Computerized time Sampling or real time analysis on different posture and activity.	Dynamic or Static tasks
TRAC [54]	van der Beek et al. (1992)	Computerized real-time analysis or time sampling on different posture and activity.	Dynamic or Static tasks
HARBO [55]	Wiktorin et al. (1995)	Computerized real-time data from work postures; Identifying the position of hands at three levels.	Long observation for various types of tasks
PEO [56]	Fransson-Hall et al. (1995)	Computerized the data that are collected in real-time on work activity and posture movement.	Analyze Trunk and Upper limb posture for dynamic tasks and manual handling
Wells [35]	Wells et al. (1994)	Computerized data analysis on repetition, EMG signals, synchronized posture and activity.	Upper limbs and low back physical exposure assessment
Yen and Radwin [35]	Yen and Radwin (1995)	Synchronized video images with analogue data recording.	Evaluation of the repetitive and arbitrary activities

For recording and motion analysis, there are several commercially systems that record body movement and posture in 2 or 3 dimensional plane as some of the important and common ones is mentioned in the following:

- PEAK Motus System [57]
- VICON System [58]
- Kinemetrix 2D/3D Motion Analysis Systems [59]
- SIMI Motion System (Reality Motion Systems) [60]
- APAS (Ariel Performance Analysis System) [61]

2.2.3 Direct/Instrumental Methods

Body posture can be illustrated by using a direct method manually or continuously. The manual method uses hand-held devices and continuous method uses electrical instruments. In the manual method, in order to measure the angles of the body segments, the device is attached to the body section and draws a trace on paper (Flexi-curve) or indicates on the device (inclinometer). With electrical instrumental methods, an electrical output signal is generated proportional to the intersegment displacement [35, 62].

2.2.4 Self-Reporting Method

This method is used to assess the physical load force, work stress or body discomfort by collecting the data on physical and psychosocial factors on the workstation through paper questionnaires, interviews and worker diaries [63, 64] or use of web base questionnaires [64, 65].

2.3 Time Study

2.3.1 Definition of time study

Time study is one of the oldest key systems ever utilized to increase productivity. So the time study is used as an important tool in manufacturing industry for analyzing and developing methods for evaluation of the employees. It is used to create employee productivity standards through the broken a complex task into simple and small steps, measuring precise time for each correct movement and detecting the wasteful motion in the task sequence [66].

According to Meyers method, the time study is about the time of producing a product in a workplace with three conditions. These conditions are a qualified operator, working at a normal pace and doing a particular task. Therefore, the time study is the time, that is determined by a qualified and prepared operator working at a normal pace to do a particular task [66, 67].

2.3.2 Objective of Time Study

Time study has many principle and objectives with considering different aspects of production. The first objective is minimizing the time that is necessary for doing a task. The second objective is making balance between the work of the workers and the product. The last objective is increasing the well-being, health and safety of all human resources an environment [67, 68].

2.3.3 Time study techniques

There are several different methods for time study while many of them utilize the same techniques in their study. The Table 3 shows the five different time study techniques. In this research a combination of Lawrences and Niebel techniques is used as a time study technique which is going to be explained in chapter 4 [67].

Table 3. Different time study techniques [67]

No.	Source	Technique
1	Barnes (1980)	• Standard Data • Work Sampling • Predetermined Time Standard System (PTSS) • Stopwatch Time Study
2	Niebel (1993)	• Stopwatch Time Study • Computerized Data Collection • Standard Data • Fundamental Motion Data • Work Sampling and Historical Data
3	Lawrences (2000)	• Time Study • Standard Data Systems • Predetermined Time Standard Systems (PTSS) • Work Sampling • Physiological Work Measurement • Labor Reporting

4	Meyers and Stewart (2002)	• Predetermined Time Standard System (PTSS) • Stopwatch Time Study • Work Sampling • Standard Data • Expert Opinion and Historical Data
5	Niebel and freivalds (2003)	• Time Study • Standard Data and Formulas • Predetermine Time Standard Systems • Work Sampling • Indirect and Expense Labor Standards

2.3.4 Time Study Instruments

The time study needs several instruments that consist of a device for measuring time and an observation board [67]. In this research a camera is utilized to capture video from equipment and labor motions and a computer with specific software to collect and analyze the data.

2.4 Virtual Reality

2.4.1 Definition of Virtual Reality

Virtual reality is described as "a 3-D environment, computer-synthesized, appropriately interfaced, and might manipulate and engage simulated physical component in the 3-D environment". So virtual reality can be illustrated as a 3-D artificial environment that is created with computer programming in order to simulate an environment that is acceptable by the users. And The goal of Virtual Reality is to make a perception and view of a real environment with utilization of multi-media that allows the users to experience and evaluate the different scenarios with low cost and time [69, 70].

2.4.2 Definition of Virtual Manufacturing

Virtual manufacturing (VM) is an artificial manufacturing environment that is used for increasing the ability to control and make decisions in a manufacture enterprise.

Virtual manufacturing simulates a model of manufacturing levels with the same parameters and takes all that information to the process, process management and control, and data product [71-74].

Chapter 3

LITERATURE REVIEW

The goal of workstation design is to minimize the stress and harmful postures on the users in order to decrease the producing time.

In this research, three different fields of mechanical and industrial science (Ergonomics, Virtual Reality and Time Study) will be utilized in order to propose an improved method for efficient workstation design. Therefore, in the following chapter, there is a literature review of the related research works that are performed in the area of Ergonomics, Virtual Reality and Time Study or their combination for different purposes.

S. Vaclav et al. (2010) studied and suggested a method for designing a manual assembly workspace in a CAD environment. Their method was intended to create good work conditions to achieve productivity and high quality of work. They used the CATIA ergonomic modules for analyzing and designing efficient solutions to optimize the layout of manual workstations [75].

Feyen et al. (2000) offered PC-based software that allows the designers to evaluate the proposed workstation design in order to measure the biomechanical risk. The program was composed of a software tool for biomechanical analysis, the Three-Dimensional static strength prediction program (3DSSPP), with a broadly used AutoCAD as a computer-aided design software package. The software allows the authors to research and study about ergonomic stuffs through designing workstation phases with taking into consideration different designs. The authors described the use of this 3DSSPP/AutoCAD interface in the analysis of an automotive assembly task and compared the results with the data that was taken from a direct independent assessment of the same task [76].

Irad Ben-gal and Joseph Bukchin (2002) introduced a new methodology for the design of a workstation. In their research, they used the integration of response surface methodology and factorial experiments to obtain the best design configuration through the graphical simulation and virtual manufacturing. In this research some method were used to bridge the gaps between them by the creation of a set of alternative design configurations [77].

Jayaram et al. (2006) suggested two different approaches to link virtual environment (VE) and quantitative ergonomic analysis tools in real time to study about industrial ergonomics. The first approach aims to create methods for integrating the virtual environment with commercially available ergonomic analysis tools, while the second approach aims to create an ergonomic analysis module that is built-in to a VE. The authors described the two strategies and tested them in a real industrial company as a case study [7].

Francesco et al. (2006) offered an assembly line for product heaters. This research studied the effects of the design of an assembly line workplace with integration of the simulation and modeling with ergonomic analyses [78].

Shao-Wen et al. (2007) used virtual dynamic simulation workstation and digital human modeling for evaluating WMSDs in automobile assembly tasks. This research used RULA system in DELMIA software for improvement ergonomic tools in automobile workstation [79].

Shikdar and Al-Hadhrami (2007) studied the designing of a smart workstation and its development to operating manufacturing assembly tasks. This research developed a design for a fully adjustable ergonomic workstation [80].

Alzuheri et al. (2010) evaluated different physical workload and work position in manual assembly tasks with RULA method. This research proposed a framework for avoiding WMSDs by assessing ergonomic stresses in manual assembly [81].

Ashraf shikdar et al. (2011) studied the comparison between the new design assembly workstation (new arrangement of bins and tools) and the common design assembly workstation (common arrangement of bins and tools). This research concluded that the new design assembly workstation improves the performance of the worker around 44% [82].

Ibrahim H. Garbie (2011) did an experimental study about smart adjustable workstation on ten persons in three experimental conditions (gender, chair adjustable and table adjustable) working on an assembly of an electrical switch that consisted of 8 parts and used Minitab Statistical Software Package to analyze the results. This research studied how to measure the rate of production in manual assembly lines in assembly workstations that are ergonomically designed [83].

Adi Saptari et al. (2011) studied about the effect of jig design, assembly design, workplace design and posture of worker on the time assembly of plugs. This research shows that these factors are significant. However, the interaction combinations of these factors are not important at assembly time. Meanwhile, this research used RULA method for evaluating working posture, and found a position that take the lowest RULA score which is safe [84].

R. Arun et al. (2013) studied the human factors and work methods for the assembly mono block pump by simulating workplace in CATIA and Pro-E software and analyze with RULA method for identifying WMSDs. In their study, they proposed several methods like use of hydraulic press, screw gun and an automatic conveyor for improvement tasks [85].

Ansari, et al. (2014) studied about 15 workers that engaged in a small-scale industry. Several video tapes from different activities of the workers were recorded and the images were cropped from them for analysis. In their study, they presented an assessment of different work postures during different activities in small-scale industry. RULA and REBA was used for evaluation of the posture and worksheet was used for assessment [86].

In this chapter, a review of some papers on the application of Ergonomics, Virtual Reality and Time Study for improvement of the workstation was mentioned. Though some of these researches have tried to use a combination of two of these methods in their designs. According to Table 4, none of these researches have considered utilizing all of these three techniques (Ergonomics, Virtual reality and Time study) for an efficient workstation design.

The approach that proposed in this research will be discussed how a combination of these three techniques lead to an improved workstation design and as a case study will be demonstrated how the redesign of a common storage bin based on proposed technique improves the productivity and efficiency of the workplace.

Table 4. litreture review summary

Method	Auther and date
Ergonomics	Feyen et al. (2000), Francesco et al. (2006), Jayaram et al. (2006), Shao-Wen et al. (2007), Shikdar and Al-Hadhrami (2007), Alzuheri et al. (2010), S. Vaclav et al. (2010), Ibrahim H. Garbie (2011), Adi Saptari et al. (2011), R. Arun et al. (2013), Ansari, et al. (2014).
Time Study	Ibrahim H. Garbie (2011), Adi Saptari et al. (2011) , Ashraf shikdar et al. (2011) .
Virtual Reality	Feyen et al. (2000), Irad Ben-gal et al. (2002), Jayaram et al. (2006), Francesco et al. (2006), Shao-Wen et al. (2007), S. Vaclav et al. (2010), R. Arun et al. (2013).
Ergo & VR	Feyen et al. (2000), Jayaram et al. (2006), Francesco et al. (2006), Shao-Wen et al. (2007), S. Vaclav et al. (2010), R. Arun et al. (2013).
Time Study & Ergonomics	Ibrahim H. Garbie (2011), Adi Saptari et al. (2011)

Chapter 4

METHODOLOGY

4.1 Case study

The selected product for this case study is a pen that composed of four parts assembled in a factory. However, these days most of big pen production assembly lines in high-tech factories are automated, but in small and medium size enterprise in most of the countries, this assembly process is still manually done with human resource. Since this assembly task is a simple task that can be generalized to any other assembly tasks, so this assembly task was chosen as a case study. The position of the worker and the bins are shown in Figure 6. The assembly task sequence is mentioned below:

A. Picking up the cover from the bin 1 and put it in the jig (number 6) on the table
B. Picking up the spring from bin 4 and put it in the cover
C. Picking up the pen pipe from bin 2 and put it in the cover
D. Picking up the pen bottom from bin 3 and assemble it on the cover
E. Picking up the complete pen from the jig and placing it in the outgoing bin (number 5)

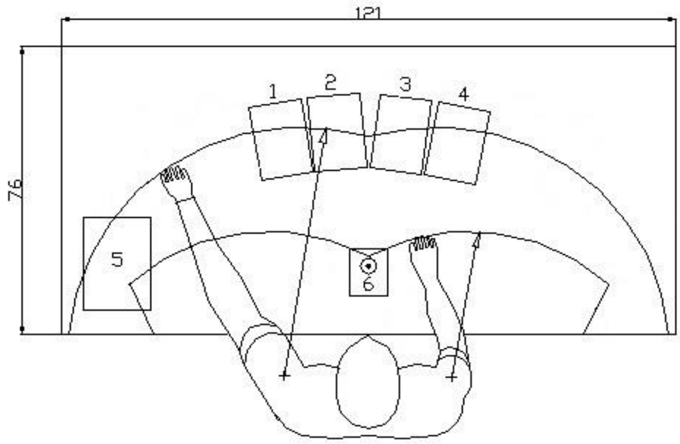


Figure 6. Layout of the pen assembly workstation

4.2 Problem

Human resources are an essential part of the assembly process in small and medium sized enterprises. The main reasons for the use of human force in assembly lines are as below:

A. The use of human force in the assembly process is less expensive than automation.

B. Sometimes products that are assembled by human (Handmade Brands) have more value than assemble in automated assembly lines (series Brand).

C. Sometimes in the assembly process, make the decision is important in unwanted events and it is hard for an automated system that makes decision in that situation.

On the other hand, using the human resources in assembly lines involves some other factors like time management, workplace-related injury and health risks, which must be managed efficiently in order to increase the profits. Therefore, designing a workstation with an enhanced environment that can increase the productivity and decrease the workforce injuries and production time, is an important objective for every enterprise.

A good design for an assembly workstation should consider the design principals of the components of a workstation that directly or indirectly affect the people that are working in that environment such as the design of the chair, desk, workplace environment, tools arrangement.

In this project, the standard Plastic Storage Bin (PSB) that is used in the ordinary workplace will be analyzed and evaluated. Based on the results of this analysis a redesigned for the PSB will be proposed that utilizes the ergonomic principles in order to decrease the injuries and fatigue in the worker's wrist. Moreover, it will be indicated how the use of the proposed ergonomic PSB will enhance the performance of the worker, which will lead to an increase in productivity during a lengthy assembly process.

To analyze a standard PSB, three major problems are considered. First, to load/unload the PSB through its entrance, if parts are located in area 1 as it shown in Figure 7, the human labor wrist angle will be in dangerous range to pick/place the part according to the RULA method. (Figure 5, 8)

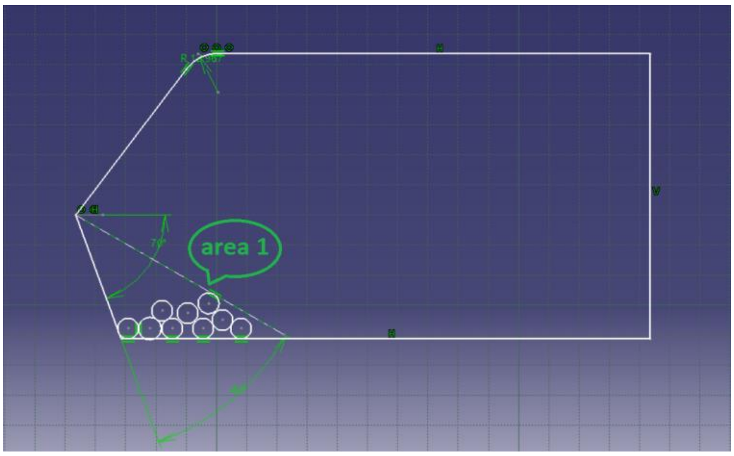


Figure 7. Harmful area for wrist for picking up a part in the normal plastic storage bin (area 1)

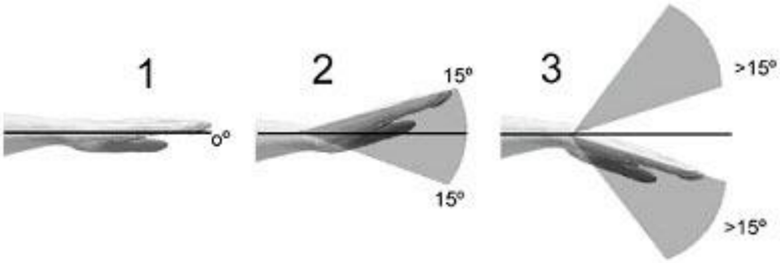


Figure 8. Dangerous range according RULA method
1) Best position 2) Acceptable position 3) Dangerous position [87]

Secondly, according to the random parts distribution pattern, when there are a few parts in PSB, labor needs more time to find a part and pick it up, since they are distributed across the bin. To achieve randomly distribution pattern shown in Figure 9, fifty parts were randomly distributed in a PSB and this experiment was repeated 100 times in order to calculate the position of a part as the average of its positions in this experiment.

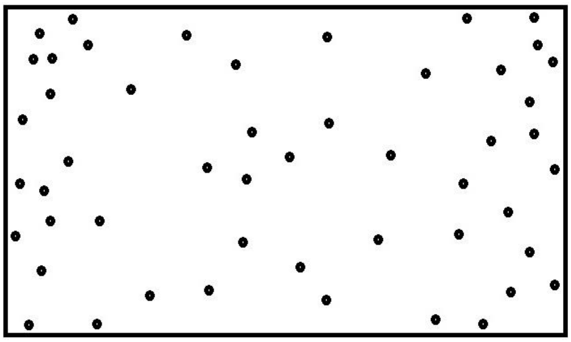


Figure 9. Random pattern of distribution for 50 parts in PSB

Finally, during the assembly process, the parts are so small that they placed at the corners or the edges of PSB, finding and picking them will be difficult and time consuming. (Figure 10)

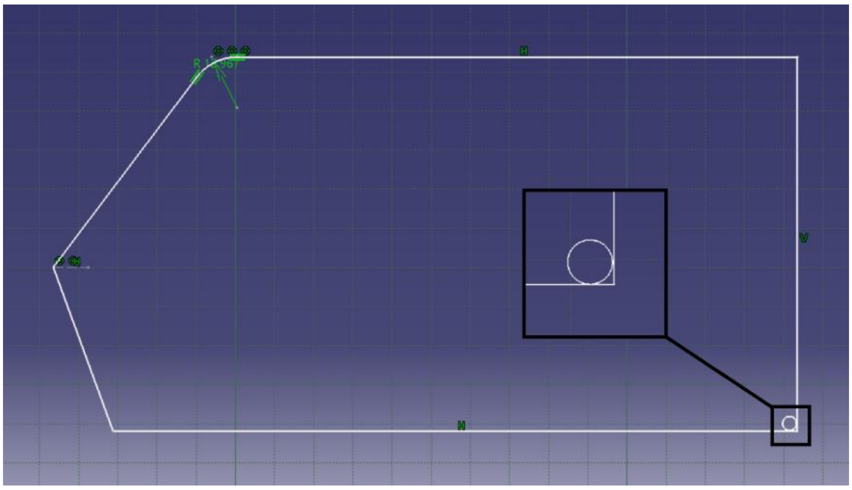


Figure 10. Bad position of parts that are so small and placed on the edge

4.3 Goals of the research:

- The first purpose of this research is offering an ergonomic design for the Plastic Storage Bin (PSB) to solve the aforementioned problems of the traditional bins that are used in assembly workstation in order to improve the productivity.
- The second purpose of this research is to study the relation between Ergonomics, Virtual Reality and Time Study as a powerful method to analyze and design of the assembly procedures in a manufacturing system.

4.4 Solution

Redesign the traditional storage bin to change several parameters to improve the workers' performance and health is a solution in order to solve the mentioned problems for the PSB. At first, tilt the bottom of the common storage bin to change its angle from 0° to around 11°, this angle value must be less than 15° and more than 10° depending on the other parameters of the storage bin (in the proposed storage bin the amount of angle is set to around 11°). The angle of the tilted bottom causes the parts gathering at the end of storage bin because of the gravity, which results in an acceptable position of hand for picking up the part based on the acceptable range from

RULA method (-15 ≤ , ≤ 15). This also makes it easier to find the parts since they all gathered at the end of the bin instead of being randomly distributed across the bin.

To solve the third problem, in the proposed bin, the inner edges are rounded off, which makes the parts stay away from the edges with some distance that helps the labor picking them up easily. Figure 11 shows 2D view of the proposed storage bin.

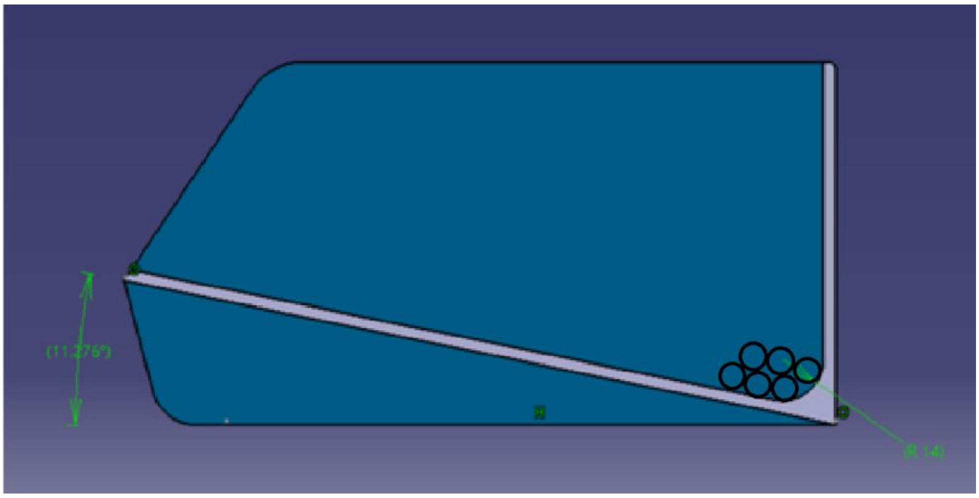


Figure 11. 2D view of the proposed storage bin

In this research, DELMIA Software simulated a workstation with utilizing a combination of Ergonomics, Time Study, and Virtual Reality. To increase the accuracy of the simulation results a program was developed to generate the distribution of the parts in the storage bin randomly. In order to perform the experiments, a database of time and fatigue values was created to store the results for each assembly scenario. The time study technique is utilized in order to generate the time values for each scenario and the fatigue values for each assembly scenario were calculated based on ergonomic analysis. After the time and amount of fatigue and WMSDs risk was calculated for different assembly scenario, all of these values were stored in the designed database for further analysis.

This research focuses on one of the steps in this assembly process, but the results can be extended to the other steps as well. The results of our research help to design an ergonomic workplace that is safe and efficient to increase the productivity.

4.5 Experiment participants:

The participants in this experimental study were 10 people, 5 men and 5 women. Acording barnes [66] for this experiment if 10 persons be tested 5 times the results will be acceptable, however, if the number of participants and tests be more the result's accuracy will be increased. The average age of the participants was 32.7 years. The range of ages was between 24 to 43 years. Their age, body weight, and stature are shown in Table 5 and Table 6. The participants did not have any previous experiences on the assembly task. They were given instructions for the assembly task and were trained for several minutes before the experiment. Since the assembly task was not a complex task, the participants with some basic knowledge could easily perform the task after two tries. They also could adjust to experimental conditions. The environment's condition factors (temperature, humidity, light and noise) were in a comfortable range and kept constant during the experiment and the participant's had worn light and comfortable clothes.

Table 5. Age, body weight, and stature of the participants

	Gender	Age (yrs)	Stature (cm)	Body weight (kg)
Participant 1	Male	40	174	82
Participant 2	Male	31	190	78.6
Participant 3	Female	43	159	78
Participant 4	Male	27	177	64
Participant 5	Male	33	184	93
Participant 6	Female	31	167	69
Participant 7	Male	32	182	81

Participant 8	Female	24	161	65
Participant 9	Female	37	174	70
Participant 10	Female	29	172	66

Table 6. The average age, body weight, and stature of the subjects

	Age (yrs)	Stature (cm)	Body weight (kg)
Male (n = 5)	32.6	181.4	79.7
Female (n = 5)	32.8	166.6	69.6

4.6 Experiment requirements

4.6.1 Standard conditions

A standard workstation environment is considered to do this experiment. This environment should contain some standard such as standard table, chair, light and etc. Figure 12 shows standard workplace.

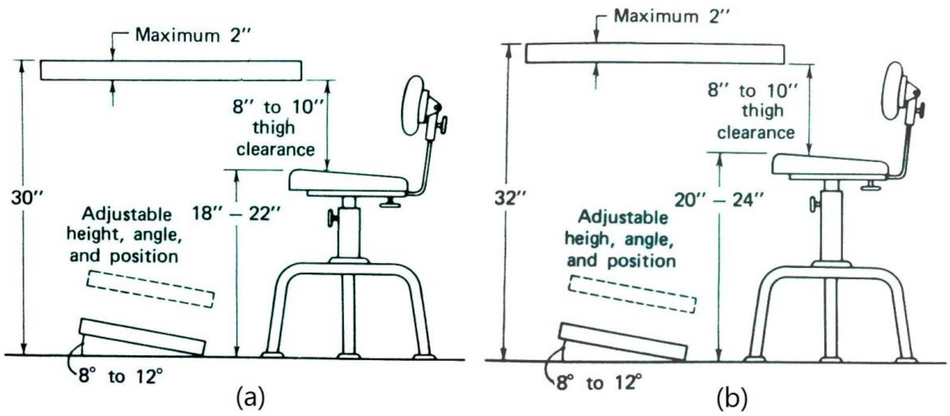


Figure 12. (a) Sitting work place for female; (b) Sitting work place for male [66]

4.6.2 Necessary sources and equipment

The part that the experiments are performed on it is a part of the pen with standard measures (Figure 13).

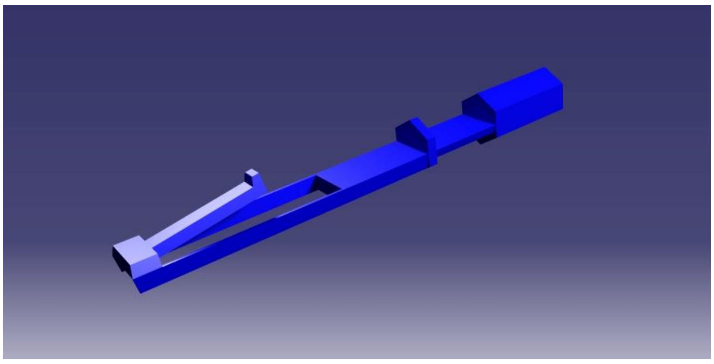


Figure 13. 3D design of the bottom of pen in DELMIA

The experiments were done on two types of bins, common and standard storage bin shown in Figure 14 and the proposed new designed bin is shown in Figure 15. In addition, a digital camera was used to record the experiments.

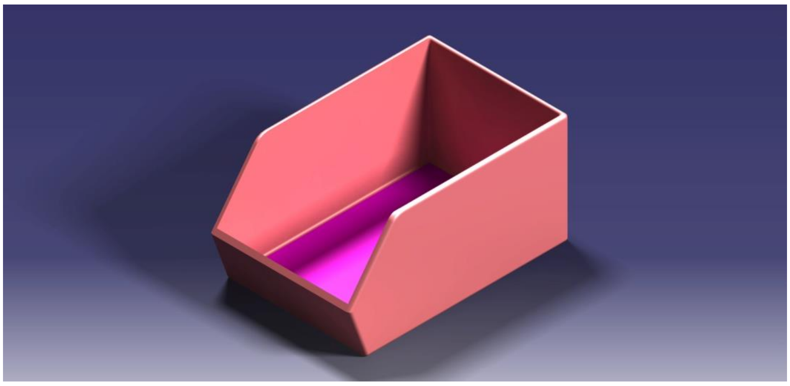


Figure 14. Standard storage bin

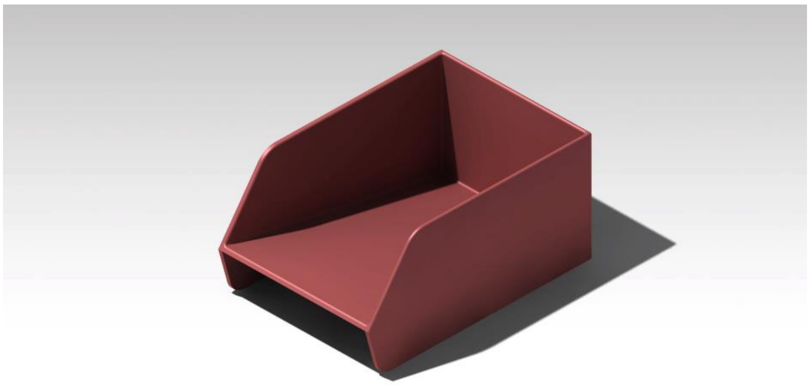


Figure 15. Proposed design for the storage bin

Two types of software are utilized to do the experiment analyzing. First, Proplanner Software (PRO TimeEstimation 2015, version: 5.2.1.0) was used for Time study and observing experiments. Second, DELMIA software was used to study the fatigue and virtual reality. The method that DELMIA Human Activity Analysis uses for analyzing worker performance is RULA for arm position assessment, with the ability to customize RULA specifications [88].

4.7 The Experimental Study

This section will be discussed the details of the ergonomically designed smart bin and utilized method that combines the Ergonomics, Time Study and Virtual Reality.

4.7.1 Experiment Steps

For all of the experiments, a database is created to store the results of the experiments for further analysis. The stored results will be used to analyze the virtual experiment and compare with the real experimental result. So create two kinds of databases are needed:

1. A database for Time Study
2. A database for Virtual Reality

4.7.1.1 Time Study Database

4.7.1.1.1 Time database related to experiment with common bin

To create the time study database for common bin (old design), the bottom of the common bin was divided into 6 segments (Figure 16). Based on these segments the participants did 6 classes of experiments. In the 1st class of the experiments, one part is placed in one of the segments that is randomly selected and the participant takes the part and put it in the buffer for assembly. When the participant's hand starts to move from the buffer for picking the part from the bin recording will be started with the video camera, and when participant puts the part in the buffer recording will be finished. These recorded times are used to calculate and study the assembly time. The participant continues this experiment until records 5 tests for each segment. After the 1^{st} class of experiments are completed, for the 2^{nd} class two parts will be placed in different segments (one part in each segment) and the participant did the same procedure. This procedure continues until 6^{th} class in which the participants should take randomly one of the parts which is placed in all of the segments.

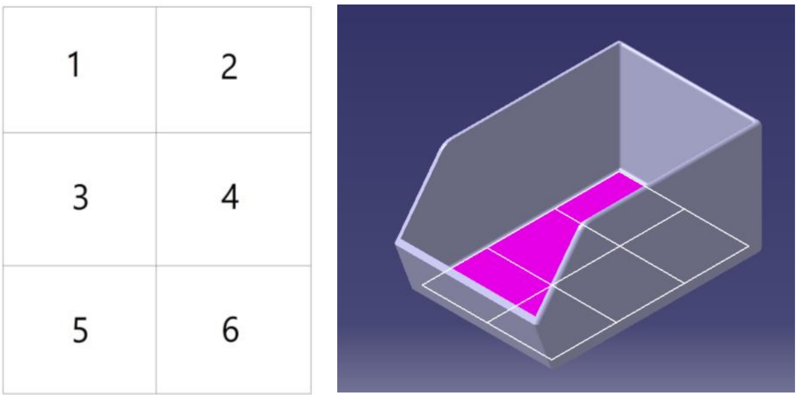


Figure 16. The partition pattern of the common bin

After recording the time for all the experiments, the records are analyzed by a time study software (Proplanner software). Proplanner calculates the process time, the segment that participant picks the part of, and specifies the pattern distribution of parts after the part is picked by the participant. This information is used to create the time study database. A part of the database is shown in Figure 17.

Data for one experiment

	Rooms	Time - Final part - Other parts
Class 1	2	T=2861 ms - Pf= (2) 2 - P1= (0) - P2= (0) - P3= (0) - P4= (0) - P5= (0) - P6= (0)
	3	T=2563 ms - Pf= (3) 3 - P1= (0) - P2= (0) - P3= (0) - P4= (0) - P5= (0) - P6= (0)
	4	T=1845 ms - Pf= (4) 6 - P1= (0) - P2= (0) - P3= (0) - P4= (0) - P5= (0) - P6= (0)
	5	T=2820 ms - Pf= (5) 6 - P1= (0) - P2= (0) - P3= (0) - P4= (0) - P5= (0) - P6= (0)
	6	T=2851 ms - Pf= (6) 6 - P1= (0) - P2= (0) - P3= (0) - P4= (0) - P5= (0) - P6= (0)
Class 2	1 , 2	T=2503 ms - Pf= (2) 2 - P1= (1) - P2= (0) - P3= (0) - P4= (0) - P5= (0) - P6= (0)
	1 , 3	T=2532 ms - Pf= (1) 1 - P1= (0) - P2= (0) - P3= (1) - P4= (0) - P5= (0) - P6= (0)
	1 , 4	T=2855 ms - Pf= (1) 1 - P1= (0) - P2= (0) - P3= (0) - P4= (1) - P5= (0) - P6= (0)
	1 , 5	T=2117 ms - Pf= (5) 5 - P1= (1) - P2= (0) - P3= (0) - P4= (0) - P5= (0) - P6= (0)
	1 , 6	T=2581 ms - Pf= (6) 6 - P1= (1) - P2= (0) - P3= (0) - P4= (0) - P5= (0) - P6= (0)
	2 , 3	T=3191 ms - Pf= (3) 3 - P1= (0) - P2= (1) - P3= (0) - P4= (0) - P5= (0) - P6= (0)
	2 , 4	T=2299 ms - Pf= (2) 2 - P1= (0) - P2= (0) - P3= (0) - P4= (1) - P5= (0) - P6= (0)
	2 , 5	T=2539 ms - Pf= (5) 5 - P1= (0) - P2= (1) - P3= (0) - P4= (0) - P5= (0) - P6= (0)
	2 , 6	T= 2530ms - Pf= (2) 2 - P1= (0) - P2= (0) - P3= (0) - P4= (0) - P5= (0) - P6= (1)
	3 , 4	T=2733 ms - Pf= (3) 3 - P1= (0) - P2= (0) - P3= (0) - P4= (1) - P5= (0) - P6= (0)
	3 , 5	T=2098 ms - Pf= (5) 5 - P1= (0) - P2= (0) - P3= (1) - P4= (0) - P5= (0) - P6= (0)
	3 , 6	T=2100 ms - Pf= (3) 3 - P1= (0) - P2= (0) - P3= (0) - P4= (0) - P5= (0) - P6= (1)
	4 , 5	T=2724 ms - Pf= (5) 5 - P1= (0) - P2= (0) - P3= (0) - P4= (1) - P5= (0) - P6= (0)
	4 , 6	T=2201 ms - Pf= (6) 6 - P1= (0) - P2= (0) - P3= (0) - P4= (1) - P5= (0) - P6= (0)
	5 , 6	T=2915 ms - Pf= (6) 6 - P1= (0) - P2= (0) - P3= (1) - P4= (0) - P5= (0) - P6= (0)
Class 3	1 , 2 , 3	T=3100 ms - Pf= (2) 4 - P1= (0) - P2= (1) - P3= (0) - P4= (0) - P5= (1) - P6= (0)
	1 , 2 , 4	T=2031 ms - Pf= (4) 4 - P1= (1) - P2= (1) - P3= (0) - P4= (0) - P5= (0) - P6= (0)
	1 , 2 , 5	T=2414 ms - Pf= (1) 3 - P1= (0) - P2= (1) - P3= (0) - P4= (0) - P5= (1) - P6= (0)

Figure 17. Structure of time database for one experiment

As the Figure 17 shows, the database has all the information that needs to calculate the processing time. The recorded information in the database is categorized to four different data.

The first column records the segments that are filled with a part in different classes. For example, (1, 2, 3) in class 3 means, there are three parts; one part in segment 1, one part in segment 2 and one part in segment 3.

The initial posture of the participant hand is assumed over the assembly buffer. *T* is the time that shows how long it takes for participants to move his/her hand to pick the part from the bin and put it in the assembly buffer. The measurement unit for this time is millisecond. For instance, for (1, 2, 3) the time is 3100 milliseconds.

P_f contains the information about the part that is chosen and taken by participants. P_f illustrating two values. The first one is, specifies the segment which participant chooses a part for taking; the second value is, specifies the segment which the part is picked by participant (because sometimes participant move his/her hand after choosing the part and pick it up from different segment). For example, for (1, 2, 3) there is P_f = 2 4 and means, in that experiment participant choose a part from segment 2 but move it to segment 4 and pick it up.

K1 to *K6* are the number of parts that occupied each segment. For example, for (1, 2, 3) the K1=K3=K4=K6=0 and K2=K5=1. It means that after this experiment, there are not any parts in segments 1, 3, 4, 6 and there is a part in segment 2 and 5.

The complete results for the experiments of class 1 are listed in appendix A.

4.7.1.1.2 Time database related to experiment with proposed bin

To create the time database for the proposed bin, the bottom of the proposed bin is divided into three segments as shown in Figure 18. Because of the gravity (bottom of the bin has 13° incline) parts are normally being placed in just segments 1 and 2. Based on this division, there are two classes of experiments that the participant must perform. In the 1st class of experiments, one part is randomly placed in one of the segments. The participant takes the part and put it in the buffer for assembly and this procedure will be recorded by video camera. The calculation and time study procedure are in the same manner as is explain for common bin. The participant continues this experiment five times for each segment. For the 2nd class of experiments, the participant puts one part in segment 1 and 2 and the participant must take one of them and put it in the buffer for assembly.

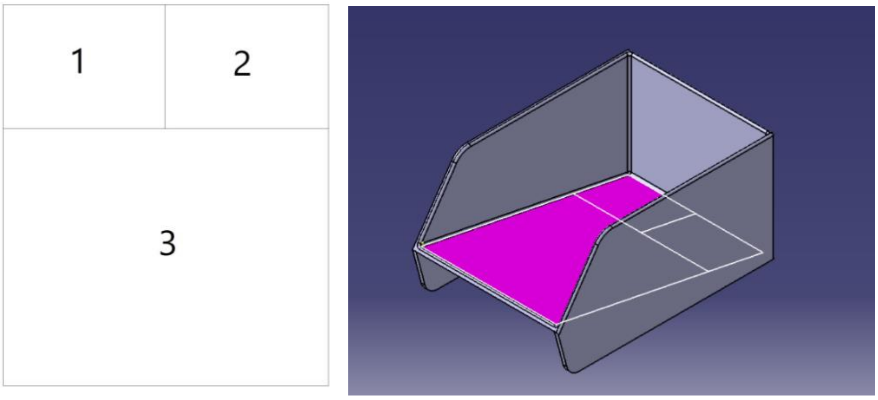


Figure 18. Partition pattern of the proposed bin

4.7.1.2 Database related to the experiment with virtual reality software

To create the database for fatigue values, the labor's hand is simulated in DELMIA Software (ergonomic module), when s/he picks a part from different segments in the storage bin. As it was explained before, the bottom of the common bin is divided into six segments and the bottom of the proposed bin is divided into three segments. The position of the hand is simulated for taking the parts from every segment. The position of the labor's hand in simulation is based on the position when s/he picks up the parts of each segment in real experiment. For instance, Figure 19 shows the simulation of hand for picking up a part from segment 1.

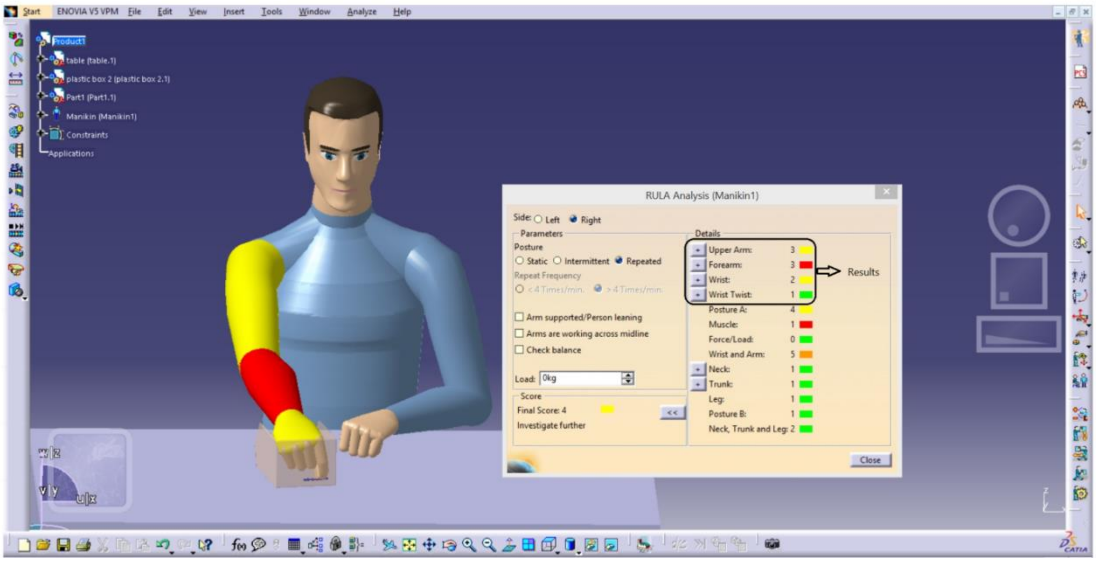


Figure 19. Simulation of a hand worker position and analysis for segment 1

After simulating the position of the labor's hand in DELMIA, his/her hand's movement and posture will be analyzed by the software. DELMIA generates a lot of information and results, but the useful results for this research are shown in Figure 19. For calculation of the fatigue value, different colors specified (Green = 0, Yellow = 1, Orange = 2 and Red = 3).

The assigned number of each color, is proportional to the amount of fatigue it happens in the hand. The higher number means the higher fatigue. Now for calculation of the fatigue value for each posture the color values will be added together as the final result. For example, in below, there is a sample of calculation of fatigue value that shown in Figure 19:

Final result = yellow + green + red + yellow = 1 + 0 + 3 + 1 = 5

Therefore, the final score for this posture is 5. Figure 20 determines the positions of the labor's hand for the common storage bin. These points cover all the hand positions that may happen for picking up and moving the parts. In addition, three different human-labor hand postures are considered when s/he tried to take a part of the segment. Posture 1 is to take the part of the right or left side of the segment, posture 2 is to take the part from top or bottom side of the segment and posture 3 is to take the part from the middle of the segment.

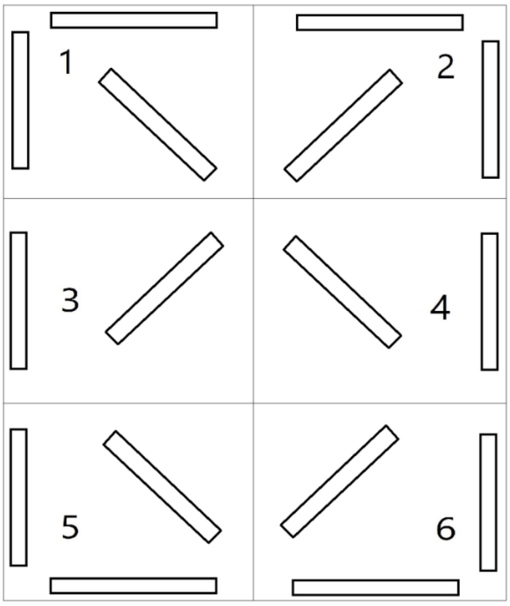


Figure 20. Pattern of different parts positions in every segment in normal bin

Same way is applied for the proposed bin to calculate the fatigue value, but just for two segments (segment 1 and 2). The complete result of fatigue value database for one person is recorded in Appendix C.

4.7.1.3 Part distribution program

After creation of the database, random distribution of the parts in the bin is needed, so a C++ program was written to distribute parts in the different segments of the bin randomly. The complete program is mentioned in Appendix D.

4.7.1.4 Calculation of the time results

In order to calculate the results of the simulation, a labor takes a part of the storage bin and assembles it. After the time and fatigue databases are created the parts are distributed in the virtual storage bin, a part will be selected to be picked up and assembled in the virtual environment. In addition, the time and fatigue values will be calculated and recorded in the database.

When the software program distributes the parts randomly, it shows the number of the parts in each segment of the storage bin. For instance, Figure 21 indicates the results for distribution of 30 parts, which are randomly distributed with the program.

Figure 21. The result that software program calculates for distribution 30 parts (A1 to A6 shows different segments in the common storage bin)

4.7.1.5 Calculation of the final time for picking up parts

As the Figure 21 shows, all of the six segments in a common bin filled with parts. Thus, from common bin time database, class 6 is chosen. In class 6, one of the experiments is chosen randomly and the time of this experiment is selected as the final time. After picking up the part, the time database determines the pattern of the remaining parts in the bin. For example, a result of class 6 is chosen randomly and the result will be calculated in the following:

- T=1677 ms , Kf= 4 4 , K1= 1 , K2= 1 , K3= 2 , K4= 0 , K5= 0 , K6= 1

  Final Time = 1677 ms
  Segment 1 = 8
  Segment 2 = 3
  Segment 3 = 7
  Segment 4 = 4
  Segment 5 = 3
  Segment 6 = 4

Now there is a new pattern of distribution in the bin. The way above is done until one of the segments is empty. After that, the class of database is changed to class 5 and randomly choose another experiment. This method is continued until all the parts are picked up from the bin and each time adds up to the final time, so when all the parts are taken out of the bin, the total final time is calculated.

4.7.1.6 Calculate the fatigue value

In order to calculate the fatigue value, each time, a part is chosen for picking up from a special segment; the fatigue value for the hand posture for that specific segment is chosen from the fatigue value database and added to the Final Fatigue Value. This procedure is based on random selection of three or two different postures of labor hand to take the part of the segment (three posture for segments 1, 2, 5, 6 and two postures for segments 3, 4). This procedure is repeated until the fatigue value for all parts is calculated.

At the end, there are total final time and total final fatigue value for all the parts. These values are used to compare the results of the common storage bin with the proposed storage bin and compare them with the real experiments to calculate the amount of errors. Figure 22 shows the complete methodology in a diagram.

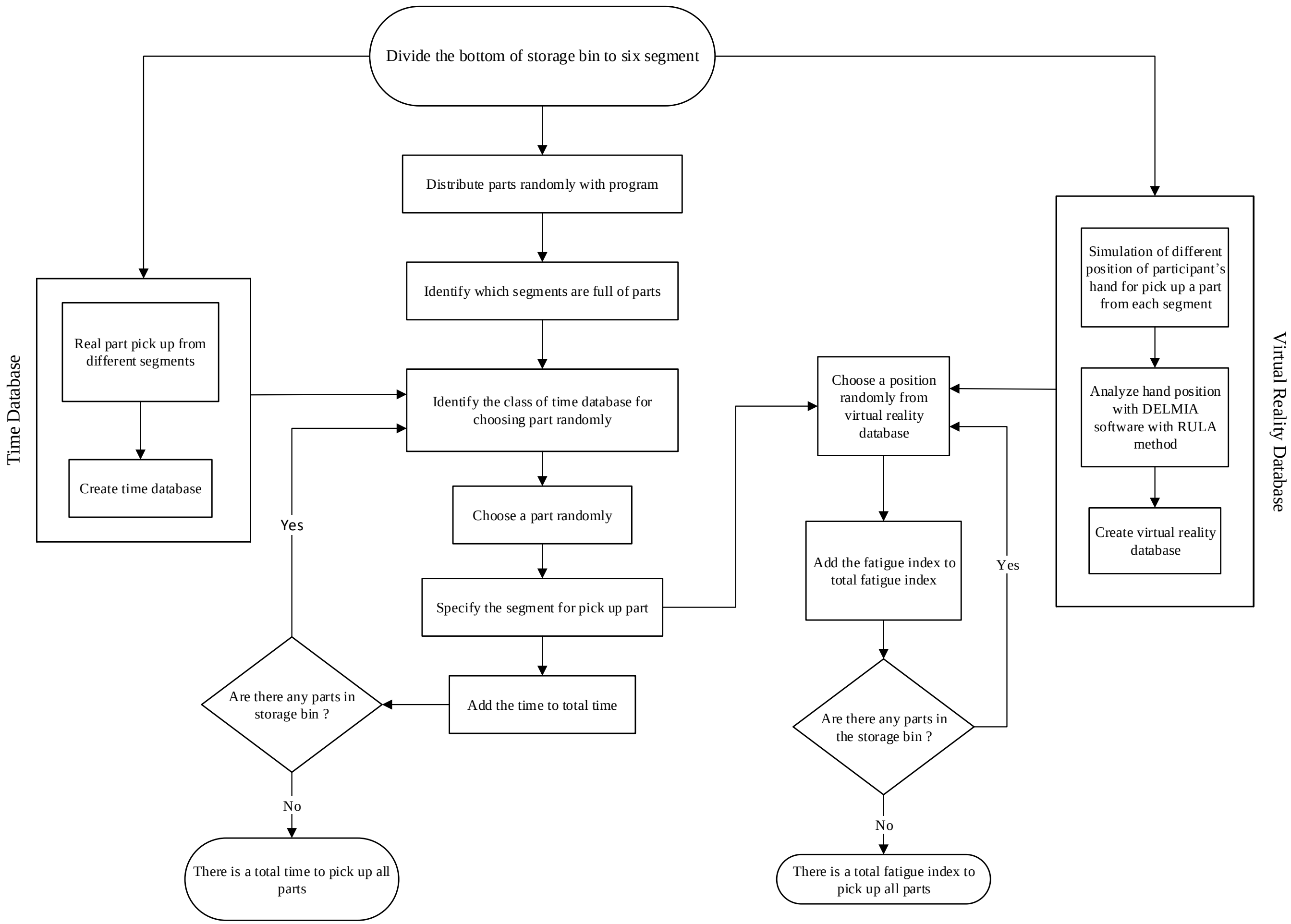


Figure 22. Applied methodology scheme for evaluating time and fatigue index

Chapter 5

RESULTS AND DISCUSSION

This chapter evaluates the results that are obtained from taking 30 parts from common and proposed storage bin, and discusses, how much the new proposed storage bin can decrease the time production and fatigue rather than common storage bin, and how it solves the mentioned problems in the methodology section.

5.1 Calculate the results for assembly time and fatigue value

In the calculation of the results, the distribution pattern of 30 parts (mentioned in chapter 3) is used as an example, and follows that procedure to calculate the final time and final fatigue value for other experiments performed on common and proposed storage bin. The distribution is:

A1 = 8 - A2 = 3 - A3 = 6 - A4 = 5 - A5 = 4 - A6 = 4

All segments are filled with parts, so it is going to be placed in class 6:

Random number: 3 (experiment number 3 is chosen out of five experiments)

T=1677 ms , Kf= 4 4 , K1= 1 , K2= 1 , K3= 2 , K4= 0 , K5= 0 , K6= 1

Final Time = 1677 ms

Final fatigue value = 6 (this fatigue value is randomly selected out of two possible postures for segment 4)

A1 = 8 , A2 = 3 , A3 = 7 , A4 = 4 , A5 = 3 , A6 = 4 (new distribution after taking part from segment 4)

Random number: 2

T=1738 ms , Kf= 4 4 , K1= 1 , K2= 1 , K3= 1 , K4= 0 , K5= 1 , K6= 1

Final Time = 1677 +1738 = 3415 ms

Final fatigue value = 6 + 6 =12

A1 = 8 , A2 = 3 , A3 = 7 , A4 = 3 , A5 = 3 , A6 = 4

The rest of this procedure is mentioned in Appendix E.

The Final Time for picking up 30 parts distributed in the common storage bin in the virtual environment is 62386 ms; and the time for picking up 30 parts when the parts are distributed in a common storage bin in the real environment is 65291 ms. The distribution of parts in the real storage bin is the same as the distribution of parts in the virtual reality). The final fatigue value of this experiment is 169. These experiments are repeated for different distributions of 30 parts and the results are shown in Table 7.

Table 7. The results of the experiments on common storage bin for 10-time experiment

Number of Experiment	**Time for Virtual Distribution (ms)**	**Time for Real Distribution (ms)**	**Fatigue Value**
1	62386	65291	169
2	65116	68419	176
3	73342	69832	170
4	62078	64611	162
5	68199	68648	184
6	65154	63132	164
7	64877	65192	172
8	67211	64909	159
9	67954	70015	166
10	65730	67449	183

The results of the experiments for the proposed storage bin are indicated in table 8.

Table 8. The results for experiment on proposed storage bin for 10-time experiment

Number of Experiment	Time for Virtual Distribution (ms)	Time for Real Distribution (ms)	Fatigue Value
1	53707	55654	96
2	54678	55945	109
3	53326	54984	89
4	57555	59585	91
5	55645	54723	112
6	58456	57465	99
7	52221	56177	93
8	55549	53168	105
9	51125	51448	97
10	56659	52843	89

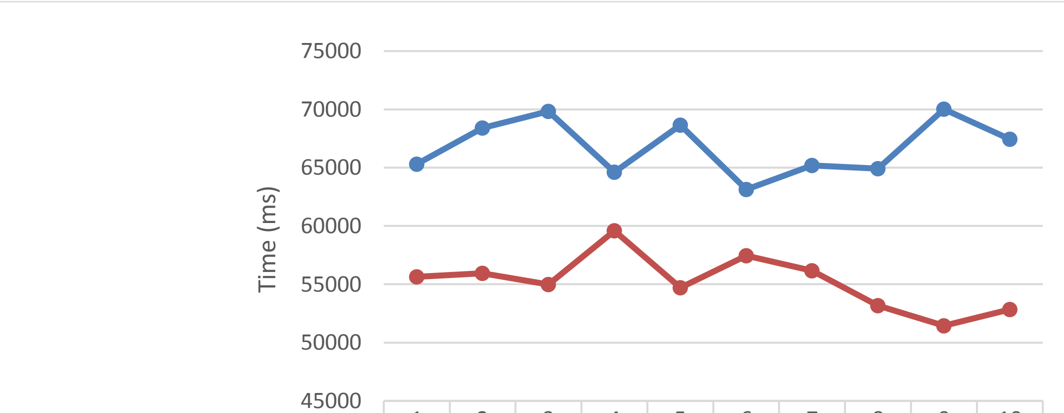
5.2 Discussion

The primary aim of this research was the improvement of the old standard storage bin that is used commonly in workstations. The standard common storage bin has two following major problems because of its design, especially when it is used in a long period assembly process.

1. Because of the shape of the common storage bin, finding and picking the parts takes more time when there are a few parts in the storage bin. The amount of these wasted times is significant for long period assembly processes.
2. When a labor in an assembly task picks the parts from a standard bin frequently for a long period, s/he feels fatigued because of the shape of the storage bin, which forms a bad position of the wrist, forearm, and upper arm after duration. If this repeats for a long period of working days, s/he faces Work-related Musculoskeletal Disorders (WSMD) in his/her hands.

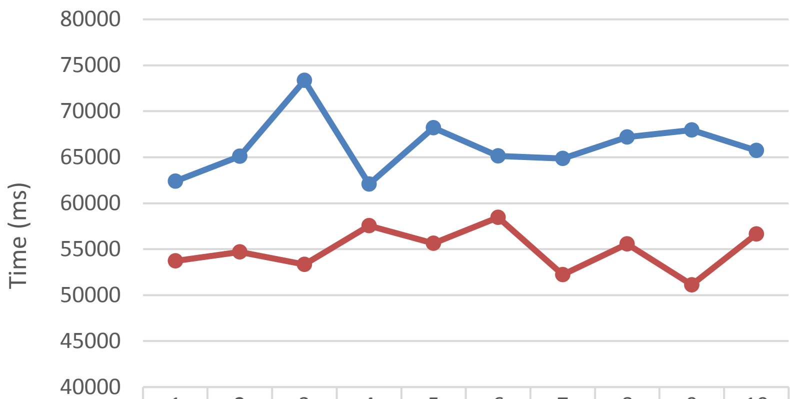
In order to solve these problems, a new ergonomic shape design was proposed for the storage bin, and the experiments showed that this new design for storage bin can solve and mitigate the aforementioned problems by decreasing the assembly time and the fatigue.

The Figure 23 and 24 show a comparison between the time to complete an assembly task using a common bin and the time using a proposed bin. The comparisons are performed for both real and virtual reality workstations. As these diagrams show the proposed new design for the storage bin can improve the assembly time around 11.5 seconds. At first glance, the saved time is not a big amount of time and does not look significant, but when this time is calculated for a long period assembly procedure, a huge amount of improvement in task time and hence a huge increase in productivity are found.



	1	2	3	4	5	6	7	8	9	10
Time for common sorage bin (ms)	65291	68419	69832	64611	68648	63132	65192	64909	70015	67449
Time for proposed storage bin (ms)	55654	55945	54984	59585	54723	57465	56177	53168	51448	52843

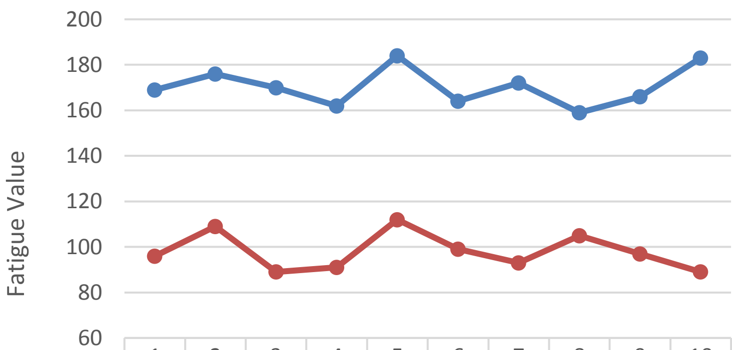
Figure 23. Comparison time of assembly for Real environment experiments between common and proposed bins



	1	2	3	4	5	6	7	8	9	10
Time for common storage bin (ms)	62386	65116	73342	62078	68199	65154	64877	67211	67954	65730
Time for proposed storage bin (ms)	53707	54678	53326	57555	55645	58456	52221	55549	51125	56659

Figure 24. Comparison time of assembly for virtual reality experiments between common and proposed bin

Regarding the fatigue that happens in the wrist, forearm, and upper arm, the Figure 25 compares the fatigue values resulted from the experiments on the proposed and common storage bin. As the Diagram shows, the average fatigue value in the proposed storage bin is reduced to around 72.5 units which is almost half of the average fatigue value in the common storage bin. Based on these results, it can be concluded that the overall posture of the worker's hand improves when s/he is taking the parts from a bin with the new ergonomic design.



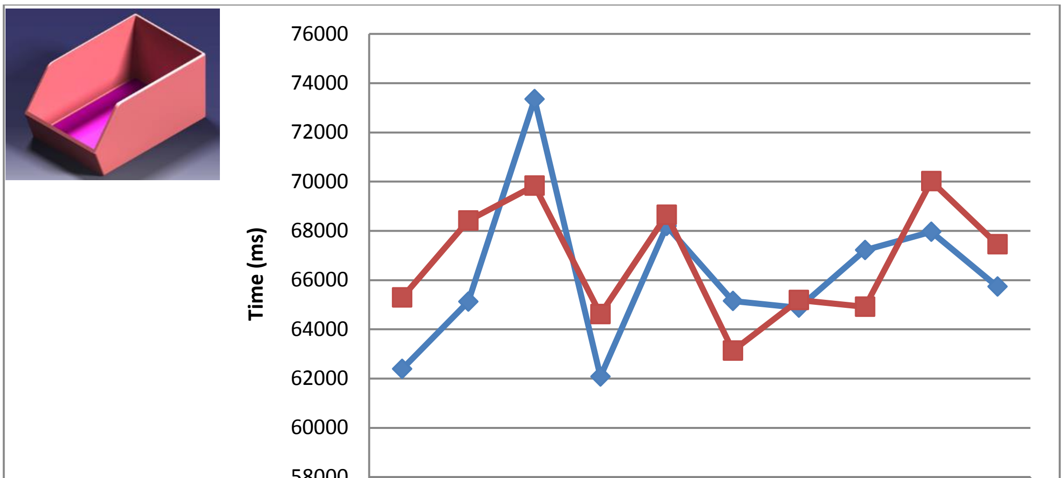
	1	2	3	4	5	6	7	8	9	10
Fatigue value for old bin	169	176	170	162	184	164	172	159	166	183
Fatigue Value for new bin	96	109	89	91	112	99	93	105	97	89

Figure 25. Comparison fatigue value between common and proposed bin

The improvement in the fatigue values is important, since it affects the productivity in long periods of the assembly process. Based on the presented results of this research and case study, it can be concluded that using the proposed ergonomic storage bin decreases the risk of WMSDs during long period assembly processes.

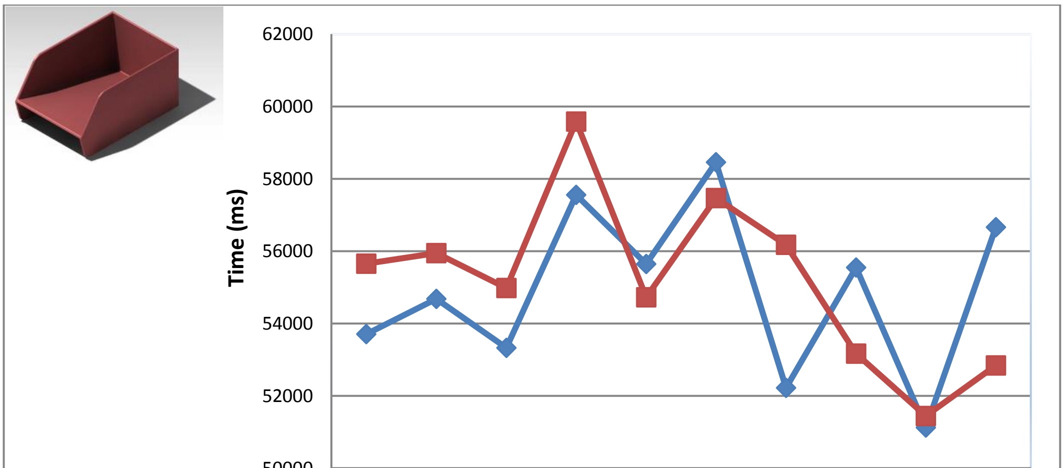
The second goal of this research was to create a methodology for analysis of the assembly tasks and processes based on a combination of Ergonomics, Time study, and Virtual reality. The Figure 26 and 27 shows the comparison of the time results of the experiments simulated in a virtual reality environment with the experiments performed in a real environment for common and proposed storage bins. The error of the VR method in calculating the time is around 5.5 seconds for common storage bin and around 3 seconds for the proposed storage bin. This means that our proposed method can estimate the time for the common storage bin with less than 8% error and estimate the time for the proposed storage bin with less than 5% error.

The amount of fatigue value in this case study is shown and compared in Figure 25. The comparison shows that the average fatigue value for the proposed storage bin is 72.5 units less than the average fatigue value for the common storage bin, it means after a long period of an assembly process, a worker that uses a common storage bin feels tired 42.5% more than a worker that has used the proposed ergonomic storage bin, and the percentage of the risk of WMSDs for the worker that uses common bin is 42.5% more than the worker that has used the proposed bin.



	1	2	3	4	5	6	7	8	9	10
Time for Virtual Experiment (ms)	62386	65116	73342	62078	68199	65154	64877	67211	67954	65730
Time for Real Experiment (ms)	65291	68419	69832	64611	68648	63132	65192	64909	70015	67449

Figure 26. Comparison time of assembly between virtual and real experiments on a common bin



	1	2	3	4	5	6	7	8	9	10
Time for Virtual Experiment	53707	54678	53326	57555	55645	58456	52221	55549	51125	56659
Time for Real Experiment	55654	55945	54984	59585	54723	57465	56177	53168	51448	52843

Figure 27. Comparison time of assembly between virtual and real experiments on a proposed bin

Chapter 6

CONCLUSION

This chapter summarizes the discussion of this study and discusses the possible future directions of the study.

6.1 Conclusion

The two following issues are studied in this research:

1. Study of an analysis method based on a combination of Ergonomics, Time Study, and Virtual Reality to calculate the time of assembly and calculate the percentage of fatigue and WMSDs risk after a long time repetitive assembly process.
2. The second contribution of the proposed work in this research is a proposal for the redesigned of the common standard storage bin to solve the several problems that it has, when is used in a long period repetitive assembly process.

As a summary of the work in this study, at first, a new analysis method was created by making a connection between Ergonomics, Time Study, and Virtual Reality. In addition, a new design for a storage bin was proposed, which solves the problems with the old standard storage bins. The new proposed analysis method was applied to analyze how the use of the new storage bin affects the productivity of the assembly line. The analysis results indicated that the proposed storage bin could solve the problems of the common storage bin in lengthy assembly processes. In addition, this analysis showed that the accuracy of our proposed method based on virtual reality is acceptable, and the method can be used in place of expensive experiments in the real environment.

The comparison of the obtained results from the application of the proposed Virtual Reality-based method to the analysis of the new storage bin, with the results of the real performed experiments in the real assembly environment, showed the proposed VR-based method could calculate the results with less than 8% error. It also showed the time for picking 30 parts from the proposed ergonomic storage bin is around 11.5 seconds less than a common storage bin, and if the workers use the proposed ergonomic storage bin the risk of the fatigue and WMSDs would be decreased by 42.5% compared to use of the common standard storage bin.

6.2 Future works

For the future of this study, several directions should be considered:

- In this research, the bottom of the storage bin divided into 6 segments for the common storage bin and 3 segments for the proposed storage bin. To increase the accuracy of the experiments and results, the bins can be divided into more segments with interstitial forms.
- This research studied the assembly process for 30 parts in the storage bin. This situation happens when there are a few parts in the storage bin. As a future work, the proposed method can be applied in cases with storage bin full of parts, and calculate the time and fatigue values to study the productivity more accurately.
- Another possible future work is regarding the fatigue analysis. In this research, fatigue values were calculated as an index of the percentage of the fatigue effect that happens in the worker's hand during a long time assembly

task. However, if this index were studied biomechanically, the amount that the fatigue affects the productivity can be calculated based on the fatigue value and based on this fatigue value can be measured how much the productivity increases or decreases.

- In this research, the proposed method was studied in the assembly process of one of the parts of the studies case (A pen with 4 parts). As a future work, the results can be extended to study the method for a complete assembly process of the pen with assembling all the parts and study the accurate performance of the method for a full assembly process.

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APPENDIX

Appendix A: The result for Virtual Common Storage Bin for one participant

Class 1

	1	2	3	4	5
1	T=3005 ms Kf= 1 3 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=3170 ms Kf= 1 1 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2418 ms Kf= 1 1 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=3564 ms Kf= 1 1 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2816 ms Kf= 1 1 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0
2	T=2861 ms Kf= 2 2 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=4170 ms Kf= 2 2 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=1993 ms Kf= 2 2 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2219 ms Kf= 2 4 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2537 ms Kf= 2 2 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0
3	T=2563 ms Kf= 3 3 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=3038 ms Kf= 3 5 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2322 ms Kf= 3 3 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=1870 ms Kf= 3 3 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=1907 ms Kf= 3 3 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0
4	T=1845 ms Kf= 4 6 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2948 ms Kf= 4 6 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2071 ms Kf= 4 4 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2563 ms Kf= 4 4 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=3008 ms Kf= 4 5 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0
5	T=2820 ms Kf= 5 6 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=3440 ms Kf= 5 5 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2246 ms Kf= 5 5 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2379 ms Kf= 5 5 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=3099 ms Kf= 5 5 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0
6	T=2851 ms Kf= 6 6 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=3380 ms Kf= 6 6 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=5717 ms Kf= 6 6 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2563 ms Kf= 6 4 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=4103 ms Kf= 6 6 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0

Class 2

	1	2	3	4	5
1 , 2	T=2503 ms Kf= 2 2 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2876 ms Kf= 1 1 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2296 ms Kf= 2 4 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2704 ms Kf= 2 2 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=3101 ms Kf= 1 3 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0
1 , 3	T=2532 ms Kf= 1 1 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2388 ms Kf= 3 3 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2275 ms Kf= 3 3 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2344 ms Kf= 3 3 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2541 ms Kf= 1 1 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1
1 , 4	T=2855 ms Kf= 1 1 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=2689 ms Kf= 1 1 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=1992 ms Kf= 4 3 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2554 ms Kf= 1 3 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=3094 ms Kf= 4 5 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0
1 , 5	T=2117 ms Pf= 5 5 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2384 ms Pf= 5 5 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=3259 ms Pf= 5 5 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2139 ms Pf= 1 3 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0	T= 2519ms Pf= 1 2 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0
1 , 6	T=2581 ms Pf= 6 6 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2477 ms Pf= 6 6 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=3052 ms Pf= 1 3 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2705 ms Pf= 6 6 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2092 ms Pf= 1 1 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1
2 , 3	T=3191 ms Kf= 3 3 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=3404 ms Kf= 2 4 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=3578 ms Kf= 2 4 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2855 ms Kf= 3 1 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2108 ms Kf= 2 2 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 1
2 , 4	T=2299 ms Kf= 2 2 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=3075 ms Kf= 2 2 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=4072 ms Kf= 4 5 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2133 ms Kf= 2 2 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=2209 ms Kf= 4 2 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0
2 , 5	T=2539 ms Kf= 5 5 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2000 ms Kf= 5 5 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2643 ms Kf= 5 5 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2341 ms Kf= 5 3 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=3061 ms Kf= 2 2 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0

Class 2

2 , 6	T= 2530 ms Kf= 2 2 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2116 ms Kf= 6 6 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2680 ms Kf= 6 6 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2553 ms Kf= 6 6 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2113 ms Kf= 2 3 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1
3 , 4	T=2733 ms Kf= 3 3 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=3023 ms Kf= 3 3 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2756 ms Kf= 4 4 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2711 ms Kf= 3 3 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=1893 ms Kf= 4 4 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0
3 , 5	T=2098 ms Kf= 5 5 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2362 ms Kf= 5 6 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2189 ms Kf= 5 5 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2389 ms Kf= 3 5 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=2844 ms Kf= 5 6 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0
3 , 6	T=2100 ms Kf= 3 3 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=1845 ms Pf= 6 6 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2594 ms Pf= 3 3 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2309 ms Pf= 3 3 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2127 ms Pf= 6 6 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0
4 , 5	T=2724 ms Pf= 5 5 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=2509 ms Pf= 5 5 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=2495 ms Pf= 4 4 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=2579 ms Pf= 5 6 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=3578 ms Pf= 4 2 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0
4 , 6	T=2201 ms Pf= 6 6 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=2528 ms Pf= 4 6 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2120 ms Pf= 6 6 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=2855 ms Pf= 4 4 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2531 ms Pf= 4 2 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1
5 , 6	T=2915 ms Pf= 6 6 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=1882 ms Pf= 5 5 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2882 ms Pf= 6 6 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= (0	T=3070 ms Pf= 5 6 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2483 ms Pf= 5 5 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1

Class 3

	1	2	3	4	5
1 , 2 , 3	T=3100 ms Pf= 2 4 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=1856 ms Pf= 3 5 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2074 ms Pf= 3 3 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2216 ms Pf= 2 4 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2216 ms Pf= 2 4 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0
1 , 2 , 4	T=2031 ms Pf= 4 4 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2745 ms Pf= 1 3 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=2866 ms Pf= 4 4 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=1974 ms Pf= 2 2 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 1	T=3414 ms Pf= 2 4 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1
1 , 2 , 5	T=2414 ms Pf= 1 3 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=2150 ms Pf= 5 5 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2662 ms Pf= 5 5 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2012 ms Pf= 5 5 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=1918 ms Pf= 2 2 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0
1 , 2 , 6	T=2330 ms Pf= 6 6 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=2309 ms Pf= 2 4 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2034 ms Pf= 2 4 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2731 ms Pf= 1 3 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2617 ms Pf= 1 1 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 1
1 , 3 , 4	T=2290 ms Pf= 4 3 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2005 ms Pf= 3 3 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=2082 ms Pf= 3 3 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=1888 ms Pf= 3 5 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=3002 ms Pf= 1 2 K1= 0 - K2= 0 - K3= 1 K4= 1 - K5= 0 - K6= 0
1 , 3 , 5	T=3384 ms Pf= 5 5 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=1835 ms Pf= 3 3 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=2506 ms Pf= 5 3 K1= 2 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=1938 ms Pf= 1 3 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 1 - K6= 0	T=2116 ms Pf= 3 4 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0
1 , 3 , 6	T=1885 ms Pf= 3 3 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=3064 ms Pf= 6 6 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=3233 ms Pf= 6 6 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2016 ms Pf= 3 4 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2315 ms Pf= 6 6 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 0
1 , 4 , 5	T=2564 ms Pf= 5 3 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=3140 ms Pf= 5 5 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=2476 ms Pf= 1 1 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 0	T=2010 ms Pf= 5 6 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=1796 ms Pf= 4 4 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0
1 , 4 , 6	T=2021 ms Pf= 4 6 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=1950 ms Pf= 6 6 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=1697 ms Pf= 4 4 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2221 ms Pf= 6 6 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=2604 ms Pf= 1 3 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 1

Class 3

1 , 5 , 6	T=2008 ms Pf= 5 6 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=2401 ms Pf= 6 6 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=1703 ms Pf= 6 6 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=1865 ms Pf= 1 2 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 1	T=2236 ms Pf= 6 5 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0
2 , 3 , 4	T=1847 ms Pf= 4 4 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2161 ms Pf= 4 4 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2316 ms Pf= 2 4 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 1	T=2911 ms Pf= 3 3 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=1975 ms Pf= 4 4 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 0
2 , 3 , 5	T=2356 ms Pf= 5 5 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2463 ms Pf= 3 3 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=3714 ms Pf= 2 2 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 1 - K6= 0	T=2190 ms Pf= 3 4 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=2676 ms Pf= 3 3 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 0
2 , 3 , 6	T=2710 ms Pf= 6 6 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=1874 ms Pf= 2 2 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 1	T=2300 ms Pf= 6 6 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2113 ms Pf= 2 4 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 1	T=2082 ms Pf= 3 1 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 1
2 , 4 , 5	T=2751 ms Pf= 5 5 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=1862 ms Pf= 5 5 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=1944 ms Pf= 4 4 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=2018 ms Pf= 2 2 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 0	T=1739 ms Pf= 5 5 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 0
2 , 4 , 6	T=1635 ms Pf= 6 6 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=1759 ms Pf= 6 6 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=2246 ms Pf= 6 6 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=2021 ms Pf= 4 6 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=1792 ms Pf= 6 6 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 0
2 , 5 , 6	T=2141 ms Pf= 2 2 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 1	T=3293 ms Pf= 6 6 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=2356 ms Pf= 6 6 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=2023 ms Pf= 5 6 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2814 ms Pf= 2 2 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 1
3 , 4 , 5	T=2385 ms Pf= 5 5 K1= 0 - K2= 0 - K3= 1 K4= 1 - K5= 0 - K6= 0	T=2585 ms Pf= 3 4 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 0	T=2990 ms Pf= 4 6 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 1 - K6= 0	T=3203 ms Pf= 5 5 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 1	T=1987 ms Pf= 4 4 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 1 - K6= 0
3 , 4 , 6	T=2616 ms Pf= 3 3 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 1	T=2186 ms Pf= 6 6 K1= 0 - K2= 0 - K3= 1 K4= 1 - K5= 0 - K6= 0	T=1762 ms Pf= 3 4 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 1	T=1848 ms Pf= 3 4 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 2	T=1705 ms Pf= 6 4 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 0

Class 3

3 , 5 , 6	T=2072 ms Pf= 5 5 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 1	T=3028 ms Pf= 3 3 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 1	T=2136 ms Pf= 3 4 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 1	T=1958 ms Pf= 3 5 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 0 - K6= 2	T=2363 ms Pf= 6 6 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 1 - K6= 0
4 , 5 , 6	T=1871 ms Pf= 5 6 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 1	T=2272 ms Pf= 5 5 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 1	T=4052 ms Pf= 6 6 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 0	T=2064 ms Pf= 4 4 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 1	T=1905 ms Pf= 4 6 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 2 - K6= 0

Class 4

	1	2	3	4	5
1 , 2 , 3 , 4	T=2424 ms Pf= 3 3 K1= 1 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=1696 ms Pf= 4 4 K1= 1 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=1744 ms Pf= 4 4 K1= 1 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=1957 ms Pf= 2 4 K1= 1 - K2= 0 - K3= 0 K4= 2 - K5= 0 - K6= 0	T=2081 ms Pf= 3 5 K1= 1 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 0
1 , 2 , 3 , 5	T=2284 ms Pf= 5 5 K1= 1 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2038 ms Pf= 5 3 K1= 2 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 0	T=1997 ms Pf= 2 4 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 0	T=1777 ms Pf= 1 1 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 1 - K6= 0	T=3034 ms Pf= 5 3 K1= 1 - K2= 2 - K3= 0 K4= 0 - K5= 0 - K6= 0
1 , 2 , 3 , 6	T=2432 ms Pf= 2 2 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 1	T=1824 ms Pf= 3 3 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2236 ms Pf= 3 3 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=2096 ms Pf= 6 6 K1= 1 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 0	T=2034 ms Pf= 3 5 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 1
1 , 2 , 4 , 5	T=2823 ms Pf= 5 5 K1= 1 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=1853 ms Pf= 4 4 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=1930 ms Pf= 4 4 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 0	T=2176 ms Pf= 2 2 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 0	T=1705 ms Pf= 4 2 K1= 2 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 0
1 , 2 , 4 , 6	T=2894 ms Pf= 6 6 K1= 1 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 0	T=1789 ms Pf= 4 4 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 1	T=1957 ms Pf= 1 2 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 1	T=2203 ms Pf= 1 1 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 1	T=1973 ms Pf= 2 1 K1= 0 - K2= 0 - K3= 1 K4= 1 - K5= 0 - K6= 1
1 , 2 , 5 , 6	T=1763 ms P_f= 2 4 K1 = 1 - K2 = 0 - K3 = 0 K4 = 0 - K5 = 1 - K6 = 1	T=2022 ms Pf= 2 2 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 1	T=1490 ms Pf= 2 4 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 1	T=1958 ms Pf= 1 3 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 1	T=1813 ms Pf= 6 6 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 0
1 , 3 , 4 , 5	T=2009 ms Pf= 4 4 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 1 - K6= 0	T=3064 ms Pf= 1 3 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 2 - K6= 1	T=1815 ms Pf= 4 6 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 1 - K6= 0	T=2064 ms Pf= 3 3 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 0	T=1793 ms Pf= 3 5 K1= 1 - K2= 0 - K3= 0 K4= 2 - K5= 0 - K6= 0
1 , 3 , 4 , 6	T=2396 ms Pf= 4 6 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 0 - K6= 1	T=2125 ms Pf= 3 4 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 1	T=1846 ms Pf= 3 3 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 1	T=2006 ms Pf= 1 1 K1= 0 - K2= 0 - K3= 1 K4= 1 - K5= 0 - K6= 1	T=1806 ms Pf= 6 6 K1= 1 - K2= 0 - K3= 1 K4= 1 - K5= 0 - K6= 0
1 , 3 , 5 , 6	T=2263 ms Pf= 1 1 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 1 - K6= 1	T=2105 ms Pf= 3 3 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 1	T=1971 ms Pf= 6 4 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 1 - K6= 0	T=1775 ms Pf= 3 1 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 1	T=1999 ms Pf= 1 5 K1= 0 - K2= 0 - K3= 0 K4= 0 - K5= 2 - K6= 1

Class 4

1 , 4 , 5 , 6	T=2261 ms Pf= 5 5 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 0 - K6= 1	T=2074 ms Pf= 1 2 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 1	T=2349 ms Pf= 4 6 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 1	T=1901 ms Pf= 6 6 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 1	T=1698 ms Pf= 1 1 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 1
2 , 3 , 4 , 5	T=1981 ms Pf= 4 4 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 1 - K6= 0	T=1999 ms Pf= 3 3 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 1 - K6= 0	T=1884 ms Pf= 4 4 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 1 - K6= 0	T=1834 ms Pf= 5 5 K1= 0 - K2= 1 - K3= 1 K4= 1 - K5= 0 - K6= 0	T=2342 ms Pf= 5 3 K1= 0 - K2= 1 - K3= 0 K4= 2 - K5= 0 - K6= 0
2 , 3 , 4 , 6	T=2061 ms Pf= 3 3 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 1	T=1993 ms Pf= 2 2 K1= 0 - K2= 0 - K3= 1 K4= 1 - K5= 0 - K6= 1	T=1952 ms Pf= 4 4 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 1	T=1709 ms Pf= 4 6 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 1	T=1549 ms Pf= 2 2 K1= 0 - K2= 0 - K3= 1 K4= 1 - K5= 0 - K6= 1
2 , 3 , 5 , 6	T=2237 ms Pf= 5 6 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 1	T=1642 ms Pf= 3 5 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 1	T=2703 ms Pf= 5 6 K1= 0 - K2= 1 - K3= 2 K4= 0 - K5= 0 - K6= 0	T=2108 ms Pf= 2 2 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 1 - K6= 1	T=1844 ms Pf= 6 6 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 1 - K6= 0
2 , 4 , 5 , 6	T=1605 ms Pf= 4 4 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 0 - K6= 2	T=2516 ms Pf= 2 4 K1= 0 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 1	T=3533 ms Pf= 5 5 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 1	T=1736 ms Pf= 4 5 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 2 - K6= 0	T=2043 ms Pf= 6 6 K1= 0 - K2= 1 - K3= 0 K4= 1 - K5= 1 - K6= 0
3 , 4 , 5 , 6	T=2099 ms Pf= 4 4 K1= 0 - K2= 0 - K3= 1 K4= 0 - K5= 1 - K6= 1	T=2275 ms Pf= 6 6 K1= 0 - K2= 0 - K3= 1 K4= 1 - K5= 1 - K6= 0	T=1692 ms Pf= 4 4 K1= 0 - K2= 0 - K3= 2 K4= 0 - K5= 0 - K6= 1	T=1790 ms Pf= 5 5 K1= 0 - K2= 0 - K3= 1 K4= 1 - K5= 0 - K6= 1	T=2394 ms Pf= 6 6 K1= 0 - K2= 0 - K3= 1 K4= 1 - K5= 1 - K6= 0

Class 5

	1	2	3	4	5
1 , 2 , 3 , 4 , 5	T=2491 ms Pf= 2 4 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 1 - K6= 2	T=1607 ms Pf= 3 3 K1= 1 - K2= 0 - K3= 0 K4= 2 - K5= 1 - K6= 0	T=1757 ms Pf= 4 4 K1= 1 - K2= 1 - K3= 1 K4= 0 - K5= 1 - K6= 0	T=1993 ms Pf= 1 1 K1= 0 - K2= 1 - K3= 1 K4= 1 - K5= 1 - K6= 0	T=2768 ms Pf= 1 3 K1= 0 - K2= 0 - K3= 2 K4= 1 - K5= 1 - K6= 0
1 , 2 , 3 , 4 , 6	T=2128 ms Pf= 3 3 K1= 1 - K2= 1 - K3= 0 K4= 1 - K5= 0 - K6= 1	T=1985 ms Pf= 4 4 K1= 1 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 1	T=2230 ms Pf= 4 4 K1= 1 - K2= 1 - K3= 1 K4= 0 - K5= 0 - K6= 1	T=1841 ms Pf= 4 6 K1= 1 - K2= 1 - K3= 1 K4= 0 - K5= 1 - K6= 0	T=2209 ms Pf= 1 3 K1= 0 - K2= 1 - K3= 0 K4= 2 - K5= 0 - K6= 1
1 , 2 , 3 , 5 , 6	T=1947 ms Pf= 2 2 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 1 - K6= 1	T=1831 ms Pf= 2 2 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 1 - K6= 1	T=2357 ms Pf= 6 6 K1= 1 - K2= 1 - K3= 1 K4= 0 - K5= 1 - K6= 0	T=1897ms Pf= 1 1 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 1 - K6= 1	T=1970 ms Pf= 3 5 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 1
1 , 2 , 4 , 5 , 6	T=1940 ms Pf= 2 2 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 1	T=1922 ms Pf= 4 4 K1= 1 - K2= 1 - K3= 0 K4= 0 - K5= 1 - K6= 1	T=1752 ms Pf= 2 4 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 1	T=2086 ms Pf= 4 4 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 2 - K6= 1	T=1958 ms Pf= 6 6 K1= 1 - K2= 1 - K3= 0 K4= 1 - K5= 1 - K6= 0
1 , 3 , 4 , 5 , 6	T=1730 ms Pf= 1 3 K1= 0 - K2= 0 - K3= 1 K4= 1 - K5= 1 - K6= 1	T=1895 ms Pf= 3 3 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 1	T=3091 ms Pf= 3 3 K1= 1 - K2= 0 - K3= 0 K4= 1 - K5= 1 - K6= 1	T=2395 ms Pf= 5 6 K1= 1 - K2= 0 - K3= 1 K4= 1 - K5= 0 - K6= 1	T=1870 ms Pf= 4 4 K1= 1 - K2= 0 - K3= 1 K4= 0 - K5= 1 - K6= 1
2 , 3 , 4 , 5 , 6	T=2081 ms Pf= 4 4 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 1 - K6= 1	T=1933 ms Pf= 6 6 K1= 0 - K2= 1 - K3= 1 K4= 1 - K5= 1 - K6= 0	T=1990 ms Pf= 4 6 K1= 0 - K2= 1 - K3= 1 K4= 0 - K5= 1 - K6= 1	T=2581 ms Pf= 3 6 K1= 0 - K2= 1 - K3= 0 K4= 0 - K5= 2 - K6= 1	T=1970 ms Pf= 2 1 K1= 0 - K2= 0 - K3= 1 K4= 1 - K5= 1 - K6= 1

Class 6

	1	2	3	4	5
1 , 2 , 3 , 4 , 5 , 6	T=1875 ms Pf= 4 4 K1= 1 - K2= 1 - K3= 1 K4= 0 - K5= 1 - K6= 1	T=1738 ms Pf= 4 4 K1= 1 - K2= 1 - K3= 1 K4= 0 - K5= 1 - K6= 1	T=1677 ms Pf= 4 4 K1= 1 - K2= 1 - K3= 2 K4= 0 - K5= 0 - K6= 1	T=1792 ms Pf= 1 5 K1= 0 - K2= 1 - K3= 0 K4= 2 - K5= 1 - K6= 1	T=1809 ms Pf= 2 3 K1= 1 - K2= 0 - K3= 0 K4= 0 - K5= 2 - K6= 2

Appendix B: The result for Virtual Proposed Storage Bin for one participant

Class 1

	1	2	3	4	5
1	T=1872 ms Pf= 1 1 K1= 0 - K2= 0	T=1638 ms Pf= 1 1 K1= 0 - K2= 0	T=1691 ms Pf= 1 1 K1= 0 - K2= 0	T=1943 ms Pf= 1 2 K1= 0 - K2= 0	T=1713 ms Pf= 1 1 K1= 0 - K2= 0
2	T=1676 ms Pf= 2 2 K1= 0 - K2= 0	T=1744 ms Pf= 2 1 K1= 0 - K2= 0	T=1833 ms Pf= 2 2 K1= 0 - K2= 0	T=1993 ms Pf= 2 1 K1= 0 - K2= 0	T=1827 ms Pf= 2 2 K1= 0 - K2= 0

CLASS 2

	1	2	3	4	5
1 , 2	T=1851 ms Pf= 1 1 K1= 1 - K2= 0	T=1787 ms Pf= 2 1 K1= 1 - K2= 0	T=1877 ms Pf= 1 2 K1= 0 - K2= 1	T=1647ms Pf= 1 1 K1= 0 - K2= 1	T=1714 ms Pf= 2 2 K1= 1 - K2= 0

Appendix C: The result of Fatigue Value for hand posture

For calculating fatigue value, special value is defined for colors:

Green = 0 , Yellow = 1 , Orange = 2 , Red = 3.

Table 9 and Table 10 shows the result of fatigue value for different positions of hand worker that simulate and analyze with DELMIA software, to calculate each value, four below parts of the hand will be evaluated:

Wrist (w) - Wrist Twist (wt) - Forearm (f) - Upper Arm (u).

Table 9. Fatigue value for common storage bin

	Posture 1	Posture 2	Posture 3
Segment 1	W 2 + wt 0 + f 1 + u 1 = 4	W 3 + wt 0 + f 1 + u 1 = 5	W 2 + wt 0 + f 1 + u 1 = 4
Segment 2	W 2 + wt 0 + f 1 + u 1 = 4	W 3 + wt 2 + f 3 + u 1 = 9	W 2 + wt 0 + f 1 + u 1 = 4
Segment 3	W 2 + wt 0 + f 2 + u 1 = 5	W 3 + wt 1 + f 1 + u 1 = 6	--------------------
Segment 4	W 2 + wt 2 + f 1 + u 1 = 6	W 2 + wt 3 + f 1 + u 1 = 7	--------------------
Segment 5	W 3 + wt 0 + f 1 + u 1 = 5	W 3 + wt 0 + f 2 + u 1 = 6	W 3 + wt 0 + f 1 + u 0 = 4
Segment 6	W 3 + wt 1 + f 1 + u 1 = 6	W 3 + wt 3 + f 3 + u 1 = 10	W 3 + wt 0 + f 1 + u 1 = 5

Table 10. Fatigue value for proposed storage bin

	Posture 1	Posture 2	Posture 3
Segment 1	W 1 + wt 0 + f 1 + u 0 =2	W 2 + wt 0 + f 1 + u 1 =4	W 1 + wt 0 + f 1 + u 0 =2
Segment 2	W 1 + wt 0 + f 2 + u 0 =3	W 1 + wt 0 + f 3 + u 1 =5	W 1 + wt 0 + f 2 + u 0 =3

Appendix D: The program for distribute the parts in different segments in common bin

```cpp
#include <iostream>
#include <stdlib.h>
#include <conio.h>
#include <time.h>
using namespace std;
int main ()
{
    int n,m,i;
    int A1,A2,A3,A4,A5,A6;
    A1=A2=A3=A4=A5=A6=0;
    int a=1, b=6;
    srand(time(0));

    cout<<"please enter the number of parts you have for assembly:";
    cin>>n;
    for(int i=1; i<=n; i++)
    {
        int p;
        p=rand()%6+1;
        cout<<p<<"\t";

        if (p==1)
            A1+=1;
        else if (p==2)
            A2+=1;
        else if (p==3)
            A3+=1;
        else if (p==4)
            A4+=1;
        else if (p==5)
            A5+=1;
        else
            A6+=1;
    }

    cout<<endl<<"A1="<<A1<<endl<<"A2="<<A2<<endl<<"A3="<<A3<<endl<<"A4="<<A4<<endl<<"A5="<<A5<<endl<<"A6="<<A6;

    getch ();
    return 0;
}
```

Appendix E: The complete calculation of one complete virtual experiment

The distribution of parts in the common storage bin is:

A1 = 8 , A2 = 3 , A3 = 6 , A4 = 5 , A5 = 4 , A6 = 4

All segments fill with parts so class 6 is chosen for taking part:

Random number: 3

T=1677 ms , Pf= 4 4 , K1= 1 , K2= 1 , K3= 2 , K4= 0 , K5= 0 , K6= 1

Final Time = 1677 ms

Final fatigue value = 6

A1 = 8 , A2 = 3 , A3 = 7 , A4 = 4 , A5 = 3 , A6 = 4

Random number: 2

T=1738 ms , Pf= 4 4 , K1= 1 , K2= 1 , K3= 1 , K4= 0 , K5= 1 , K6= 1

Final Time = 1677 +1738 = 3415 ms

Final fatigue value = 6 + 6 =12

A1 = 8 , A2 = 3 , A3 = 7 , A4 = 3 , A5 = 3 , A6 = 4

Random number: 3

T=1677 ms , Pf= 4 4 , K1= 1 , K2= 1 , K3= 2 , K4= 0 , K5= 0 , K6= 1

Final Time = 3415 + 1677 = 5092 ms

Final fatigue value = 12 + 7 = 19

A1 = 8 , A2 = 3 , A3 = 8 , A4 = 2 , A5 = 2 , A6 = 4

Random number: 4

T=1792 ms , Pf= 1 5 , K1= 0 , K2= 1 , K3= 0 , K4= 2 , K5= 1 , K6= 1

Final Time = 5092 + 1792 = 6884 ms

Final fatigue value = 19 + 6 = 25

A1 = 7 , A2 = 3 , A3 = 7 , A4 = 3 , A5 = 2 , A6 = 4

Random number: 2

T=1738 ms , Pf= 4 4 , K1= 1 , K2= 1 , K3= 1 , K4= 0 , K5= 1 , K6= 1

Final Time = 6884 + 1738 = 8622 ms

Final fatigue value = 25 + 6 = 31

A1 = 7 , A2 = 3 , A3 = 7 , A4 = 2 , A5 = 2 , A6 = 4

Random number: 1

T=1875 ms , Pf= 4 4 , K1= 1 , K2= 1 , K3= 1 , K4= 0 , K5= 1 , K6= 1

Final Time = 8622 + 1875 = 10497 ms

Final fatigue value = 31 + 7 = 38

A1 = 7 , A2 = 3 , A3 = 7 , A4 = 1 , A5 = 2 , A6 = 4

Random number: 5

T=1809 ms , Pf= 2 3 , K1= 1 , K2= 0 , K3= 0 , K4= 0 , K5= 2 , K6= 2

Final Time = 10497 + 1809 = 12306 ms

Final fatigue value = 38 + 5 = 43

A1 = 7 , A2 = 2 , A3 = 6 , A4 = 0 , A5 = 3 , A6 = 5

Now results are chosen from class 5, because the segment 4 is empty; and because A1, A2, A3, A5, A6 are fill with parts so the results is chosen from sub class (1, 2, 3, 5, 6).

Random number: 3

T=2357 ms , Pf= 6 6 , K1= 1 , K2= 1 , K3= 1 , K4= 0 , K5= 1 , K6= 0

Final Time = 12306 + 2357 = 14663 ms

Final fatigue value = 43 + 5 = 48

A1 = 7 , A2 = 2 , A3 = 6 , A4 = 0 , A5 = 3 , A6 = 4

Random number: 5

T=1970 ms , Pf= 3 5 , K1= 1 , K2= 1 , K3= 0 , K4= 0 , K5= 1 , K6= 1

Final Time = 14663 + 1970 = 16633 ms

Final fatigue value = 48 + 6 = 54

A1 = 7 , A2 = 2 , A3 = 5 , A4 = 0 , A5 = 3 , A6 = 4

Random number: 3

T=2357 ms , Pf= 6 6 , K1= 1 , K2= 1 , K3= 1 , K4= 0 , K5= 1 , K6= 0

Final Time = 16633 + 2357 = 18990 ms

Final fatigue value = 54 + 10 = 64

A1 = 7 , A2 = 2 , A3 = 5 , A4 = 0 , A5 = 3 , A6 = 3

Random number: 2

T=1831 ms , Pf= 2 2 , K1= 1 , K2= 0 , K3= 1 , K4= 0 , K5= 1 , K6= 1

Final Time = 18990 + 1831 = 20821 ms

Final fatigue value = 64 + 4 = 68

A1 = 7 , A2 = 1 , A3 = 5 , A4 = 0 , A5 = 3 , A6 = 3

Random number: 4

T=1897ms , Pf= 1 1 , K1= 0 , K2= 1 , K3= 1 , K4= 0 , K5= 1 , K6= 1

Final Time = 20821 + 1897 = 22718 ms

Final fatigue value = 68 + 4 = 72

A1 = 6 , A2 = 1 , A3 = 5 , A4 = 0 , A5 = 3 , A6 = 3

Random number: 4

T=1897ms , Pf= 1 1 , K1= 0 , K2= 1 , K3= 1 , K4= 0 , K5= 1 , K6= 1

Final Time = 22718 + 1897 = 24615 ms

Final fatigue value = 72 + 5 = 77

A1 = 5 , A2 = 1 , A3 = 5 , A4 = 0 , A5 = 3 , A6 = 3

Random number: 3

T=2357 ms , Pf= 6 6 , K1= 1 , K2= 1 , K3= 1 , K4= 0 , K5= 1 , K6= 0

Final Time = 24615 + 2357 = 26972 ms

Final fatigue value = 77 + 10 = 87

A1 = 5 , A2 = 1 , A3 = 5 , A4 = 0 , A5 = 3 , A6 = 2

Random number: 2

T=1831 ms , Pf= 2 2 , K1= 1 , K2= 0 , K3= 1 , K4= 0 , K5= 1 , K6= 1

Final Time = 26972 + 1831 = 28803 ms

Final fatigue value = 87 + 4 = 91

A1 = 5 , A2 = 0 , A3 = 5 , A4 = 0 , A5 = 3 , A6 = 2

Now results are chosen from class 4, and from sub class (1, 3, 5, 6).

Random number: 3

T=1971 ms , Pf= 6 4 , K1= 1 , K2= 0 , K3= 1 , K4= 0 , K5= 1 , K6= 0

Final Time = 28803 + 1971 = 30774 ms

Final fatigue value = 91 + 6 = 97

A1 = 5 , A2 = 0 , A3 = 5 , A4 = 0 , A5 = 3 , A6 = 1

Random number: 2

T=2105 ms , Pf= 3 3 , K1= 1 , K2= 0 , K3= 0 , K4= 0 , K5= 1 , K6= 1

Final Time = 30774 + 2105 = 32879 ms

Final fatigue value = 97 + 5 = 102

A1 = 5 , A2 = 0 , A3 = 4 , A4 = 0 , A5 = 3 , A6 = 1

Random number: 5

T=1999 ms , Pf= 1 5 , K1= 0 , K2= 0 , K3= 0 , K4= 0 , K5= 2 , K6= 1

Final Time = 32879 + 1999 = 34878 ms

Final fatigue value = 102 + 4 = 106

A1 = 4 , A2 = 0 , A3 = 3 , A4 = 0 , A5 = 4 , A6 = 1

Random number: 5

T=1775 ms , Pf= 3 1 , K1= 0 , K2= 1 , K3= 0 , K4= 0 , K5= 1 , K6= 1

Final Time = 34878 + 1775 = 36653 ms

Final fatigue value = 106 + 5 = 111

A1 = 3 , A2 = 1 , A3 = 2 , A4 = 0 , A5 = 4 , A6 = 1

In this step when participant took the part from segment 3, the part that is in segment 1, move to segment 2. Therefore, now there are 5 segments that fill with parts and again results are chosen from class 5, sub class (1, 2, 3, 5, 6).

Random number: 3

T=2357 ms , Pf= 6 6 , K1= 1 , K2= 1 , K3= 1 , K4= 0 , K5= 1 , K6= 0

Final Time = 36653 + 2357 = 39010 ms

Final fatigue value = 111 + 5 = 116

A1 = 3 , A2 = 1 , A3 = 2 , A4 = 0 , A5 = 4 , A6 = 0

Now results are chosen from class 4, sub class (1, 2, 3, 5)

Random number: 2

T=2038 ms , Pf= 5 3 , K1= 2 , K2= 1 , K3= 0 , K4= 0 , K5= 0 , K6= 0

Final Time = 39010 + 2038 = 41048 ms

Final fatigue value = 116 + 5 = 121

A1 = 4 , A2 = 1 , A3 = 1 , A4 = 0 , A5 = 3 , A6 = 0

Random number: 1

T=2284 ms , Pf= 5 5 , K1= 1 , K2= 1 , K3= 1 , K4= 0 , K5= 0 , K6= 0

Final Time = 41048 + 2284 = 43332 ms

Final fatigue value = 121 + 4 = 125

A1 = 4 , A2 = 1 , A3 = 1 , A4 = 0 , A5 = 2 , A6 = 0

Random number: 4

T=1777 ms , Pf= 1 1 , K1= 0 , K2= 1 , K3= 1 , K4= 0 , K5= 1 , K6= 0

Final Time = 43332 + 1777 = 45109 ms

Final fatigue value = 125 + 5 = 130

A1 = 3 , A2 = 1 , A3 = 1 , A4 = 0 , A5 = 2 , A6 = 0

Random number: 3

T=1997 ms , Pf= 2 4 , K1= 1 , K2= 0 , K3= 0 , K4= 1 , K5= 1 , K6= 0

Final Time = 45109 + 1997 = 47106 ms

Final fatigue value = 130 + 6 = 136

A1 = 3 , A2 = 0 , A3 = 0 , A4 = 1 , A5 = 2 , A6 = 0

Now the class 4 change to class 3, subclass (1, 4, 5)

Random number: 2

T=3140 ms , Pf= 5 5 , K1= 1 , K2= 0 , K3= 0 , K4= 1 , K5= 0 , K6= 0

Final Time = 47106 + 3140 = 50246 ms

Final fatigue value = 136 + 6 = 142

A1 = 3 , A2 = 0 , A3 = 0 , A4 = 1 , A5 = 1 , A6 = 0

Random number: 5

T=1796 ms , Pf= 4 4 ,K1= 1 , K2= 0 , K3= 0 , K4= 0 , K5= 1 , K6= 0

Final Time = 50246 + 1796 = 52042 ms

Final fatigue value = 142 + 7 = 149

A1 = 3 , A2 = 0 , A3 = 0 , A4 = 0 , A5 = 1 , A6 = 0

Now the class 3 change to class 2, subclass (1, 5)

Random number: 4

T=2139 ms , Pf= 1 3 , K1= 0 , K2= 0 , K3= 0 , K4= 0 , K5= 1 , K6= 0

Final Time = 52042 + 2139 = 54181 ms

Final fatigue value = 149 + 5 = 154

A1 = 2 , A2 = 0 , A3 = 0 , A4 = 0 , A5 = 1 , A6 = 0

Random number: 2

T=2384 ms , Pf= 5 5 , K1= 1 , K2= 0 , K3= 0 , K4= 0 , K5= 0 , K6= 0

Final Time = 54181+2384 = 56565 ms

Final fatigue value = 154 + 5 = 159

A1 = 2 - A2 = 0 - A3 = 0 - A4 = 0 - A5 = 0 - A6 = 0

Now the class 2 change to class 1, subclass 1

Random number: 1

T=3005 ms - Pf= 1 3 - K1= 0 - K2= 0 - K3= 0 - K4= 0 - K5= 0 - K6= 0

Final Time = 56565 + 3005 = 59570 ms

Final fatigue value = 159 + 5 = 164

A1 = 1 - A2 = 0 - A3 = 0 - A4 = 0 - A5 = 0 - A6 = 0

Random number: 5

T=2816 ms - Pf= 1 1 - K1= 0 - K2= 0 - K3= 0 - K4= 0 - K5= 0 - K6= 0

Final Time = 59570 + 2816 = 62386 ms

Final fatigue value = 164 + 5 = 169

A1 = 0 - A2 = 0 - A3 = 0 - A4 = 0 - A5 = 0 - A6 = 0