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Virtual Human Factors Tools for Proactive Ergonomics: Qualitative Exploration And Method Development

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VIRTUAL HUMAN FACTORS TOOLS FOR PROACTIVE ERGONOMICS
QUALITATIVE EXPLORATION AND METHOD DEVELOPMENT

By

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B. Eng., Technological Institute of Tepic, Mexico, 2003

A thesis

Presented to Ryerson University

In partial fulfillment of the
requirements for the degree of
Master of Applied Science
in the program of
Mechanical and Industrial Engineering

Toronto, Ontario, Canada, 2011

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ABSTRACT

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This thesis presents two studies that explore the use of Virtual Human Factors Tools (VHFT), such as Predetermined Motion Time Systems (PMTS), Digital Human Models (DHM) and Discrete Event Simulation (DES). Study 1 investigated the needs and expectations of ergonomist and engineers through a series of explorative workshops. Nine characteristics of concern to participants were identified in the tools: time, cost, training, difficulty to use, trustworthiness, graphics, flexibility, usefulness and report presentation. These characteristics can influence VHFT uptake and application decisions. Study 2 explored the integration of DES, PMTS, DHM and existing fatigue models, in an assembly context, to predict the accumulation of muscular fatigue. This study demonstrated the feasibility of using VHFT in conjunction and that DES can predict ergonomic outcomes such as work-related fatigue and recovery. The study also uncovered some problems with the existing fatigue models, highlighting the need for further research and development of those models.

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NOMENCLATURE:

$fMVC_i$ = Fraction of Maximum Voluntary Contraction when performing task i
MET_i = Maximum Endurance Time (in seconds) for task i as a function of $fMVC_i$
F_i = Fatigue rate after task i .
fF_i = Fraction of fatigue contribution per task i
fR_i = Fraction of recovery received after task i
r_i = Total pause/break duration at time t_i (seconds)
t_i = Time a worker needs to perform task i (seconds)
R_i = Recovery time (in seconds) needed after task i to bring fatigue down to 0.

1. INTRODUCTION

Ergonomics, a term exchangeable with Human Factors (HF), has been defined as “*the theoretical and fundamental understanding of human behavior and performance in purposeful interacting socio-technical systems, and the application of that understanding to the design of interactions in the context of real settings*” (Wilson, 2000). The importance of ergonomics to work practices has been recognized in the literature; it ranges from prevention of issues such as absenteeism related to Musculoskeletal Disorders (MSD) (e.g. Arnets et al., 2003) and Health & Safety (e.g. Coyle et al., 1995) to the increase of productivity and quality, as well as costs reduction (e.g. Helander and Burri, 1995; Yeow et al., 2006). Regardless of its recognized importance, ergonomics has been traditionally used as a reactive tool to assess and solve issues emerging once the system is operating, rather than as a preventive tool (e.g. Moore et al., 1996; Laing et al., 2005). Although the history of HF as a formal discipline can be traced back to WWII (Meister, 1999), its application early in the design stages of process and products is uncommon. Although some authors have recently addressed the importance of switching the focus of ergonomics from reactive to proactive (Broberg, 1997; Neumann et al., 2004), this proactive approach remains uncommon and an opportunity for further research. The consideration of ergonomics early in design to create better working conditions is done through different tools, most of them computer based (e.g. Shaikh et al., 2004; Fulder et al., 2005). These tools are known as the Virtual Human Factors Tools (VHFT).

1.1 The topic under investigation

The topic studied in this thesis is the means that allow the application of HF early during the design stage of systems and processes: the Virtual Human Factors Tools (VHFT). From the definition of HF provided by the IEA Council (2000), Virtual Human Factors (VHF) can be explained as “*the scientific discipline concerned with the understanding of the interaction amongst humans and other elements of a ‘virtual’ system, in order to optimize human well-being and overall system performance*”; therefore, VHFT can be defined as those tools that allow the application of ergonomics in virtual systems – systems that do not exist yet. This thesis focus on the study of some of the existing VHFT. Examples of these tools are Predetermined Motion Time Systems (PMTS), Digital Human Models (DHM), Discrete Event Simulation (DES) and Virtual Reality (VR). This thesis is divided in two related studies about VHFT. The first study explores the ways in which the VHFT are being used and/or perceived by some of the design stakeholders (engineers, ergonomists and managers), their possible advantages, disadvantages and opportunities for improvement. The second study experiments with the integrated use of three of the VHFT (PMTS, DHM and DES) to predict the accumulation of fatigue under three proposed work/rest schedules. The simulation model was based on an existing production line.

1.2 Why HF in design?

The application of HF in the design of products, as well as service and production systems, has been discussed in scientific literature in the last decades (Shackel, 1986; Sanders and McCormick, 1993; Jensen, 2002; Wilson et al., 2009). More recently, Neumann and Dul (2010) identified a number of negative effects (Table 1) that can have an impact on humans and systems when HF are not considered early in design.

Table 1. The no inclusion of HF in design can manifest in negative effects both in humans and system (Neumann and Dul, 2010).

Human Effects	System Effects
- Health	- Productivity
- Attitudes	- Quality
- Physical workload	- Implementation of new technology
- Quality of work life	- Intangible benefits

It is assumed that using ergonomics early in design will prevent some of the issues that may emerge later when the systems are operational, but given the interaction between humans and systems both kinds of effects need to be considered together in design (Neumann and Dul, 2010). The consequences of not considering HF in design may vary from human error and resulting accidents and losses of quality (Eklund, 1997), to health related issues (e.g. Chen 1986; Sluiter et al., 2003; Neumann et al., 2001) and huge monetary costs (e.g. Ricci et al., 2007). The impact of badly designed processes can manifest almost immediately (after few hours of work) or at long term. Figure 1 illustrates some of the negative effects of poor ergonomics in design after the interaction between workers and systems. This model, its elements and pathways will be further explained in the following section.

Figure 1. Badly designed work processes could lead to short and long term consequences which could be product of an accident (almost immediate consequence) or a continuous exposure to risk factors (long term). 2

Performance

As seen in figure 1, the first and almost immediate effect in the workplace will be a reduction of the workers and systems performance (equally in service and production systems). The performance of a system as a whole can be affected by important ergonomic factors such as cycle times and its variations, operator's experience, loads, workers interaction and teamwork (Neumann et al., 2006; Kazmierczak et al., 2007), as well as supply chains and materials handling (Neumann and Medbo, 2010). Kazmierczak et al. (2007) showed how the poor consideration of some of these factors can make a system underperform when compared to the design specifications. Workers performance can be reduced as a consequence of exposure to physical or/and mental stressors. Physically, when a worker starts feeling discomfort after exposure to the system the natural body reaction will be to slow the pace down and reduce effort to minimize the accumulation of that discomfort, and avoid or reduce the manifestation of pain. Psychologically, when the worker starts to feel fatigue, his motivation to keep performing at optimal levels gets significantly reduced (Govindaraju et al., 2001). The reduced performance, first manifested in fatigue, could translate into some negative results such as increases in human errors – which in turn increases the risk of accidents – and loss of quality.

Fatigue

Fatigue is a complex concept, a phenomenon that has been defined as “a *loss of efficiency and a disinclination for any kind of effort*” (Grandjean, 1979) that can be classified into two categories: mental and physical. Fatigue is considered a consequence of badly designed systems and a precursor of different negative consequences in work environments when HF is not properly considered during the design of systems (figure 1). These consequences range from human error and resulting accidents and losses of quality, to health related issues and huge monetary costs. Eklund (1997) cited fatigue as one of the factors behind “*quality deficiencies, human error and other ergonomic problems*”. Work-related fatigue, according to Åhsberg (1998), can be classified in physical or psychological and has some of the following manifestations:

- Physical: Lack of energy, exertion, pain and discomfort.
- Mental: lack of motivation and sleepiness.

Human error – Accidents and quality loss

Human errors, particularly when they occur often, could be an indication of a badly design system. Human error has been cited as one of the immediate effects of fatigue in work environments. Baker et al. (1994) demonstrated that the accumulation of both mental and physical fatigue causes an increase in human errors. According to the Nuclear Regulatory Commission (NRC, 1989) in the US, up to 50% of the safety issues in the industry are attributed to human error. Human error is precursor to *accidents*, which could lead to injury and/or property damage (Grandjean, 1979; Baker et al., 1994; Brown, 1994; Dinges, 1995; Folkar et al., 2004; Fisman et al., 2007; Parijat, 2008), as well as a loss in quality of products and services (Gaba, 2002). It has also been recognized as a potential risk of nuclear disasters such as Chernobyl (Baker et al., 1994). Of the two classes of fatigue, psychological seems to have a bigger impact on the incidence of human error and accidents than physical fatigue; especially in monotonous systems and

processes, where workers are generally exposed to very low load levels but very high performance demands. Finkelman (1994) found that *“the physical demands of a job assignment had the lowest correlation with reported job fatigue”* compared to psychological fatigue. Although to a lesser degree, physiological fatigue is also a contributor to human error and accidents, since it leads to some degree of impaired coordination, which could produce accidents (Grandjean, 1979). The relation between psychological and physical fatigue produced by ill designed systems as precursor of accidents can be explained as twofold, mental fatigue *“decreases the ability to process information about a hazardous situation”* while muscular fatigue *“decreases the ability to adequately respond to hazardous situations”* (Swaen et al., 2003). The importance of considering Human Factors in the design of products and systems, for a quality gain purpose, has also been recognized in the literature (Carayon et al., 1999; Drury, 2000). Reduced performance and resulting human errors caused by bad postures, high repetitions, high loads, fatigue and other results of a bad design can manifest in a decrease of the quality of the work being performed in both production and service systems (Eklund, 1995; Axelsson, 2000; Oliva et al., 2001; Beckers et al., 2004). Human error could be minimized by applying HF early in the design of products and systems.

Health – Stress, injuries and MSD

Poor ergonomics in design can have negative impacts on workers health and safety in short (mainly the result of accidents provoked by human errors) or long (continuous exposure to risk factors) term (Figure 1). The exposure to work systems has been related to both physical and mental health problems, especially whenever the recovery needs are not met (Sluiter et al., 2003). Work-related activities are directly associated with medical conditions such as anxiety, asthma, emphysema, anemia, depression, arthritis and stress (Chen, 1986), as well as cardiovascular diseases (Collins, 2009), the continuous exposure to work practices can also exacerbate the gravity of pretty much any medical conditions (Ricci, 2007). Work-related practices have also been associated with membrane rupture during the first pregnancy, the risks increases as the exposure to fatiguing task also increases (Newman et al., 2001). Work-related musculoskeletal disorders (WMSD) represent another important consequence of the exposure to bad designs. Buckle (2002) found evidence to support that force and repetition – two of the main components of any work-related activity and known causes of fatigue – were behind reports of WMSD. In their case study Neumann et al. (2006) demonstrated that supply chains and workstation’s designs can lead to WMSD when biomechanical loads are not properly considered. Alexopoulos et al. (2003) found that some physiological demanding tasks such as repetitions, heavy lifting and awkward postures, as well as some psychosocial factors, could lead to back, neck and shoulder WMSD among nurses. Furthermore, they documented that the need for recovery (result of the accumulation of fatigue in badly planned schedules) was the single most important risk factor for WMSD. Occupational lifting compromises the spinal stability, hence posing an increase in the risk of spinal injuries and MSD (Granata et al., 2004). Lower extremities MSD and discomfort are also very common in industrial environments, particularly in assembly and packaging lines where workers have to spend most of their shifts standing in front of conveyor belts. The increase of psychological demands produce some tension at the muscle level, which in turn could lead to back, neck or other kinds of musculoskeletal problems (Sauter et al., 1996). Stress, apathy, angeriness and other signs of psychological demands could manifest in badly design systems, affecting the

way in which a worker performs his duties. For instance, a bored worker could adopt an incorrect back posture; an angry operator could apply excessive levels of force; these two examples, at long term, may lead to WMSD (Carayon et al., 1999). Furthermore, the risk of developing WMSD could be exacerbated by other factors such as overtime or the increase in pace in order to meet deadlines. Feuerstein et al. (1987) found that low back pain produces an increase in the reported levels of fatigue. If this fatigue worsens the existent pain, as suggested by Carayon, then the worker would be trapped in a “vicious circle” until an appropriated recovery time is allowed – a recovery time that also needs to be considered in the design. The minimization of all these many possible health issues resulting from humans exposure to work-related should be one of the main motivators for the inclusion of HF in the design of systems.

Cost

Performance decreases, quality loss and health related problems derived from badly designed systems translate in huge costs for governments and industries. In the U.S. alone, the loss of productive time of workers with fatigue costs employers more than USD\$136 billion every year (Ricci et al., 2007). This loss of productive time in workplaces, according to Ricci, is composed of absenteeism and presenteeism (when the employee is at work but performing below his full capacity). The annual cost of WMSD in the USA in 1999 was calculated between \$13 to 20 billion a year, and is rising with time (National Academy of Sciences, 1999). It is also been estimated that injuries can cost industries up to one third of its total profits (Prevent, 2004). But the cost companies pay by not considering HF proactively could be even higher, Rose et al. (2010) suggested that besides these evident economic losses, firms pay “hidden costs” that are hard to identify, such as the portion of the quality losses related to bad ergonomics. The inclusion of HF in systems design could lead to substantial savings/gains for companies; for instance, it is estimated that IBM saved more than \$130 million after some ergonomic changes to its systems (Helander and Burri, 1995).

1.3 Virtual Human Factors effectiveness reduced by time

In order to reduce the risks of human errors and accidents, maximize operators and systems performance, protect workers health and safety and minimize costs, it is important to consider HF as early in the design process as possible because its effectiveness is constrained by time. Miles and Sift (1998) explained the relation between ease of change and time. As seen in Figure 2, the longer it takes to apply HF in design the harder and more expensive it is to make changes to products and systems, since the window of opportunities gets contracted in time. A clear example of the importance of considering HF during the design

Figure 2. This graphic shows how important it is to use HF early in concept design. As time pass, ease of change is reduced and cost of change increased (Miles and Swift, 1998).

of systems as a whole – not just in the design of isolated workstations or tasks – can be found in a case study conducted by Neumann et al. (2002). In their analysis of a newly implemented production strategy, these researchers found an increase in the risk of work-related disorders for workers; unfortunately, by the time these issues were identified an investment in the automation of some segments of the production line had already been done. The application of HF early in design, however, could be difficult in many cases since most of the existing ergonomic tools are based on observation and, at this stage of the design process, neither ergonomists nor engineers or designers have much to observe (Daniellou and Garrigou, 1992; Neumann, 2007; Sinclair, 2007). One way to consider ergonomics early in design, when there are no systems to observe, is VHF. VHF gives ergonomists, engineers and designers access to reliable information when there are no existing systems to collect data from.

1.4 The Virtual Human Factors Tools

The consideration of ergonomics in the design of process and products is possible thanks to the application of different tools, most of them computer based, which in this thesis are identified as the Virtual Human Factors Tools (VHFT). The VHF tools considered in this thesis include Predetermined Motion Time Systems (PMTS), Discrete Event Simulation (DES), Digital Human Models (DHM) and Virtual Reality (VR). The following is a brief overview of each one of these tools and some examples of their current use for both ergonomic and none-ergonomic purposes.

1.4.1 Predetermined Motion Time Systems (PMTS)

MTM Analysis					
	Job description:		Analyst: E J H		
	Assemble r.f. transformer to base-plate		Date: 3 May		
El.	Description	LH	tmu's	RH	Description
1	Move hand to washer	R14C	15.6	R14B	Move hand to transformer
2	Grasp first washer	G4B	9.1	G1A	Grasp transformer
3	Move hand clear of container	M2B	---	---	Hold in box
4	Palm washer	G2	5.6	---	ditto
5	To second washer	R2C	5.9	---	ditto
6	Grasp washer	G4B	9.1	---	ditto
7	Move washers to area	M10B	16.9	M14C	Transformer to plate

Figure 3. Example of PMTS evaluation table.

PMTS is a tool mainly used to evaluate time needed to perform a tasks, based on activity requirements and standard durations stipulated in a table of predetermined times for given movements. Figure 3 presents an example of a PMTS evaluation. These systems are especially useful to evaluate and set workloads (line balancing) in assembly tasks (Laring et. al, 1985). Examples of PMTS are Methods Time Measurement (MTM), Maynard Operation Sequence Technique (MOST), Universal

Analysis System (MTM-UAS, or MTM-SAM in Sweden). The available literature explores different application for PMTS, from the reduction of times in production operations (Cakmakci and Karasu, 2007), to job rate allocation (McDonald et al, 1999) and software design (Fernández-Sanz et al., 2009). Regardless of the popularity of PMTS in the Industrial Engineering field, only two PMTS include an ergonomic component: ErgoSAM, a tool to asses risk

levels (Laring et al., 2005) and ErgoMOST, a tool helpful to “*pinpoint possible ergonomic problems*” in work-related operations (Zandin et al., 1996). Although some other ways to evaluate times exist, such as stopwatch and video analysis. PMTS was selected for the reliability it offers and the fact that can be applied virtually.

1.4.2 Discrete Event Simulation

Discrete Event Simulation is the representation of a system in terms of sequence and times of the process’ stages (Banks et al., 2005), a tool especially useful for analysis of system design alternatives (Neumann and Medbo, 2005), production times analysis and resource allocation. Thanks to different software available today, it is possible to model different events to predict outcomes based on the combined dynamics of all of the system elements. An examples of DES software is Rockwell’s Arena (Figure 4 presents an example of DES in Rockwell Arena). Although DES is a tool widely available in industry today, its application in the ergonomic field remains underexplored (Baines et al. 2002; 2004), very few studies of DES conducted from an ergonomic perspective can be found in the literature. Examples of these applications are the analysis of the impact that fatigue and rotation schedules have on military operations (Walters et al., 2000), workers performance in assembly tasks (Neumann and Medbo, 2005) and the combined use of DES and SDHM in the performance analysis of work systems (Kazmierczak et al., 2007).

Figure 4. Discrete Event Simulation model created in Rockwell Arena software.

1.4.3 Digital Human Models (DHM)

A Digital Human Model is the computerized representation of the human body and its interaction with the environment (Chaffin, 2001). This kind of tool is particularly useful to evaluate reach, fit and risk levels based on postures, forces and task durations. Although all DHM rely on the same kind of anthropometrics databases and calculations (Bean et al., 1988) to evaluate tasks performed by different sizes of people in the same system (large man, small woman, etc.), some clear differences exist amongst the software available in the market. Because of these differences, DHM are grouped in this thesis into two subcategories: Simple Digital Human Models (SDHM) and Complex Digital Human Models (CDHM).

Simple Digital Human Models (SDHM)

Simple Digital Human Models are, mostly, simple 2D human modeling software, although some 3D models exist - e.g. the 3DSSPP model (Beck et al., 1993; Chaffin, 1997). These programs allow the manipulation of a mannequin to resemble different postures and take in account data such as task, force and time (Neumann, 2007). The biomechanical models produced by this kind of software allow the user to explore tasks in detail and makes it easy to guess and check postural effects and risks (Jozwiak et al.; 1993, Chaffin, 2001). One example of a SDHM is WATBAK (Figure 5), whose practical application has been explored by Neumann et al. (1999). This kind of DHM is relatively affordable, with a price in the range of \$600-\$1,000 for a single license.

Figure 5. Evaluation of postures using WATBAK

Complex Digital Human Models (CDHM)

Complex Digital Human Models are more elaborated kind of human modeling systems that have the capacity to incorporate a 3D CAD drawing of a workplace to check risk and fit along biomechanical load information. The risk level is then indicated by colors (or numbers depending on the analysis subroutines available). This tool can provide a wide variety of information useful for ergonomist, engineers and designers, with the additional advantage of a three-dimensional representation of workers and their interaction with working environments and tools. Some examples of CDHM are JACK, HumanCAD and Santos (Figure 6). This kind of DHM tools are more expensive than the SDHM (ranging from \$8,000 to \$75,000+), with some models costing much more depending on the 'add-ons' purchased. The application of CDHM has been largely documented, a great number of articles can be found in the scientific literature. Jung et al. (1999) explored the use of CAD drawings and human models to assess postures. Chaffin (2001) presented in his book a variety of examples of how to use CDHM (as well as SDHM) to predict the human-machine interaction during the design stage in the manufacturing field (vehicles). Gore et al. (2001) analyzed the use of CDHM to predict human performance based on environmental and ergonomic conditions in aviation. Li et al. (2006) used a combination of JACK and Virtual Reality to study the way of improving MTM machines design to offer better accessibility to people in wheelchairs.

Figure 6. Representation of assembly work on Santos, the most advanced CDHM. (University of Iowa's VSR program)

1.4.4 Virtual Reality (VR)

Figure 7. Example of VR using Ergomix
(www.tno.nl).

Virtual Reality is the electronic representation of environments (Coates, 1992), that allows users to interact with their surroundings through a collection of technological hardware that may include computers, goggles, gloves and joysticks (Steuer, 1993). Examples of VR tools are Ergomix (Figure 7) and Vizendo. Ergomix is a participative VR tool that uses blue screen technology to evaluate workstations and systems (Vink et al., 2008; Hallbeck et al., 2009). Vizendo is a computer program designed for cognitive training of manual assembly tasks (Vizendo, 2009), a kind of first person videogame. The use of VR has been proposed for different situations in and outside of the manufacturing world, such as verifications

in assembly lines (Gomes de Sá et al., 1999), to train surgeons and medical personnel (McCloy, 2001), or analyze the human-machine interaction during the system design phase (Khanna and Nema, 2007).

1.4.5 SIMTER

A prototype hybrid VHFT was presented during some of the workshops as an example of future approaches. SIMTER is a new Scandinavian software tool for the simulation of manufacturing systems. It allows the integration of ergonomics, levels of automation and environmental concerns in a single platform (Berlin, 2009). The software allows users to create a 3D production environment, combining CDHMs and DES, with tables of environmental impact of chosen equipment. Since SIMTER is still under development and is not yet available in the market, it was presented as an example of how different tools can be combined into a single platform. The information provided by the participants, perhaps due to that situation, was not enough as to support the same kind of assessment done to the other tools; therefore, SIMTER was not considered part of the research.

1.5 Aim

The aim of this thesis is to analyze the VHFT, in order to create knowledge to better understand their applicability early in the design of products and systems, to prevent the wide variety of issues that can emerge once a process is operational. Equally important is to explore the feasibility of the integration of different VHFT as a proactive approach to the ergonomic issues. To meet these objectives, this thesis was divided in two different studies, each one with a particular set of objectives, methodologies, results and discussions.

Study 1 – A Workshop Explorative Research of VHFT

For this study, an exploration of some of the VHFT available to designers was conducted using a workshop approach. This section of the thesis summarizes a qualitative research conducted to users and potential users of the VHFT, with the objective of understanding how these tools are being utilized by the different design players and what could be done to improve them.

Study 2 – Discrete Event Simulation, a platform for the integration of different VHFT

This study – based on an existing production system and conducted in close collaboration with researchers from the Netherlands Organization for Applied Scientific Research (TNO) – uses Discrete Event Simulation as a platform for the integration of different VHFT. DES was chosen based on some of the results obtained from Study 1, which indicated that it was not seen as an ergonomic tool by some design stakeholders. This study also included the use of PMTS and SDHM, as well as some mathematical models used for the calculation of fatigue and recovery needs. A simulation model was created to predict the accumulation of fatigue throughout a day-long work shift, under different rest schedules, to determine which alternative was better suited to assure a balance between productivity and workers well-being. This study's objective was to explore the feasibility of using different VHFT for the prediction of realistic ergonomic outcomes of proposed rotation schemes. Study 2 presents an example of how different VHFT can be used in a same project, to prevent possible adverse outcomes in work-related processes

2. STUDY 1 - A WORKSHOP EXPLORATIVE RESEARCH OF VHFT

2.1 Introduction

While significant research has been conducted about VHFT and how it could be used in the design process (McAtamney et al., 1993; Jayaram et al., 1997; Feyen et al., 2000; Laring et al., 2002; Chaffin et al., 2005; Kelton et al., 2010), much less has been done to better understand them from a user's perspective. Understanding the user needs is one of the most important discriminators between the success and the failure of new products (Cooper and Kleinshmidt, 1984). Experiences and opinions expressed by target user groups (ergonomists and engineers), as well as some other potential users of the VHFT, were analyzed in this study to better understand their needs, expectations and preferences. To help developers further improve the VHF tools, it was necessary to explore the ways in which engineers and ergonomists are using those tools, as well as the stages of design in which they are being applied. It was also important to find out if the potential of the tools is being exploited and, if not, the reasons why users are not taking advantage of that potential.

2.2 Methodology

An explorative investigation was conducted using a day-long interactive workshop approach. This approach, widely used in qualitative research (Chrzanowska, 2009), was selected because it allowed interaction among the researchers and the final users and potential users of different VHF tools, focusing in the discussion of the “real life” issues the users face when utilizing the tools (Klatt, 1999). Four workshops were conducted in two phases, with a pilot session in the first stage followed by a series of 3 day-long workshops in the second. Five VHF tools (PMTS, DES, SDHM, CDHM and VR) were presented to the participants by researchers, who also acted as coordinators of the discussions that followed the presentations. A total of 46 industry representatives (12 engineers, 34 ergonomists) with and without experience in the use of VHF tools under consideration, from both public and private sectors attended the workshops; including ergonomists and engineers responsible for developing and administrating production and service systems, some of them with managerial positions. Having engineers, ergonomists and managers in the workshops was particularly important in order to understand the different needs and expectations the users have, depending on their level of expertise and their immediate responsibilities in the design process. By including both users and non-users, it was possible to obtain some insight of the factors affecting the uptake of the VHF tools. After the presentation of each tool, participants were invited to ask questions and/or express comments. A break-out discussion was then conducted, where participants were encouraged to talk about relevant issues in a free manner within groups (assigned at the beginning of the day). A series of questions were presented to each group in order to control the flow of the conversations:

- Could the tools just presented help you and why?
- Where would you like to see development in the future?

- Is there any other issues or ideas related to this tool that you would like to share?

A representative for each group collected and presented the main points of the break-out discussion to the rest of the participant; after all the groups had shared their findings, participants were given a brief break followed by the presentation of the next tool. At the end of every workshop a final plenary discussion was conducted to review all the material covered throughout the day, with the idea of exploring how participants' opinions of the VHFT had changed, if any, after the presentations of the tools and the feedbacks of their fellow attendants.

Data collection and analysis

Note takers were assigned to each one of the break-out groups, they were responsible for capturing the main ideas, comments and experiences shared by the participants to the workshops during the presentations, break-out sessions and plenary discussions. Digital audio recording devices were also utilized to capture all comments. Participants were also asked to provide some written feedback about the tools during the first and second phase of the research. In the pilot workshop participants were asked to write a brief summary of the things they had learned during the presentation of the tools, as well as some ideas about what they thought could improve the quality of future workshops and some insight about the VHFT. All this information was used not only to prepare the following three workshops, but to create a questionnaire that was also presented to participants during the second stage of this research.

All the information collected throughout the four workshops was evaluated using and *Inductive Analysis*, consisting of detailed and repetitive readings of raw data to produce concrete and reliable findings (Thomas, 2006). Data obtained during the workshops through note takers' reports, audio tapes and questionnaires was distilled into an initial summary. This summary was revised repetitively to identify the main and most common comments which were organized into categories. This process was repeated until no new information emerged (Marshall, 1999). The findings were then organized in a final report (Perez and Neumann, 2010), which was sent to all the participants as part of the validation process in preparing of the current research paper. No contradictory comments were received.

2.3 Results

Although the bulk of the information obtained from the workshops was tool-specific, it was possible to identify a set of "general" findings – which apply to all the tools. In this thesis, the tool specific results are showed first, in the same order that the tools were presented during the workshops and represent the reactions participants had to each tool. General findings represent the ideas, comments and characteristics expressed by participants shared by all the tools.

2.3.1 PMTS

Predetermined Motion Time Systems were seen by participants as tools widely used in industrial engineering practices with few ergonomic applications – work rate allocation being the only one identified during the four workshops. Although engineers in the audience familiar with the use of PMTS described it as a quick and easy to use tool, ergonomist failed to see its advantages and remained skeptical. Learning how to use PMTS was not considered a very complicated process, and those with experience in the use of this tool explained all it took them was to “*learn how to read the tables*” to start experimenting with the tool. Using the tool, however, could be difficult since the user would need to familiarize himself with the particularities of every different task in the process, and every movement represents an entry point. Apparently, this was precisely the motive why ergonomists seemed to reject the use of PMTM. In this regard, one of the participants summarized what seemed to be a consensus among ergonomists as follows: “*Just imagine how hard and how long it would take to analyze different categories for each body part, for each finger, for the right arm, for the left arm and for every task. That could be a very slow and difficult process*”. Participants also manifested some concern about the potentially high cost of a lengthy PMTS study. They pointed out as well “*the lack of graphic capabilities*” as a disadvantage. Participants, however, identified PMTS as a tool that could be used as a “*bridge*” to connect engineering and ergonomics; for instance, one ergonomist in the audience expressed that “*PMTS could be used to collect data for DHM or DES*”. Comments similar to this one were expressed in all workshops.

2.3.2 DES

Although engineers seemed to be more receptive to DES than Ergonomists, overall participants expressed their skepticism on this tool’s ergonomic application. Ergonomist pointed out DES doesn’t consider HF such as fatigue, force, posture and time of exposure; as well as some psychosocial factors like sense of control, autonomy, integration and especially communication with coworkers. Mistrust was another concern expressed by the participants, who showed a great caution in the veracity of the results yielded by DES, not because of the tool’s capabilities, but more for the possibility of human error in programming and, more important, in the data collection process. Data collection and processing, however, is a problem that has been analyzed before (Skoogh and Johansson, 2008). Another factor contributing to the mistrust was that, as with some other tools, DES “*can’t simulate people’s unpredictability*”. DES was also regarded by participants as a rather complicated process whose output veracity depends on the skill of the expert in charge of the simulation, something that has been recognized in the literature before (Kellner et al., 1999). One of the participants said that, due to all these complications, DES “*is not worth the pain*” from a purely ergonomic perspective. Since simulation takes so much time and requires many different activities (data collection from actual systems, data analysis, programming, output analysis, report writing, etc.), some participants thought that it should be more a “*team*” (ergonomist and engineers) project than just a “*one expert’s*” project. The training process represents, according to the participants, another obstacle for the use of DES. Learning how to use the tool could become a very complicated process. The user would need to learn different

programming languages, probability and statistics in order to perform an adequate analysis. This kind of team effort, they warned, could result in high costs for the company. Costs – including software price, “team” wages and training – were also a great concern for the participants. A license for DES could start at \$1,000, and sometimes requires powerful computer equipment to be utilized. The need of additional high investments, such as training, could make of DES a none-optimal tool for some industries, *“particularly those whose lines and processes barely change”*. The “dynamic” graphics some DES software offer was seen as an advantage for this tool, particularly by ergonomists. *“When you see the movement, it gives you a greater sense of reality”* explained one of the ergonomists. *“It could be useful to convince managers of accepting changes”* said another.

2.3.3 DHM

Digital Human Models, particularly CDHM, quickly emerged as the most widely used and popular design tool both for engineers and ergonomists attending the workshops. According to participants, SDHM and CDHM are both useful for calculating ergonomic limits, to identify risks of injuries and MSDs, optimize process and to reduce design iterations. But they also shared some common disadvantages, for instance, some of them generally leave the unpredictability of the human behavior out, don’t evaluate hands, wrists or fingers, which according to participants *“sometimes the hands look more like a bunch of bananas”*. Neither SDHM nor CDHM seem to have been widely adopted by industry design teams and they were perceived as difficult to master. Contrary to DES, engineers don’t seem to trust the results and were less receptive to DHM than ergonomists. Some participants express that the lack of interest in the use of DHM as an ergonomic tool was the fact that this software don’t consider human factors such as learning curves, sickness, fatigue, etc. At the end, they said, all these situations can lead to very costly mistakes in the designs. Participants also identified two main differences between CDHM and SDHM: the cost and the graphic’s capacity. The results of the ergonomic evaluations, however, is not that different, especially since the core biomechanical “engines” of these models are the same or at least very similar.

SDHM

Some participants saw SDHM as a useful tool for an initial evaluation of the risk that postures, loads and times of exposure suppose for the worker; to quickly establish some safe/unsafe limits early in the design. However, they expressed some degree of mistrusts in SDHM even for that initial evaluation. This lack of trust, they said, was not because of the tools evaluative capabilities, but due to the fact that some of the safe/unsafe limits and guidelines used by SDHM “don’t reflect the reality of today”. “Some of the safe/unsafe limits are based on calculations done 30-40 years ago. They may not reflect the anthropometric reality of today’s society. Today, workers tend to be larger than they were in the 60s or 70s, when these limits were calculated” expressed one of the participants. Those with experience in the use of SDHM explained that learning how to manipulate software such as WATBAK is relatively easy, “a process that takes only a few hours and that people can do by themselves”. Using the tool in a real ergonomic evaluation could become a complicated process if the user does not have sufficient ergonomic knowledge to interpret the results, but if the user has the required knowledge, the evaluation is a fairly quick process that would

take only some minutes if the task being evaluated is simple, and no more than a few hours if the evaluation is more complicated. Overall, SDHM was perceived as a relatively cost accessible tool, the price can be somewhere from \$600- \$1,000.

CDHM

Complex Digital Human Models clearly emerged as the most popular design tool amongst ergonomists, mainly due to its graphic capabilities. Participants tended to trust the CDHM outputs, sometimes, solely based on the quality of the graphics and not on the quality of the analysis itself. The powerful graphics offered by CDHM, according to some participants, have two main advantages:

1. They allow the analyst to perform visual evaluations of operators fit and reach when interacting with the proposed workstations, tools and components. One of the participants, who worked in the ergonomic department for an automobile company, explained this as follows: “... *There are three things we are very concerned about: vision (can the worker see it?), reach (can the worker get it?) and strength (can the worker handle it?)*”. By manipulating the human mannequin to make it interact with a 3D-CAD work-environment, designers can get the answers to those questions without having to build and analyse mock-ups.
2. The realism of the graphics can become a powerful tool to support arguments presented to managers, in order to convince them of accepting changes to the designs and justifying some ergonomic decisions. One participant expressed it this way: “*Sometimes managers reject an analysis just because the mannequin doesn’t look realistic, without even judging the postures or the outputs*”.

Cost seemed to be a greater deterring factor for CDHM than for the rest of the tools, especially considering that the price for these tools could be up to tens of thousands of dollars and the fact that this software is always evolving. This cost/obsolescence problem is particularly important for smaller companies with lower budgets. One of the participants, representative of a small ergonomics-consulting company, even suggested that CDHM could be only a viable choice for “*big and rich corporations. By the time that a small company starts getting some return from its investment, the tool could be obsolete*”. In this regards, participants suggested that software developers could offer a “*pay-per- use*” option, to help small companies to have access to this technology. Another perceived disadvantage for CDHM was the diversity of options offered by each software. These differences make it hard for companies to choose or find “the best” or most appropriated CDHM for all of its different processes. “*There isn’t such thing as ‘the best’ or universal DHM, since that perception would vary depending on the user’s needs. For an instance, one CDHM such as JACK could be better to represent real problems while other like Santos can offer better simulation [graphic] details*”, explained one of the engineers experienced in the use of diverse SDHM and CDHM. While ergonomist favoured CDHM over all the other VHF tools, engineers appeared to adopt a more wary attitude towards this software and preferred a physical mock-up to evaluate designs. “*A mannequin can’t simulate when an operator is tired. When workers are tired they tend to adopt awkward postures and try to cut corners in the process*” explained an engineer presenting a case for mock-ups. An interesting debate emerged at this point between engineers and ergonomists during one of the workshops, with engineers arguing that CDHM, regardless of how

advanced they were, will never be capable of simulating the *“human variability component”* that could be found in a physical mock-up. Instead, they explained, CDHM could be used in *“a preliminary analysis”* of systems, *“as a tool to determine when a physical mock-up is needed”*. Ergonomist replied that CDHM is a better option than physical mock-ups for two important reasons: computer models offer a *“higher level of detail”* and allow designers to *“see through a screen what operators would see and face in the assembly lines”*. Ergonomists also said that the fact that CDHM cannot consider factors such as those that lead operators to *“adopt awkward postures and to cut corners”*, makes it the perfect tool to design the right processes with the optimal postures. Time was considered a big obstacle for the use of CDHM. It takes too long not only to learn how to use these tools, but also to create a virtual 3D CAD environment for the simulation. Some of the participants with experience using CDHM explained that the most time consuming task was not using CDHM as much as drawing the CAD environments. Participants were also concerned with the training process. They explained that in order to properly use a CDHM, the user would first have to learn how to manipulate the mannequin, then he would have to learn how to use a CAD system and finally, he would need to acquire enough ergonomic knowledge to be able to read the results and identify right postures. They also thought that using CDHM could be a difficult process, one that may call for the participation of some line workers to act as models, and even some degree of cooperation between ergonomists and engineers.

2.3.4 Virtual Reality

Although none of the participants had experience working with VR, they showed interest in this tool for the wide variety of opportunities it offers. Among those opportunities participants mentioned: design proofing, training and retraining, as well as workers abilities’ testing – in which an operator is asked to perform task in simulators to evaluate his performance. VR, they said, could help designers to identify flaws in their prototypes *“way before they are implemented”*. Companies can start training workers long before the system is set up; once the system is running, in case of an unexpected change to the workstations workers could be quickly re-trained with VR while the changes to the station are being finished. Participants also suggested VR as a *“hiring”* tool, since it can be used to evaluate operators’ performance to find the best candidate for each position. As with the other tools, participants found some room for improvement in this tool. They lack important components such as weight, force and volume; in consequence, *“the results may be not worth the time or the investment”*. Cost was also mentioned as a concern, participants said companies would need to invest in different hardware (computers, screens, projectors, etc.) and software. Wages for engineers, ergonomists and line workers would also have to be covered. Learning how to use this tool didn’t seem a complicated process for the participants, since most of the devices consist only of simulators and screens, neither of them requiring the worker to perform tasks different to the ones he/she would have to conduct while working. The correct use of the tools, however, would be difficult and most likely would require a team effort (engineers, ergonomists, computer specialist and line workers). Overall, the tool was seen as very flexible, since it could be used for many different purposes and in conjunction with other tools.

2.3.5 General findings

Through the analysis of the data collected from the 4 workshops, the user's needs and expectations of the tools were classified into 9 critical categories: time, cost, training, difficulty to use, reliability, graphics, flexibility, usefulness and report presentation. These characteristics are, sometimes, intertwined and can be defined as follows.

Time: This category refers to how long it would takes to use the tool from the data collection stage to getting the results.

Cost: The total amount of money necessary to purchase and operate the tool. It includes the tool's price, as well as some other expenses such as the investment needed for training and usage, salaries and additional equipment.

Training: Denotes the level of difficulty and effort needed to master the tool. Learning how to properly use these tools sometimes implies acquiring knowledge not directly related to the tool's operation itself, but the interpretation of complex statistical or ergonomic information.

Difficulty to use: The level of complexity to use the tool before obtaining results. Even after receiving enough training, using some tools can still be a difficult process. Some tools require difficult data collection, complicated analysis, various iterations, integration of different technologies and even team efforts.

Trustworthiness: The capacity to generate accurate results, information that reflects the reality of the processes being designed and analyzed, and that can be used to make design decisions. This emerged as one of the most common concerns among the participants who detected some mistrust in the tools. The reasons behind the mistrust depend on the particular characteristics of each tool.

Graphics: Perhaps the most appreciated characteristics in the tools was their graphic capacity. Participants seemed to favor tools with powerful visual effects. The incorporation of 3D environment drawings and animation adds sense of reality to the tools, and in some cases allows the user to evaluate reach, space and fit for a given task.

Flexibility: The quality of being adaptable to and useful in different situations, as well as a complement to other tools. Participants appreciate the capacity of using two or more tools in conjunction, and a single tool for different kinds of evaluations.

Usefulness: The overall benefit a potential user thinks he could get from each tool. Usefulness is the most subjective of all the categories identified, since it can be influenced by the user's perception of the other 8 categories, which in turn may not always be accurate. As a general rule, however, usefulness could become the main reason for a positive or negative decision towards the use of any VHF tool.

Report presentation: The way in which results are presented was identified as another one of the most important aspects that should be considered by all the tools. Sometimes, some participants said, the reports can be very complex, overloaded with all kinds of information and hard to interpret. Therefore, participants suggested modifying the layouts in such a way that the most relevant information (such as risk of injuries and maximum loads) is presented in the first pages, in a simple language and maybe using some indicators such as charts and colors, while the most complex details are included in further sections of the report. The importance of the results presentation has been identified before (Laring, 2006). In regards to the risk indicators, participants also expressed some concern about the way in which risk levels are presented. Some of the tools show risk levels with numerical scales, others

with a simple color code. Participants explained that although using a color risk indicator could simplify interpretation for some by associating colors and risk levels (red – danger, yellow – caution, green – safe), it also leaves room for interpretations that can be made based on personal judgment. For an instance, someone can associate a “yellow” situation with caution when in reality it could be very close to the dangerous status. Having this kind of indicators can easily lead to miscalculations and hence to possible accidents. Alternatively, a numerical indicator can be hard to interpret for someone with limited knowledge of ergonomics. As a solution, participants suggested that in order to have an accurate interpretation, the risk description should be complemented with a numerical ranking as illustrated in figure 8.

All these 9 categories identified in this thesis represent the main characteristics shared by the tools; characteristics that can act as a motivational or deterring factor for the use of the VHF tools. Table 2 shows how participants perceived each tool’s performance in each one of those key factors.

Table 2. This table presents the way participants perceived the VHF tool’s performance in 8 of the 9 main characteristics identified. The mark ‘X’ implies that that particular tool may present some problems in that aspect.

	DES	PMTS	SDHM	CDHM	VR
Time	X	X		X	X
Cost	X			X	X
Training	X		X	X	
Difficulty	X	X		X	
Reliability	X		X	X	X
Graphics		X			
Flexibility			X		
Usefulness	X

Figure 8. If based only in a color indicator, a worker might consider a situation “level 6” (yellow) as somehow safe, when in reality is closer to be dangerous

2.4 Study 1 discussion

This study considers ergonomists and engineers as the “consumers” of a product that is meant to help them ease their job. Very few people had spent time thinking how to design products for designers; after a thorough search in the literature, only one example of research conducted based on this same premise was found (Rosson et al., 1988); and even this case is limited only to the development of software tool’s interface. No research that we are aware of has ever discussed ways to improve ergonomic tools from the user’s perspective before. The study of the user’s experiences has become a key factor for the development of computer based tools (Hassemzahl and Tractinsky, 2006). Carroll and Thomas (1988) explained that studying the user experience is fundamental for the development of “systems people really want to use” since it could be “a very potent determinant of subjective judgments of [the tool’s] usability”. Considering the VHF tools users’ experiences is also essential for the development or further improvement of tools ergonomist and engineers really want to use.

2.4.1 For the developers of the VHFT

How can the results presented in this thesis help tool's developers and industry (users and potential users)? The answer to this question will depend entirely on the developers of each tools to consider these findings, a decision that will be influenced by some of the opportunities for improvement here identified. For instance, the lack of weight and volume associated with some of the VR tools could be solved by implementing "haptic" devices similar to the technology employed by the popular Nintendo Wii (Lee, 2008). Although the incorporation of physical and psychological factors was mentioned by participants in each one of the workshops, in reality the inclusion of some of those aspects (such as illumination, sound levels and even some psychological factors) would be practically impossible in tools like DHM and DES (Stanney et al., 1998); it would be possible, however, to consider some of those environmental aspects in VR. In the specific case of DES, we believe the inclusion in the software of some crucial human factors is needed if this tool is going to be used for real ergonomic purposes. Developers could create subroutines (similar to the ones for statistic data) in which an ergonomist could include forces and time of exposures for a given tasks; the results should be later included in the final report. The creation of a "pay per use" choice for expensive tools such as DHM could be beneficial not only for the "small" companies, but also for the creators of the tools. Software could be uploaded to the developer's websites, where people could have access to them by paying a fee. Also, the use of different tools for a same project could be motivated by the developers, to deal with the trustworthiness issues. For instance, to evaluate the design of a new workstation PMTS could be used to calculate task duration while SDHM would be employed to evaluate the loads, then all this data would be entered in DES software. Although DHM are the most popular of the VHF tools, there is still a need for development to reflect the ever evolving complexity of the processes. In today's industry many of the manufacturing processes call for very detailed tasks involving the handling and assembly of tiny components. These jobs are hard to represent by DHM, some of which don't even consider articulations in the mannequin's fingers. More important, the safe/unsafe limits on which DHM based their calculations need to be reviewed to reflect the reality of the anthropometrics of today's society.

2.4.2 Perceived misconceptions of the tools

One of the biggest obstacles for the VHFT is the apparent mistrust on their results. One of the reasons for that mistrust, as expressed by the participants, is the way the input data is collected. DES is particularly sensitive to data collection processes, however, there is available specific methodology for the collection and management of quality data for DES (Skoogh and Johansson, 2008). Another obstacle for the VHF tools is misconceptions of the tools usage, capabilities and stages of the design process in which they are employed. A clear example of this misconception emerged around DES; during the workshops none of the ergonomists was familiar with this tool, only some of the engineers knew the principles of DES, which may be the reason why this group was more receptive to the tool than the ergonomists. This lack of knowledge and experience prevented participants from seeing DES as a potential ergonomic tool. Another perceived misconception is when to use each tool during the design process.

Neumann and Wells (2008) analyzed the ways and design stages in which some ergonomic tools are being or could be utilized by industries (see Figure 9), their analysis suggest that the potential of the tools is not being fully understood by users. For instance, no VHF tool is listed as used during the “project specifications” stage, where ergonomist prefer to depend “*on the knowledge of previous production systems*” to determine the initial key requirements of the new system to be designed. Although there is no doubt the experience acquired in previous projects should be considered, the use of tools like VR at this stage could be suitable.

Figure 9. This graphic illustrates the design stages in which the VHFT are commonly used. As time passes and design advances, the opportunities for virtual ergonomics decrease. Once the system is operational, the application of ergonomics switches from proactive to reactive only (Adapted from Neumann & Wells, 2008)

The potential of the VHF tools could be as large as the creativity and the ways they could be used shouldn't be set on stone. Tools like VR and DES could be used in different stages of the design process, in combination with other tools for a variety of purposes such as evaluation of workers with future stations (fit, reach and space) or the analysis of possible accumulation of fatigue, learning rates, recovery needs and such; just like the example presented in Study 2 of this thesis, in which DES, PMTS and SDHM were used for a single ergonomic analysis.

2.4.3 The nine key characteristics

Other unique aspect of this thesis is that for the first time the common characteristics present in all the VHFT are presented to the industry to facilitate their development. This research allowed the identification of 9 main aspects shared by the VHF tools; this findings are identified similarly in line with other investigations such as the one conducted by Ranganathan and Ganapathy's (2002), who found 4 “*key dimensions*” or characteristics that make commercial websites effective: information content, design, security and privacy. Carroll and Thomas (1988) stated that a good software interface should be, among other things, easy to learn and easy to use. In this research we found ‘training’ and ‘difficulty to use’ were seen by participants as key components of the VHF tools. In the marketing literature some benchmark can also be found that helps to further validate these results. If we think of VHFT users as “consumers”, we could assume their needs and expectations are similar to the needs of the users of any other goods and/or services. Therefore, some of the 9 characteristics identified for the VHF tools could be compared to the characteristics consumers seek in products and services available in the market. As an example, research has proven

that product's presentation provokes responses that can sometimes influence the decisions of the consumers, without taking into account "*performance or functional attributes*" (Bloch, 1995). Similarly, the graphic capabilities of some VHF tools could convince designers to choose one tool over another, without fully considering other attributes. In the markets, the success of products depends sometimes on the relation between costs and consumers overall perception of the products' different characteristics (Kotler and Rath, 1984). In the same fashion, the cost of buying and operating the VHF tools can be a powerful decisive factor, particularly when evaluated against the tool's perceived usefulness.

2.5. Study 1 conclusions

The following conclusions can be obtained from Study 1:

Nine identified characteristics shared by the VHFT can act as a motivational or deterring factor for the use of each tool. These characteristics are: time, cost, training, difficulty to use, trustworthiness, graphics, flexibility, usefulness and report presentation. These characteristics should be considered by developers as "requirements" (see figure 2), one of the first steps in the design process.

Some degree of misconception seems to be influencing the decisions of the users and potential users of the VHFT, causing them to overlook or underestimate the potential of some of the tools. Among the tools presented to participants during the workshops, CDHM was regarded by ergonomist as the most useful, while DES's ergonomic application remained underappreciated.

One of the most recurrent suggestions offered by participants was the integration of different VHFT for ergonomic analysis, similar to the way in which SIMTER integrates ergonomics, levels of automation and environmental concerns into a single tool.

Several research opportunities were identified in this study, including the importance of a further analysis of engineers' needs and expectations of the VHFT, the integration of different tools in a single project and the use of DES for the prediction of possible ergonomic issues.

3. STUDY 2 - DISCRETE EVENT SIMULATION, A PLATFORM FOR THE INTEGRATION OF DIFFERENT VHFT

3.1 Introduction

This thesis presents an approach for the integration of fatigue and recovery models to conventional Discrete Event Simulation (DES). The results obtained from Study 1 suggested a possible misunderstanding or underestimation of the DES capabilities for ergonomic purposes. Ergonomists amongst the participants to the workshops were rather cautious about DES, a tool they regarded as intended for production engineers. A few examples can be found in the literature that demonstrate that it is in fact possible to use DES successfully in the ergonomic field (Walters et al., 2000; Baner and Mason, 2004; Neumann and Medbo, 2005; Neumann et al., 2006; Neumann and Medbo, 2009). But no example could be found in the literature that utilized DES as a primary tool to directly predict some of the effects of the exposure of workers to systems, such as learning curves, muscular fatigue accumulation and recovery needs. Ergonomist attending the workshops conducted for Study 1 consistently manifested disbelief in the capacities of DES as an ergonomic tool. Furthermore, one of the most frequent suggestions presented by participants in Study 1 was the integration of different VHFT into a single ergonomic project. These findings obtained in Study 1, therefore, set the stage for a new research presented in this Study 2. As illustrated in figure 1, fatigue is considered a precursor for human errors, which in turn leads to reduced quality, accidents and different health issues that affect workers and system performance and increase costs (as explained in section 1.2 of this thesis). It was decided then to use DES in an attempt to predict the accumulation of fatigue in a manufacturing process.

The aim of this study is to explore the feasibility of the integration of different VHFT as a proactive approach to the ergonomic issues, using DES as a platform to predict fatigue accumulation under three work/rest schedules.

3.1.1 The concept of fatigue

Before deciding on the best way to calculate the fatigue trace in the simulation, it was important to understand its concept. Fatigue is a phenomenon that has been defined as “a *loss of efficiency and a disinclination for any kind of effort*” (Grandjean, 1979) and can be classified into two categories, physical (muscular) and psychological (mental) fatigue (Grandjean, 1979). The physical aspect of fatigue is usually related to soreness and pain; while the mental aspect manifests as tiredness, boredom and sleepiness.

Psychological fatigue:

Psychological or mental fatigue has been defined as a “*diffuse sensation which is accompanied by feelings of indolence and disinclination for any kind of activity*” (Grandjean, 1979). Mental fatigue can have negative consequences both in cognitive and physical activities, and it is mainly measured with self-report techniques (Åhsberg, 1998) such as:

- Borg scale (Borg, 1990).
- Visual analogue scale (Bond and Lader, 1974).
- Body part discomfort rating (Corlett and Bishop 1976).
- Checklist Individual Strength (CIS) (Vercoulen et al., 1994).
- Dutch questionnaire on perception and judgment of work (Van Veldhoven, 1994).
- Visual analogue scale (Scott and Huskisson, 1976).
- Fatigue/Risk index for work schedules (Folkard et al., 2007).
- Swedish Occupational Fatigue Inventory (SOFI) (Åhsberg et al., 1997).

Since the evaluation of mental fatigue is based on “self-reported” techniques, it can be assumed this evaluation is “subjective”. Currently, to my knowledge, there is no mathematical model to predict mental fatigue similar to the ones utilized for muscular fatigue. However, some examples exist in which subjective estimates of mental fatigue have been used as input to predict some fatiguing effects on human performance. One example is the study conducted by Walters et al. (2000), in which sleep deprivation, the disruption of the circadian rhythm, work shift rotation, and different crew sizes were analyzed in Discrete Event Simulation (DES) to measure their affect in military operations performance. For this project, it was decided that an “objective” measurement of fatigue was needed for the simulation purpose; therefore, physiological fatigue was favored over mental fatigue for our research purpose.

Physiological fatigue:

Physiological or muscular fatigue has been defined as “an exercise induced reduction in the maximal capacity to generate force or power output” (Vøllestad, 1997). Muscular fatigue is the result of static and/or dynamic exertion, and its manifestation can be influenced by personal characteristics such as sex, age, health history (Williamson et al., 2005). It can also quickly lead to a reduction of the capacity to generate force, lower performance, increased reaction times and slowing of the sensory abilities (Åhsberg, 1998). The accumulation of physical fatigue leads to a reduction of eye-hand coordination, and to increase time in movement and muscle contraction (Gage, 1974). The process of muscular fatigue starts with the activation of motoneurons, which in turn trigger the activation of motor units by sending signals transferred through the nervous system producing muscle contraction. The activation of the muscles then results in the generation of force and finally in the manifestation of fatigue (Vøllestad, 1997). This process is illustrated in Figure 10.

Muscular fatigue can be evaluated in an “objective” way – sometimes quantification – thanks to different devices and methods (Kankaanpää, 1997; DeBuke et al., 1979; Sluiter et al., 2009; Zenz et al., 1966):

- Electromyography (EMG)
- Maximum Endurance Time (MET)
- Heart rate
- Blood pressure
- Levels of oxygenation
- Blood perfusion

➤ Respiration rate

Figure 10. The process of fatigues starts with an order send by the brain to the motor units, which in turn activate muscles generating forces, the continuous generation of those forces will produce accumulation of fatigue.

EMG and MET are, arguably, the most common methods to measure muscle fatigue (Frey-Law and Avin, 2010; El ahrache et al. 2006). The “objective” quantification of muscular fatigue offered by some of these methods and devices can be used for the creation of mathematical models to predict possible fatigue outcomes, most of them based on MET.

3.1.2 Maximum Endurance Time (MET) models

In static fatigue analysis, Maximum Endurance Time (MET) represents the maximum time that a muscle can sustain a load during an isometric exertion (El ahrache et al., 2006). MET is calculated as a function of a Maximum Voluntary Contraction (MVC) – the peak force produced by a muscle as it contracts. The relative voluntary level of muscle’s exertion is expressed as a fraction or a percentage of the Maximum Voluntary Contraction ($fMVC$ or $\%MVC$) (El ahrache et al. 2008). When the worker reaches the MET, it is assumed that he has also reached 100% level of fatigue hence been unable to maintain the load. These calculation of MET based on MVC is seen as “*the gold standard to identify if fatigue occurs or not*” (Vøllestad, 1997). Several MET prediction models can be found in the literature, some are considered “general” and some of them are specific to different body parts such as shoulder, elbow and hands. These models have been reviewed by El ahrache et al. (2006).

3.1.3 Recovery and Rest Allowance (RA)

Other important concept for this simulation project is recovery. Recovery is defined as “*the need to recuperate from work induced fatigue*” (Swaen et al., 2003). Excessive workloads produce an increase in the worker’s neurological and physiological activity levels (Sluiter et al., 2003), creating a need for recovery after every task and/or at the end of the day-shift. When not fully satisfied, recovery becomes an independent risk (Swaen, 2003) and it contributes to exacerbate the accumulation of fatigue. Insufficient recovery can accelerate the process of fatigue, which in turn would produce a greater need for recovery thus creating a vicious cycle not to be broken until enough recovery is granted, either by planned breaks or until the individual cannot perform anymore. One way to predict the recovery need is through the calculation of rest allowance (RA). El ahrache and Imbeau (2008) defined RA as the “*time needed for adequate rest following a static exertion, and is generally expressed as a percentage of holding time, i.e., the time during which a static exertion, static posture or a combination of both is maintained without interruption*” and presented four different RA models: Rohmert’s (1973), Milner’s (1985), Rose et al. (1992) and Byström & Fransson-Hall (1994).

3.2 Methodology

In collaboration with the Netherlands Organization for Applied Scientific Research (TNO), it was decided to create a DES model to simulate the accumulation of fatigue throughout a day-long work shift. TNO researchers had been recently experimenting in ways to increase production outputs without compromising the worker’s wellbeing (Van Rihjn et al., 2006; de Looze et al., 2010). For the proposed solution, the researchers created and tested three different work/rest schemes to find the one which yielded the highest output with lowest discomfort rates. The work/rest schemes were tested at Philips DAP (producer of electric shavers). The data collected from the Philips case study offered a real process opportunity to base this experiment, as well as some validation potential to support the development of the methodology.

Figure 11 illustrates the process followed in this study. The project was initially divided in two components: A biomechanical analysis to produce task times and loads and a DES model to obtain process time patterns. Existing fatigue and recovery models were then used to calculate the fatigue trace throughout the work-shift, based on the information yielded by the biomechanical analysis and the DES model.

Figure 11. Biomechanical analysis performed in WATBAK and PMTS, and a DES model, were used to obtain data needed for the calculation of the accumulation of fatigue throughout a work-shift.

3.2.1 Biomechanical analysis

For the prediction of fatigue two sets of data were needed, the loads expressed in %MVC and times required to perform each task. Most of these data was obtained from an MTM analysis conducted by TNO researchers and company's engineers on the Philips plant in the Netherlands (Table 3). Three of the loads were directly provided as a %MVC by TNO researchers, the rest were shown in Newtons. Loads in Newtons and task durations, as well as postures observed in a video provided by TNO were evaluated in WATBAK to calculate the missing %MVC. Table 3 shows the results of the MTM analysis of a duty-cycle – the amount of work performed within one cycle (Mathiassen and Winkel, 1991; Moore, 2000) – conducted by TNO researchers. Each duty-cycle consisted of 9 tasks, with 4 repetitions per task. The final %MVC are also included in Table 3. Figure 12 illustrates the average durations (in percentage of cycle time) of the 9 tasks in relation to their respective *f*MVC.

Table 3. Some of the most significant results of the MTM analysis provided by TNO (time in seconds).

	Total (secs)	Duration (%Cycle time)	Estimated force (N)	%MVC
Task 1	3.00	6.4%	N/A	2%
Task 2	6.33	6.8%	N/A	15%
Task 3	20.29	21.7%	40	4%
Task 4	15.38	33%	10	14%
Task 5	9.60	10.3%	30	18%
Task 6	9.60	10.3%	30	22%
Task 7	4.15	4.4%	N/A	15%
Task 8	5.89	6.3%	20	11%
Task 9	0.38	0.8%	10	16%
Cycle time		100%

Figure 12. This diagram illustrates the 9 task performed by worker #3 in every cycle, in relation to their respective *f*MVC.

3.2.2 DES model

A Rockwell Arena DES model was created based on the Philips production line illustrated by Figure 13, consisting of four different work stations and two buffers connected by conveyor belts. All stations involved light and repetitive assembly work, with similar movements, postures and forces. The simulation was run using a gamma distribution, with mean times and 10% variability as indicated by TNO. Some other important input for the DES model, such as the specifications of the conveyor belts and arrival times, were not provided and had to be calculated through video analysis. The diagram of the simulation model is presented in Figure 13. A sub-model was created at workstation 2 level (Final assembly in Figure 13).

This sub-model, based on the times presented in Table 2, simulated each duty-cycle performed by *the subject under investigation* (worker #3 in Figure 13). The task times produced by the sub-model, as well as each task loads (Figure 13), were recorded on an Excel spreadsheet, which in turn used that information to perform a series of calculations that resulted in the fatigue trace. The calculations performed in Excel are explained in a following section.

Figure 13. This diagram represents the existing Philips assembly line modelled in Rockwell Arena.

Rotation schemes

Three different rotation schemes (S1, S2 and S3) presented by De Looze et al. (2010) were evaluated in the simulation (Figure 14). Scheme 1 (S1) consisted of 12 operators and 5 breaks: a 30 minutes lunch recess and 4 shorter breaks distributed over the shift. All workers took their breaks at the same time. Scheme 2 (S2) consisted of 12 workers assigned to the line and 2 more who would take over the work of the operators on break; the 30 minutes launch break would be taken as a group. The second alternative, Scheme 3 (S3), was similar to S2 with the inclusion of an extra 10 minutes break, and the reduction of the 15 minutes break down to 10 minutes in the second part of the shift.

Figure 14. The three rotation schemes evaluated in the simulation (Van Rihjn et al., 2006; De Looze et al., 2010).

3.2.3 Fatigue and Recovery Models

A total of 7 MET models were selected amongst the ones presented by El ahrache et al. (2006) (see Table 4). Five of those are general models: Rohmert (1960), Sato (1984), Manenica (1986), Sjogaard (1986) and Rose (1992). The other two models Rohmert (1986) and Mathiassen and Åhsberg (1999) are shoulder specific models. Two of the five general models, Rohmert and Sato, were used considering there is no accumulation of fatigue below 15%MVC. Of the four Rest Allowance (RA) models presented by El ahrache and Imbeau (2008) only two were selected for this research: Rohmert's (1973) and Rose's (1992). The selection of these two models was based on the ability they have to be used for different muscular group, while the Milner (1985) and Byström & Fransson-Hall (1994) were rejected due to their muscle/posture constraints. The Milner RA model assumes a hand posture of 50% shoulder height and 100% forward reach, while the Byström & Fransson-Hall model only considers hand/wrist intermittent work.

Table 4. The five MET general models, two MET shoulder-specific models and two Rest Allowance Models used in this study.

Models	MET General	MET Shoulder Specific	Rest Allowance (RA)
Rose (1992)	$7.96 * e^{-4.16 fMVC}$	-	$RA = 3 * MET^{-1.52}$
Rohmert (1960, 1986, 1973)	$-1.5 + \frac{2.1}{fMVC} - \frac{0.6}{fMVC^2} + \frac{0.1}{fMVC^3}$	$0.2955 * fMVC^{-1.658}$	$RA = 18 * fMET^{1.4} * (fMVC - 0.15)^{0.5}$
Sato (1984)	$0.3802 * (fMVC - 0.04)^{-1.44}$	-	-
Manenica (1986)	$14.88 * e^{-4.48 fMVC}$	-	-
Sjogaard (1986)	$0.2997 * fMVC^{-2.14}$	-	-
Mathiassen (1999)	-	$40.6094 * e^{-9.7 fMVC}$	-

As seen in Table 5, the selected MET and RA models were paired based on two premises: those which consider accumulation of fatigue under 15%MVC, and those who assume there is no fatigue when the level of exertion is inferior to that threshold. Since the Rohmert models don't consider the accumulation of fatigue under loads lower than 15%MVC, his RA model was used in combination with the MET models that follow that principle. The Rose RA model was used in combination with the MET models that do consider accumulation of fatigue below 15%MVC. The combination of RA and MET models is presented in Table 5.

Table 5. The Rose RA model was used to calculate the recovery needs in conjunction with 4 MET models: Manenica, Sjoogard, Rose general and Rose muscle specific. The Rohmert RA model was paired with Sato, Rohmert and Rohmert muscle specific MET models.

	Rose RA model (Fatigue accumulates below 15%MVC)	Rohmert RA model (Fatigue doesn't accumulate below 15%MVC)
Rose	✓	X
Rohmert General		✓
Sato	X	✓
Manenica	✓	X
Sjogaard	✓	X
Mathiassen (shoulder)	✓	X
Rohmert (shoulder)	X	✓

3.2.4 Calculations

The principle of the calculations of the fatigue model was based on the assumption that, if MET is the maximum time a muscle can hold a load hence reaching 100% of its fatigue quota, then $\frac{\text{tasktime}}{\text{MET}}$ would represent the fraction of fatigue (f_F) reached by the muscle after performing a single task. Similarly, the fraction of recovery (f_R) was obtained by dividing the resting time given to the muscle after performing a task by the total resting time needed to fully recover from the fatigue accumulated. The graphic in Figure 15 (assumed to be linear only for illustrative purposes) represents the process of fatigue accumulation after performing one task, and the subsequent recovery of the muscle achieved until the start of the next task.

Thus, fatigue is given by:

Where:

$$F = fF_{t-1} + \frac{\Delta t}{MET_i} - \frac{\Delta t}{R_j}$$

Figure 15. The behaviour of fatigue accumulation while trying to simulate a dynamic process using static MET models.

Procedure:

The calculations of the fatigue trace were performed in an Excel spreadsheet linked to the simulation software through a read/write module. The simulation model sent the times and load information after each task to the Excel spreadsheet, which in turn calculated the fatigue accumulation following this procedure (each step corresponds to one column in the spreadsheet, every task performed corresponded to one row):

1. Based on task time (t_i) and $fMVC_i$ obtained from the DES model, calculate Maximum Endurance Time (MET_i) using each of the selected MET models presented in Table 3.
2. For each task, calculate the fraction of fatigue (fF_i) contribution by dividing the time (t_i) obtained from the DES simulation by the MET_i calculated in step 1.

$$fF_i = \frac{t_i}{MET_i}$$

3. Based on MET_i obtained in step 1 calculate RA_i using each of the models presented in Table 3.
4. Based on the RA_i obtained in step 3, calculate the resting time needed to fully recover from task i .

$$R_i = t_i * RA_i$$

- Calculate the accumulation of recovery need.

$$\text{Accumulated } R_{i+1} = R_{i-1} + R_i - r_i$$

- Obtain the fraction of the recovery received at time i .

$$fR_i = \frac{r_i}{\text{Accumulated } R_i}$$

- Calculate the fatigue accumulation after task _{i} (F_i)

$$F_{i+1} = (F_{i-1} + fF_i) * (1 - fR_i)$$

3.3 Results

3.3.1 Utilization rates

In this project, regardless of the scheme, the simulation suggested an underutilization of some of the operators in station 2 (Figure 16). In the specific case of the subject under investigation – employee 3 (see figure 13), the maximum utilization rate was slightly above 62%. These low utilization rates allowed for extra time for recovery, which in turn reduce the fatigue accumulation rates.

Scheme 1		Scheme 2		Scheme 3	
	Inst Util	Instantaneous Utilization	Average		Inst Util
Buffer 1	0.00	Buffer 1	0.01203738	Buffer 1	0.03
Buffer 2	0.03	Buffer 2	0.0974	Buffer 2	0.09
Employee 1	0.86	Employee 1	0.8750	Employee 1	0.88
Employee 10	0.65	Employee 10	0.6512	Employee 10	0.66
Employee 11	0.61	Employee 11	0.6120	Employee 11	0.61
Employee 12	0.13	Employee 12	0.1264	Employee 12	0.13
Employee 2	0.59	Employee 2	0.5895	Employee 2	0.60
Employee 3	0.62	Employee 3	0.6209	Employee 3	0.59
Employee 4	0.54	Employee 4	0.5037	Employee 4	0.53
Employee 5	0.01	Employee 5	0.03639272	Employee 5	0.07
Employee 6	0.00	Employee 6	0.05560866	Employee 6	0.06
Employee 7	0.72	Employee 7	0.7258	Employee 7	0.73
Employee 8	0.70	Employee 8	0.7081	Employee 8	0.70
Employee 9	0.67	Employee 9	0.6884	Employee 9	0.69

Figure 16. Utilization rates as shown by the Arena software report for each simulated scheme.

3.3.2 Fatigue analysis

The simulation provided an opportunity to graphically track the accumulation of fatigue at any time of the work shift – after only one cycle, three cycles, 10 cycles or at the end of shift. Figure 17 illustrate how fatigue accumulates differently depending on the model been utilized.

Figure 17. Illustration of the accumulation of fatigue under three different models after one cycle (left), after three cycles (centre) and after 10 cycles (right). The simulation allowed to graphically track the accumulation of fatigue throughout the work-shift.

Great variability between fatigue model outputs was detected regardless of the rotation scheme. Although the same calculations were performed with each model based on the same levels of MVC and times of exposure; some models built up fatigue very fast, while others remained in or close to zero. The results produced by the MET models were particularly sensitive to time of exposure, perhaps even more than to the load level itself. As seen in Figure 18 (which show the accumulation of fatigue in just one cycle in relation to the $fMVC$), for some models fatigue accumulated in a fast rate, reaching up to 16% of the workers daily quota in only one duty-cycle shorter than 50 seconds. However, fatigue quickly decreased to 0 during the idle times in between duty-cycles, that allowed for not scheduled recovery opportunities.

Figure 18. Regardless of the low MVC levels, fatigue tended to build up in some modes as fast as it went back down to 0. In this graphic, the accumulation of fatigue plotted against the $fMVC$ of each of the nine tasks in one duty-cycle.

The Rose general model was consistently the fastest fatigue builder, followed by the Manenica's model and the Mathiassen muscle specific model (see figure 19). All other models continuously yielded no fatigue at all, or levels very close to 0. Only Rose's general model consistently registered a significant fatigue trace in the three schemes.

Figure 19. The Rose model consistently reports higher levels of fatigue, considerably above the other 6 models. These graphics show the fatigue accumulated at the end of the shift for each scheme.

The low accumulation of fatigue was caused by the unscheduled recovery allowed by long pauses between duty-cycles. The idle time workers spent in the simulation waiting for the next carrier to arrive sometimes exceeded the length of a full cycle-time. In order to simulate an intensification in the workloads to further explore the models behavior it was decided to reduce the length of the pauses. The analysis of the simulation results was conducted using 100%, 90%, 75%, 50%, 25% and 10% of the time lost during the pauses – sometimes scheduled, some times the result of disturbances in the process; 17% (approximately 1/6) of the pause time obtain from DES was also used, since research has shown that static exertion could lead to complete fatigue almost 6 times as fast as dynamic exertion (Bakke et al., 1996). This variability created an opportunity to analyze the ways in which the pauses (both scheduled and disturbances) affected the accumulation of fatigue (results are presented in table 6). Even after reducing the scheduled resting time and other pauses, all the models that do not consider the accumulation of fatigue below 15%MVC remained unaltered; while the only significant differences in the accumulation of fatigue were detected on the Rose and Manenica Models.

Table 6. Accumulation of fatigue at the end of the shift using 100%, 90%, 75%, 50%, 25%, 17% and 10% of the pauses time yielded by the simulation.

Accumulated fatigue at the end of the shift (using 100% of the breaks/pauses time)							
	No fatigue Below 15%MVC		Fatigue Above 15%MVC			Muscle specific	
	Rohmert	Sato	Manenica	Sjogaard	Rose	Rohmert	Mathiassen
Scheme 1	0.0002	0.0002	0.0122	0.0036	0.0264	0.0002	0.0082
Scheme2	0.0001	0.0001	0.0034	0.0000	0.0063	0.0001	0.0014
Scheme 3	0.0284	0.0342	0.0957	0.0386	0.1711	0.0425	0.0755

Accumulated fatigue at the end of the shift (using 90% of the breaks/pauses time)

	No fatigue Below 15% MVC		Fatigue Above 15%MVC			Muscle specific	
	Rohmert	Sato	Manenica	Sjogaard	Rose	Rohmert	Mathiassen
Scheme 1	0.0002	0.0002	0.0122	0.0036	0.0759	0.0002	0.0082
Scheme2	0.0001	0.0001	0.0034	0.0000	0.0063	0.0001	0.0014
Scheme 3	0.0284	0.0342	0.0957	0.0386	0.1711	0.0425	0.0755

Accumulated fatigue at the end of the shift (using 75% of the breaks/pauses time)

	No fatigue Below 15% MVC		Fatigue Above 15% MVC			Muscle specific	
	Rohmert	Sato	Manenica	Sjogaard	Rose	Rohmert	Mathiassen
Scheme 1	0.0002	0.0002	0.0122	0.0036	0.3123	0.0002	0.0082
Scheme2	0.0001	0.0001	0.0034	0.0000	0.1410	0.0001	0.0014
Scheme 3	0.0284	0.0342	0.0957	0.0386	0.2069	0.0425	0.0755

Accumulated fatigue at the end of the shift (using 50% of the breaks/pauses time)

	No fatigue Below 15% MVC		Fatigue Above 15% MVC			Muscle specific	
	Rohmert	Sato	Manenica	Sjogaard	Rose	Rohmert	Mathiassen
Scheme 1	0.0002	0.0002	0.0122	0.0036	0.9933	0.0002	0.0082
Scheme2	0.0001	0.0001	0.0034	0.0000	0.8823	0.0001	0.0014
Scheme 3	0.0284	0.0342	0.0957	0.0386	0.5407	0.0425	0.0755

Accumulated fatigue at the end of the shift (using 25% of the breaks/pauses time)

	No fatigue Below 15% MVC		Fatigue Above 15% MVC			Muscle specific	
	Rohmert	Sato	Manenica	Sjogaard	Rose	Rohmert	Mathiassen
Scheme 1	0.0002	0.0002	0.3502	0.0036	14.8816	0.0002	0.0906
Scheme2	0.0001	0.0001	0.3222	0.0000	10.5833	0.0001	0.0014
Scheme 3	0.0284	0.0342	0.1604	0.0386	13.3740	0.0425	0.0854

Accumulated fatigue at the end of the shift (using 17% of the breaks/pauses time)-static fatigue accumulates 6 times faster

	No fatigue Below 15% MVC		Fatigue Above 15% MVC			Muscle specific	
	Rohmert	Sato	Manenica	Sjogaard	Rose	Rohmert	Mathiassen
Scheme 1	0.0002	0.0002	1.3022	0.0036	28.7235	0.0002	0.3280
Scheme2	0.0001	0.0001	1.5111	0.0000	26.6420	0.0001	0.3266
Scheme 3	0.0284	0.0342	1.0293	0.0386	29.1847	0.0425	0.1465

Accumulated fatigue at the end of the shift (using 10% of the breaks/pauses time)

	No fatigue Below 15% MVC		Fatigue Above 15% MVC			Muscle specific	
	Rohmert	Sato	Manenica	Sjogaard	Rose	Rohmert	Mathiassen
Scheme 1	0.0002	0.0002	9.1674	0.0494	40.8338	0.0002	1.6011
Scheme2	0.0001	0.0001	6.8942	0.0014	40.6911	0.0001	2.2080
Scheme 3	0.0284	0.0342	8.4421	0.0450	43.0202	0.0425	2.1291

The pauses in the process were so long that the results yielded by the models remained almost unaltered until the pauses were reduced to 50%. At this point, a significant increase in the Rose model fatigue accumulation was registered. All the combination of models used under the assumption that there is no accumulation of fatigue below 15% MVC (see Table 5) remained unaltered regardless of the idle time variability. Mathiassen muscle specific model showed only a slight increase in the fatigue accumulation trace at the lowest levels of resting time (below 25% of the total pauses obtained from DES); something similar occurred with Sjogaard's model. Figure 20 illustrates the models behaviour in relation to the rest variability. Given these results, it was decided to use only the general models, at 50% rest variability, to compare the simulation results against the data obtained by the TNO researchers. In their results, TNO researchers (De Looze et al., 2010) measured discomfort amongst Philips workers every 25 minutes throughout a work-shift, in the same fashion, fatigue accumulated by the simulation model was measured every 25 minutes. The results are presented in Table 7.

Figure 20. Accumulation of fatigue at the end of the shift for different break/pauses times allowance, represented in a logarithmic scale.

Table 7. After reducing the pauses and scheduled breaks in 50%, some of the recesses were long enough as to bring fatigue down to 0. The lunch break (12:00 pm) is so long that any accumulation of fatigue will disappear.

Time	Scheme 1			Scheme 2			Scheme 3		
	Manenica	Sjogaard	Rose	Manenica	Sjogaard	Rose	Manenica	Sjogaard	Rose
7:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7:25	0.00	0.00	0.75	0.00	0.00	0.75	0.00	0.00	0.75
7:50	0.03	0.00	0.22	0.03	0.00	0.22	0.03	0.00	0.22
8:15	0.08	0.03	1.26	0.96	0.04	2.78	0.96	0.04	2.78
8:40	0.07	0.02	0.13	0.00	0.00	0.83	0.00	0.00	0.83
9:05	0.02	0.00	0.87	0.00	0.00	0.00	0.10	0.04	1.66
9:30	0.02	0.00	0.76	0.00	0.00	0.26	0.00	0.00	0.00
9:55	0.00	0.00	0.10	0.06	0.02	0.76	0.01	0.00	0.98
10:20	0.00	0.00	0.12	0.10	0.04	0.92	0.00	0.00	0.82
10:45	0.06	0.02	0.53	0.08	0.03	0.54	0.02	0.00	0.64
11:10	0.07	0.02	1.88	0.12	0.02	1.69	0.10	0.04	1.29
11:35	0.00	0.00	0.57	0.00	0.00	0.68	0.09	0.04	1.05
12:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12:25	0.06	0.02	0.92	0.00	0.52	0.03	0.03	0.00	0.76
12:50	0.00	0.00	0.15	0.00	0.00	0.24	0.09	0.04	0.45
13:15	0.00	0.00	0.90	0.08	0.03	0.17	0.00	0.00	0.31
13:40	0.05	0.02	0.95	0.00	0.00	0.00	0.00	0.00	0.15
14:05	0.00	0.00	1.50	0.00	0.00	0.31	0.53	0.17	2.57
14:30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14:55	0.06	0.02	1.52	0.01	0.00	0.58	0.09	0.04	1.02
15:20	0.00	0.00	0.31	0.05	0.02	0.24	0.00	0.00	0.00
15:30	0.01	0.00	0.99	0.03	0.00	0.49	0.00	0.00	0.26
15:45	-	-	-	0.05	0.02	1.10	0.03	0.00	1.06
16:10	-	-	-	0.01	0.00	0.47	0.02	0.00	0.21
16:20	-	-	-	0.00	0.00	0.88	0.10	0.04	0.62
16:25	-	-	-	-	-	-	0.10	0.04	0.54

The study conducted by the TNO researchers identified scheme 3 (which they presented as alternative 2) as the work/pause schedule plan with the lowest accumulation of discomfort after one shift; with scheme 2 (alternative 1) producing the highest accumulation of discomfort. The results produced by the simulation experiment using the Rose model suggest that scheme 3 causes the lowest accumulation of fatigue, which is in line with the findings obtained by TNO researchers (Figure 21). The simulation, however, indicated that the highest accumulation of fatigue was produced by scheme 1, whereas TNO found that scheme 2 produced the highest level of discomfort at

the end of the shift. Some spikes in the fatigue accumulation were registered at different times in the simulation, they can be explained by the fast accumulation of fatigue in the MET models.

Figure 21. TNO researchers measured discomfort levels every 25 minutes. At the end of the shift, schedule 2 (A1) registered the highest level of discomfort, followed by scheme 1 (T). Scheme 3's discomfort trace remained very low.(De Looze et al., 2010). The simulation results using the Rose model put Scheme 3 as the one with the lowest accumulation of fatigue, followed by scheme 2, while scheme 1 yielded the highest fatigue.

The results produced by the models, however, were sensitive to the pauses. When using 100% of the pause time scheduled for the simulation, all 7 models ranked scheme 3 as the one with the highest accumulation of fatigue, with scheme 2 as the one with the lowest accumulation (see Figure 22).

Figure 22. At 100% pause time all seven MET models produced very low accumulation of fatigue compared to the accumulation of discomfort reported by TNO researchers (left). However, all the models consistently ranked scheme 3 as the one with the highest accumulation of fatigue and scheme 2 as the one with the lowest fatigue (right).

As the models started to build a bigger accumulation of fatigue, after reducing the pause times, the ranking of scheme's fatigue trace produced by each model at the end of the work-shift changed. For example, as seen in Figure 23, when reducing pause times by 50%, the accumulation of fatigue produced by the Rose model jumped considerably while the accumulation of fatigue produced by the other six models remained stable. As a result, while the ranking of schemes remained the same for most models, it changed for the Rose model.

Figure 23. At 50% pause time the accumulation of fatigue produced by the Rose model increased significantly, but remained stable for the other six MET models (left). But while the scheme ranking remained unaltered for six of the MET models, it changed for the Rose model (right). the lowest fatigue (right).

3.4 Study 2 discussion

Study 2 demonstrates that it is feasible to use Discrete Event Simulation for the prediction of fatigue, and possibly for other ergonomic purposes such as learning and possible development of MSD. Although the use of DES as a mean to predict fatigue and human performance in working systems had been attempted in the past (Walters et al., 2000, Neumann and Medbo, 2005; Kazmierczak et al., 2007) to the authors knowledge no step has been taken to embed some recognized muscle fatigue and recovery models into a computer simulation. The DES model created in Rockwell Arena not only produced a fatigue trace but allowed the graphic and numerical analysis of the accumulation of fatigue at any given point during the work-shift. This study presents a first step towards a wide array of opportunities for similar analysis that may also include learning curves, the development of work-related musculoskeletal disorders and other possible hazards.

Some difficulties faced during the creation of the DES model, such as the implementation of workers rotations and loads, showed that this kind of software has not been created for ergonomic purposes. The potential application of DES in the ergonomic field could be increased by including some ergonomic 'add-ons' in the software, similar to the way in which developers have already added other applications such as cost-analysis. According to the results obtained in Study 1, *flexibility* is one of the 9 main characteristics shared by the VHFT; furthermore, participants to

the workshops (Study 1) suggested the use of different VHFT for a single ergonomic project; in Study 2 three of the VHFT were applied: PMTS, SDHM and DES.

3.4.1 The fatigue models - Static or Dynamic?

Although the objective in Study 2 was to explore the integration of different VHFT for the analysis of possible ergonomic outcomes (in this case the accumulation of fatigue), the focus of the investigation switched to the fatigue prediction models. One of the initial questions for this study was what kind of model was more suitable for the present research, a dynamic or MET based static model? The difference between static and dynamic exertion in work practices has been analyzed before (Ma et al., 2009). Sustained efforts seemed to produce fatigue much quicker than dynamic efforts; regardless of these differences, existing fatigue and recovery models mainly based on static conditions. In reality, almost any job is performed under dynamic situations, where times, exerted forces and postures are constantly changing. In order to apply any of the available MET based fatigue prediction models, it would be necessary to reproduce strict lab conditions under which workers would have to sustain unchanged postures and force levels. Although the limitations of these models had been clearly recognized before (Iridiastadi et al., 2006; El ahrache et al., 2006), researchers continue investing time and resources in the development of new static models that, according to the evidence, most likely would not have a real applicability. No example of static fatigue models being applied in the 'real' world could be found in the literature; however, some examples exist of attempts to use static models in an almost dynamic manner (Iridiastadi, 2006).

The development of dynamic models has proven to be a rather complicated task. Mathematically, both static and dynamic fatigue can be predicted. However, the prediction of fatigue under dynamic conditions calls for a wide array of inputs such as maximum forces, force levels at different times, torque loads and joint movement ranges. This makes of the creation of good dynamic models a complicated, and sometimes a case-specific endeavor. Some examples of dynamic prediction of fatigue include the mixed-integer linear programming model proposed by Jaber and Neumann (2010), the muscular fatigue model based on worker's own characteristics and external loads presented by Ma et al. (2009), or the muscle activation and deactivation model proposed by Xia et al. (2008).

Static models present some challenges of their own. The accuracy of using these kind of models to predict fatigue in a real life activity remains an unanswered question. Some evidence, however, suggested that static models cannot mimic dynamic activities due to big differences in the rate of accumulation and manifestation of fatigue. Research has shown that static exertion could lead to complete fatigue almost 6 times as fast as dynamic exertion (Bakke et al., 1996). In their study, Bakke et al. found that after static exertion subjects reported higher levels of pain (more than twice as much) than after dynamic exertion; blood pressure also increased more (about 3 times more) under static conditions than during dynamic tasks. According to Bakke et al. (1996), although fatigue seems to accumulate faster under static than under dynamic situations, the recovery need is greater for dynamic tasks than for static loads. More evidence of the fast accumulation of fatigue under static exertions can be found in other studies. DeBusk et al. (1979), for instance, suggest that static efforts contribute to a fast and large increase in blood pressure and heart rate. Stone et al. (2003) found that under dynamic exertions it is possible to handle (lift) more weight than under static

exertions. In their study they found that, at low force (MVC) levels, the subject's power output was bigger under dynamic circumstances; at high force levels, however, the power output was higher during static exertion. Researchers should recognize the applicability problems faced by static models in real work systems, as well as the barriers faced by the existing dynamic models mainly due to their complexity, then focus their efforts on the development of dynamic models with real application in work-systems and processes.

3.4.2 Study limitations

During the experiment some evidence emerged that showed the difficulties of using a static model to predict the accumulation of fatigue under dynamic circumstances. The simulation produced big differences in the results yielded by each model, even though they were being applied under the same circumstances; the accumulation of fatigue was so high in some models that had the potential to reach 100% in no more than 6-7 duty-cycles, while in some other models fatigue levels remained close to 0. According to El ahrache (2006), the static fatigue models that have been developed by different authors so far show considerable discrepancies in their results when applied to the same kind of situations. This finding is consistent with the results of this study, creates some doubt on the reliability of the existing MET models and proved to be an important issue in Study 2.

The accumulation of fatigue is influenced by other physiological and psychological stressors besides loads and times of exposure, however, this study doesn't consider other variables analyzed in literature. One clear example is the learning curve, which could lead to an increase or decrease in the accumulation of fatigue. Experienced workers tend to perform their duties in a faster pace than new employees, which in turn could lead to an increase in the number of cycles or repetitions performed, hence increasing fatigue. At the same time, these experienced workers are less susceptible to mistakes such as excessive use of forces or bad postures. Frey-Law and Avin (2010) suggested the consideration of muscle fiber types, motor unit activation and neural activation. Vøllestad (1997) expressed the need to specify the kind of contraction and movements highlighting the fact that, so far, the MET models are only valid for isometric activities. The need for considering all these precursors in the modeling of fatigue has been supported by some scientific studies, such as the one performed by Jones et al. (1989) who demonstrated that, as Vøllestad (1997) had said, the rate of the fatigue accumulation depends on the kind of movement being performed, with eccentric movement producing a faster accumulation of fatigue than concentric movements. Another challenge for the application of MET based models is the fact that the levels of fatigue are significantly different depending on the body region being analyzed (El ahrache et al. 2006; Frey-Law and Avin, 2010), reason why body part-specific models had been created.

Other problems presented by the MET based models and faced during the development of Study 2 are the differences in the use of exponential, power or linear functions; as well as the argument of the lack of accumulation of fatigue when the levels of exertion are lower than 15% MVC.

Exponential and power functions

For the prediction of MET, researches have based their models on two main functions: power and exponential. Three of the MET models used in this thesis are based on exponential functions, Rose's (1992), Mathiassen's (1999) and Manenica's (1986). Three of the models are power functions, Rohmert's (1986), Sato's (1984) and Sjogaard (1986). Which one of these functions is more accurate remains an unanswered question and may depend on different factors. It is known that exponential models can under-predict MET when the %MVC is very low (Frey-Law and Avin, 2010), as is typically the case with light assembly work such as the one simulated in this project. Therefore, it may be better to utilize power function models when the MVC is lower than 25%. The graphic representation of some studies suggests that at even lower levels of force (below 15%MVC) fatigue accumulates in a linear manner (Pan et al., 1996).

Accumulation of fatigue below 15%MVC

The manifestation of fatigue at very low force levels has been a controversial and underexplored topic, and it poses another challenge for the validity of MET models. Some researchers argue that there is no accumulation of fatigue when the force levels are lower than 15%MVC (Rohmert, 1973; Byström, 1994), while others have presented a case for the existence of fatigue in prolonged activities with low forces (De Looze et al., 2009).

3.4.3 Fatigue Vs. Discomfort - Comparison Validity

The Philips case study is based on a perceived rate of "discomfort" reported by the workers during different times of the work-shift. The Borg Scale, as a measurement of fatigue, is influenced by "psychological" factors, therefore, it is a subjective measure that could depend on mental states that are difficult to simulate.

For the computer simulation purposes an objective (mathematical) measurement was needed, the decision was made to use MET models based on the limited set of data available. However, in order to accurately predict the fatigue process in work environments, it would be necessary to apply a combination of methods and models that include psychological and physical aspects of fatigue. This idea has been explored before; Kankaanpää et al. (1997) found a high degree of correlation between the results of EMG and Borg Scale based reports of fatigue. Kumar et al. (2006) employed a number of psychological and physiological methods to measure localized spinal fatigue.

3.5 Study 2 conclusions

Study 2 demonstrated that it is possible to use Discrete Event Simulation as an ergonomic tool that can be applied in design to predict, and therefore prevent, possible negative outcomes of the exposure of humans to work related practices. Furthermore, it offers an example of how to combine different VHFT for a single analysis.

The difficulties faced during the creation of the DES model reinforce some of the concerns expressed by participants to the workshops (Study 1): it is in fact hard to use Discrete Event Simulation in an ergonomic analysis, mainly due

to the low degree of interest shown by developers towards human factors. Users and potential users' perception of DES *difficulty to use*, *trustworthiness* and *usefulness* (all part of the 9 characteristics identified in Study 1) could be improved if developers considered some of human factors when creating new software. Examples of human factors that could be included in DES are loads, number of repetitions, postures, learning curves and times of exposure, to mention a few.

Study 2 built upon two of the main results obtained in Study 1: that ergonomists amongst participants to the workshops failed to see DES as tool with ergonomic potential and the possibility of using different VHFT together for a single ergonomic project. By using DES to predict fatigue outcomes, the results presented in this thesis demonstrate that the ergonomic use of this tool is feasible. The combination of DES, PMTS and SDHM represents an example of how different VHFT can complement each other.

Study 2 represents an exploration of the feasibility of the use of DES for the prediction of fatigue and recovery, but it could also be used to virtually evaluate other outcomes of the exposure of humans to work systems. This study represents the first step in a research that needs further development, and should be considered only as a first step towards a more comprehensive integration of DES and fatigue prediction models that include both psychological and physiological factors, as well as a full set of data.

4. DISCUSSION

The two studies conducted for this thesis presented some challenges to the nature of the methodology. For instance, in the case of the VHFT workshops, determining the correct sample size in qualitative research is rather a complicated task (Sandelowski, 2007), particularly if the nature of the methodology impairs the capacity to control such samples. Although a workshop based research approach provides some advantages, such as interaction and constant feedbacks, the attendance levels cannot be fully predicted. With this in mind, it was intended to conduct as many workshops as considered sufficient to obtain a reasonable sample size. Although having an equal representation of ergonomists and engineers in the audience, the participation of the former exceeded more than three times the attendance of the latter. In consequence, the flow of some of the discussions might have been determined or at least influenced by a majority of ergonomists and some important feedback from engineers could have been lost. Further research, particularly with engineers, may be required to explore this issue.

Another possible weakness of Study 1 was the participants' lack of experience in the use of DES. None of the participants had previous experience using DES; in the best scenario, some of the engineers *"had seen some colleagues using it in the company"*, but none of them had real hands-on experience with the tool. This could have influenced the responses participants had towards this VHFT.

The written feedback from participants was rather low; this was mainly due to the fact that the sessions were too full of discussions as to give participants enough time to write about the tools. Although questionnaires were handed out to participants, very few took the time to fill them up. Only 17 questionnaires were received back from participants, and not a single one was completed; for these reasons, it was decided to use the questionnaires only as a supplementary source of information. None of the participants got back to the research team with some feedback after receiving the report, which was interpreted as a confirmation of the validity of the findings.

With regards to Study 2, one weakness is the limitation in the application of work-related fatigue prediction models. The selection of the models did not necessarily reflect the suitability of the model for the topic being analyzed, but rather the fitness of the model to the data provided by the researchers at TNO. Although the Philips case provided the opportunity of a real system to be simulated, TNO research was not originally intended for a DES project.

5. CONCLUSION

5.1. With regards to the VHFT investigation

Nine categories or characteristics of critical concern to the VHFT's users and potential users group were identified. These categories are: time, cost, training, difficulty to use, trustworthiness, graphics, flexibility, usefulness and report presentation. These 9 characteristics could be used as a starting point for new investigations that evaluate specific VHF tools; they could also be taken by developers as a guide when creating or improving their products. Improvement opportunities specific to each of the VHFT analyzed in this thesis have been identified, such as the consideration of additional physical (i.e. haptics for VR, fingers articulation for SDHM and CDHM) and psychological human factors (i.e. fatigue and learning curves). A misconception of some of the tools exist amongst users and potential users; work system designers need to broaden their array of tools to open the door to new or non-traditionally ergonomic tools such as DES and PMTS. Important opportunities for further research on the VHF tools were also identified in this research, such as possible new applications, integration of different VHFT and further analysis to each VHFT in the context of the 9 identified characteristics.

5.2 With regards to the DES/fatigue study

It was demonstrated that DES can be used as an ergonomic tool for the prediction of the accumulation of physical fatigue and recovery during a work-shift. Other similar applications could include mental fatigue, learning curves and the development of MSD. It was also demonstrated that it is possible to use different VHFT in a single ergonomic evaluation, in this case DES was utilized in conjunction with PMTS and SDHM. Study 2 also uncovered a need for the development of new and reliable fatigue and recovery prediction models that can be applicable during the design of work systems. DES offers an opportunity for developers interested in exploring the addition of HF to this tool, and for ergonomists to experiment with this prediction tool.

6. RESEARCH OPPORTUNITIES

Most of the VHF research being conducted today focuses on the technical aspects of the tools, particularly on CDHM. Very few studies consider the user's perspective, with one of the few exemptions being Blomé's et al. (2006), who studied how to improve efficiency by reducing time consuming tasks. To further evaluate and understand the needs of users and potential users of the VHFT, a series of questionnaires and interviews to engineers and ergonomist could be a valuable contribution. The identification of the 9 characteristics shared by the VHFT could be used as a platform upon which more focused research can be done, for instance, investigating how a particular VHFT performs in each one of the 9 characteristics. The integration of different VHF tools in a single platform, as suggested by some of the participants, could also be an important development for the application of ergonomics early in design. An example of this kind of integration is SIMTER, a software that allows the integration of ergonomics, level of automation and even environment in a single platform (Berlin et al., 2009). SIMTER users can create a 3D production environment, combining CDHMs and DES with tables of environmental impact of chosen equipment. DES represents a largely unexplored field for human factors purposes. The application of DES in ergonomics is still in its first stages, with very limited examples found in the literature (Water et al., 2000; Neumann and Medbo, 2005; Kazmierczak et al., 2007). DES could become, with the proper development, a powerful tool for prediction of work-related fatigue, injuries, learning rates and other ergonomic issues. Another research opportunity emerged from this thesis is the development of new fatigue and recovery prediction models, models that reflect the reality of the working processes. Fatigue, an apparently well documented topic, offers still many opportunities for research, particularly in relation to its contribution to accidents, MSDs, absenteeism, cost increases and other inherent aspects of work environments.

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