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The Integration of Human Factors into Discrete Event Simulation and Technology Acceptance in Engineering Design

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THE INTEGRATION OF HUMAN FACTORS INTO DISCRETE EVENT SIMULATION AND TECHNOLOGY ACCEPTANCE IN ENGINEERING DESIGN

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ABSTRACT

THE INTEGRATION OF HUMAN FACTORS INTO DISCRETE EVENT SIMULATION AND TECHNOLOGY ACCEPTANCE IN ENGINEERING DESIGN

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This action research thesis aimed to: 1) develop and test a viable Discrete Event Simulation and Human Factors Modeling approach for an Ontario based telecommunication company, and 2) identify the factors that affect the uptake and application of the approach in work system design. This approach, which was validated at the Company, incorporated fatigue dose and learning curves in a Discrete Event Simulation model. The barriers to uptake included: Time constraints, lack of technological knowledge and initial cost. The uptake facilitators were: High frequency products produced, clear value added to leadership, defects reduction and the Company being open to new technology. In addition to helping design a manual assembly line with fewer bottlenecks and reduce the human factors risks for the employee, the developed approach showed a 26% correlation with quality defects. Further research is recommended to identify additional human factors and their benefits.

ACKNOWLEDGEMENTS

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Sincere thanks to our industry partners RP, ES, AB, TC, SM, and TA for their dedication and contributions to the success of this collaboration; and especially to AD for his additional review and feedback on this report.

I would also like to thank my family for their support and encouragement throughout this journey. Without you I would have not finished this thesis.

In conclusion, I recognize that this research would not have been possible without the financial assistance of MITACS Accelerate Ontario, the Workplace Safety and Insurance Board and Ryerson University's Department of Mechanical and Industrial Engineering and express my gratitude to them.

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NOMENCLATURE

Acronym	Term	Definition
%MVC	Fraction of MVC	Fraction of MVC when performing a task
AME	Advanced Manufacturing Engineering	Department at the Company
Company	Company	A Waterloo, Ontario based telecommunication company, which this project was done in collaboration with.
CT	Cycle Time	The measured time that takes the manual assembly employees to perform all the assigned tasks
DES	Discrete Event Simulation	"an operational research technique that allows the end user to assess the efficiency of an existing or proposed system" (Jun et al., 1999).
ED	Engineering Design	" effective decision making which requires that alternative options to be evaluated against some objective measure of 'goodness' " (Love & Barton, 1996).
FD	Fatigue Dose	Cumulative fatigue obtained during a defined time period.
HF	Human Factors	"the scientific discipline concerned with the understanding of interactions among humans and other elements of a system and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance" (IEA Council, 2000).
HFM	Human Factors Modeling	An ergonomic research technique which assesses the mechanical loading that humans are subject to when performing a specific task.
LC	Learning Curve	The relationship of "of reasonable competence at industrial and many other skills" vs. time (Welford, 1968)
ME	Manufacturing Engineering	Department at the Company
MET	Muscular Endurance Time	"the maximum time that a muscle can sustain a load during an isometric exertion" (El Ahrache et al., 2006)
MVC	Maximum Voluntary Contraction	"the peak force produced by a muscle as it contracts" (Perez, 2011).
PAR	Participatory Action Research	"research aiming at solving specific problems within a program, organization, or community, explicitly and purposefully becoming part of the change process by engaging the people in the program or organization in studying their own problems in order to solve those problems" (Patton, 2002).
PEOU	Perceived Ease Of Use	Variable in the Technology Acceptance Model shown in Figure 6

Acronym	Term	Definition
PT	Pause Time	The measured time from the end of one CT to the beginning of the next consecutive CT
PU	Perceived Usefulness	Variable in the Technology Acceptance Model shown in Figure 6
RA	Rest Allowance	"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" (El Ahrache & Imbeau, 2008).
TAM	Technology Acceptance Model	Illustrated in Figure 6

The caveat ***(Note: all figures are fictitious)*** is used to denote figures that have been adjusted to preserving the Company's confidentiality. The adjustment preserves the relationship of the results without showing the exact numbers.

Chapter 1 - Introduction

Human Factors (HF) is defined by the International Ergonomics Association as “the scientific discipline concerned with the understanding of interactions among humans and other elements of a system and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance” (IEA Council, 2000). As it can be seen by this definition, HF is concerned not only with the human in the system but with the system itself.

According to the Canadian Council of Professional Engineers (CCPE), the first obligation that a professional engineer has to fulfill is “hold paramount the safety, health, and welfare of the public, and the protection of the environment, and promote health and safety within the workplace” (Canadian Engineering Qualifications Board, 2009). This point aligns well with the definition of Human Factors. More attention should be paid to Human Factors related health disorders as they cost about the same as all cancers combined (Leigh et al., 1997). Work system design practices tend to be system performance-focused and don’t always include attention to HF. Considering humans in work system design has the potential to help companies improve their performance in ways that are humanly sustainable, that is, HF can help to prevent quality and productivity problems while eliminating health hazards for employees. According to Industry Canada statistics, 75% of Manufacturing employees, or greater than 1.3 million individuals in Canada, work in Production (Industry Canada, 2008), and are at risk within the manufacturing industry which has the highest number of work-related injuries per annum (Industry Canada, 2009). Manufacturing companies commonly leave HF efforts to ‘retrofitting’ production systems late in the development process if at all (Dul & Neumann, 2009; Jensen, 2002), and do not realize the direct costs and hidden indirect costs (Rose et al., 2011), and increased difficulty of late consideration retrofitting (Miles & Swift, 1998). However, the most efficient means of minimizing human factors related losses occurs upstream in the production system design stage, and through effective integration of human factors within the production system design process (Neumann et al., 2002). This is echoed by The Ministry of Labour’s ‘Ontario Subcommittee on Ergonomics’ (OSE) which has stated that “A proactive approach and early intervention strategies are integral to the reduction and elimination of the incidence of work-related MSD” (Ontario Ministry of Labour, 2005). The challenge of integrating human factors into work system design is an area needing investigation. The simultaneous monitoring of production and human factors indicators not only promotes higher production and worker health, but allows a company to increase productivity and profit (Oxenburgh et al., 2004).

Despite its importance, HF has not traditionally been used proactively in systems' design but rather reactively (Laing et al., 2005; Neumann & Dul, 2010). Miles and Swift (1998) and Bonney et al., (2000) show that the effectiveness of changes in design is greater when used early in the engineering design process, as it results in lower cost, ease of change and higher quality as shown in Figure 1. Only recently some authors have tried to shift the HF focus from reactive to proactive (Broberg, 1997; Neumann et al., 2004) however proactive use of HF is still uncommon. Research shows that using HF early in design will prevent some of the issues, (i.e., defect rates, fatigue, musculoskeletal disorders, absenteeism, etc.), 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 (Perez, 2011; Neumann & Dul, 2010).

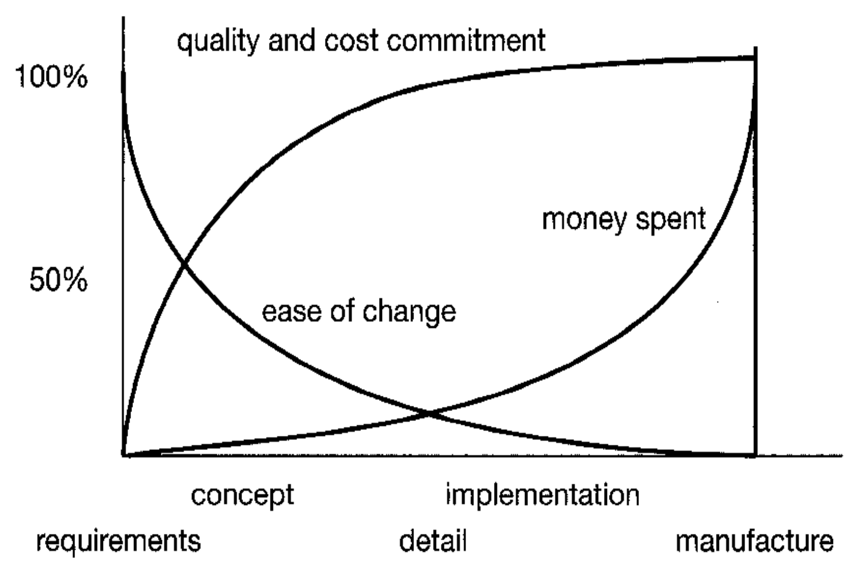

Figure 1 - Effectiveness of HF when used early in the design process (Miles & Swift, 1998) – *Quality and cost of the product improve when HF is used early in the design process.*

Not including HF in the early stages of the design process has negative effects both to the human and the system (Neumann & Dul, 2010). Some of these effects are tabulated below in Table 1.

Table 1 – Effects of HF omission in the design process (Neumann & Dul, 2010) – *HF affects not only the people involved in the system but also the system itself.*

Human effects	**System effects**
Health	Productivity
Attitude	Quality
Physical workload	Implementation of new technology
Quality of work life	Intangible benefits

Waterson & Kolose, (2010) state that accounts of the problems involved in applying human factors within industry have a long history, dating back to some of the earliest examples of research and practice within this field. The positive effects of HF may be greatly increased through the integration of HF with DES (Neumann & Medbo, 2009), due to the fact that HF can be used through DES which is already present in most engineering design processes. Engineering Design (ED) is defined as "effective decision making which requires that alternative options to be evaluated against some objective measure of 'goodness' " (Love & Barton, 1996). Tools are needed to provide the alternative options to the engineering designers during ED (Perez, 2011). These tools should be able to provide a clear view of the effects the alternative options have both on the system and the humans in it. Figure 2 illustrates the relations between design and HF risks in a system. This figure shows that the HF effects in a system are the result of a chain of decisions made at different levels in a company. The chain starts with organizational strategic decisions, continues in the production system design and has its effects in the production system and consequently, in the profitability of the system. Systems designers' decisions affect HF issues in different stages of the process, and that is why tools should be made available to them to minimize the negative and capitalize on the positive HF effects.

This project aims to assist a company in developing Discrete Event Simulation (DES) and Human Factors modeling (HFM) capabilities. Simultaneously, the project aims to explore and identify the factors that affect the uptake and application of the DES and HFM in work system design.

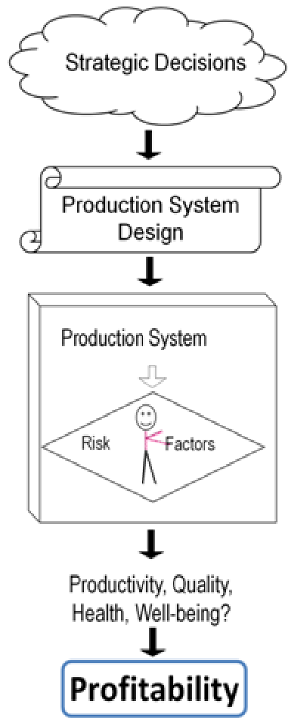

Figure 2– Design and HF relations in a system (Neumann & Winkel, 2006) – *Decisions made in the system design stage will first of all affect the system and secondly the humans.*

1.1 Why Discrete Event Simulation (DES)?

Discrete Event Simulation (DES) is an operational research technique that allows the user to assess the efficiency of an existing or proposed system (Jun et al., 1999). It is used to represent a system via a computer program that enables the testing of engineering design changes without disruption to the system being modeled (Rossetti, 2010). This operational research technique allows the engineering designers with the exploration of ED alternative options. Simulation can be used to solve problems which are too complex to be solved by mathematical methods. By using mathematical methods like calculus, probability theory or algebraic methods, there can be only one final solution (Kelton et al., 2008). Additionally simulation is faster to use than using mathematical methods. The speed of performing the necessary calculations and obtaining the answers to the questions posed is very important in industry. When simulation is used the better insight can be obtained in the final solution and it is also useful when multiple system resources are present, (Banks et al., 2005) as it can provide the simulator with the option of studying additional different scenarios. Comparison of the feasible solutions would give the researcher the option to choose, leading to the optimal one applicable to the real world. The system evaluated in this thesis is considered to be complex due to the variables present and that is why simulation was used in this project. Some of the variables present in the simulation include material arrival rate (material required for each station to perform the assigned tasks), the number of employees (break schedules, number of employees per station, employee utilization), the processing time (value added cycle time, non value added pauses) and line defect rates.

Changing simulation inputs and observing the resulting outputs can produce valuable insight into which variables are the most important and into how variables interact (Banks et al., 2005). The importance of the variable would dictate the amount of focus paid to them as it would affect what decisions to make when designing. By using simulation, the simulator doesn't interfere with the existing system's operations. Furthermore the employees' performance is not affected as the simulator is mainly out of sight and does not distract them. Minimized interference with the daily operations of the system is crucial to the system's stakeholders.

1.2 Why Human Factors Modeling (HFM)?

In this thesis, Human Factors Modeling (HFM) is defined as an ergonomic assessment approach which assesses the mechanical loading that humans are subject to when performing a specific task. It offers the human factors/ergonomics specialists or engineering designers "the promise of an efficient means to simulate a large variety of ergonomics issues early in the design of products and manufacturing workstations" (Chaffin, 2008). Since engineering design has a big impact on all parts of a company (Love & Barton, 1996), including effects on humans in the system, mechanical loading of the manufacturing line workers can be traced back to the decisions that engineers make (Neumann et al., 2006). HFM in this thesis is concerned with the optimization of the human well-being and performance in the manufacturing line system in two ways: Fatigue accumulation and Learning curves.

1.2.1 Muscular fatigue model

Muscular fatigue has been defined as "an exercise induced reduction in the maximal capacity to generate force or power output" (Vøllestad, 1997). Muscular fatigue leads to the reduction of the capacity to generate force, lower performance, increased times and slowing of the sensory abilities (Åhsberg, 1998). Lower employee performance and increased time are factors that affect a manufacturing line resulting in bottlenecks, and fewer products produced. The process of muscular fatigue is shown in Figure 3.

One of the ways to calculate muscular fatigue quantitatively is through Muscular Endurance Time (MET) models. The 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 (Perez, 2011). The relative voluntary level of muscle's exertion is expressed as a fraction or a percentage of the Maximum Voluntary Contraction (%MVC) (El Ahrache & Imbeau, 2008). When the worker reaches the MET, it is assumed that he has also reached 100% level of fatigue is therefore unable to maintain the load (Perez, 2011). The calculation of MET based on MVC is seen as "the gold standard to identify if fatigue occurs or not" (Vøllestad, 1997). El Ahrache et al., (2006) present a summary of 24 MET models in literature.

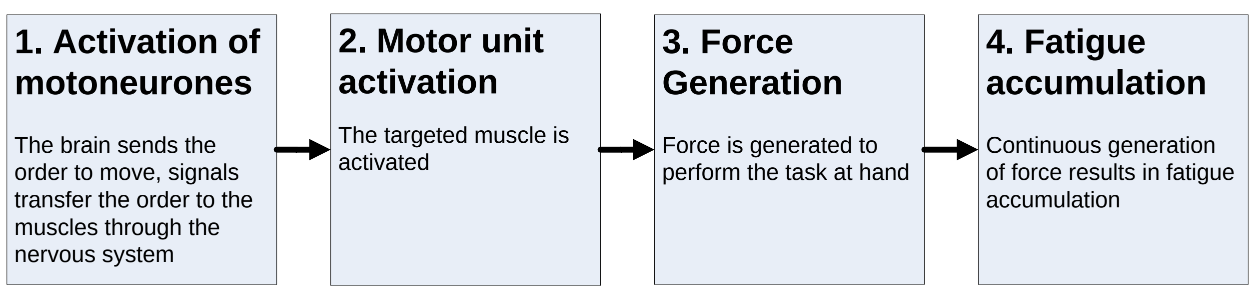

Figure 3 – Muscular fatigue process - *the process of muscular fatigue starts with an order sent by the brain to the motor units, which in turn activate muscles generating forces. The continuous generation of those forces will result in the accumulation of fatigue* (Perez, 2011).

The Rose general MET model (El Ahrache et al., 2006; Rose et al., 1992), shown below in Equation 1, was used for the purpose of this thesis as it is not specific to any particular muscle, i.e: shoulders, but it can be applied to any muscle in the human body (Perez, 2011). Another reason that this model was used is that it considers fatigue accumulation below 15% MVC (Perez, 2011).

MET = $(7.96)e^{-4.16(\%MVC)}$ **(Eq 1)** – Rose et al., 1992 *general MET model*

1.2.2 Muscular recovery model

Muscular recovery is complementary to muscular fatigue accumulation. Recovery is defined as "the need to recuperate from work induced fatigue" (Swaen et al., 2003). When enough recovery is not provided the results "contribute to exacerbate the accumulation of fatigue" (Swaen et al., 2003). Insufficient recovery can accelerate the process of fatigue, which in turn would produce a greater need for recovery; creating a vicious cycle not to be broken until enough recovery is granted (Perez, 2011).

An individual's recovery need is calculated as Rest Allowance (RA), which is defined 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" (El Ahrache & Imbeau, 2008). The RA model chosen from El Ahrache & Imbeau (2008) is the Rose model, shown below in Equation 2.

$$RA = 3MET^{-1.52}$$ **(Eq 2) –** Rose et al., 1992 *Rest Allowance model*

The Rose general RA model was used for the purpose of this thesis as it is not specific to any particular muscle and considers fatigue accumulation below 15% MVC (Perez, 2011), and also allowed consistency with the fatigue model.

1.2.3 Fatigue Dose (FD)

As mentioned in section 1.2, fatigue accumulation is the first human factor used to optimize the human well-being in the manufacturing line. The principles of muscular fatigue and recovery were combined to obtain the FD for the employees of the system being simulated. They were combined together to account for the fatigue accumulated during the performance of a task and the recovery of fatigue during the following pause. The combination of these two elements is shown in Figure 4 which illustrates the process of fatigue accumulation and recovery per task used in the simulation. Figure 4 shows that the recovery obtained by the employee could either be sufficient to reach full recovery or not.

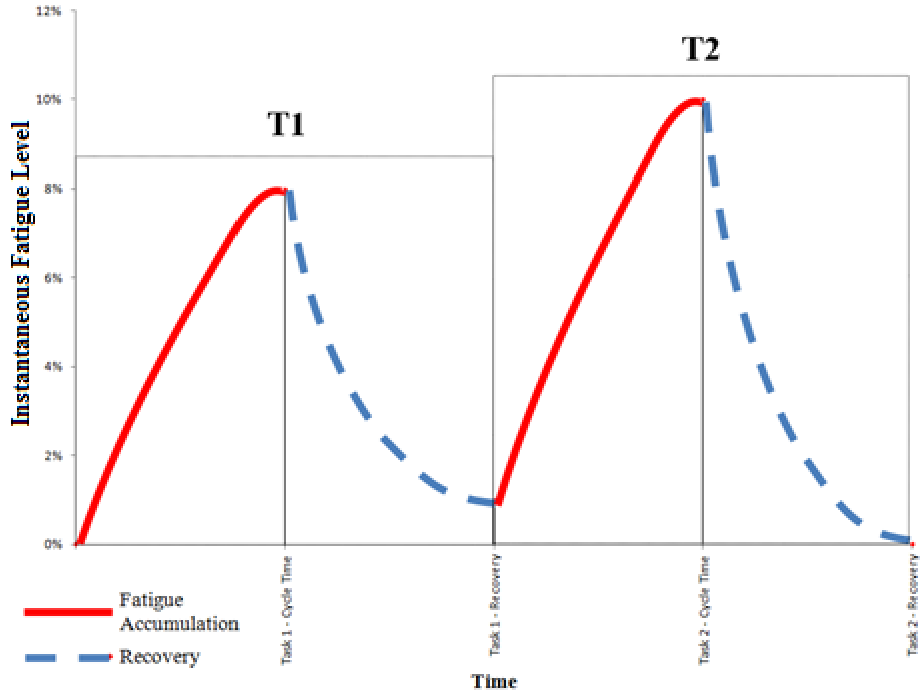

Figure 4 – Fatigue accumulation and recovery per task principle – *the solid line shows the fatigue accumulation during which the employee performs one cycle time. The dotted line shows the recovery obtained from the employee during the pause between two consecutive cycles. As can be seen from the Figure, the employee can fully recover the fatigue (Task 2) or is not provided with enough recovery time (Task 1).*

In some cases, the fatigue level considered could reach zero and would not reflect a good estimate of the total musculoskeletal challenge to the employee. In the case where the employee is provided with enough recovery time, and the fatigue level reaches zero, the measurement of fatigue can be changed from instantaneous fatigue to cumulative fatigue (fatigue dose). This way of capturing the total challenge to the musculoskeletal system is analogous to Norman et al., (1998) where cumulative fatigue provides additional information when compared to instantaneous fatigue. Cumulative fatigue can capture the dose throughout a day. To obtain this FD the area under the curve of Figure 4 needs to be calculated. The integral of the curve will provide us with the area value. The principle used to calculate the fatigue dose is illustrated in Figure 5. The relevance of the fatigue dose principle to this thesis is due to the fact that the manufacturing line employees at the Company being studied undergo prolonged loadings of relatively low loads; therefore the fatigue level indicator would not be sufficient in understanding the HF effects in the line. Therefore FD is used to better understand the fatigue effects in the manual assembly line.

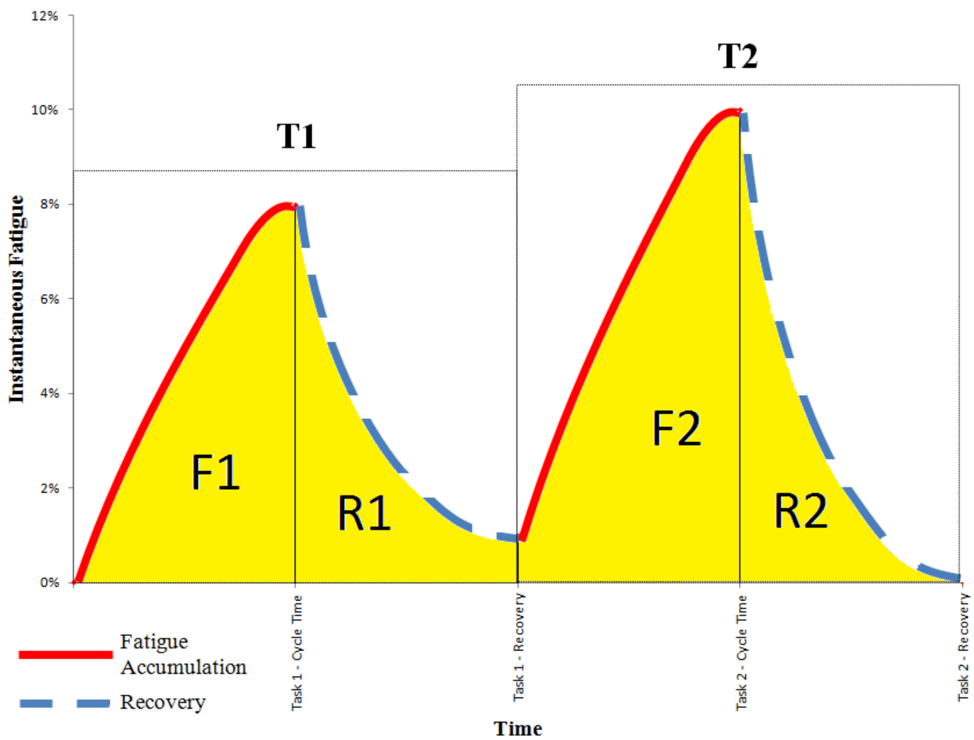

Figure 5 – Fatigue Dose (FD) calculations principle – *to calculate the FD for one task, the integral of the cycle time portion was computed first. Secondly, the integral of the recovery portion was computed and added to the first integral. Namely, the fatigue dose for the first cycle time is F1+R1, whereas the fatigue dose for the second cycle time is F2+R2.*

1.2.3.1 Fatigue and Quality relationship

González et al (2003) have stated that a positive relation exists between improved human factors and better product quality. Yeow and Sen (2003) show that this relation applies to the electronics industry and improved human factors results in "reduction in rejection cost, reduction in rejection rate, and improvement in productivity and quality" among other benefits. Discomfort from strained parts of the body, which results in fatigue, has a direct result in quality deficiencies (Eklund J. , 1995). The relationship and effects of fatigue on the manufacturing line quality yield were explored in this thesis, to illustrate that fatigue affects the system performance and costs. HF consideration in the electronics industry results in a "tremendous increase in productivity and yearly revenue (US$4,223,736) and a huge reduction in defects and yearly rejection costs (US$956,136)" (Yeow & Sen, 2003). Therefore, it would be beneficial to the Company to design their processes with HF , especially FD, in mind as it affects their yield and costs.

1.2.4 Learning curve (LC)

Welford (1968) states that "It is well known that the initial attainment of reasonable competence at industrial and many other skills is followed by a long period of further improvement during continued exercise of the skill". Researchers have observed that unit production costs tend to fall with cumulative output and experience, and have formed LCs to express this relationship (Nembhard & Uzumeri, 2000). These curves have been valuable, in areas such as cost control, forecasting, and strategic planning (Badiru, 1992). In the engineering world, LCs have been modeled to better understand manufacturing costs (Yelle, 1979) and for line balancing of new production runs (Dar-El & Rubinovitz, 1991). The learning improvement results in a decrease in the manufacturing cost of the product and consequently in inventory costs savings (Jaber & Bonney, 2011). When faced with manufacturing and inventory costs reductions "learning cannot be ignored" (Jaber & Bonney, 2011). Jaber and Guiffrida (2004) have stated that "The earliest learning curve models; i.e., of Wright, states that the total quantity of units produced doubles and the time per unit declines by some constant percentage". The assumption made in Wright's learning curve is that "all the units produced are of acceptable quality" (Jaber & Guiffrida, 2004). However, it is not the intent of this thesis to explore the learning curve with the effect of defective units produced.

The relationship between performance time (Tn) and the number of trials follows the power law of practice (Welford, 1968; Helander, 2006; De Jong, 1957). Welford (1968) has proposed that the time taken to perform a repetitive task falls exponentially until it approaches some "incompressible" minimum. The relationship is shown in Equation 3.

$$T_n = T_\infty + \frac{T_1 - T_\infty}{n^k}$$ **(Eq 3) –** *Welford's LC equation*

where T_n is the *n*th cycle time (CT), T_∞ is the incompressible minimum time – that is the time that would be taken if the task was continued for an infinite number of cycles (De Jong, 1957) –

and T_1 is the time taken by the first cycle. The exponent *k* expresses the rate at which improvement takes place with practice (Welford, 1968; De Jong, 1957). This formula was used by Crossman (1959) who found that this relationship gave a reasonably good fit to the data from several laboratory studies and industrial operations. The study of the learning curve effects on production in this thesis provides engineering designers with better insight of the system's behavior under the learning curves effects. This knowledge is provided at the design stage which in turn allows for alternative design options to be explored before the physical system is built and in turn will allow companies to take advantage of the "manufacturing and inventory costs reductions" (Jaber & Bonney, 2011) which results from the employees performing faster.

1.3 Participatory Action Research (PAR)

As mentioned earlier, one of the aims of this project is to explore the impact of alternative engineering designs with a Human Factors (HF) focus. In any type of simulation, the primary concern is the input data. When it comes to DES and HFM, the input data can be in either qualitative or quantitative form and in some cases both (Yoxall et al., 2007; Garani & Adam, 2005). In order to obtain quantitative input data, traditional research methods such as Positivist Science (Barton et al., 2007) are applied. Positivist Science research methods are considered the classical way of performing research. These methods are slowly showing their limitations due to the fact that better results are seen when an interactive research approach is taken (Holmquist, 2009) especially when addressing organizational change and technology uptake research questions.

In the operations research context, the term Participatory Action Research (PAR) is defined as "research aiming at solving specific problems within a program, organization, or community, explicitly and purposefully becoming part of the change process by engaging the people in the program or organization in studying their own problems in order to solve those problems" (Patton, 2002). This is research in which the researcher has to allow the situation to take him/her where it will, whose focus is the knowledge change process itself rather than some hypothesis under test (Checkland, 1985).

This way of thinking is relatively new compared to the more traditional ways of doing experimental research. The origins are traced back to "the social experiments of Kurt Lewin in the 1940s" and the "socio-technical experiments at the Tavistock Institute" (Barton et al., 2007). Even though this new way of thinking has not been around for long, "it has been used in so many different ways that it has lost some of its original importance. The action research family includes a wide range of approaches and practices, each grounded in different traditions and in different philosophical and psychological assumptions, pursuing different political commitments" (Reason & Bradbury, 2001; Rosenberg, 2001; Raelin, 2009). Since action research can be applied in many fields, "many variations of action research exist and not all involve the rigor involved in the processes developed by Lewin" (Reason & Bradbury, 2001).
PAR is "useful for the investigations of the mysteries of management and especially innovation management and change management" (Ottosson, 2003; Huxham & Vangen, 2003). Therefore in this thesis PAR can be useful in the investigation of simulation uptake by the Company, and understanding the facilitators and barriers of this uptake.

Barton et al. 2007 suggest that the PAR framework follows a circular pattern. It all begins by going into the field with the intent to collect data, and not to test a hypothesis which is how Positivist Science research works (Barton et al., 2007). Usually in Positivist Science the hypothesis is generated in the academic world and data are collected to prove the hypothesis. This paradigm does not apply in the action research world where the data collected in the field are evaluated in order for a trend or hypothesis to be generated. The last step is Monitor implementation which allows for feedback and if changes to the hypothesis are required the researcher can go back to the academic world and reformulate and re-evaluate the hypothesis. The challenge stands in the fact that the researcher "should be an inside 'object' acting as a manager/entrepreneur/team member at the same time as s/he has access to the scientific environment. To compare findings, the researcher also has to conduct complementary classical research" (Ottosson, 2003).

The interaction between the "scientific environment" and the "environment under study" falls under the first stage of action research. The researcher collects data from the environment under study and goes back to the scientific environment to develop the hypothesis that comes out of the data (Ottosson, 2003). In order to develop the research questions, the researcher has to pay attention to the traditional/quantitative research that currently exists in the academic world. This interaction with the traditional way of doing research shows that Positivist Science and PAR complement each other (Barton et al., 2007). The interaction between the “scientific environment” and the “environment under study” is a two way interaction. Once the researcher has developed a hypothesis to test, they have to apply it to the real world and foster the necessary change that is needed to be adapted by the real world. Indirectly, a circular path is created between theory (academia), the researcher and practice.

1.4 Theory

PAR is widely used in organizational change in fields such as business, project management, software process improvement and workplace design (Meglio & Risberg, 2010; Aubry et al., 2010; Kilker, 1999; Müllera et al., 2010, Zickar & Carter, 2003; Struker & Gille, 2010). Due to their success and usage in these fields, PAR could potentially be used to help understand the factors affecting the implementation of DES and HFM in engineering design, which would lead to organizational change (OC).

“The main technological OC tool that currently exists” is the Technology Acceptance Model (TAM) (Lee et al., 2003). This model relies heavily on action research in order to determine its two main variables: Perceived Usefulness (PU) and Perceived Ease of Use (PEOU) (Davis, 1989). TAM states that in order for Customer Adaptation to occur either the PU and/or PEOU need to change. In some cases, these two variables will affect Customer Attitude before Customer Adaptation occurs. A graphical representation of TAM is shown in Figure 6.

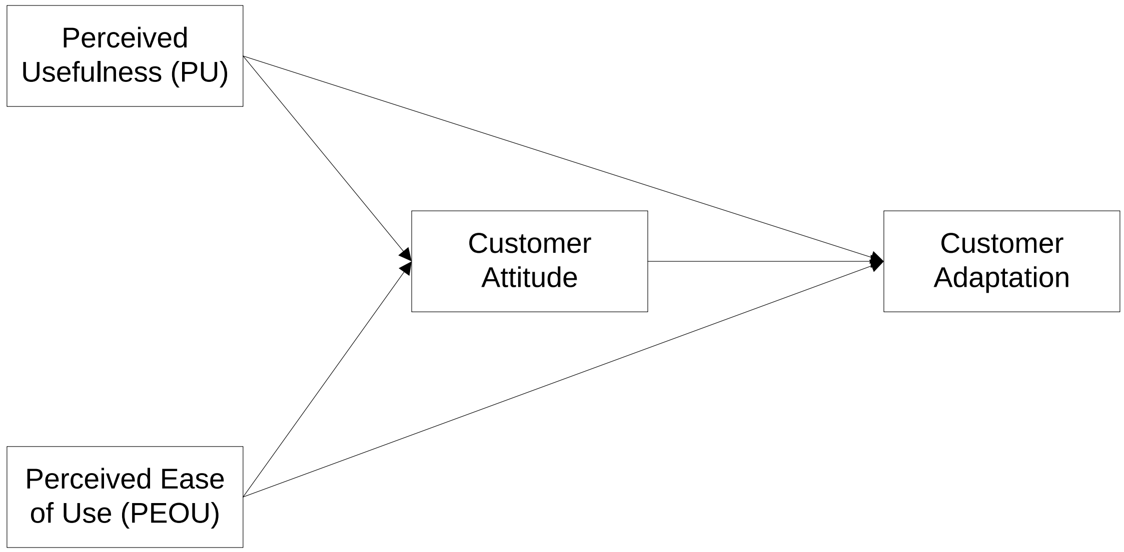

Figure 6 – Technology Acceptance Model (Davis, 1989) **–** *The PU and PEOU in this model are the only variables that affect people's attitude and adaptation towards new technology. Sometimes these variables change the people's attitude which leads to technological adaptation and other times they can lead straight to technological adaptation without changing any attitudes.*

One limitation of TAM is the lack of the variables that need to be present for HFM to be fully absorbed in an OC. Other than PU and PEOU, the environment where the change is occurring should be taken into consideration. The technology diffusion process proposed by Beal and Bohlen, (1957) considers some of the HF variable that TAM is lacking. The technology diffusion process, shown in Figure 7, was developed by studying farmers' acceptance of new technology; specifically the introduction of new fertilizers. It all starts with the "awareness stage" represented by the innovators of new technology. New technology is adopted by a small minority which leads to the majority being aware of it. It then continues with the interest stage when it is taken up by the early adopters. The new technology is exciting and is producing somewhat acceptable results and more people are being attracted to that. However, the new technology has not been fully tested and there are still some who are too sceptical to use it. That the new technology still needs to be fully tested leads to the next stage, the "evaluation stage," which is represented by early majority. The new technology has attracted the big players' attention, consisting of either people or companies, and has been evaluated by them.

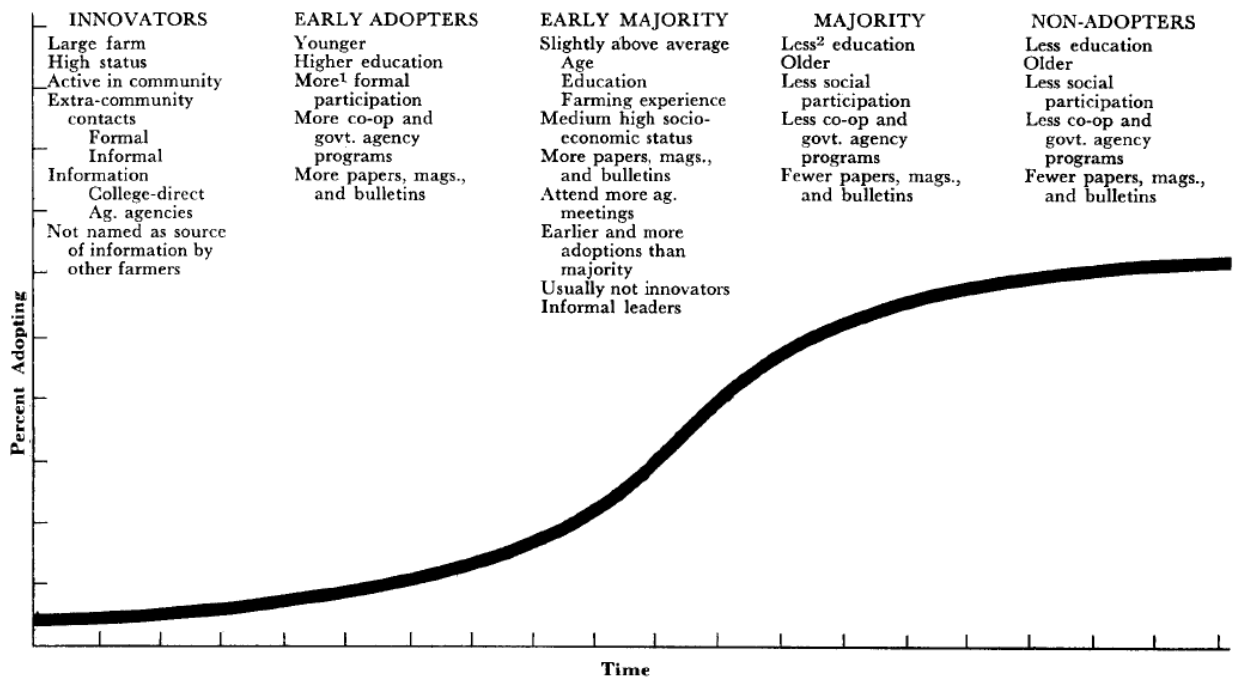

Figure 7 – The diffusion process (Beal & Bohlen, 1957) – *The process is divided into five parts: 1) Awareness stage (Innovators), 2) Interest stage (Early adopters), 3) Evaluation stage (Early majority), 4) Trial stage (Majority), 5) Post trial stage (Non-adopters)*

This is the turning point for the new technology: if a change is accepted by an industry's front runner, everyone else will follow suit, thus leading to the next stage, called the "trial stage." The trial stage is represented by the majority group in Figure 7. In this stage, the new technology becomes the new fad and it is almost mandatory to incorporate it. The mentality in this stage is "if the big hitters are using it and it works for them, why shouldn't small and medium hitters use it too?" Late during this stage is when even non-adopters will conform and accept the new technology.

TAM can be easily incorporated in every stage of the technology diffusion process model. TAM treats technology acceptance as a one-time event while the technology diffusion process treats it as a continuous process. However, both models lack the feedback loop which is very valuable for learning from the application of theory. Therefore, by combining these two models most of the variables involved in technology/innovation acceptance will be taken into consideration. A combination of these two models, shown in Figure 8, will consider the continuous acceptance process with TAM's main variables and at the same time facilitate feedback.

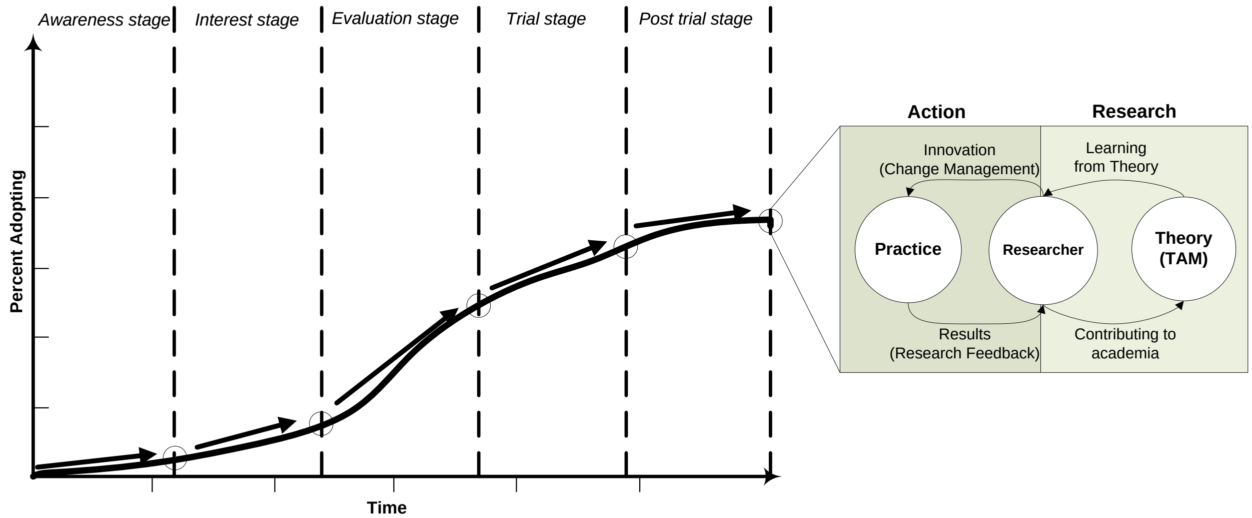

Figure 8 – Combined Innovation Acceptance Model – *TAM and the diffusion process are combined together in order to supplement each other.*

The researcher in the context of Figure 8 develops, reconciles research questions and tests them in the application world. The feedback loop allows the researcher to consult with academic knowledge to better support the changes required.

1.5 Aim

This project aims were twofold: 1) Develop and test a viable DES and HFM approach for an Ontario based telecommunication company. What is the impact of alternative engineering designs with a HF focus? Additionally would improved simulation capabilities enable the Company to work towards optimizing its production process? 2) Identify the factors that affect the uptake and application of the DES and HFM in work system design. What are the barriers and facilitators for the application of the newly developed approach?

Chapter 2 - Methods

The methods used in this project are categorized into two major groups: 1) Participatory Action Research (PAR), and 2) Modeling. As mentioned in section 1.3, PAR was used to understand the factors that affect the uptake and application of the DES and HFM in work system design. Modeling was used to develop DES and HFM capabilities for the Company in order to explore the impact of alternative engineering designs with a HF focus.

2.1 Participatory Action Research (PAR)

PAR for this thesis started with the familiarization of the department at the Company and it was part of a larger action research project which investigates the integration of HF into engineering design. The familiarization was done through introduction to the department's members. Subsequently, the department members who would be able to provide the input data to the modeling component of the project were identified. It continued by identifying potential users of the simulation capabilities being developed.

Base simulation models were presented to the Company employees in the form of progress reports and meetings. The updates were on a bi monthly basis in the beginning of the project and eventually progressed to a monthly basis. Field notes and audio recordings were made during the meetings. The general inductive approach (Thomas, 2006) was used to process and categorize the field notes in the lab. These notes were used to make refinements to the simulation models, where possible, and at the same time understand the barriers and facilitators for the technological change at hand.

In addition to the progress reports and the meetings, the office employees were administered questionnaires. Two office employees also agreed to participate in "exit" interviews at the end of the project.

2.1.1 Exit interviews

Individual exit interviews were performed with two office employees who were involved in this project. Other office employees did not participate due to time constraints. Open ended questions were asked to the Company's office employees. These questions were divided into 4 topics: 1)

Discrete Event Simulation, 2) Human Factors, 3) DES and HFM and 4) Change Management. The exit interviews' questions are shown in Table 2.

Table 2 – Exit interview topics and questions used – *two engineering office employees responded to the questions above.*

Topic	Questions
1) Discrete Event Simulation	**a)** Are you familiar with the DES software that was used in the Ryerson Simulation project? **b)** Do you have any previous experience with simulation projects? If so, could you tell me a little about your experience? **c)** What do you think the benefits of Discrete Event Simulation could be to the [Company]?
2) Human Factors	**a)** What does Human Factors mean to you? What does Human Factors Modeling mean to you? **b)** Are you familiar with the Human Factors concepts used in the Human Factors Modeling part of the project? **c)** Have you ever been involved in projects that involved Human Factors or Human Factors Modeling in them? Could you tell me a little about these projects?
3) DES and HFM	**a)** In your opinion what is the [Company's] benefit from doing this project? **b)** Were there difficulties encountered during the process in this project? If yes, what would you change to increase the [Company's] benefits? **c)** Were there difficulties encountered in outcome during this project? If yes, what would you change to increase the [Company's] benefits?
4) Change management	**a)** What were the facilitators for this project? **b)** What were the barriers for this project? **c)** Who/Which department do you think should be the end user? In the design stage, in the implementation stage or in the operations stage? Why?

2.1.2 Office employees' questionnaires

In addition to the exit interviews, questionnaires were administered to the office employees who were involved in this project. These questionnaires had both closed and open-ended questions. Similar to the exit interviews the questions were divided into four topics: 1) Discrete Event Simulation, 2) Human Factors, 3) DES and HFM and 4) Change Management. The purpose of these questionnaires was to obtain a better insight into the Company's facilitators and barriers for issues like DES, HFM and technology acceptance. Samples of these questionnaires are found in Appendix A – Questionnaires – Office Employees.

2.2 Modeling

Two manual assembly lines were simulated, an existing and a proposed one. The proposed line was developed by the Advanced Manufacturing Engineering (AME) department at the Company. The modeling was divided into two parts: 1) Discrete Event Simulation (DES), which simulated the manual assembly line, and 2) HF Modeling (HFM), which simulated the humans in the manual assembly line and was part of the DES.

2.2.1 Discrete Event Simulation (DES)

DES was used to simulate the manufacturing line. The software used to develop the simulated system was Rockwell Automation's Arena 13.5. For the purpose of this project, DES was performed in the following steps: 1) Model conceptualization, (S. Zolfaghari, personal communication, Fall 2009) 2) In-Data collection, 3) Model translation, 4) Validation (Rossetti, 2010) and 5) Documentation and Reporting.

2.2.1.1 Model conceptualization

At this stage, system familiarization with the existing manufacturing line was performed. The system layout and stations' sequences were observed. The task order performed by each employee was noted alongside line hourly input volumes. After familiarization, a basic DES model was developed with mock inputs. The basic DES model served as the planning stage for data collection. Selection of appropriate data is crucial in simulation. Once the required information was determined the data collection stage began.

2.2.1.2 In-Data Collection

DES input data is analyzed to determine the nature of the data and to determine further data collection needs and necessary data are also classified by area (Rossetti, 2010).

<u>Manual assembly line hourly input</u> – For the basic DES modeling, materials volume that was fed to the line was obtained from the Manufacturing Engineering (ME) specialist.

<u>Planned task Cycle Times (CT)</u> – During the first refinement of the basic model, tasks' CTs were obtained from the ME specialist. The task CTs were summed to obtain the stations' CTs.

<u>Actual task Cycle Times (CT)</u> – During the second refinement of the basic model actual task CTs were obtained from two studies performed by ME from a different manual assembly line than the

system currently being studied. These studies involved video recording of the operators while they were performing their assigned tasks. The CTs were extracted from the videos by using the Captiv-L2100 and Video Time Study (VTS) software. These software allow the user to mark the beginning and the end of the cycle in the video, and they calculate the time difference which is the CT to perform the specific task. There were on average four readings for each task performed in each station. The CTs were also used in HFM for the fatigue calculations.

Actual Pause Times (PT) distributions – During the refinement of the basic model, the amount of time that an employee takes from the end of one CT to the beginning of the next CT were obtained. The actual PTs were obtained from the same studies used to obtain actual task CTs. These times were extracted from the video recordings using Captiv-L2100. The PTs were also used in HFM for the fatigue calculations.

Buffer capacity –obtained from ME for the existing system and from Advanced Manufacturing Engineering (AME) for the proposed system.

Break schedule – During the refinement of the basic model, the break schedule was obtained from the line production manager. There are three 15 minute, two stretch and one 30 minute meal break for the manual assembly line in a 12 hour shift. The 15-minute breaks are: 9:00-9:15, 14:00-14:15 and 16:30-16:45. The two stretch breaks, each 2-5 minutes long, start at 15:30 and 17:45. The meal (lunch) break is at 11:30.

Manual assembly line defects rate – During the refinement of the basic model, the manual assembly line defects rate was obtained from the Quality Data group. The Company collects and stores defect data in their databases. The defect data for 29 shifts was obtained from the Company. The defect data were then divided into hourly defect rates and were used in the DES model to reflect the hourly variability in the manual assembly line.

2.2.1.3 Model translation

Model translation is "the act of implanting the model in computer code, including timing and general procedures and the translation of the conceptual models into computer simulation program representations" (Rossetti, 2010). The data collected was used as input to the basic DES model previously developed. Based on the data collected, the actual CTs, PTs and defect rate variability were calculated. Statistical distributions were fitted to these data. Due to the similarity in tasks of the system measured and the system being studied the same distributions were used.

However different parameters were used in the proposed system for these distributions. These parameters were provided by the Company. For example, the mean and standard deviation was changed but the normal distribution shape was maintained. The fitting was performed by using Palisade's BestFit software. BestFit performed the statistical distribution fitting based on the Chi-Square test. The Chi-Square test is any statistical hypothesis test in which the sampling distribution of the test statistic is a chi-square distribution when the null hypothesis is true, meaning that the sampling distribution can be made to approximate a chi-square distribution as closely as desired by making the sample size large enough (Greenwood & Nikulin, 1996). The Chi-Square test is shown mathematically in Equation 4 (Banks et al., 2005).

$$\chi_0^2=\sum_{i=1}^{k}\frac{(O_i-E_i)^2}{E_i}$$ **(Eq 4) –** *Chi-Square test equation.*

where O_i is the observed frequency, i is interval number, and the E_i is the expected frequency.

Observations are arranged into k equal-width class intervals. The expected frequency is calculated by using $E_i = np_i$ where n is the total number of observations and p is the probability corresponding to the i^{th} interval. The tested distribution has (k-s-1) degrees of freedom where s is the number of parameters of the distribution. Once the χ_0^2 statistic is obtained, it is compared with $\chi_{\alpha,k-s-1}^2$ obtained from statistical tables. If $\chi_0^2 > \chi_{\alpha,k-s-1}^2$ then the distribution is rejected, where α is the significance level expressed in percentage.

2.2.1.4 Validation

Validation of the simulation model is performed to determine whether the simulation model adequately represents the real system (Rossetti, 2010). The resulting DES model from the Model Translation stage was verified in two ways: 1) performing an output analysis, and 2) confirming that the results produced are consistent with the planning that the Company performs internally.

Output analysis is divided into three steps: a) Reducing the initialization bias and finding the point estimator and a confidence interval, b) Obtaining the minimum number of runs, and c) Obtaining the run-length for a given number of runs.

a) *Reducing the initialization bias and finding the point estimator and a confidence interval*

Output analysis' first step was to determine what type of simulation the model follows. It was observed that the simulation had two phases, the initialization and steady state phase. A graphical representation of the steady-state simulation type is shown in Figure 9. Initialization represents the potential shift in the simulation output mean that is introduced by running the simulation (Schruben, 1982). Steady-state, on the other hand, represents the lack of a potential shift in the simulation output mean for the entire run of the simulation. (Schruben, 1982).

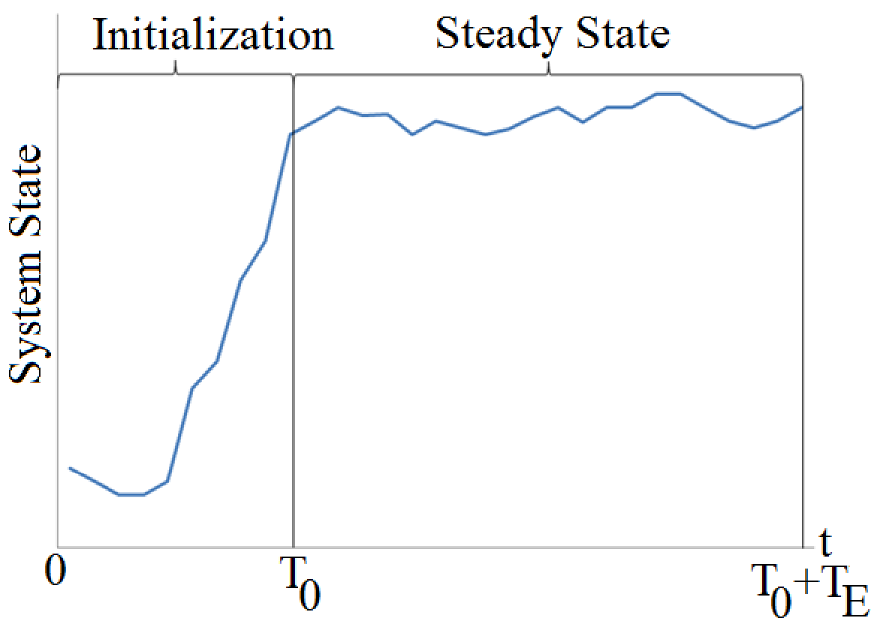

Figure 9 – Steady-state simulation type pictorial representation – *the steady-state simulation type is divided into two parts: the initialization and steady-state parts.* T_0 *represents the warm-up period at which point the simulation software starts collecting statistics.* $T_0 + T_E$ *is the simulation time length.*

The system was considered to be without run-in effects, and run-in effects were not included in the result analysis. Since manual assembly line buffers can be filled prior to the start of a shift, employees will always have enough material to work at the start of their shift. To find the point estimators the performance measures of the simulation model had to be defined. A sample table with the performance measures is shown below in Table 3. The performance measures were defined by the Company. These measures are the key ones which the Company would like to look at for the manufacturing line evaluation. Average Employee

Utilization is the summation of the amount of time that an employee is performing a task during each shift. Average Employee Fatigue Dose is the average FD accumulated during a shift and is illustrated in Figure 5. Number of Defects per shift and Number of Non-Defects per shift are the components of the line's yield. Ten replications were performed for each performance measure and as mentioned above, there were no truncations due to the system being without run-in effects.

Table 3 – DES performance measures – *these four measures are the ones that affect the simulation output the most.*

Performance Measure
Average Employee Utilization
Average Employee Fatigue Dose
Number of Defects per shift
Number of Non-Defects per shift

The point estimator for 10 reps and 0 truncations. $\bar{Y}_{\cdot\cdot(10,0)}$ was found by using the formula shown in Equation 5 (Banks et al., 2005).

$$\bar{Y}_{\cdot\cdot(n,d)} = \frac{1}{n-d}\sum_{j=d+1}^{n}\bar{Y}_{\cdot j}$$ **(Eq 5)** – *Point estimator equation*

where *n* is the total number of observation and *d* is the non-deleted observations.

Once the sample mean was obtained, the sample variance was calculated by using Equation 6 (Banks et al., 2005). The sample variance is a measure of the amount of variation within the values of the sample mean.

$$S^2 = \frac{1}{R-1}\sum_{r=1}^{R}(\overline{Y_{r.}} - \bar{Y}_{..})^2$$ **(Eq 6)** – *Sample variance equation*

where *R* is the number of replications.

The confidence interval is used to indicate the reliability of the estimate. The value for *α*, which is the confidence level, was chosen to be 5%. The confidence interval was calculated using Equation 7 (Banks et al., 2005).

$$\bar{Y}_{..} - t_{\alpha/2,R-1}\frac{S}{\sqrt{R}} \leq \theta \leq \bar{Y}_{..} + t_{\alpha/2,R-1}\frac{S}{\sqrt{R}}$$ **(Eq 7)** – *Confidence interval equation*

where $t_{\alpha/2,R-1}$ can be found from the *t*-distribution statistical tables once *α* and *R* are known.

Once the initialization bias was determined and the simulation was identified as following the steady-state type, the following steps were taken:

b) Obtaining the minimum number of runs

Once all the aforementioned parameters were obtained, the minimum number of runs for a level or accuracy smaller than 10% of the sample mean with confidence interval 100(1- α)% was found.

c) Obtaining the run-length for a given number of runs

The run-length for the shift was not calculated due to the Company's policy that each shift was 12 hours long.

All the calculations performed in steps a) through c) can be found in Appendix B – DES Output analysis.

Another technique to validate the model is to compare the output of the simulation model to the output from the real system and to analyze whether there is a difference between the two (Rossetti, 2010). First of all, the simulation results were compared to the line balancing planning sheets that the Company uses internally. Additionally, production reports were used to compare the model results.

2.2.1.5 Documentation and Reporting

The results obtained from the DES model were communicated back to the Company in the form of update reports. The methodology and results of the DES simulation were documented in the aforementioned reports. The update reports were shown to the Company in meetings in intervals of approximately two months. The workshops included employees from the ME, AME, Process Quality, Continuous Improvement, Quality Data, Ergonomics, and Operational Excellence departments. Employees' comments were also taken into consideration when validating the models.

2.2.2 HF Modeling (HFM)

The calculations for the FD were performed in a Microsoft Excel spreadsheet. The CTs were obtained from the DES model output in Microsoft Excel through a read/write module. The %MVC for each station in the manual assembly line were obtained from the method of a doctoral thesis performed at the time of the study. This method calculated the shoulder load as %MVC based on the x-y-z hand coordinates and repetitions required to perform the tasks as observed in the existing system. The process of obtaining the %MVC values is outlined in (Greig et al., 2011). The doctoral thesis together with this thesis are part of a bigger project at the Company to integrate HF in systems design. The FD calculations process is shown in Table 4.

Table 4 – FD calculations sample – *The area under the curve was calculated by using the trapezoid formula* (Rahman & Schmeisser, 1990).

Description	Unit	Column Name	Formula	Data Source
Current Simulation Time	s	A		DES model
Process Time (CT or PT)	s	B		DES model
%MVC	%	C		(Greig et al., 2011)
MET (Equation 1)	s	D	$(7.96)e^{(-4.16\cdot C)}$	Calculated in MS Excel
Fraction of Instantaneous Fatigue	%	E	B/D	Calculated in MS Excel
Rest Allowance (RA) (Equation 2)	%	F	$3D^{(-1.52)}$	Calculated in MS Excel
Full Recovery time (Ri)	s	G	F B	Calculated in MS Excel
Recovery Need	s	H	G-B	Calculated in MS Excel
Recovery Received	%	I	H/B	Calculated in MS Excel
Fatigue level accumulation	%	J	E (1-I)	Calculated in MS Excel
Area under the Curve	%/ s	K	$\frac{J_{i+1} + J_i}{A_{i+1} - A_i}$	Calculated in MS Excel

The results obtained from the FD trace were compared with the musculoskeletal load trace. The sum of '%MVC' and 'Area under the Curve' rows in Table 4 were compared. This step was performed to understand the usefulness of the FD trace, and whether the musculoskeletal load trace would have been a more appropriate measure to model fatigue in the systems.

2.2.2.1 Manual assembly line workers' questionnaires

The manual assembly line workers were also administered questionnaires which were used to validate the HFM. These questionnaires included closed ended questions. The questions were divided into questions regarding fatigue and learning. The questions regarding fatigue involved the workers rating their answers. The Borg scale was used for these rating questions (Borg, 1990). The purpose of the questionnaires was to validate the HFM by comparing the answers to the questionnaires and the results that the modeling produced. The questions regarding learning were used to validate the LC modeling. Samples of these questionnaires are found in Appendix C – Questionnaires – Line Employees.

2.2.3 DES and HFM

A schematic of DES and HFM and their components used in this thesis is shown in Figure 10.

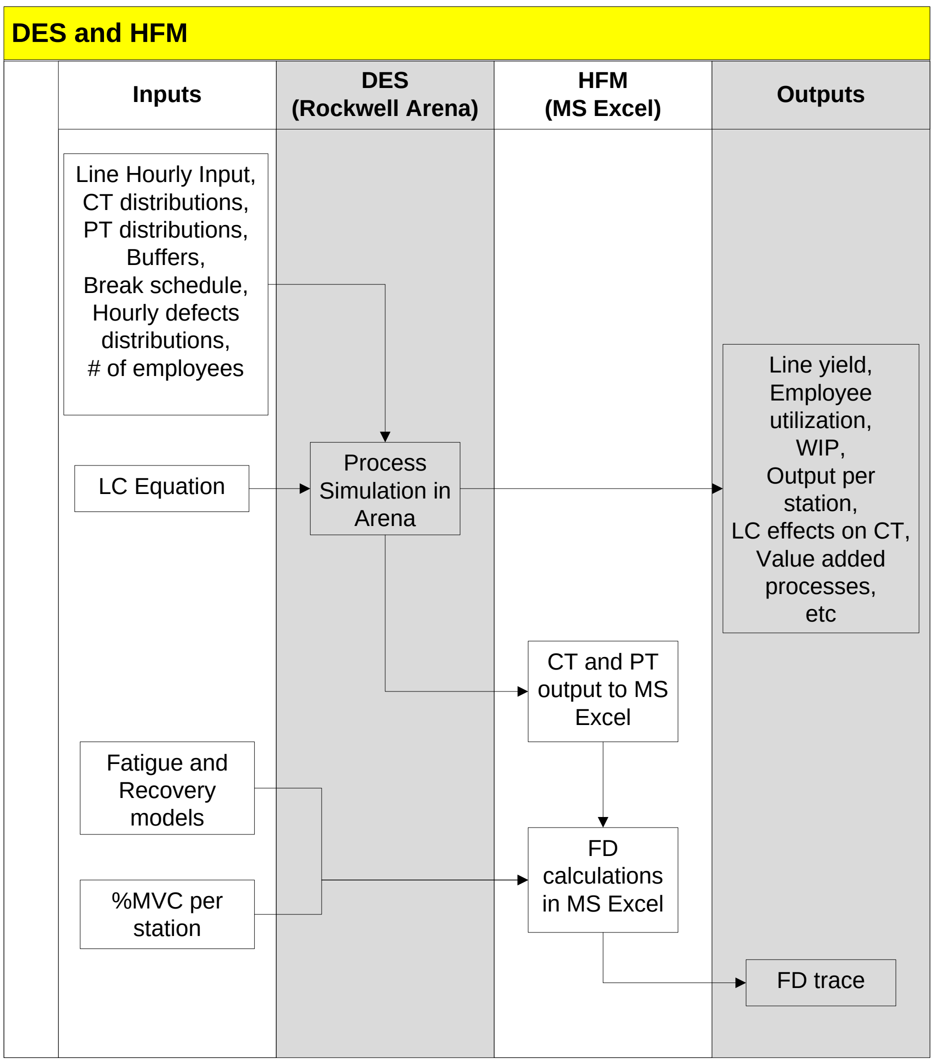

Figure 10 – System and Human Factors modeling – *DES is concerned with the system performance part of the modeling. HFM is concerned with the human part of the system which includes LC and FD.*

The Input section in Figure 10 shows all the information that was required for the simulation. The DES section simulates the manual assembly line. At this stage, the LC equation is applied to the CT. The LC effects' calculations are performed in Visual Basic for Applications, which is the supporting language for Arena. The defect rate distributions change on a simulated hourly basis. The defect rates distribution change is performed in a Visual Basic for Applications module. The system results are produced at this stage. The LC affected CT and PT are extracted in a MS Excel file through a read/write module where the fatigue and recovery models will be applied. The HFM section processes the simulated data from DES to obtain the fatigue trace. The MS Excel file where the DES information was extracted to already had the necessary fatigue and recovery models information, including the %MVCs. The fatigue and recovery models are applied to the simulated data through macros written in Visual Basic for Applications to obtain the FD trace.

2.2.4 Fatigue Dose (FD) and Quality

In order to observe the relationship between FD and Quality, the hourly defect rates obtained from the Quality Data group and the modeled FD for the existing line were correlated in MS Excel. After the correlation, a cost analysis was performed to express the monetary benefits of designing a low FD manual assembly line. Identifying the correlation between defect rates and FD was considered a necessary step to increase the Perceived Usefulness of DES and HFM, which would affect the Customer Attitude and lead to Customer Adaptation as stated in TAM shown in Figure 6.

2.2.5 Learning Curve (LC)

The initial CT for each station was provided by the Company. This CT was considered to be T_1 in Equation 3. Line balance planning data were obtained from ME for the months of November 2010 and June 2011. The data showed the CTs per task per station, and the cumulative number of units produced for each respective month. The learning rate, *k*, in Equation 3 was found by equating the two expressions below:

$$T_{\text{June 2011}} \cdot 20{,}000^{-k} = T_{\text{November 2010}} \cdot 1{,}000^{-k} \text{ (Jaber \& Bonney, 2011)}$$

where $T_{June\ 2011}$ is the CT in June 2011, $T_{November\ 2010}$ is the CT in November 2010 and 1,000 and 20,000 are the cumulative number of units produced the respective months. **-** *(Note: all figures are fictitious).*

The two expressions above were equated only for the same tasks in the same stations for both months. The average percentage improvement in CTs was used to obtain T_{∞} , or the lower limit, in Equation 3. T_1 for each station was provided by the Company The lower limit is necessary such that the simulated CT will not be affected by the LC to the point that they are not realistic or that it converges to zero.

T_n was calculated for each product that passed through each modeled station. Every time that a unit passed through a station the value of *n* in Equation 3 was increased by one. At the same time k, T_1 and T_{∞} were not changed in Equation 3.

2.3 Sensitivity analysis

A variability analysis was performed to understand the sensitivity of results in relation to the models' inputs. A DES variability analysis was performed for the four performance measures shown in Table 3. The steps taken to perform the sensitivity analysis are outlined in the validation part of the methods section. Additionally, a FD variability analysis was performed to understand the effects of MVC variability on the FD results. The MVCs were modified by ±8% and the FD variation was observed. The Wilcoxon rank test (Wilcoxon, 1945) was used to determine whether the perceived and modeled fatigue rank had statistically significant differences.

Chapter 3 - Results

The results were divided into two parts: 1) Modeling, and 2) Participatory Action Research (PAR). The layouts of the two manual assembly virtual lines were as follows:

i) **Existing system**: Composed of One (1) preparation and Five (5) manual assembly stations.

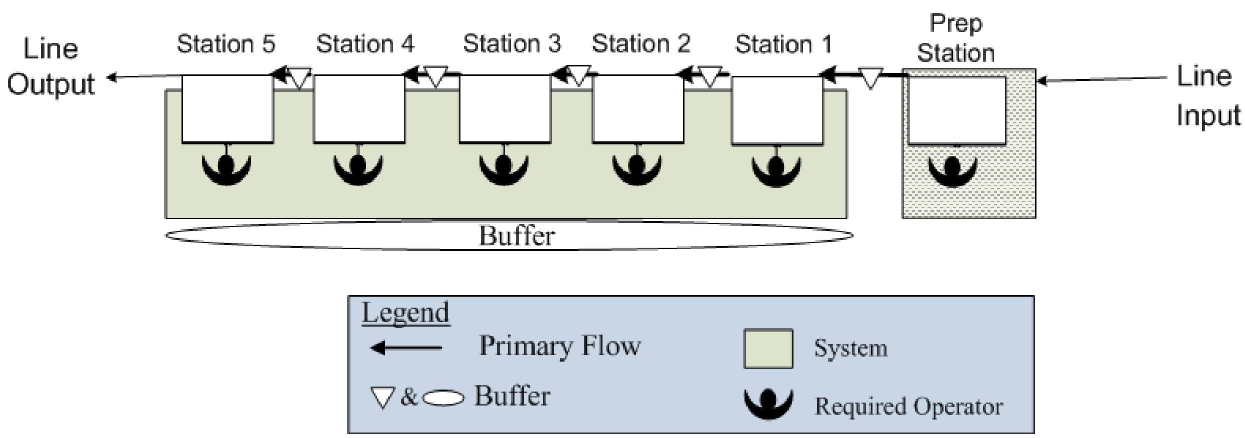

Figure 11 – Graphical representation of the existing system

ii) **Proposed system**: Composed of Four (4) manual assembly stations, Two (2) press machines and One (1) screw insertion machine. Developed by AME at the Company.

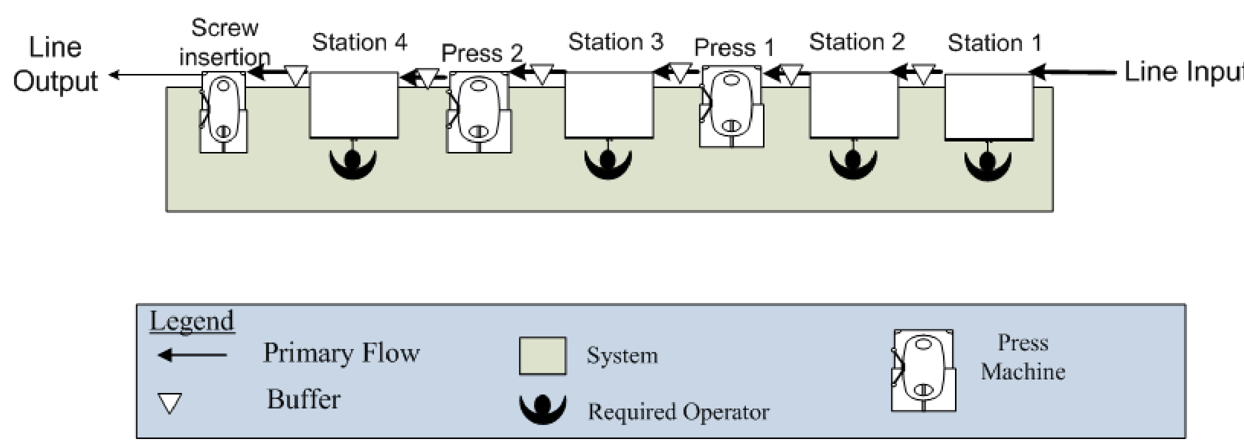

Figure 12 – Graphical representation of the proposed system

3.1 Modeling Results

The %MVCs were obtained for each task performed in each station by using the method outlined in Greig et al., (2011). For the purpose of this thesis, the tasks in each station were grouped together to find the %MVC of the CT. The absolute variations for the tasks' specific %MVC and station's specific %MVC was -0.78% and therefore negligible. A sample calculation used to obtain the stations' %MVC is shown in Table 5. The difference between the Weighted Average and the Average methods of calculating the %MVCs for each station is negligible as shown in Table 6.

Table 5 - %MVC sample calculations – *the %MVC were obtained for the existing system only. (Note: all figures are fictitious)*

A) Description	B) CT (Seconds)	C) % CT	D) % MVC	E) % MVC Weighted Average	F) MET (Seconds)	G) Fraction of Fatigue (%)
	Measured	**Bi/Sum[B_i]**	**Measured**	**E=C_i*D_i**	**Measured**	**G=F_i/B_i**
Task #1	5.3	17.85%	7.22%	1.29%	353.66	1.50%
Task #2	4.9	16.50%	7.22%	1.19%	353.66	1.39%
Task #3	7.8	26.26%	7.22%	1.90%	353.66	2.21%
Task #4	2.1	7.07%	8.24%	0.58%	338.95	0.62%
Task #5	9.6	32.32%	6.77%	2.19%	360.31	2.66%
Cycle	**29.7**	**100%**	**7.34%**	**7.15%**		**8.37%**

Table 6 – Differences between two methods of calculating MVCs – *The weighted average method calculates %MVCs for each task performed in a CT. The average method groups together all the tasks and calculates an average %MVC for the CT. The difference between the two methods is negligible. In this particular case the difference is -0.78%.* **-** *(Note: all figures are fictitious).*

Weighted Average Method	Total Station CT	Sum(E_i)	MET	Fraction of Fatigue
	29.7	7.15%	354.7	**8.37%**
Average Method	Total Station CT	Average(D_i)	MET	Fraction of Fatigue
	29.7	7.34%	352.0	**8.44%**

The hourly defect rates obtained from the Data Quality group are shown in Figure 13. The purpose of this figure is to use a data driven realistic line yield percentage instead of a theoretical approach. As it can be seen from Figure 13, the line yield decreases towards the end of the shift.

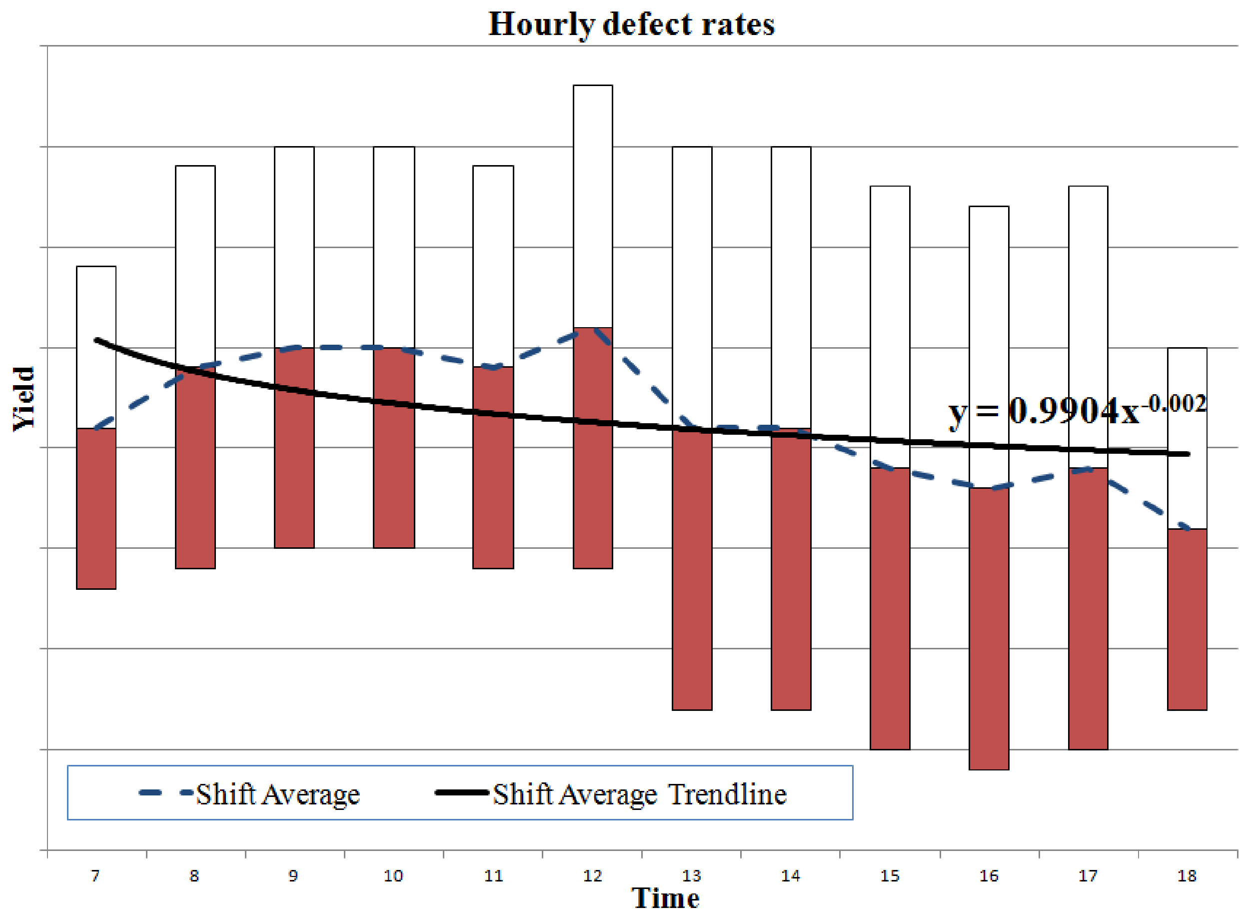

Figure 13 – Hourly line yield – *The sample size for these data was n=29 shifts. The data were collected during the morning shift. The coloured bars represent –σ from the average. The non-coloured bars represent +σ from the average. The meeting point between coloured and non-coloured bars represent the shift average.*

3.1.1 Sensitivity Analysis Results

The DES variability analysis was performed for the four performance measures shown in Table 3. The results showed that the minimum number of runs is six, the warm-up period is 6 hours for a confidence level of 95%. The sensitivity calculations for the existing and proposed systems are found in Appendix B – DES Output analysis. The results of DES were within 7% of the production reports results.

The MVCs were modified by ±8% as shown as shown in Table 7. The results in FD change from the MVCs variability is shown in Figure 14. The results show that for 1% change in MVC there is on average a 4.1% change in FD during one shift.

Table 7 – Stations' MVCs input variability analysis – *Each station's average %MVC was increased/decreased in increments of 1% from the measured %MVC.*

% Δ of average %MVC from baseline	All Stations Average	Station's % MVC 1	2	3	4
-8%	1.91%	0.96%	1.55%	1.09%	4.03%
-7%	2.91%	1.96%	2.55%	2.09%	5.03%
-6%	3.91%	2.96%	3.55%	3.09%	6.03%
-5%	4.91%	3.96%	4.55%	4.09%	7.03%
-4%	5.91%	4.96%	5.55%	5.09%	8.03%
-3%	6.91%	5.96%	6.55%	6.09%	9.03%
-2%	7.91%	6.96%	7.55%	7.09%	10.03%
-1%	8.91%	7.96%	8.55%	8.09%	11.03%
Measured	**9.91%**	**8.96%**	**9.55%**	**9.09%**	**12.03%**
1%	10.91%	9.96%	10.55%	10.09%	13.03%
2%	11.91%	10.96%	11.55%	11.09%	14.03%
3%	12.91%	11.96%	12.55%	12.09%	15.03%
4%	13.91%	12.96%	13.55%	13.09%	16.03%
5%	14.91%	13.96%	14.55%	14.09%	17.03%
6%	15.91%	14.96%	15.55%	15.09%	18.03%
7%	16.91%	15.96%	16.55%	16.09%	19.03%
8%	17.91%	16.96%	17.55%	17.09%	20.03%

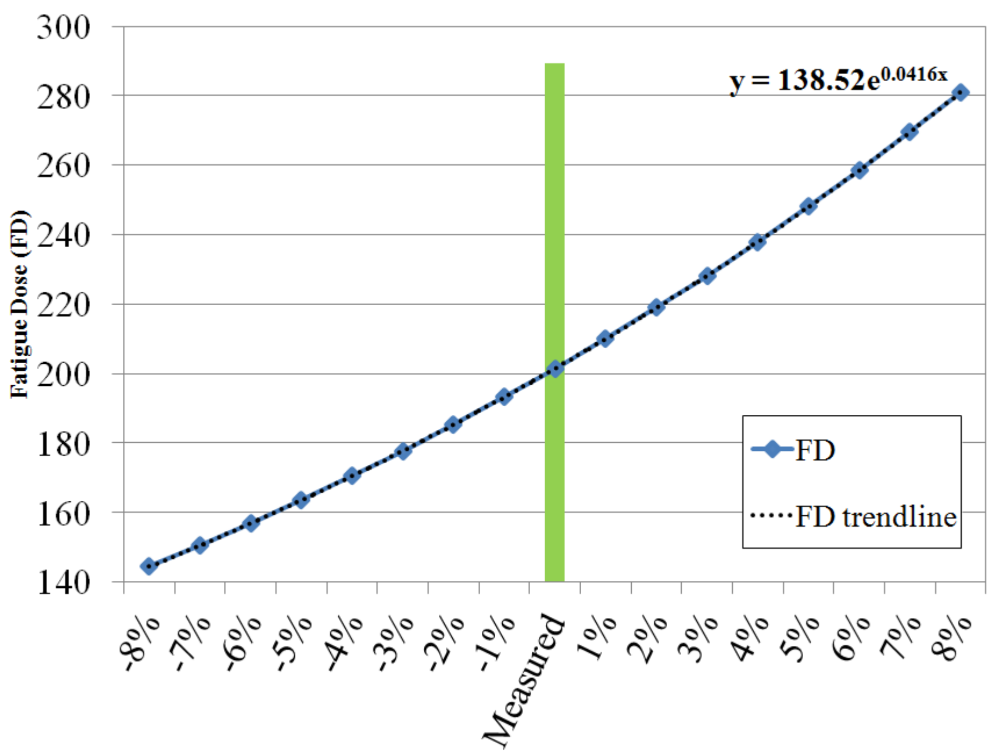

Figure 14 – FD variability as a result of MVCs variability – *for each 1% change in MVC, FD per shift in the proposed system changes on average 4%.*

3.1.2 System Performance Results

The results obtained from the modeling part of this project were divided into three parts: a) System performance results, b) Operators performance results and c) Learning Curve (LC) results.

Table 8 shows the line output results for both modeled systems. In the existing system some stations act as bottlenecks, namely Station 1 followed by Station 3. The model of the proposed system does not show any major bottlenecks. The defective/ non-defective ratio as modeled in the proposed line is better than the actual line. The %Units seized per shift is the number of units seized by each operator divided by the input units to the line.

Table 8 – Lines output results – % *units seized are the number of products that each resource worked on divided by the total number of units available. The proposed system's imbalance is negligible. The existing system has imbalances throughout the line. Stations with high CTs starve the other stations down the line resulting in imbalances. Fewer imbalances in the line result in more and better product quality.*

Proposed System	
Station/Machine	**% Units Seized per shift**
Station1_Employee	100.00%
Station2_Employee	99.87%
Station3_Employee	99.87%
Station4_Employee	99.87%
Press Machine # 1	99.87%
Press Machine # 2	99.87%
Screw Insertion Machine	99.87%
Line Total Produced	**99.87%**
Defective Units	*6.14%*
Non-Defective Units	*93.86%*

Existing System	
Station	**% Units Seized per shift**
Preparation_Employee	100.00%
Station1_Employee	88.10%
Station2_Employee	87.96%
Station3_Employee	87.82%
Station4_Employee	87.25%
Station5_Employee	87.11%
Line Total	**87.11%**
Defective Units	9.45%
Non-Defective Units	90.55%

Table 9 shows the resources utilization as modeled for the two virtual systems. The proposed system seems to have all of its resources utilized below 80%, with the exception of Station 2's operator. The existing system on the other hand has all but one resource above 80% utilization. Station 1 in the existing system is above 100% utilization. This means that the employee takes time off from his/her break to finish the product at hand.

Table 9 – Resources Utilization – *scheduled utilization is the time that a resource is expected to be working for. For example, an employee is expected to be working for 10.5 hours. (12 hours shift minus breaks). Up to 80% employee utilization is considered to be an acceptable limit.* (Zulch et al., 2002). *The proposed system has more human resources under the 80% utilization limit than the existing system does. - (Note: all figures are fictitious).*

Proposed System	
Resource	**Scheduled Utilization**
Station1_Employee	75.5%
Station2_Employee	85.1%
Station3_Employee	77.2%
Station4_Employee	63.6%
Press Machine # 1	38.1%
Press Machine # 2	38.1%
Screw Insertion Machine	49.5%

Existing System	
Resource	**Scheduled Utilization**
Preparation Employee	38.1%
Station1_Employee	100.4%
Station2_Employee	84.2%
Station3_Employee	93.1%
Station4_Employee	83.7%
Station5_Employee	97.9%

3.1.3 FD Results

The average hourly musculoskeletal load was calculated by summing up the %MVCs and FD by summing up the 'Area under the Curve' results. Figure 15 shows the comparison between the average hourly musculoskeletal load, FD excluding recovery, and FD as illustrated in Figure 5.

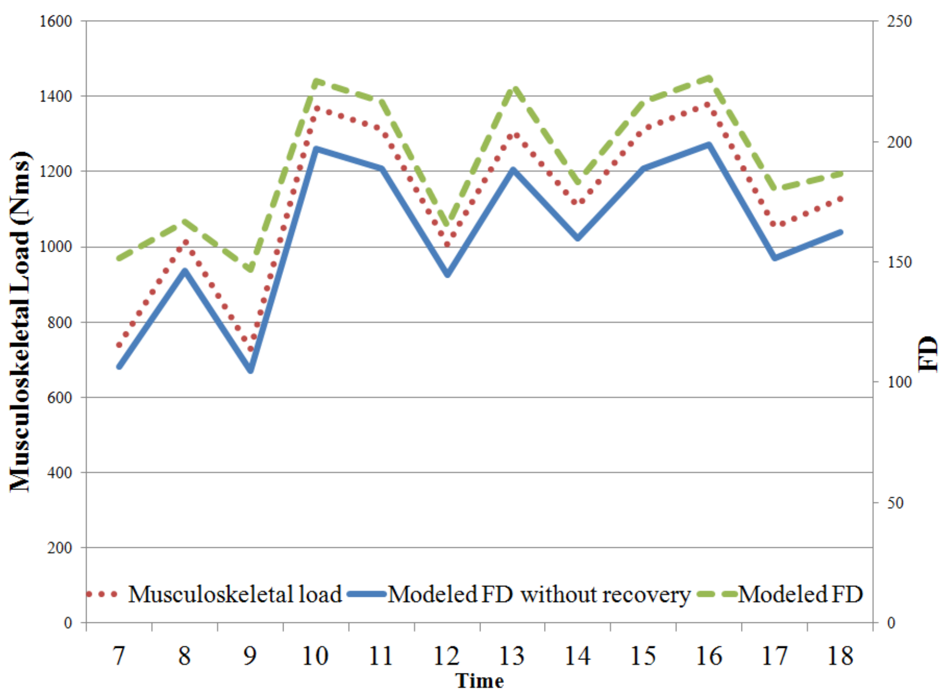

Figure 15 – Musculoskeletal load and FD traces comparison – *the musculoskeletal load does not consider the recovery time while FD does. (Note: all figures are fictitious).*

Figure 16 shows the hourly fatigue dose for both modeled lines. This figure depicts stations' average fatigue dose for each respective line. Individual cumulative fatigue doses for each station are shown in Appendix D – Hourly Fatigue Dose per Station.

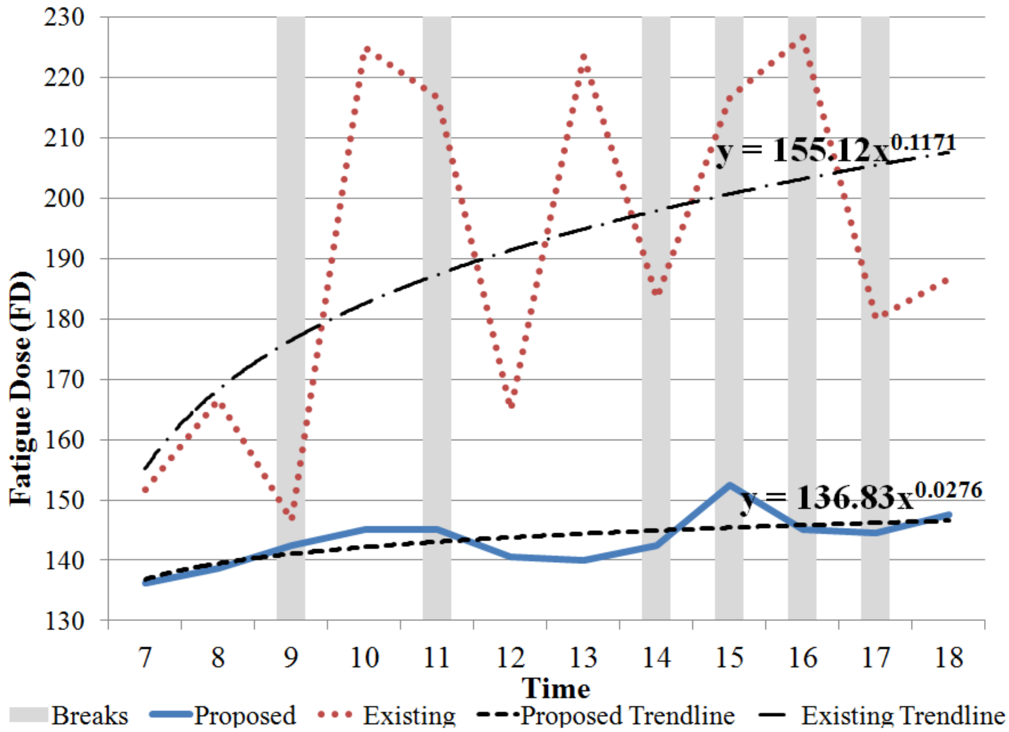

Figure 16 – Hourly FD per operator for the modeled lines – *the FD for the proposed line follows a stable trend. The proposed line as modeled has little variances and low levels of fatigue dosage per employee (μ=143, σ=4). The average fatigue dose is higher in the existing line than in the proposed system and the variability is a result of the line imbalances and break schedule patterns (μ=190, σ=29). The two tailed T-test value for the modeled and existing system is* $1.8 \cdot 10^{-5}$*- (Note: all figures are fictitious).*

The fatigue dose in the existing line is higher than the proposed line. The existing line's FD range is [146 to 227]. The proposed line's FD range is [136, 152]. This shows that the proposed line is between 7% and 33% less from the fatigue dose point of view when compared to the existing line. Figure 17 shows the modeled FD per station for the proposed system during one shift.

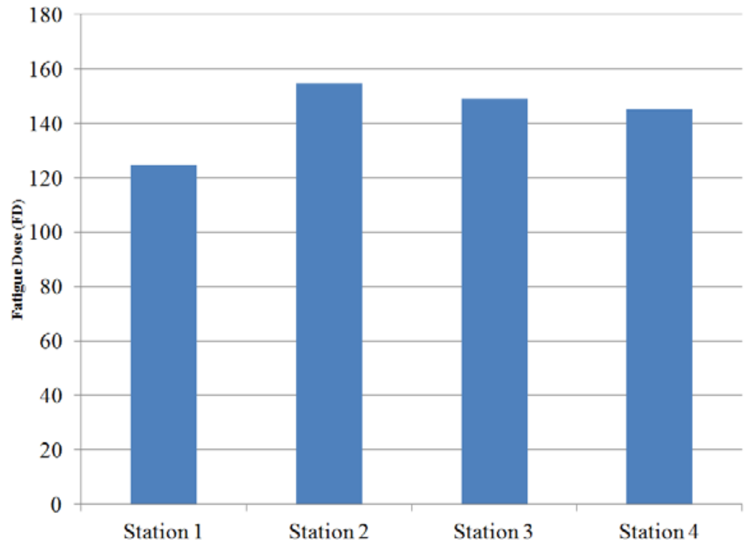

Figure 17 – Modeled Fatigue Dose (FD) per station – Proposed System – *the modeled stations in the proposed system show differences in fatigue dosage. The FD stations rank from the highest to the lowest is: Station 2, Station 3, Station 4 and Station 1. - (Note: all figures are fictitious).*

Figure 18 shows the modeled FD per station for the existing system during one shift.

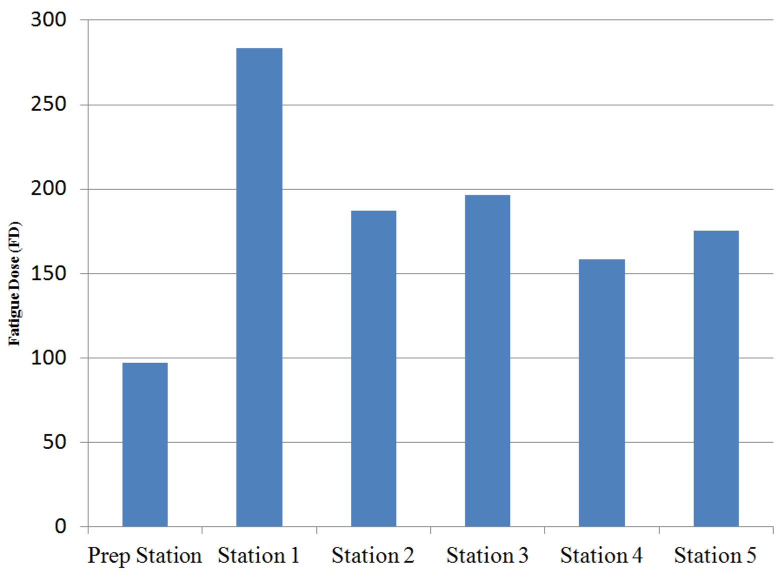

Figure 18 – Modeled Fatigue Dose (FD) per station – Existing System – *the modeled stations in the existing system show differences in fatigue dosage. The FD stations rank from the highest to the lowest is: Station 1, Station 3, Station 2, Station 5, Station4 and the Prep Station. - (Note: all figures are fictitious).*

Based on the results above the average FD per product produced were calculated for both systems. The existing system has an average of 0.31 FD/product and standard deviation of 0.05 FD/product. The proposed system has an average of 0.19 FD/product and standard deviation of 0.01 FD/product. This shows that the employees accumulate less fatigue in the proposed system than in the existing one. The two tailed T-test value for the modeled and existing system is $1.8 \cdot 10^{-5}$.

3.1.4 Questionnaires – Manual assembly line employees

There were nine out of nine respondents to the questionnaires administered to the manual assembly line employees. Four were males and five were females. The age range of the respondents is from 20 to 47 years old. The results obtained from the question which asked the respondents to rate their hourly fatigue dose are shown below in Figure 19.

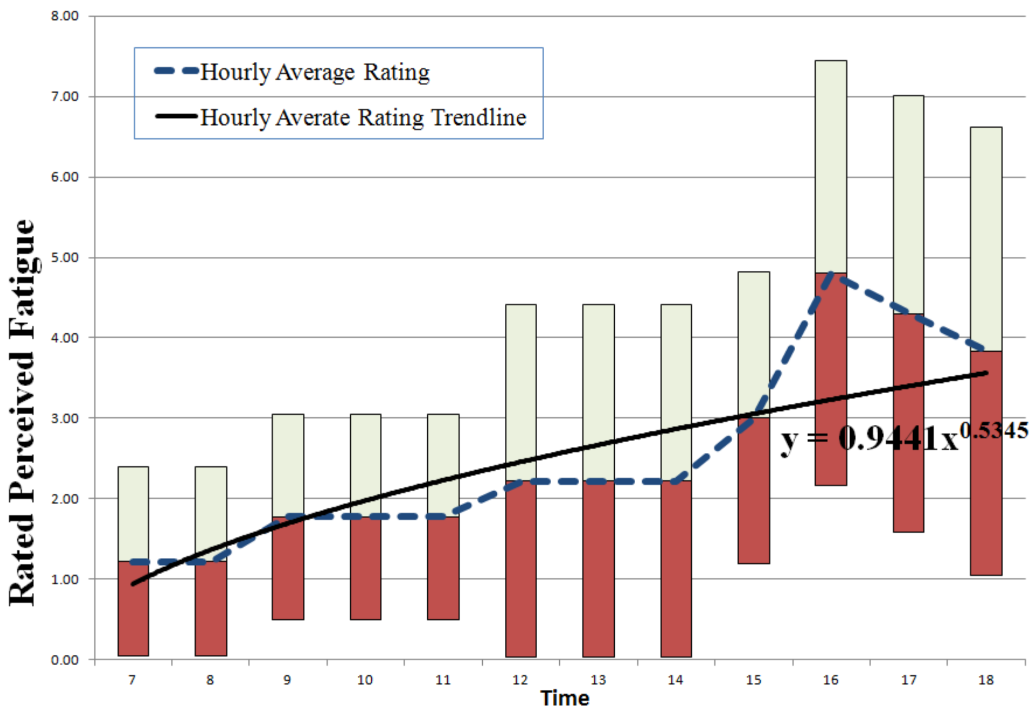

Figure 19 – Hourly average Fatigue Level rating – *the results obtained from the manual assembly line employees (n=9) show that FD increases during the shift.-(Note: all figures are fictitious).*

The results obtained from the question which asked the respondents to rate their stations based on their FD demands are shown below in Figure 20.

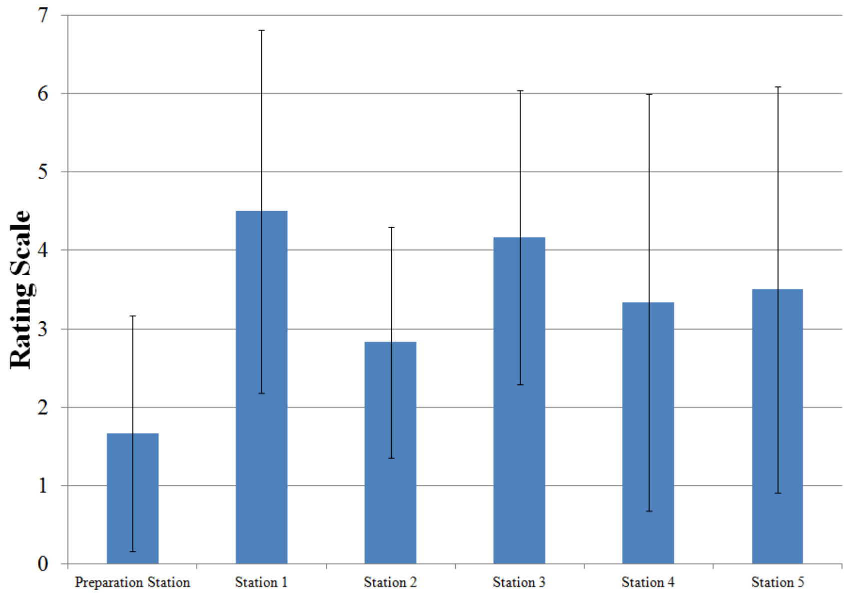

Figure 20 – Average Perceived Fatigue per station as rated by the respondents – *the results obtained from the manual assembly line employees (n=9) show that the stations are different from the fatigue dosage point of view. - (Note: all figures are fictitious).*

The end of shift Rated Perceived Fatigue obtained by the questionnaire and the modeled FD for the existing systems were correlated together. The correlation is shown in Figure 21.

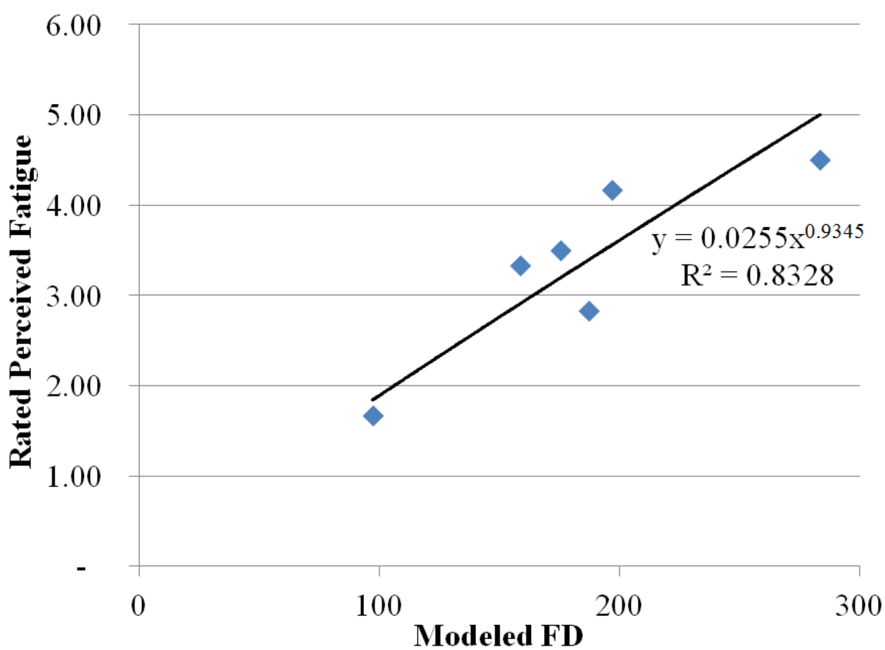

Figure 21 – Correlation between Rated Perceived Fatigue and Modeled FD for each station

Figure 18 and Figure 23 were also used to validate the modeled and perceived FD for the existing system. Table 10 shows the ranked modeled and perceived FD for the existing system. The Wilcoxon rank test performed showed that the modelled FD and Perceived FD stations ranking is unlikely to occur by chance. The Wilcoxon statistics obtained were W_+=0 and W_-=21.

Table 10 – Existing system's ranked modeled and perceived FD – *the modeled and perceived FD are similar to each other with the exception of Station 2. The Wilcoxon rank test concluded that the ranking are unlikely to occur by chance.*

Rank	Modelled FD Stations Ranking	Perceived FD Stations Ranking
1	Station 1	Station 1
2	Station 3	Station 3
3	Station 2	Station 5
4	Station 5	Station 4
5	Station 4	Station 2
6	Preparation Station	Preparation Station

The results obtained from the LC questions indicated that it took the respondents on average 3 hours to reach their optimal assembly speed. The respondents answers' showed that they were on average 1.8 times slower the first time (T_1) when they assembled a unit when compared to their optimal assembly speed.

3.1.5 Fatigue Dose (FD) and Quality Results

The existing system's modeled data from Figure 16 and the exiting system's line yield data from Figure 13 were combined together in Figure 22 to graphically show the relationship between FD and Quality.

The data shown in Figure 22 has a statistical correlation of R^2=0.26 between the FD and line yield variables. The trendlines show that these two variables co-vary and the co-variation would be stronger if there was less variability.

The cost analysis performed to show the financial benefits of accounting for FD in the engineering design stage is shown in Table 11 and Table 12. It was assumed that it costs the Company $1 to produce one unit. To repair a defective unit it costs the Company from $2 to $50.

A fictitious line yield of 97% was used. The improvement in defect rates is 26%, which is the value of R^2 obtained from Figure 22. The cost analysis assumptions are shown in Table 11 while the cost analysis itself is shown in Table 12.

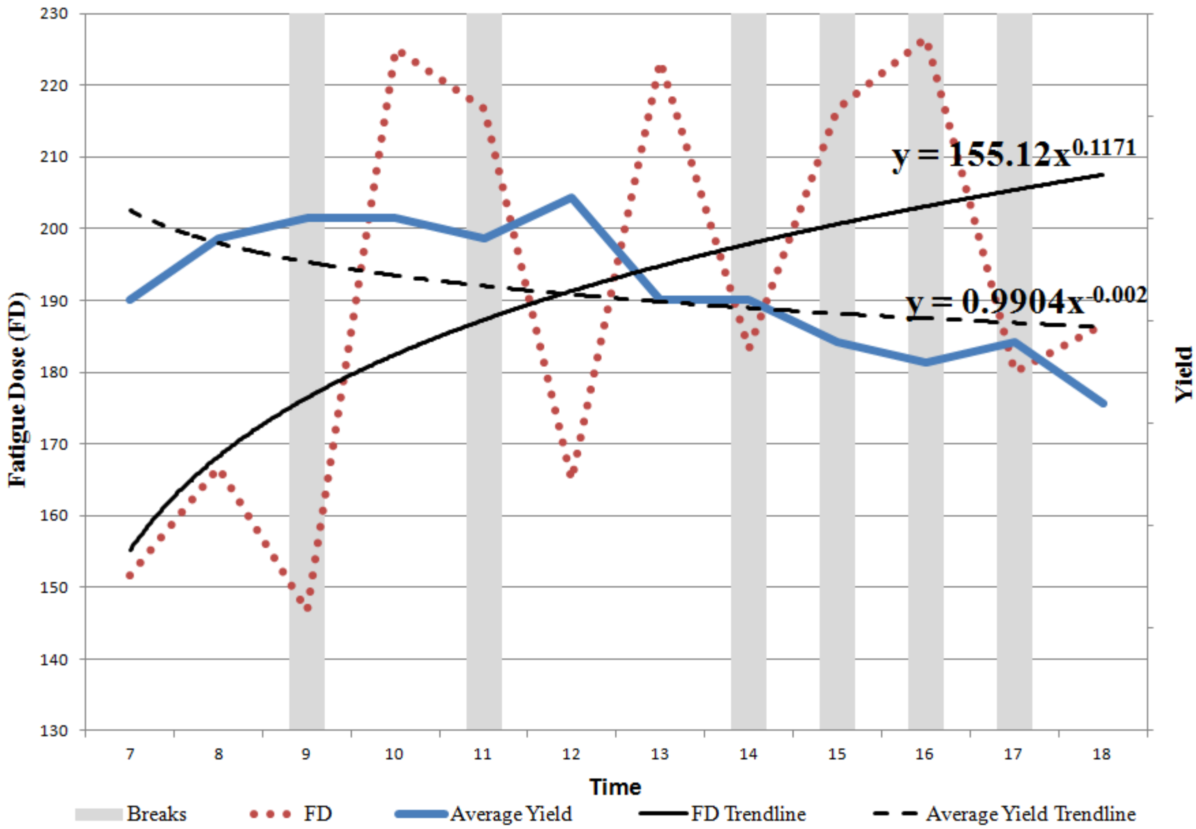

Figure 22 – Modeled Fatigue Dose (FD) per employee and Line yield relationship – *the trendlines for the modeled FD and line yield show that FD increases when yield decreases.*

Table 11 – Assumptions sample used for cost analysis

HF gains	Units (A)	Manufacturing Cost/Unit (B)	Repair Cost/Unit Lower (C)	Repair Cost/Unit Upper (D)	Yield (E)	HF Effect (F)	Defective Units (G)= [1-(E)]·[1-(F)]·(A)
Without	1,000	$1	$2	$50	97%	0%	30
With	1,000	$1	$2	$50	97%	26%	22

Table 12 – Sample cost analysis – *HF incorporation in the engineering design stage can result in savings from $0.016 to $0.39 per unit produced. In a hypothetical scenario of 50,000 units produced, the savings would be almost $20,000.*

		Total Repair Cost		Total Costs	
HF gains	Total Manufacturing Cost (H)=(A)·(B)	Lower (I)=(G)·(C)	Upper (J)=(G)·(D)	Lower (K)=(H)+(I)	Upper (L)=(H)+(J)
Without	$1,000	$60	$1,500	$1,060	$2,500
With	$1,000	$44	$1,110	$1,044	$2,110
			Savings	**$16**	**$390**
			Savings/Unit	**$0.016**	**$0.390**

3.1.6 Learning Curve (LC) Results

The learning rate, *k*, was found to be 0.483. T_∞ was calculated to be 0.8885xT_1. Figure 23 shows the LC effects on instantaneous CTs for the proposed line for one shift.

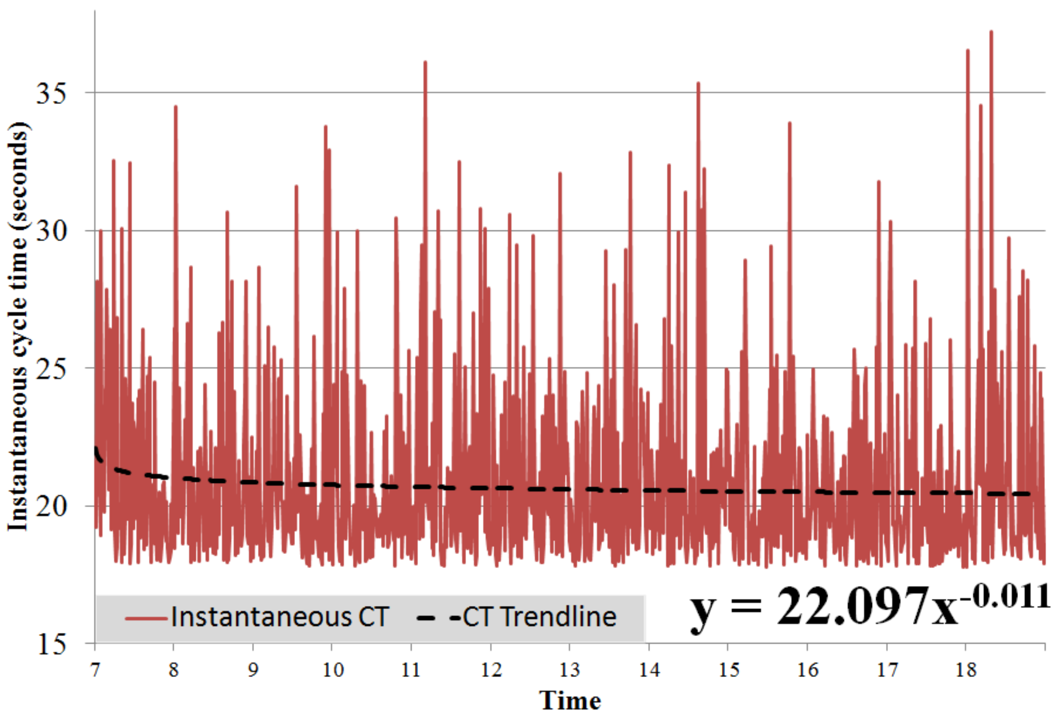

Figure 23 – LC effects on instantaneous CT – *the variability in CTs is a result of the input data to the model.*

The LC effects on CT showed that the modeled existing system produced 10.5% more products when compared to the modeled existing system without the LC effects on CT. Regarding FD the

LC effects on CT showed that the employees in the modeled existing system accumulated fatigue 10.9% more when compared to the employees in the modeled existing system without the LC effects on CT.

3.2 Participatory Action Research (PAR) Results

The PAR results have been divided into five parts: 1) Project Participation, 2) Questionnaires – Manual assembly line employees, 3) Fatigue Dose (FD) and Quality, 4) Questionnaires – Office employees and 5) Exit interviews.

3.2.1 Project Participation

The project ran over a period of 14 months, from the beginning of September 2010 to end of October 2011. The project was divided into five phases: 1) Project initiation, 2) Data collection, 3) Base model development, 4) Base model refinement/Final model, and 5) Validation. The author had interactions with 31 Company employees in nine departments. Namely, the departments involved were: 1) Manufacturing Engineering, 2) Global Ergonomics, 3) Advanced Manufacturing Engineering, 4) Production, 5) Quality Systems and Continuous Improvement, 6) Operational excellence, 7) Manufacturing Quality, 8) Technical Process Quality, 9) Technical Capacity Planning. Table 13 shows a summary of the Company's involvement per phase. Employee participation follows an increasing trend. Office employees' interest increased towards the completion of the project as the potential benefits became clearer to them. In addition to the progress reports and meetings, employees were involved through email communication and informal meetings.

Table 13 – Company's involvement during the project – the data in this table is obtained from the employees' presence in the meetings and progress reports presentations.

Study Phase	Cumulative # of employees involved	# of departments involved
Project initiation	10	5
Data collection	11	6
Base model development	14	7
Base model refinement/ Final model presentation	29	8
Validation	32	9

3.2.2 Questionnaires – Office employees

There were 8 respondents to the office employees' questionnaires. The respondents were part of the Advanced Manufacturing Engineering, Quality Systems and Improvement, Manufacturing Ergonomics and Manufacturing Engineering. Respondents' employment with the Company ranged from 1 to 5.5 years, with an average of 3.08 years. Table 14 shows the answers to the questionnaires' quantitative questions.

Table 14 – Questionnaires' quantitative answers – *the above table shows the change in office employees' (n=8) knowledge regarding DES, HF and HFM.*

		$\bar{x}$	σ	Min	Max	p-value
Level of Experience with DES	At the beginning of the project	3.43	2.30	1	7	0.52
	At the end of the project	5.43	1.51	4	8	
	Overall change range	4.43	2.14	1	8	
Level of Experience with HF	At the beginning of the project	5.14	1.46	3	7	0.51
	At the end of the project	6.57	0.53	6	7	
	Overall change range	5.86	1.29	3	7	
Level of Experience with HFM	At the beginning of the project	2.71	2.06	1	7	0.53
	At the end of the project	4.57	1.72	2	7	
	Overall change range	3.64	2.06	1	7	

The results from the qualitative part of the questionnaire for the office employees are shown in Table 15. The responses were grouped together based on the main topic they addressed. Table 15 shows that the Company employees had expectations that aligned with the incorporation of HF in the design stage as shown in Figure 2. The expectations were that a "predictive model" would be produced which result in the "improvement in production efficiency", would reduce "workmanship errors identify line bottlenecks" and "increase knowledge and application of HF to the manufacturing process.

Even though the expectations at the beginning of the project were aligned by both the research team and the Company, difficulties arose during the execution stages of the project. New Company employees entered the project which resulted in a "misalignment in expectations". According to the employee reports the misalignment resulted from the employees' perception that the research team were consultants, who would provide specific solutions to incorporate, instead of researchers which would facilitate and coach the employees to adopt simulation and

HF in their processes. Change of leadership, lack of resources attributed to the project, continuous engagement and busy schedule from the Company's side were also some difficulties reported by participants. The employees' busy schedule resulted in status update postponements, and the Company's reduced engagement. Lack of resources attributed to the project was reported to result in coordination and employee interest issues. Change of leadership in the Company also resulted in employees being transferred to other projects and new employees coming on board.

Table 15– Qualitative questions results – *answers to the qualitative questions were grouped based on the factors affecting operations in the project.*

Groups	Answers			
Difficulties that were encountered by the Company and/or Ryerson University on this project	Mostly misalignment in expectation	Change of leadership in the Company	Continuous engagement from the Company	
	Not a high volume production area	Company's schedule	Lack of resources attributed to the project	
What would you improve?	Communications between groups	Milestones schedule	Assign resources from the Company/ have a focal person	
Facilitators to the project	Frequent products produced	Environment which is open to new technology	Value added is clear to management/ Leadership support	
Expectations that you had at the beginning of this project	Predictive model	Improvement in production efficiency	Workmanship errors reduction objectives	Increased application of HF to manufacturing processes
	Determine line bottlenecks	Operators' low injury risks	Increased knowledge of HF	
Barriers to the project	Data collection is not detailed enough	No clear end-user	New product development line	Lack of resources assignment from Company
	Lack of technological knowledge	Time constraints	Lack of business advantage knowledge	Changing priorities and mandates at the Company

The Company's employees suggested that to minimize the aforementioned difficulties "communication between groups" should be enhanced. The different groups involved in the project needed to communicate between them to help data gathering and ensure timely update meetings. According to the participants communication between the groups would be enhanced when a “focal person” specific to this project is assigned from the Company. The focal person which would act as a project manager would work together with the researcher and ensure that a “milestones schedule” is developed and understood by the participating groups within the Company. Additional barriers to the project were identified by the employees. The first barrier was that “data collection is not detailed enough”. As stated earlier the Company is open to the adaptation of DES and HFM in the design process but “time constraints” and lack of detail in the data prevents the application of the “technological knowledge”.

One of the major facilitators at the Company, which were also identified by the employees, was the leadership support that this project had. The participants reported that it was apparent to the leadership team that incorporating HF in the design process, as shown in Figure 2, is beneficial to the Company. Frequent products produced at the Company were seen by employees to be another facilitator for this project.

3.2.3 Exit Interviews

There were two participants to the exit interviews. The two individuals had responded to the questionnaires previously administered to them. The additional topics of discussion which were obtained from the exit interviews but were not previously captured by the questionnaires are shown in Table 16. The topics were three: 1) Discrete Event Simulation, 2) Human Factors and 3) Change Management topics.

The Discrete Event Simulation topic included questions regarding its usefulness in the Company and the cost to adopt it. The Human Factors topic included questions regarding its effects and ease of use. The Change Management topic included questions regarding the technical knowledge, including validation and perception, to use the new technology. Time constraints that the Company is under which affect the change, the costs that the Company needs to absorb and identifying the end user of the new technology. Questions regarding the research team perception from the Change Management point of view were also asked. Some of the comments that the employees had regarding each question are shown in quotes in Table 16.

Table 16 – Exit interviews qualitative results – *additional topics that were not captured by the questionnaires were identified during the exit interviews. Topics are in bold and responses are inside quotation marks.*

Discrete Event Simulation Topics
Usefulness: "line balancing" , "plan out all of our lines", "look differently at the efficiencies of the process", "we can get better at predicting where our true bottlenecks are upfront", "the other piece that was interesting from your model that I want to validate is the quality impact", "simulation is very effective in the way you apply it", "will help you give us more objective analysis, because sometimes people usually predicting an event by perception only, it doesn't give you any objective numbers but in using your tool"
Cost: "new technology that costs more money than we're used to spending, if I can demonstrate that we are going to get a quality benefit out of it I can justify the initial capital required", "we don't use Arena here, we have looked at purchasing it, and it's pretty expensive for us"
Human Factors Topics
Effects: "I think of how it affects an assembly line in terms of repetitive motions, fatigue, and physical harm to the person", "how it affects productivity, and how you need to balance out things" **Ease of Use:** "I am looking for something that's easier to incorporate human factors in the line, I just don't want guidelines"
Change Management Topics
Technical Knowledge: "we don't want to be coming to you guys all the time", "some guys on the test team are using simulation", "but here we don't do that" – referring to simulation **Time Constraints:** "A member of my team has a simulation license but he hasn't started using it actively. It's something on our roadmap that we want to use, but we just haven't had the time to develop that piece yet." **Licensing Costs:** "I don't know that were going to have traction in the short term to purchase something like that, we have a tool here Extensim, maybe the right thing would have been to get you guys to working in that" **Validation:** "we can go and validate those things but obviously its better if you guys can be involved in that evaluation", "I think another barrier is obviously trying to match up the simulation work with products here" **Simulation perception:** "I think it changed a little; I think it's got a long way to go. When I came here, I would mention simulation and everyone would kind of look blankly. Now I'm actually here and a couple other groups here talk about simulation for once." **Usage:** "The product focused teams. I don't think they have a lot of representation right now on the steering committee but they could potentially be using simulation in the future.", "Operations could certainly use it as well in terms of predicting factory outputs." **Research team perception:** "in the employees mind you are consultants that will improve the process by 20 %."

Chapter 4 - Discussion

The DES and HFM model that amalgamates system performance with FD and LC simulations is a viable approach for the Company. System comparisons were performed and the factors that affect the uptake of DES and HFM applications were identified. Furthermore improved simulation capabilities provide the Company to potentially improve both system performance and minimize the workers HF risks. The discussion of the results obtained is divided into two parts: 1) Modeling and 2) PAR.

4.1 Modelling Discussion

Due to the nature of simulation In-data, there were limitations to the models. First of all, no yield data per station could be collected. The defective units are measured at the end of the line, and the origin of the defect is hard to identify from the company collected data. Secondly, no variability could be obtained for the manual assembly line hourly input and buffer capacity. Manual assembly line hourly input changes based on different factors at the Company and data collection was difficult. Buffer capacity in the real system changes based on the individual operator's preference and only a constant buffer was used in the simulation model.

4.1.2 DES Discussion

Table 8 in the results section shows that the proposed system has fewer bottlenecks than the existing system due to improved CT alignment and buffer size. In the proposed system, there is no major difference between the numbers of units seized for each station which is a result of the small CTs difference between the stations. This allows the parts to flow in the assembly line without any major bottlenecks. Fewer bottlenecks results in more units produced. The simulation software successfully helped identify potential areas of improvements from the line yield point of view. The simulation analysis performed predicts that the number of non defective units will be higher in the proposed rather than in the existing line. The fact that fewer bottlenecks are present in the proposed system is also shown in Table 9. However Table 9 looks at the line bottlenecks from the resource utilization point of view. This table is useful to determine employee rotation schedules or better tasks allocation insight. For example, tasks from Station 1 in the existing system could be reallocated to the Preparation station such that the bottleneck in

Station 1 can be minimized and the employee utilization can be reduced. Additionally low utilization employees can be rotated with the high utilization employees.

4.1.3 DES and HFM Discussion

The results in Figure 15 show that the musculoskeletal load does not include the load during the recovery time that the employees are subject to. The Modeled FD without recovery and Musculoskeletal load traces in Figure 15 have the same slopes and trends and the only difference between them is the scaling of the individual values. However the modeled FD trace in Figure 15 is an appropriate measure to fully capture fatigue in the system as it considers FD during the recovery time. FD provides additional information when compared to instantaneous fatigue or musculoskeletal load and is analogous to Normal et al., (1998) where the total challenge to the musculoskeletal system is captured.

Figure 16 shows that the existing system has a higher average FD per employee than the proposed system and the employees accumulate fatigue faster throughout the shift. The fluctuations in the existing system's FD are a result of the bottlenecks that exist in this system. This means that there are times when the workers work more, i.e., FD increases, to minimize the material in the buffer. The results are less recovery time and higher load absorbed by the musculoskeletal system. The proposed system has fewer bottlenecks, which result in smaller FD fluctuations; the workers work constantly and recover from fatigue during the PT which the system allows for. FD for the existing system in Figure 16 is validated by Figure 19. The employees' answers show that fatigue level increases throughout the shift. This shows that the modeled FD and the perceived FD for the existing systems are in agreement with each other. Furthermore Figure 21 shows that the correlation between Perceived Fatigue and modeled FD is strong, R^2=0.83. This means that the modeled FD is suggesting what is being perceived by the employees in the real system. Therefore the muscular fatigue and recovery models used (El Ahrache and Imbeau, 2008) were capable of predicting fatigue in the real system. The regression function shown in Figure 21 can be used to adjust the modeled fatigue in further simulations. However this function is specific to the system at hand and further research is required for general modelling. Particular attention should be paid in further research to the sample size to be used. Further evidence is shown in Table 10 where the modeled FD is in line with what is perceived from the employees in real life. Further research is required in other simulation systems.

LC effects on instantaneous CT can be seen in Figure 23. The modeled LC was aligned with the results obtained from the questionnaires however further research needs to be done to validate this point. Additionally, obtaining T1 data is necessary and can potentially be used to examine production ramp-up.

Figure 22 shows that a relationship exists between FD and line yield/quality. This information can be used by the engineering designer at the design stage, as suggested by Neumann & Winkel (2006) and as shown in Figure 2, to minimize the repair costs, increase line yield and reduce the FD for the employees. The covariance of the variables in Figure 22 has an R^2=0.26, which means that 26% of the defect that occur are potentially related to FD. Production line yield has been identified as a critical performance area where HF can help (González et al, 2003). Eklund , (1995) has shown statistically significant linkages between quality bottlenecks and human factors deficiencies. As mentioned above modeled FD and Perceived Fatigue by the employees are strongly related, therefore the Company is able to predict line yield at the design stage. The sample cost analysis in Table 12 shows that the savings obtained from designing a low FD manufacturing line are notable. One particular study in electronics assembly has shown that production quality savings resulting from improved HF can be up to US$956,136 (Yeow & Sen, 2003).

4.2 Participatory Action Research (PAR) Discussion

The office employees questionnaires' quantitative answers in Table 14 show that during this project the office employees' level of experience for DES, HF and HFM has increased. The T-test values show that the results obtained are statistically significant. The research team exchanged knowledge with the Company's employees in these areas. By increasing the employees' level of experience the Perceived Ease Of Use (PEOU) variable in Figure 6 (Davis, 1989) changed, which in turn affects the employees' attitude towards the new DES and HFM technology. The Customer Attitude variable in TAM as shown in Figure 6 (Davis, 1989), namely employees' attitude in this project, leads to Customer Adaptation of the new technology. The

Company adaptation is further identified by the employees' comments in Table 16. However there were some departments that were more open to the new technology and its application and some departments that were more reserved, which illustrates the fact that different departments involved in this project went through both the diffusion process outlined in Figure 7 (Beal & Bohlen, 1957) and TAM outlined in Figure 6 (Davis, 1989).

Frequent new product introduction at the Company means that production engineering processes are constantly being designed and HF incorporation can be applied in multiple processes. Also once the HF incorporation is visible in one design process, it is easier for the following processes to adopt such a change (Beal & Bohlen, 1957). The design process change in the subsequent processes is in line with TAM, as shown in Figure 6 (Davis, 1989). The Customer Attitude variable will be relatively easy to change in the following design processes when compared to the first design process. Change in Customer Attitude leads to Customer Adaptation of the new technology. Ease of Customer Adaptation was identified by the employees as an "environment which is open to new technology". The Company should allocate resources to benefit from the application of this knowledge. The resources allocated could either be in the form of external consultants or Company's internal employees. To fully capitalize on the application of DES and HFM the necessary information technology structures needs to be present (Jun et al., 1999). Therefore the Company needs to allocate resources and establish a focal point which results in the current resources time constraints not being affected (Jun et al., 1999). Holden et al., (2008) state that the focal person should "have the highest possible technical and interpersonal skills in order to lead the change, manage the change, or consult the change team." However in order for the application of DES and HFM to be successful a cross functional team should be used. Table 13 shows that during this project up to 9 departments were involved. There is no evidence in the literature regarding the application of DES and how many people are involved in successful DES projects, however it is clear from Table 13 that there is a need for a cross functional team.

The exit interview results, shown in Table 16, show that the DES and HFM technological change is accepted by the Company. However the application of the technological knowledge needs to increase. By allocating a resource to apply this knowledge the Company may benefit in increased line yield and productivity costs as found in other cases by Yeow and Sen (2003) and reinforced by Figure 22. The potential savings in repair costs obtained from the application of DES and HFM justify the initial cost required for such an application. The initial cost of applying DES and HFM at the design stage can be justified by the increase in quality. Therefore Company's concern as shown by the quote "new technology that costs more money than we're used to spending, if I can demonstrate that we are going to get a quality benefit out of it I can justify the initial capital required" in Table 16 is directly addressed. DES and HFM can be applied not only in one department of the Company but in multiple ones. Since multiple departments/groups benefit from the application of DES and HFM a focal person should be identified to ensure correct "communication between groups". Broberg & Hermund, (2007) identify the focal person as a boundary shakers which will act as a "broker" between groups.

4.3 Limitations and Research Opportunities

The LC equation used did not consider the effects of defective units produced. Jaber & Guiffrida (2004) state that the LC equation used assumes that "all the units produced are of acceptable quality" and as such further research is required to integrate such curves with DES and HFM. Additionally further work should consider the relationship of FD and quality simultaneously with the LC effects.

The resource utilization results shown in Table 9 could be used to calculate the costs incurred in the assembly line. Employee utilization rates can be used to calculate labour costs, while machine utilization rates can be used to calculate the machines' return on investments. Such information will help the designer better chose what machines to use and how to allocate employees in the line. The lines output results in Table 8 and the resources utilization results in Table 9 were obtained based on the assumptions used to model the assembly lines. Potential areas of improvement can be identified from these tables and changes can be made to the model's assumptions. However for each potential area of improvement that is deemed correct to be implemented in the real system, further simulation should be conducted to test the newly implemented assumptions (Jun et al., 1999).

Further research is required to determine the statistical correlation between Quality and FD such that line yield can be improved at the design stage. The quality data that were obtained for this thesis could have included biases. Further research is required to minimize these biases, if any, and determine a more accurate statistical correlation between Quality and FD. The author believes that better data would be obtained if the yield per station was used instead of the line yield. The data would be more accurate when compared to the line yield which averages all the stations. Once a better statistical correlation is determined, a cost analysis can be performed which will show the financial benefits of applying HF at the design stage. The cost analysis can potentially increase the Perceived Usefulness (PU) of DES and HFM which would affect the Customer Attitude and lead to Customer Adaptation as stated in TAM shown in Figure 6 (Davis, 1989).

Other areas of HF can be incorporated in the DES and HFM approach presented in this thesis. Further studies should address the incorporation of mental fatigue. Additionally fatigue functions that are better suited to low level repetitive and dynamic work tasks should be developed for similar systems where effort to failure tests functions might not be optimal. The main limitation of Rose et al., (1992) models was the fact that they were not developed for low level repetitive, dynamic work. Together with the FD presented in this thesis, mental fatigue will provide a better picture of the humans in the system.

Chapter 5 - Conclusions

Through the collaboration with the Company, this thesis developed and tested a viable DES and HFM approach which can be used to incorporate HF in the current engineering design processes. Two manual assembly lines were simulated, an existing and a proposed one. The DES modeled the manual assembly line's performance namely bottleneck, WIP, employee utilization and breaks schedule. DES showed that the proposed system has fewer bottlenecks, better employee utilization and produces fewer defects than the existing system. HFM simulated the humans in the manual assembly line namely their fatigue dosage, their learning curves and fatigue dosage and defects relationship. Fatigue dosage was between 7% to 33% lower in the proposed system. The learning curve effects in the modeled existing system showed that 10.5% more products were produced when compared to a modeled existing system without the learning curve effects. Fatigue dose correlated with quality showed that up to 26% of defects can potentially be accounted for based on workers' fatigue dosage, which results in substantial potential savings to the Company. The DES results were validated with the production and planning data at the Company. The fatigue dose and learning curve results obtained from the HFM were validated with questionnaires that were administered to the manual assembly line workers. The validation of DES and HFM allows the engineering designers to use such an approach with confidence early in the design process, and help them to potentially reduce human factors issues.

This study also identified some of the barriers and facilitators for simulation uptake by the Company in their engineering design process. The main barriers for simulation uptake identified were time constraints, lack of technological knowledge and initial cost. The main facilitators for simulation uptake identified were high frequency of products, clear value added to leadership, defects reduction and the Company being open to new technology. The number of departments involved increased as the project progressed, reaching a maximum number of nine departments. The office employees' level of experience with DES, HF and HFM also increased as the project progressed. Overall the Company's office employees accepted the new DES and HFM approach developed. The application of the DES and HFM approach used in this thesis will potentially increase the Company's efficiency of its production launch due to the modeled learning curves and the relationship between defects and fatigue dose. Simultaneously this approach will potentially reduce the risk exposure to workers through improved human factors. However the application of the DES and HFM approach should increase in order for the Company to make the most of the potential benefits of incorporating HF in their engineering design processes.

It is recommended that further research should be performed in incorporating mental fatigue in the DES and HFM approach, in order to complement physical fatigue. Additionally, LC equation that takes into consideration defective units should be incorporated in the approach. Further research is required to determine a general statistical correlation between Quality and FD. Action research studies should be performed to identify the application barriers and facilitators of the DES and HFM approach uptake in the engineering design process of a manufacturing company

Appendices

Appendix A – Questionnaires

Office Employees

Personal Information

Please specify your:

A) Department:

____

B) Years with the company:

____

C) Years of experience in the industry:

____

Project Specific Information

Please answer the following questions:

A) *On a scale of 1 to 10, with 1 being the lowest and 10 the highest,* what was your level of experience with Discrete Event Simulation:

At the beginning of the project (September 2010)?

○	○	○	○	○	○	○	○	○	○
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Currently (September 2011)?

○	○	○	○	○	○	○	○	○	○
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Please explain your rating: ____

____

____

____

____

B) *On a scale of 1 to 10, with 1 being the lowest and 10 the highest*, what was your level of expertise with Human Factors:

At the beginning of the project (September 2010)?

○ **1** ○ **2** ○ **3** ○ **4** ○ **5** ○ **6** ○ **7** ○ **8** ○ **9** ○ **10**

Currently (September 2011)?

○ **1** ○ **2** ○ **3** ○ **4** ○ **5** ○ **6** ○ **7** ○ **8** ○ **9** ○ **10**

Please explain your rating: ____

____

____

____

____

C) *On a scale of 1 to 10, with 1 being the lowest and 10 the highest.* what was your level of experience with Human Factors Modeling:

At the beginning of the project (September 2010)?

○ **1** ○ **2** ○ **3** ○ **4** ○ **5** ○ **6** ○ **7** ○ **8** ○ **9** ○ **10**

Currently (September 2011)?

○ **1** ○ **2** ○ **3** ○ **4** ○ **5** ○ **6** ○ **7** ○ **8** ○ **9** ○ **10**

Please explain your rating: ____

____

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____

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D) Please describe the expectations that you had at the beginning of this project

____

____

____

____

E) What do you think were some of the difficulties that were encountered by the Company and/or Ryerson University on this project?

____

____

____

____

F) Based on the difficulties encountered above what would you improve?

____

____

____

____

G) In your opinion what are some of the facilitators/barriers for simulation and human factors at the Company?

Facilitators: ____

____

____

____

Barriers: ____

____

____

____

Appendix B – DES Output Analysis

Ro =	10
To =	20
T = To + Te	12
Accuracy =	1
Alpha =	0.1
Number of Runs (R) =	1

Table B1 – Existing and Proposed systems' sensitivity analysis inputs for all performance variables.

Existing System's Analysis

Initialization Bias and Truncation Analysis:																	
Batch (*j*)	Simulation Length (T)	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Mean (Y.*j*)	0-Truncate Cumulative Mean	1-Truncate Cumulative Mean	2-Truncate Cumulative Mean	3-Truncate Cumulative Mean	4-Truncate Cumulative Mean	5-Truncate Cumulative Mean
1	0-60	44	42	44	40	46	45	45	42	46	45	**44**	44					
2	61-120	53	54	51	52	48	52	49	52	49	47	**51**	47	51				
3	121-180	40	40	39	37	39	40	35	39	39	39	**39**	44	45	39			
4	181-240	50	46	50	43	52	47	52	43	48	40	**47**	45	46	43	47		
5	241-300	25	27	24	23	26	27	24	27	26	30	**26**	41	41	37	37	26	
6	301-360	47	44	50	49	48	46	50	43	49	48	**47**	42	42	40	40	37	47
7	361-420	52	54	53	50	51	50	50	50	53	52	**52**	44	44	42	43	42	49
8	421-480	40	40	41	38	37	38	42	40	40	40	**40**	43	43	42	42	41	46
9	481-540	39	38	35	39	36	39	36	39	40	39	**38**	43	42	41	42	40	44
10	541-600	40	37	39	38	40	40	40	36	38	36	**38**	42	42	41	41	40	43
11	601-660	43	43	39	39	35	39	40	35	39	38	**39**	42	42	41	41	40	42
12	661-720	50	52	46	47	49	53	47	52	50	51	**50**	42	42	42	42	41	43

Table B2 – Existing system's initialization bias and truncation analysis (Non defective units performance measure) – *The values for each run are obtained from the existing system's DES model. - (Note: all figures are fictitious).*

Run-Length & Number of Runs Analysis:									
0-Truncate Non Defective Units in Replication *r*									
Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
44	43	43	41	42	43	43	42	43	42

Mean Non Defective Units in Replication *r*, *Yr*.(10,0)									
Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
44	43	43	41	42	43	43	42	43	42

Y..(10,2)	Sum (*Yr*.)^2	S^2	S	S/sqrt(10)	Alpha/2	*t* (alpha/2, 4)	*z* (alpha/2)	Accuracy	[*z* (alpha/2)*S / Accuracy]^2
42	18060	0.545	0.74	0.23	0.05	1.833	1.645	1.00	**1.000**

Table B3 – Existing system's run length and number of runs analysis (Non defective units performance measure) – *(Note: all figures are fictitious).*

Confidence Interval		Error
Y..-*t* S/sqrt(5)	Y..+*t* S/sqrt(5)	*t* S/sqrt(10)
42	43	0.43

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
1		
2	6.314	21.743
3	2.920	4.651
4	2.353	3.021
5	2.132	2.479

Table B4 – Existing system's confidence interval and number of runs analysis (Non defective units performance measure) – The minimum number of runs for this specific performance measure is 4 – *(Note: all figures are fictitious).*

Initialization Bias and Truncation Analysis:

Batch (*j*)	Simulation Length (T)	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Mean (Y.*j*)	0-Truncate Cumulative Mean	1-Truncate Cumulative Mean	2-Truncate Cumulative Mean	3-Truncate Cumulative Mean	4-Truncate Cumulative Mean	5-Truncate Cumulative Mean
1	0-60	3	5	3	6	3	4	3	5	2	4	**4**	4					
2	61-120	2	2	5	4	7	5	7	4	6	8	**5**	4	5				
3	121-180	3	2	3	5	3	2	7	3	3	3	**3**	4	4	3			
4	181-240	6	10	4	12	5	9	3	12	8	15	**8**	5	6	6	8		
5	241-300	3	2	5	5	3	3	5	3	3		**4**	5	5	5	6	4	
6	301-360	8	10	4	6	7	7	6	10	6	7	**7**	5	5	6	6	5	7
7	361-420	3	1	4	8	5	4	5	5	2	4	**4**	5	5	5	6	5	6
8	421-480	2	1	1	3	4	3	1		2		**2**	5	5	5	5	4	4
9	481-540	1	3	5	3	6	2	5	5	5	2	**4**	5	5	5	5	4	4
10	541-600	1	4	4	4	1	1	2	5	3	5	**3**	4	4	4	5	4	4
11	601-660	1	2	9	5	9	6	5	10	5	6	**6**	5	5	5	5	4	4
12	661-720	3	1	5	6	4		5	2	3	3	**4**	4	5	4	5	4	4

Table B5 – Existing system's initialization bias and truncation analysis (Defective units performance measure) – *The values for each run are obtained from the existing system's DES model. - (Note: all figures are fictitious).*

Run-Length & Number of Runs Analysis:

0-Truncate Defective Units in Replication *r*									
Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Run 10**
3	4	4	6	5	4	5	6	4	6

Mean Defective Units in Replication *r*, Y*r*.(10,0)									
Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Run 10**
3	4	4	6	5	4	5	6	4	6

Y..(10,2)	Sum (Y*r*.)^2	S^2	S	S/sqrt(10)	Alpha/2	*t* (alpha/2, 4)	*z* (alpha/2)	Accuracy	[*z* (alpha/2)*S / Accuracy]^2
5	214	0.874	0.93	0.30	0.05	1.833	1.645	1.0	**2.000**

Table B6 – Existing system's run length and number of runs analysis (Defective units performance measure) – *(Note: all figures are fictitious).*

Confidence Interval		Error
Y..-*t*S/sqrt(5)	Y..+*t*S/sqrt(5)	*t*S/sqrt(10)
4	5	0.54

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
2	6.314	34.826
3	2.920	7.449
4	2.353	4.838
5	2.132	3.970
6	2.015	3.547

Table B7 – Existing system's confidence interval and number of runs analysis (Defective units performance measure) – The minimum number of runs for this specific performance measure is 5 – *(Note: all figures are fictitious).*

Initialization Bias and Truncation Analysis:

Batch (*j*)	Simulation Length (T)	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Mean (Y.*j*)	0-Truncate Cumulative Mean	1-Truncate Cumulative Mean	2-Truncate Cumulative Mean	3-Truncate Cumulative Mean	4-Truncate Cumulative Mean	5-Truncate Cumulative Mean
1	0-60	43.79	43.02	43.56	41.34	44.41	44.74	43.75	43.60	43.17	45.05	**44**	44					
2	61-120	47.60	46.84	47.18	46.41	46.93	48.73	47.59	47.70	46.87	46.84	**47**	45	47				
3	121-180	38.73	37.87	37.68	37.07	38.36	38.23	38.14	37.88	37.77	37.68	**38**	43	43	38			
4	181-240	48.79	48.71	47.22	47.60	49.39	49.02	48.21	48.13	48.31	48.56	**48**	44	45	43	48		
5	241-300	27.86	28.37	27.38	26.97	28.37	28.10	28.17	28.98	28.32	29.06	**28**	41	40	38	38	28	
6	301-360	50.31	49.53	49.23	49.79	50.28	49.08	50.50	48.53	49.31	49.91	**50**	43	42	41	42	39	50
7	361-420	48.47	48.07	49.50	49.59	48.84	47.67	48.80	48.11	48.00	48.75	**49**	43	43	43	44	42	49
8	421-480	39.19	38.41	38.78	38.71	38.92	38.45	39.97	38.19	39.89	38.21	**39**	43	43	42	43	41	46
9	481-540	38.31	38.27	38.63	39.26	39.26	38.96	38.72	39.97	40.94	38.05	**39**	42	42	42	42	41	44
10	541-600	39.08	39.60	40.46	38.71	39.10	39.22	40.07	39.54	38.79	39.15	**39**	42	42	41	42	41	43
11	601-660	41.25	41.44	43.03	41.36	41.11	40.96	41.00	41.86	40.45	41.07	**41**	42	42	41	42	41	43
12	661-720	47.14	47.64	46.64	47.67	47.47	48.07	48.01	47.80	48.12	48.00	**48**	42	42	42	42	42	44

Table B8 – Existing system's initialization bias and truncation analysis (Average employee utilization performance measure) – *The values for each run are obtained from the existing system's DES model. - (Note: all figures are fictitious).*

Run-Length & Number of Runs Analysis:

0-Truncate Average employee utilization in Replication *r*									
Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
43	42	42	42	43	43	43	43	42	43

Mean Average employee utilization in Replication *r*, Y*r*.(10,0)									
Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
43	42	42	42	43	43	43	43	42	43

Y..(10,2)	Sum (Y*r*.)^2	S^2	S	S/sqrt(10)	Alpha/2	*t* (alpha/2, 4)	*z* (alpha/2)	Accuracy	[*z* (alpha/2)*S / Accuracy]^2
42	18057	0.040	0.20	0.06	0.05	1.833	1.645	1.0	**0.000**

Table B9 – Existing system's run length and number of runs analysis (Average employee utilization performance measure) – *(Note: all figures are fictitious).*

Confidence Interval		Error
Y..-*t*S/sqrt(5)	Y..+*t*S/sqrt(5)	*t*S/sqrt(10)
42	43	0.12

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
0		
1		
2	6.314	1.613
3	2.920	0.345
4	2.353	0.224

Table B10 – Existing system's confidence interval and number of runs analysis (Average employee utilization performance measure) – The minimum number of runs for this specific performance measure is 2 – *(Note: all figures are fictitious).*

Initialization Bias and Truncation Analysis:

Batch (*j*)	Simulation Length (T)	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Mean (Y.*j*)	0-Truncate Cumulative Mean	1-Truncate Cumulative Mean	2-Truncate Cumulative Mean	3-Truncate Cumulative Mean	4-Truncate Cumulative Mean	5-Truncate Cumulative Mean
1	0-60	221.05	216.29	218.98	212.87	213.29	210.54	216.86	216.29	214.95	212.29	**215**	215					
2	61-120	230.92	245.39	229.20	245.09	238.81	243.10	237.05	237.20	233.81	238.63	**238**	227	238				
3	121-180	228.40	217.95	236.53	216.57	220.32	217.51	223.95	226.06	223.92	222.71	**223**	226	231	223			
4	181-240	234.41	231.18	230.12	229.56	230.30	229.30	231.71	232.31	231.19	228.87	**231**	227	231	227	231		
5	241-300	235.16	233.93	238.70	233.76	227.31	229.93	231.15	232.45	232.28	228.81	**232**	228	231	229	232	232	
6	301-360	228.24	229.10	228.48	228.85	231.99	232.45	227.96	228.10	231.53	230.45	**230**	228	231	229	231	231	230
7	361-420	234.75	231.71	228.20	236.16	233.77	231.11	228.64	230.39	230.79	237.48	**232**	229	231	230	231	231	231
8	421-480	230.06	233.19	230.69	224.69	237.31	230.07	228.64	230.65	230.90	223.65	**230**	229	231	230	231	231	231
9	481-540	238.77	233.43	232.38	239.49	228.29	233.44	231.33	230.49	226.09	236.14	**233**	229	231	230	231	231	231
10	541-600	233.66	232.57	226.77	231.52	229.63	232.02	229.51	230.20	229.03	231.44	**231**	230	231	230	231	231	231
11	601-660	240.70	237.92	237.73	240.43	239.04	235.48	235.68	241.55	248.38	231.88	**239**	230	232	231	232	232	232
12	661-720	214.55	212.52	210.36	214.65	211.95	212.28	214.68	210.87	213.35	210.34	**213**	229	230	229	230	230	230

Table B11 – Existing system's initialization bias and truncation analysis (Average employee FD performance measure) – *The values for each run are obtained from the existing system's DES model. - (Note: all figures are fictitious).*

Run-Length & Number of Runs Analysis:

0-Truncate Average employee FD in Replication *r*									
Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Run 10**
231	230	229	229	229	228	228	229	229	228

Mean Average employee FD in Replication *r*, Y*r*.(10,0)									
Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Run 10**
231	230	229	229	229	228	228	229	229	228

Y..(10,2)	Sum (Y*r*.)^2	S^2	S	S/sqrt(10)	Alpha/2	*t* (alpha/2, 4)	*z* (alpha/2)	Accuracy	[*z* (alpha/2)*S / Accuracy]^2
229	524017	0.845	0.92	0.29	0.05	1.833	1.645	1.0	**2.000**

Table B12 – Existing system's run length and number of runs analysis (Average employee FD performance measure) – *(Note: all figures are fictitious).*

Confidence Interval		Error
Y..-*t*S/sqrt(5)	Y..+*t*S/sqrt(5)	*t*S/sqrt(10)
228	229	0.53

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
2	6.314	33.695
3	2.920	7.207
4	2.353	4.681
5	2.132	3.842
6	2.015	3.432

Table B13 – Existing system's confidence interval and number of runs analysis (Average employee FD performance measure) – The minimum number of runs for this specific performance measure is 5 – *(Note: all figures are fictitious).*

Proposed System's Analysis

Initialization Bias and Truncation Analysis:																	
Batch (*j*)	Simulation Length (T)	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Mean (Y.*j*)	0-Truncate Cumulative Mean	1-Truncate Cumulative Mean	2-Truncate Cumulative Mean	3-Truncate Cumulative Mean	4-Truncate Cumulative Mean	5-Truncate Cumulative Mean
1	0-60	80	78	78	79	83	83	81	80	74	78	**79**	79					
2	61-120	83	80	80	85	81	83	83	84	76	86	**82**	81	82				
3	121-180	68	60	63	64	59	63	63	61	62	68	**63**	75	73	63			
4	181-240	81	91	86	88	92	91	92	89	95	89	**89**	79	78	76	89		
5	241-300	39	42	41	43	43	36	38	43	41	42	**41**	71	69	64	65	41	
6	301-360	89	83	95	84	89	91	94	88	100	96	**91**	74	73	71	74	66	91
7	361-420	98	92	88	99	93	92	99	88	96	92	**94**	77	77	76	79	75	92
8	421-480	74	72	74	71	74	73	74	75	69	69	**73**	76	76	75	77	74	86
9	481-540	74	72	75	72	71	76	71	71	74	74	**73**	76	76	75	77	74	83
10	541-600	71	71	74	74	72	75	72	74	73	77	**73**	76	75	75	76	74	81
11	601-660	61	68	70	68	68	68	66	71	67	66	**67**	75	75	74	75	73	78
12	661-720	100	96	100	95	96	93	102	97	95	97	**97**	77	77	76	78	76	81

Table B14 – Proposed system's initialization bias and truncation analysis (Non defective units performance measure) – *The values for each run are obtained from the proposed system's DES model. - (Note: all figures are fictitious).*

Run-Length & Number of Runs Analysis:									
0-Truncate Non Defective Units in Replication *r*									
Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
77	75	77	77	77	77	78	77	77	78

Mean Non Defective Units in Replication *r*, *Yr*.(10,0)									
Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
77	75	77	77	77	77	78	77	77	78

Y..(10,2)	Sum (*Yr*.)^2	S^2	S	S/sqrt(10)	Alpha/2	*t* (alpha/2, 4)	*z* (alpha/2)	Accuracy	[*z* (alpha/2)*S / Accuracy]^2
77	59115	0.482	0.69	0.22	0.05	1.833	1.645	1.00	**1.000**

Table B15 – Proposed system's run length and number of runs analysis (Non defective units performance measure) – *(Note: all figures are fictitious).*

Confidence Interval		Error
Y..-*t*S/sqrt(5)	Y..+*t*S/sqrt(5)	*t*S/sqrt(10)
76	77	0.40

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
1		
2	6.314	19.206
3	2.920	4.108
4	2.353	2.668
5	2.132	2.190

Table B16 – Proposed system's confidence interval and number of runs analysis (Non defective units performance measure) – The minimum number of runs for this specific performance measure is 4 – *(Note: all figures are fictitious).*

Initialization Bias and Truncation Analysis:																	
Batch (*j*)	Simulation Length (T)	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Mean (Y.*j*)	0-Truncate Cumulative Mean	1-Truncate Cumulative Mean	2-Truncate Cumulative Mean	3-Truncate Cumulative Mean	4-Truncate Cumulative Mean	5-Truncate Cumulative Mean
1	0-60	6	8	8	7	3	3	5	6	12	8	**7**	7					
2	61-120	5	8	8	3	7	5	5	4	12	2	**6**	6	6				
3	121-180	2	8	5	3	10	7	5	8	6	1	**6**	6	6	6			
4	181-240	22	14	20	18	13	13	13	14	11	15	**15**	8	9	10	15		
5	241-300	5	3	3	2	1	8	4	2	4	2	**3**	7	8	8	9	3	
6	301-360	12	19	10	19	14	11	11	13	5	9	**12**	8	8	9	10	8	12
7	361-420	9	11	17	6	13	13	5	13	8	11	**11**	9	9	9	10	9	11
8	421-480	3	7	2	6	2	5	3	5	6	8	**5**	8	8	9	9	8	9
9	481-540	4	7	5	5	5	4	6	6	7	6	**6**	8	8	8	9	7	8
10	541-600	8	6	5	4	5	4	6	6	3	4	**5**	7	8	8	8	7	8
11	601-660	17	12	11	13	13	12	14	10	14	13	**13**	8	8	8	9	8	9
12	661-720	3	8	3	7	4	9	3	2	5	5	**5**	8	8	8	8	7	8

Table B17 – Proposed system's initialization bias and truncation analysis (Defective units performance measure) – *The values for each run are obtained from the proposed system's DES model. - (Note: all figures are fictitious).*

Run-Length & Number of Runs Analysis:									
0-Truncate Defective Units in Replication *r*									
Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Run 10**
8	9	8	8	8	8	7	7	8	7

Mean Defective Units in Replication *r*, Y*r*.(10,0)									
Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Run 10**
8	9	8	8	8	8	7	7	8	7

Y..(10,2)	**Sum (Y*r*.)^2**	**S^2**	**S**	**S/sqrt(10)**	**Alpha/2**	***t* (alpha/2, 4)**	***z* (alpha/2)**	**Accuracy**	**[*z* (alpha/2)*S / Accuracy]^2**
8	601	0.482	0.69	0.22	0.05	1.833	1.645	1.0	**1.000**

Table B18 – Proposed system's run length and number of runs analysis (Defective units performance measure) – *(Note: all figures are fictitious).*

Confidence Interval		Error
Y..-*t*S/sqrt(5)	Y..+*t*S/sqrt(5)	*t*S/sqrt(10)
7	8	0.40

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
1		
2	6.314	19.197
3	2.920	4.106
4	2.353	2.667
5	2.132	2.189

Table B19 – Proposed system's confidence interval and number of runs analysis (Defective units performance measure) – The minimum number of runs for this specific performance measure is 4 – *(Note: all figures are fictitious).*

Initialization Bias and Truncation Analysis:

Batch (*j*)	Simulation Length (T)	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Mean (Y.*j*)	0-Truncate Cumulative Mean	1-Truncate Cumulative Mean	2-Truncate Cumulative Mean	3-Truncate Cumulative Mean	4-Truncate Cumulative Mean	5-Truncate Cumulative Mean
1	0-60	73.47	71.51	72.90	70.41	70.78	71.27	72.01	71.43	71.39	71.30	**72**	72					
2	61-120	66.24	64.84	65.11	65.10	64.57	64.75	66.30	65.83	64.66	65.33	**65**	68	65				
3	121-180	57.51	55.12	55.39	54.43	55.64	56.22	56.28	55.93	55.53	55.79	**56**	64	61	56			
4	181-240	74.85	74.92	75.10	75.03	74.60	73.53	74.98	75.47	75.04	75.40	**75**	67	65	65	75		
5	241-300	42.04	41.42	41.59	42.06	40.97	41.55	39.66	41.81	42.40	42.36	**42**	62	59	57	58	42	
6	301-360	78.56	79.29	81.75	79.37	80.76	78.36	81.95	77.98	81.25	80.09	**80**	65	63	63	65	61	80
7	361-420	81.51	78.80	80.12	79.62	79.98	79.66	79.90	78.74	79.70	79.44	**80**	67	66	66	69	67	80
8	421-480	64.16	64.33	63.23	63.34	63.10	62.84	62.13	64.70	62.82	63.25	**63**	67	66	66	68	66	74
9	481-540	64.83	64.74	65.34	63.24	62.54	65.59	63.79	64.31	65.47	66.18	**65**	66	66	66	67	66	72
10	541-600	65.90	64.71	66.17	65.30	64.59	65.24	65.67	65.59	64.55	66.46	**65**	66	66	66	67	66	71
11	601-660	66.02	66.49	66.80	67.04	66.62	66.47	66.95	67.01	66.10	65.95	**67**	66	66	66	67	66	70
12	661-720	81.76	82.00	82.58	81.19	79.62	81.32	82.69	80.91	79.98	81.59	**81**	68	67	67	69	68	72

Table B20 – Proposed system's initialization bias and truncation analysis (Average employee utilization performance measure) – *The values for each run are obtained from the proposed system's DES model. - (Note: all figures are fictitious).*

Run-Length & Number of Runs Analysis:									
0-Truncate Average employee utilization in Replication *r*									
Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
68	67	68	67	67	67	68	67	67	68

Mean Average employee utilization in Replication *r*, Y*r*.(10,0)									
Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
68	67	68	67	67	67	68	67	67	68

Y..(10,2)	Sum (Y*r*.)^2	S^2	S	S/sqrt(10)	Alpha/2	*t* (alpha/2, 4)	*z* (alpha/2)	Accuracy	[*z* (alpha/2)*S / Accuracy]^2
68	45584	0.129	0.36	0.11	0.05	1.833	1.645	1.0	**0.000**

Table B21 – Proposed system's run length and number of runs analysis (Average employee utilization performance measure) – *(Note: all figures are fictitious).*

Confidence Interval		Error
Y..-*t*S/sqrt(5)	Y..+*t*S/sqrt(5)	*t*S/sqrt(10)
67	68	0.21

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
0		
1		
2	6.314	5.137
3	2.920	1.099
4	2.353	0.714

Table B22 – Proposed system's confidence interval and number of runs analysis (Average employee utilization performance measure) – The minimum number of runs for this specific performance measure is 3 – *(Note: all figures are fictitious).*

Initialization Bias and Truncation Analysis:

Batch (*j*)	Simulation Length (T)	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Mean (Y.*j*)	0-Truncate Cumulative Mean	1-Truncate Cumulative Mean	2-Truncate Cumulative Mean	3-Truncate Cumulative Mean	4-Truncate Cumulative Mean	5-Truncate Cumulative Mean
1	0-60	149.08	146.23	142.38	141.66	150.80	146.23	142.51	151.58	148.85	146.06	**147**	147					
2	61-120	178.71	182.73	176.18	174.76	182.58	175.96	177.37	182.36	172.68	179.36	**178**	162	178				
3	121-180	114.66	104.90	112.66	115.36	111.20	111.43	104.48	114.93	117.18	103.56	**111**	145	145	111			
4	181-240	153.11	148.18	151.31	156.22	150.88	147.43	151.25	146.90	149.69	151.99	**151**	147	147	131	151		
5	241-300	140.93	140.76	139.80	143.22	149.61	138.38	140.62	140.37	137.99	141.26	**141**	146	145	134	146	141	
6	301-360	155.33	146.03	147.05	148.91	143.37	143.96	148.20	144.64	143.74	144.93	**147**	146	146	137	146	144	147
7	361-420	148.22	149.93	167.68	154.79	157.28	143.96	147.44	147.27	162.25	169.11	**155**	147	147	141	148	148	151
8	421-480	146.45	152.42	131.75	139.46	133.09	151.33	148.03	147.43	144.48	150.07	**144**	147	147	141	148	147	149
9	481-540	145.00	144.13	147.33	145.01	152.36	149.92	145.82	148.32	155.73	148.29	**148**	147	147	142	148	147	149
10	541-600	151.36	141.64	146.15	151.12	145.64	152.86	151.75	147.22	152.63	151.01	**149**	147	147	143	148	147	149
11	601-660	154.56	146.87	157.93	150.73	146.94	145.87	147.64	145.95	160.22	149.15	**151**	147	148	144	148	148	149
12	661-720	132.95	134.79	131.18	135.20	131.68	133.37	134.68	133.38	130.07	134.15	**133**	146	146	143	147	146	147

Table B23 – Proposed system's initialization bias and truncation analysis (Average employee FD performance measure) – *The values for each run are obtained from the proposed system's DES model. - (Note: all figures are fictitious).*

Run-Length & Number of Runs Analysis:

0-Truncate Average employee FD in Replication *r*									
Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Run 10**
148	145	146	146	146	145	145	146	148	147

Mean Average employee FD in Replication *r*, Y*r*.(10,0)									
Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Run 10**
148	145	146	146	146	145	145	146	148	147

Y..(10,2)	Sum (Y*r*.)^2	S^2	S	S/sqrt(10)	Alpha/2	*t* (alpha/2, 4)	*z* (alpha/2)	Accuracy	[*z* (alpha/2)*S / Accuracy]^2
146	213842	1.228	1.11	0.35	0.05	1.833	1.645	1.0	**3.000**

Table B24 – Proposed system's run length and number of runs analysis (Average employee FD performance measure) – *(Note: all figures are fictitious).*

Confidence Interval		Error
Y..- *t* S/sqrt(5)	Y..+*t* S/sqrt(5)	*t* S/sqrt(10)
146	147	0.64

R	t(alpha/2, R-1)	[t*S/Accuracy]^2
3	2.920	10.470
4	2.353	6.801
5	2.132	5.581
6	2.015	4.986
7	1.943	4.637

Table B25 – Proposed system's confidence interval and number of runs analysis (Average employee FD performance measure) – The minimum number of runs for this specific performance measure is 6 – *(Note: all figures are fictitious).*

Appendix C – Questionnaires

Line Employees

Human Factors Engineering Lab
Department of Mechanical and Industrial Engineering
350 Victoria Street, Toronto, ON
Canada M5B 2K3

Personal Information

Please specify your:

A) Age: ______ B) Gender: M F C) Experience: ___Year(s) and ___Month(s)

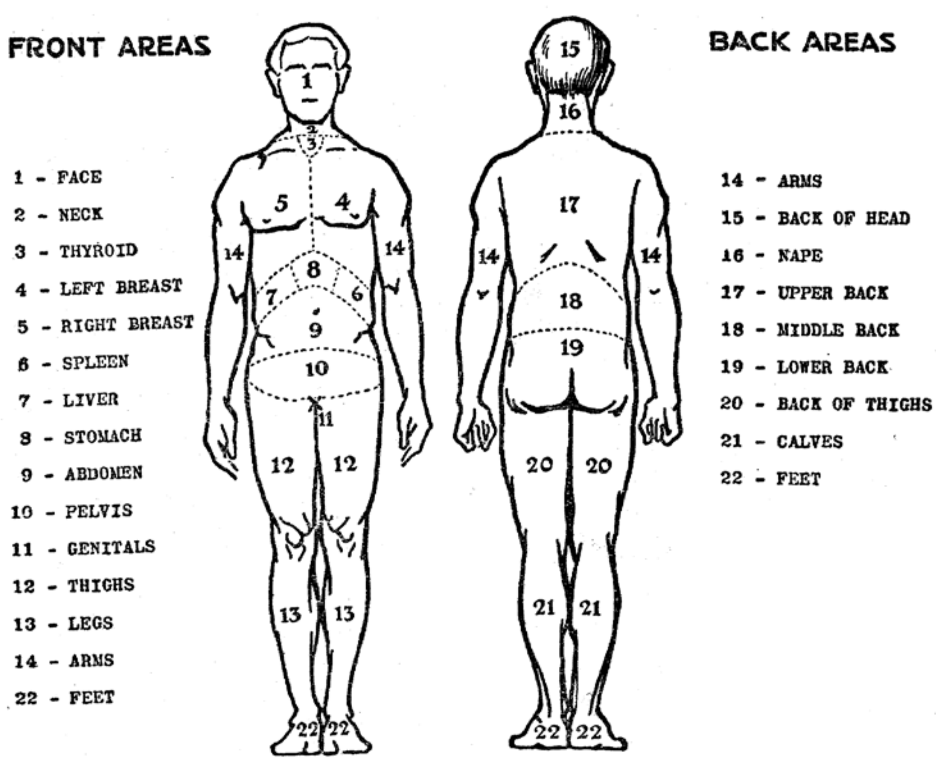
Apollo line related information

Please answer the following questions:

A) After a shift, are there parts of your body that are in pain or sore?

○ **Yes** ○ **No**

B) If Yes, Please circle which areas of your body are in discomfort after a shift



C) *On a scale of 0 to 10, as shown in the scale below*, please indicate your fatigue (tiredness) at each hour of the shift?

Scale

Numeric Value	**Meaning**
0	Nothing at all
0.5	Extremely weak
1	Weak
2	Weak
3	Moderate
4	
5	Strong
6	
7	Very Strong
8	
9	
10	Extremely Strong

Response

Time	**Fatigue (tiredness)**
Before the first 15 min break	
After the first 15 min break and before lunch	
After lunch and before the second 15 min break	
After the second 15 min break and before the first stretch break	
After the first stretch break and before the third 15 min break	
After the third stretch break and before the second stretch break	
After the second stretch break	

D) *On a scale of 0 to 10, as shown above*, please indicate the fatigue level that you feel from working on each station in the manual assembly manufacturing line.

Response

Station	**Fatigue (tiredness)**
Preparation Station	
Station 1	
Station 2	
Station 3	
Station 4	
Station 5	

E) How long ago was the first time that you worked on a unit?

___Month(s) and / or ___Day(s)

F) Compared to now, how much longer did it take you the first time to perform the tasks assigned to your station for **One** unit?

___ Same ___2 times, ___3 times, ___4 times, ___5 times, ___Other

---

G) How long did it take you to reach your fastest speed in assembling **One** unit?

_________ Hour(s)/ Day(s)/ Week(s)/ Month(s)

Appendix D – Hourly Fatigue Dose per Station

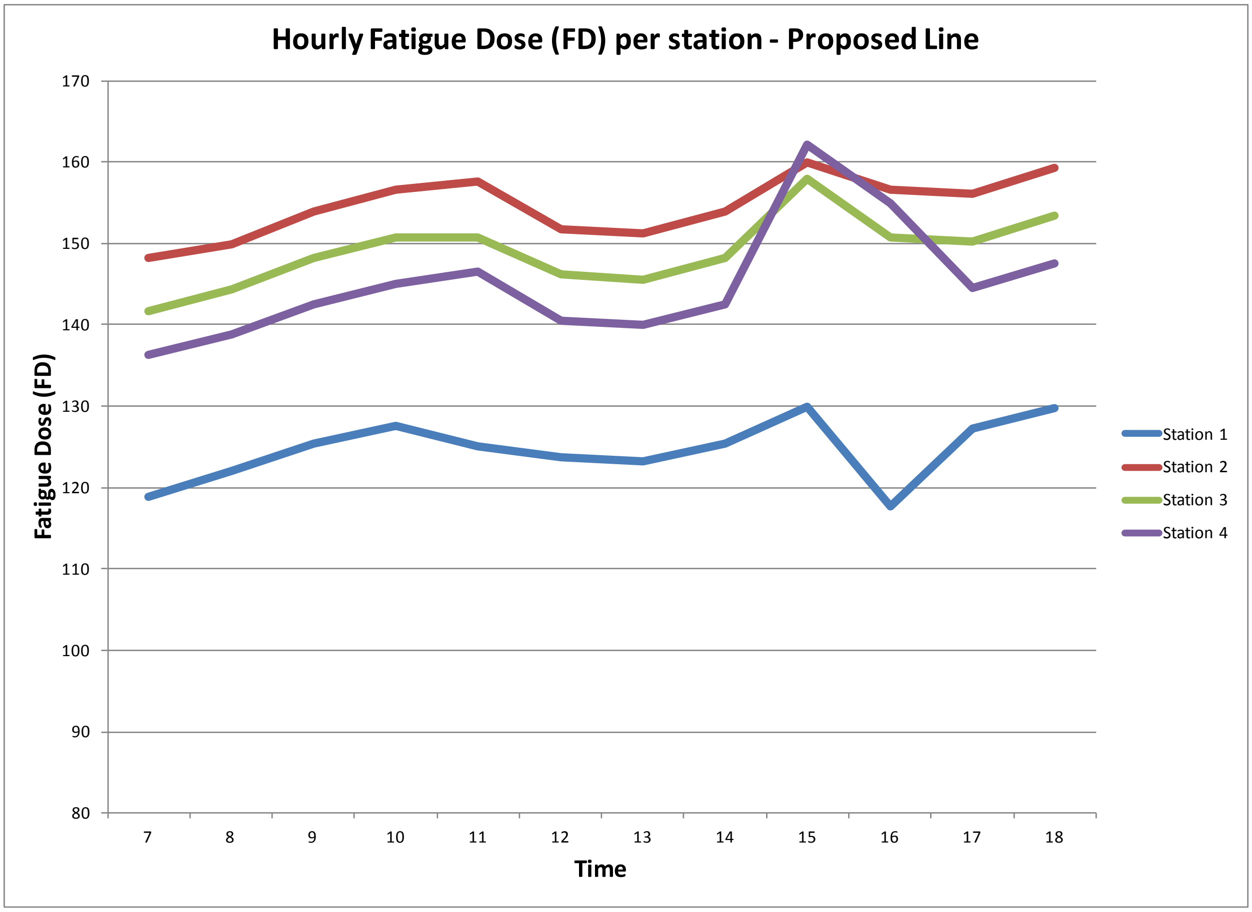


Figure D1 – Proposed line's hourly fatigue dose per station – *the fatigue dose for each station is consistent throughout the shift. The consistency reflects the fact that line imbalances are small and negligible. The fatigue dose values are smaller than the actual line.* **-** *(Note: all figures are fictitious).*

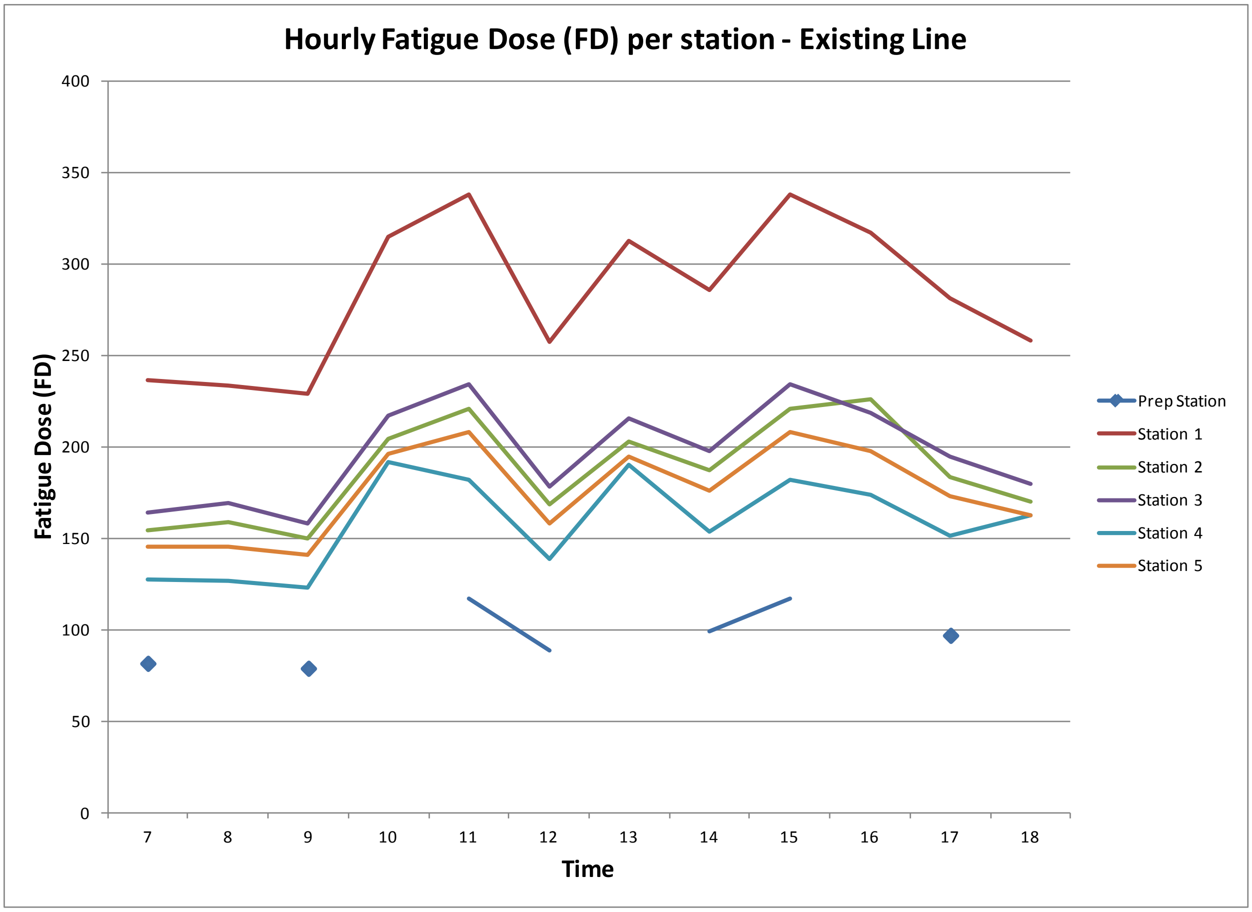


Figure D2 – Actual line's hourly fatigue dose per station – *the fatigue dose for each station is not consistent throughout the shift as compared to the proposed line. Fatigue dose fluctuations show that the line is not properly balanced and resources are not constantly used. - (Note: all figures are fictitious).*

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