THE EFFECT OF JOB ROTATION AND SINGLE-PIECE FLOW IN A HUMAN-BASED ASSEMBLY SYSTEM

by

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DEDICATION

I would like to dedicate this thesis to my family for the inspiration, encouragement and guidance throughout my life.

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LIST OF ABBREVIATIONS

Abbreviation	Description
BP	Batch Process
MOST	Maynard Operation Sequence Technique
MSD	Musculoskeletal Disorders
PFD	Personal Fatigue and Delay
SI	Strain Index
SPF	Single-Piece Flow

ABSTRACT

This research aims in comparing the batch versus single-piece flow systems with respect to the impact of the operator's fatigue variation on the throughput and resource utilization. A predetermined motion study technique, Basic Maynard Operation Sequence Technique (MOST), is used for establishing the time standards with and without the influence of fatigue. Simulation experiments are designed to measure throughput, takt time and operator's utilization when the system configurations (batching vs. single piece flow) are subjected to factors such as job rotation frequency and operator's fatigue index. The fatigue index is obtained from two different models, such as the Personal Fatigue and Delay (PFD) and Strain Index (SI). The result of the simulation experiments indicates that single-piece flow outperforms batch processing in all the scenarios including the models where fatigue is varied by +/-10%. Based on this result, single-piece flow is further studied to understand the impact of job rotation on the throughput. The simulation models were designed with various rotation frequencies, and the analysis shows that frequent job rotations results in higher throughput. Although the resulting analysis provides an insight to select the appropriate rotational frequencies in the single-piece flow environment that best fits the needs of the organizations, research recommends introducing job rotation every time when the operators returns from break to save the setup time without impacting production.

Keywords: Single-Piece Flow, Basic MOST, Job-Rotation, Simulation

1. INTRODUCTION

1.1 Motivation and Problem Description

Lean practices in manufacturing attempt to reduce production costs and increase productivity by eliminating waste [1] . Single-piece flow (SPF) is a fundamental element of lean manufacturing. In SPF, operators process one part at a time without interruption [2]. SPF reduces inventory levels, reduces manufacturing lead times and improves customer service levels [3]. SPF also facilitates defect detection [4], improves scalability and production [5] simplifies the material replenishment process, frees up floor space [6], and increases productivity as well as operator's efficiency [7].

In contrast, Batch Processing (BP) processes parts in groups rather than in a continuous stream [8]. BP is believed to cause a high level of WIP and increase the risk of producing defective parts [4]. BP has other disadvantages, such as:

- Downtimes: Manufactures may have to shut down the machines and reconfigure them for every new batch, causing the productivity to stop completely in which case, the operators sit idle. In case of higher frequency of failures and lower repair rate, system efficiency can be very poor and under-utilized.
- Space: Norzaimi [3] mentions that batches need space to keep the inventory and hold incomplete and batched orders, also the employee potential is wasted in stacking and restacking the order. To process large batches manufactures normally tend to buy big equipment and hence face space constraints.
- Fatigue: Fatigue is the state of feeling very tired, weary or sleepy resulting from insufficient sleep, prolonged mental and physical work, extended periods of stress or anxiety. The Occupational Safety and Health Administration (OSHA) states that employers can reduce the risk of operator fatigue in the workplace by examining staffing

issues such as workload, work hours, understaffing and operator absences, scheduled and unscheduled, which can contribute to operator fatigue. Padula [9] studies that employee potential can be used to the maximum level when they are not affected by fatigue/repeated load conditions.

Due to high product demand, manufacturers often lean towards traditional batch processing. The perception is that running large batches is economically feasible particularly when the equipment capital costs are high. While SPF addresses capacity loss factors such as rework and poor quality, research indicates that the impact is measured only through the company's production rates [9]. In assembly lines where there is significant human involvement, the processing methodologies need to be defined carefully considering the fatigue impact on the physical and mental health of the production operators. Yung [10] explains that fatigue is a result of the prolonged activity and is directly associated with psychological, socioeconomic and environmental factors. Mossa [1] discusses that in the assembly operations, operators are often exposed to repetitive tasks, and hence fatigue causes musculoskeletal risks, and it leads to less attention from the operators in performing the task resulting in poor quality.

Employers and supervisors should be considering factors causing operational fatigue in the workplace. Moore [11] discusses that in any assembly line operation, exertion factors, posture, speed and duration of work are crucial in defining the strain index, and this is derived based on physiological, biomechanical and epidemiological principles. One of the ways to reduce fatigue is to incorporate a job rotation program where operators rotate between the jobs at the same business performing each job for a relatively short time. The literature shows that job-rotation improves product quality [4], reduces musculoskeletal disorders [6], [10] , and creates healthy working environments. The operational fatigue experienced by the operator increases the risk of accidents as it includes both mental and physical fatigue [10].

1.2 Research Objectives

The objectives of this research are defined below:

1. Develop a discrete-event simulation model to simulate the workflow of a manual assembly operation for both single-piece flow and batch processing.

2. Design and analyze an experiment and evaluate the hypothesis that single-piece flow produces lower processing times than batch processing techniques with respect to various fatigue factors.

3. Analyze the various job rotation intervals in the single-piece flow environment and its impact on production rate.

- **Research Hypothesis**

This thesis fills the gap in understanding the impact of single-piece flow in manufacturing with respect to fatigue contributing factors. To achieve this objective, we are going to address the following questions;

1. How is SPF achieving higher productivity in comparison to batch processing, but with a reduced workforce?
2. How does the fatigue factor impact the productivity?
3. How does the job rotation impact throughput of the system?

In order to test the hypothesis, batch processing and single-piece flow are studied on a small set of operations. In batch processing, a single operator has to perform all operations on the job from start to finish, whereas in the single-piece flow with a small assembly line, each operation is performed by an operator. The first phase of the research focuses on comparing the throughputs of SPF and BP under various fatigue conditions, and the second phase focuses more on SPF validating the hypothesis on the impact of job rotation frequencies on the throughput.

1.3 Organization of Thesis

The organization of this thesis is as follows: Section 2 gives a review of the literature of single-piece flow, personal fatigue and delay, and job rotation. Section 3, the methodology, proposes a model using the discrete-event simulation for the iterative framework to measure the impact of job rotation in a single-piece flow manufacturing environment. Section 4 shows the simulation experiments and result analysis. Section 5 states the conclusion and future work.

2. LITERATURE REVIEW

Ergonomics is the key to worksite design. This research focuses on improving the productivity of the manufacturing industries through the implementation of single-piece flow, thereby involving job rotation to meet the organization's safety needs. The fatigue factor is one of the main deciding factors to schedule job rotation. Hence, this research is based on three main pillars: job rotation, single-piece flow, and personal fatigue and delay.

2.1 Job Rotation

Yung [10] studies in detail the temporal development of fatigue in various workload conditions. The reliability and sensitivity for these measures are observed and evaluated in a controlled laboratory setting for contraction, intensity, and body segment. Based on all these detailed evaluations, the pattern of fatigue development and responsive measures were defined and finally, the measures were evaluated over an eight-hour task concerning responsive measures and fatigue development.

Moore [11] discusses the "safe" and "hazardous" types of the working environment and identifies that a combination of physiology, epidemiology, and biomechanics are the guiding principles to understand and define the distal upper extremity disorders. The study is based on multiplicative interactions between six task variables: the intensity of exertion, duration of exertion per cycle, efforts per minute, wrist posture, speed of exertion, and duration of task per day. A Strain Index (SI) score is defined as the product of all six variables, and only one task type throughout the day is considered. As an outcome of the detailed experimentation applied to 25 relatively simple jobs from the same type of work, it is observed that professionals and ergonomists can use the SI score to assess the distal upper extremity disorders as the preliminary analysis indicates that strain can be measured to define the hazard potential.

Otto [12] investigates the storage-based assignment problem in the picker-to-part manual operation and considers order picking time and the human energy expenditure factor to define a bi-objective analysis. The popularity of the product, the order profile and the dimensions of the shelf are varied to compare the two algorithms- time-based storage assignment and the energy-based one. Pareto charts are developed to assess the impact on the objective function. Based on the outcome of the quantitative study, it introduces the rest allowance to integrate the energy expenditure and time to define a general order picking process.

Mossa [1] develops a mixed integer non-linear programming model to evaluate the performance of the operators based on training and skillset in high-low load manual tasks. The problem and solution show great flexibility in maximizing production under ergonomic constraints. With the job rotation model, the production-oriented formulation maximizes productivity while assigning the most suitable operator to the work. Results indicate that operator training helps develop a flexible workforce, increase productivity, and improve ergonomic standards.

Michalos [4] takes a slightly different approach in addressing the requirement of job rotation by bringing in the quality of the product, whereas most of the other studies use the traditional approach based on the operator's musculoskeletal issues. Human Error Probability (HEP) index and Fatigue scorecard are considered. This research study shows that fatigue distribution and enrichment of the working environment can lead to the reduction of assembly errors. In the HEP modelling, various human factors such as operator competence, task repetitiveness, and fatigue are evaluated in detail. Two scenarios are considered: work plan with and without job rotation. Results have indicated that job rotation reduces fatigue and task monotony. In one of the cases presented, it's observed that the error rate reduces from 64% to 14%. Padula [9] conducts a systematic review of job rotation design to prevent musculoskeletal disorders and to understand the associated psychosocial elements. The paper shows that there is a positive correlation between job rotation and higher job satisfaction. The effect of job rotation is studied with regards to Musculoskeletal Disorders (MSD), exposure to physical factors and psychosocial work factors.

Michalos [13] takes the traditional approach in discussing the job rotation approach to balance the work in a human-based assembly system. The paper discusses the job rotation criteria as: competence, operator's fatigue accumulation, distance traveled, cost, and repetitiveness of tasks. Algorithm and modeling are applied to all the rotation criteria and fatigue risk level is analyzed. Further Matlab is used to program and generate all the possible alternatives. Mamana [14] discusses that physical fatigue is hard to deal with since it lowers productivity and increases ergonomic and safety issues. The objective of the study is to examine the wearable sensors to measure physical fatigue, and accordingly, estimate the fatigue level over time. The study is based on Borg's scale with rankings of perceived exertions, and a Least Absolute Shrinkage and Selection Operator (LASSO) penalized logistic regression model with Random Under Sampling (RUS) sampling is developed to detect the fatigue; a LASSO multiple linear regression model is developed to estimate fatigue level. Results show that the wrist, torso and hip sensors are dominant and required to detect the fatigue and the working hours for critical workers need to be divided into short intervals.

Gunesoglu [15] conducts the observations in a garment industry based on a work sampling technique. In this study, details are laid out on the number of observations, the number of observers, and the flow of the process. A binomial distribution is considered as along with a 99% confidence interval and +/-1% accuracy. Various productive and non-productive activities are grouped for better analysis. In total, 13500 observations are made for productive activities, unavoidable delays, personal activities, and avoidable delays. As a result, the non-productive activities are observed in detail and suggested necessary actions to improve the productivity of the system.

RuizTorres [16] discusses the association of workers satisfaction and on-time deliveries through a job scheduling model. In this study, the operators are assigned jobs based on the preferences and the performance is estimated based on the on-time deliveries. Here the objective is to maximize the percentage of on-time deliveries and maximize worker satisfaction, and a prototype tool is developed using Excel and Visual Basics for demonstration. The computational experiments considers several factors such as job type to satisfaction scores, job types and number of workers. The results of some of the heuristics shown constant values however had limitations of finding the feasible solution.

Asensio-Cuesta [17] discusses the importance of job-rotation in the manufacturing systems and develops a multi-criteria genetic algorithm to design the job-rotation schedules to prevent MSD. In this research, an Ergonomic and Competent Rotation (ECR) model is developed which has two objectives; first is to evaluate the quality of job-rotation schedules and second is to improve the worker performance. The model is validated through a case study in an assembly line. The results indicate that the ECR model provides an opportunity for the planners to select the solutions, which are less time consuming and less repetitive, by maximizing the workers performance and competence.

Gonzalez-Cruz [18] discusses a preventive strategy to reduce MSD in the operators who are working at a very highly repetitive environment. In this study, the model is genetic developed to identify the operations that are highly repeated and has an impact on MSD, and those operators are rotated to a less exerted job which supports their recovery. The genetic algorithm is evaluated through a case study at an automobile parts assembly line, which has five critical jobs with highly repeated movements. The results of the model indicates the risk of highly repeated job profiles in a short computing time, and provides solution by defining the sequence of job-rotation for those critical jobs to avoid MSD. It is emphasized in the research that although the job rotation significantly reduces the MSD risk, the organizations should consider redesigning the critical jobs. Azizi [19] discusses the importance of workforce flexibility and the ways to achieve it through cross training. With the varied product demands and the labor resources, it is difficult for the manufacturing industries to keep up for an unplanned event; hence, a flexible workforce could potentially save the organization. In order to prove the hypothesis, an objective model is developed with constructive-search heuristic to minimize the total costs incurred for training, flexibility and productivity loss costs. The results of the research presented a model that assigns the workers to tasks, schedules the job rotation events, and determines the training schedule.

Tharmmaphornphilas [20] develops a heuristic model to implement job-rotation with the objective to reduce the low back injury possibilities due to lifting operation. The research is based on the job severity index and the number of days the operators were absent because of the injuries. The results proves that the by using the central limit theorem of sums with heuristic interchange models, rotations can be scheduled to avoid the lower back injuries, and hence the absenteeism of the operators. The study can be applied to maximize the productivity at the manufacturing line. This research provides a platform to further study the factors affecting job rotation such as, employee satisfaction, willingness of workers for job rotation, etc.

2.2 Single-Piece Flow

Li [2] studies single-piece flow to adopt just-in-time production by using straightforward schedule policies, relaxing the Takt time and reducing the risk of machine failures and operator mistakes. The single-piece flow system is evaluated based on five different factors using a multi-objective design model aiming to reduce cycle time, changeover count, cell load variation, cell count and the extent to which items are completed in a cell. Several experiments are run and compared with different approaches like Genetic Algorithm, Compact Genetic Algorithm, Particle Swarm Optimization, Ant Colony Optimization, Fuzzy Ant Colony Optimization-1 and Ant Colony Optimization-2, and results indicate that Fuzzy Ant Colony Optimization-2 is better than any other approach. Norzaimi [3] discuss the effectiveness and impacts of a single-piece flow manufacturing technique detailing out the basics of single-piece flow activities. The paper compares the batch processing and single-piece flow. The authors explain that single-piece flow strongly promotes teamwork, is fast in responding, creates a sense of ownership and easy to implement 5S.

Zadin [21] indicates work measurement is very critical in defining the health of the manufacturing line as it measures the time and effort required for an operator to perform the task. One of the several ways of estimating the time standards is using the MOST technique. Studies have indicated that MOST is preferred over other time study methodologies to establish baseline process time standards using pre-defined industry metrics rather than capturing cycle times from the highly subjective manual environments. MOST analysis can be applied to the processes with both shorter and longer repetitive cycles. Depending on the type of move and frequency of operation, indexes are assigned, and the normal cycle time is estimated for each process step breakdowns. Black [8] discusses the primary principles of Toyota Production Systems with “make one, check one, and move one on” basis. It elaborates on the potential benefits of single-piece flow production and emphasizes the pull system in the assembly operations. Kanban links are introduced in this paper as the linkage between various sub-processes and thereby suggests the WIP inventory control methods. The overall conclusion indicates that through lean implementation the organization will experience increased productivity, elimination of wastes, on-time delivery of quality goods, and maximum utilization of resources.

Oduza [22] discusses the lean thinking constraints in a traditional batch manufacturing environment detailing how scheduling and planning work. The paper emphasizes the fact that defect prevention is better than rectification and details the differences between Push and Pull systems. The case study considers the voice of operators and indicates that lean production creates teamwork and results in flexible operations. A detailed documentation is prepared based on the survey and supports strongly with five of the key lean concepts: value to the customer, value stream operations, and the flow of creating operations with minimal waiting time for batching and constant machine utilization, pull concept and waste minimization. Results indicate that 80% of the waste was caused by 20% of the deviations.

Dotoli [23] proposes a novel lean manufacturing approach to systematically and dynamically model the warehouse management by using integrated and iterative frameworks such as- Unified Modeling Language (UML) to draw the sequence of operations, Value Stream Mapping (VSM) to understand the anomalies in the system and Genba Shikumi philosophy to prioritize the top contributing anomalies and plan necessary actions. The case study conducted through this paper explains the simplicity and effectiveness of using the warehouse management tools to increase the yield at an Italian interior design production unit.

Botti [7] discusses the impact of integrating hybrid assembly line with ergonomics and lean manufacturing principles for safe assembly work. The paper aims at providing an effective, efficient line design based on physical work on the operators (OCRA index is referred) as well as various cost factors incorporated by both the automated and manual lines such as labor cost, programming cost, utility cost, defect cost and installation cost. A bi-objective integer linear programming model drives the choice between manual and assembly workstations which is based on human-paced work principle. In this model, machine pace is set by manual workstations in an optimal layout with various design options. The effectiveness of the model was validated through a case study, and the results indicate that worker ergonomics is a key parameter of the assembly process design. Ganorkar [24] discusses the implementation of time-based activity driven costing using MOST approach. MOST combines work study and time study at a granular level, thus it is easy to identify the time-consuming activities and take necessary actions. A case study is conducted in the manufacturing industry to assess the cost impact based on the MOST equations and concludes that the study not only streamlines the process, but it also identifies the improvement areas.

Battini [25] defines a novel approach to integrate ergonomic and economic objectives in manual material handling based on Energy Expenditure Rates and Rest Allowance. This paper declines the traditional approach of reducing the number of trips to save the overall operational cost. The authors also consider the ergonomic issues of the operator. Various cost factors such as picking, traveling, storing and resting costs are considered as a part of the mathematical model. Saurin [6] discusses a case study of a harvester assembly line using lean production tools to enhance the working conditions. The author provides detail discussions regarding the impacts of lean production on Push and Pull systems.

Abdulmalek [26] discusses implementation issues of the lean tools in discrete and continuous manufacturing, with focus on their feasibility in real case applications. The author also uses a simulation model using ARENA to evaluate work-in process inventory and lead time. Simulation results indicate that using a hybrid production system and Total Productive Maintenance (TPM) leads to almost 70% reduction in lead-time. Satoglu [27] discusses the sequential approach to facilitate one-piece flow environment where the model comprises of a mathematical model and a heuristic approach. This approach is studied for the design of a Hybrid Cellular Manufacturing System. The objective of the mathematical model is to minimize the inter-cell travels. In this research, a NP integer model is developed using GAMS Cplex solver to find an optimal solution to implement one-piece flow for a medium-sized problem. However, the proposed model cannot solve for the larger size problems.

Santos [5] discusses the outcome of lean manufacturing and ergonomic working conditions in the automotive system, and this study is based on the Toyota Production System. A detailed analysis of the production layout is conducted using Value Stream Mapping, and the voice of the operators is considered. The paper emphasizes that repetitive stress injuries play a vital role in the health and safety of the operators as well as the organization. The degree of importance is assessed based on the survey outcome: reducing absenteeism, increased quality product, operating time, increased productivity, and elimination of accidents.

2.3 Fatigue Factor

Margaret [28] discusses the importance of optimizing the work between humans and robots. To reduce the physical stress where the operator is exposed to repetitive motion and fatigue, careful distribution of work is very important. In this study, both time and ergonomics are considered in computing and scheduling the tasks. Strain Index (SI) is introduced to quantify the ergonomics risk which is measured based on rating six factors on a scale of 1-5: intensity of exertion(IE), duration of exertion (DE), efforts per minute (EM), hand/wrist posture (HWP), speed of work (SW), and duration per day (DD).

Moore [29] indicates that one of the many ways of assessing the issues related to the operator's musculoskeletal disorder is using the Strain Index (SI). Fifteen raters are given 61 video segments to first individually assess the risk of exposure, followed by the group assessment. Results indicated that the reliability factor was slightly better for teams than for individuals. This tool enhances the chances of predicting the risk associated with the operation in an early life cycle and is best assessed when used by multiple safety and health practitioners.

Neibel [30], in his book "Motion and Time Study," considers allowances in standard time to account for ergonomic issues. There are three main categories of allowances: Personal, Fatigue, and Unavoidable Delays. The allowance factors include general fatigue, rest periods, the time required to discuss and learn from supervisors, unavoidable delays, personal needs, setup time, and irregular operations. In this context, a detailed analysis of their design of experiments results in rating the operation-specific fatigue factors.

Radwin [31] measures physical stress associated mainly with manual and highly repetitive workloads by using biomechanical data measured from sensors. This paper aims at establishing a quantifiable metric by categorizing the datasets based on the frequency of repetitiveness, duration and exertion domain. Based on psychophysical data resulting from repetitive movements of different amplitudes and frequencies, this model helps easily assess the fatigue impact on the worker, and identifies the areas highly impacted with repeated motion. The analysis concludes that the frequency-weighted filters based on various frequency responses helps to establish the quantitative limits. Brown [32] discusses the performance issues related to batch processing, and hence, the smooth transfer to lean manufacturing. Standard formulations and mathematical equations related to lean production factors are proposed.

Yazdani [33] discusses the main factors that act as a barrier to the prevention of musculoskeletal disorders in the workplace. There are other several factors that are contributors, including the lack of time resources, communication, management, support commitment, and participation, knowledge and training, resistance to change; changing work environment, scope of activities, lack of trust, fear of job loss, or loss of authority, process deficiencies, and the difficulty of implementing controls. To mitigate these factors, the research identifies and proposed three facilitators: training, knowledge and ergonomist's support; communication, participation and support; and effective implementation of the process using the management system approach.

Paulsen [34] discusses qualitative and semi-quantitative assessment tools to measure the impact of physical strain on the operators. This study characterizes the most commonly used physical exposure assessment methods of the upper extremity: The Strain Index (SI) and Occupational Repetitive Actions (OCRA) Checklist. A case study is conducted in the cheese manufacturing industry. The outcomes of the study indicate that the reliability of the OCRA Checklist assessments was higher than the SI assessments. However, the time required to conduct a study was longer for the OCRA Checklist.

Eliasson [35] provides an extensive survey of the research with regards to the optimization models developed on physical ergonomic risks in the assembly line balancing and job scheduling problems. The study details out how the assembly line balancing through job rotation helps reduce the ergonomic risks and provides strong evidence to support the claim. .In this study, 21 OHS ergonomists participated and used their knowledge and experience to categorize the risk levels as low, moderate and high; and intra-observer reliability was carried out by asking 9 of the ergonomists to repeat the procedure at least for three weeks after the first assessment. The outcome of the study for inter-reliability shows the global risk was 53% with a corresponding 0.32 kappa value indicating fair reliability; for intra-reliability, the global risk and kappa factors were 61% and 0.41 respectively indicating that an explicit observational method is recommended. Overall, the paper emphasizes the fact that researchers, production managers and ergonomists should consider incorporating the ergonomic factors in the very early stage of the assembly line design.

Ferguson [36] discusses the 8-hour and 12-hour shift patterns. The factors deriving the shift lengths can be the shift start times, shift pattern, associated overtime, demographics and characteristics of the workforce. In this study, 8-hour and 12-hour shifts are also studied in detail to understand the impact of the domestic life of the operators. The model developed consists of independent variables such as shift timing, shift length, break frequencies and the mediating variables such as work tasks, gender and age, domestic circumstance of the operator. Based on the intensive study of the literatures and the shift systems, set of dependent variables are formulated which has an effect on the outcome such as productivity, satisfaction, morale, physical and psychological health etc. Susan [37] studies the fatigue impact on the operators in the manufacturing facility in detail through the Strain Index method. The Strain Index tool developed by Moore [11] is used to categorize the risks as safe and hazardous based on the six different Strain Index scores on a scale of 5.0. The real case study is conducted to assess the Strain Index factors in the participants. The intensity of exertion task variable influenced the SI score. The study indicates to further extensively study the subjective variables, as they should be promptly reported as and when the pain occurs in the operator. The manufacturing environments where there are complex multi-faceted jobs and longer cycles must be evaluated to study the behavior in the Strain Index.

Smith [38] compares the two manufacturing shifts of duration 8-hours and 12-hours. In the research, the two systems are studied to understand the impact on fatigue and job performance, safety, physical and psychological health of the workers. An extensive manual and electronic search is conducted to gain the information to compare these systems. The results are equivocal; however, the factors such as quality, physical and psychological health of the operators are good in case of 12-hour shifts. On the other hand, 8-hour shifts are preferred when it comes to fatigue and safety. Hence, the research has to be studied and analyzed in different situations to draw more conclusions that are robust. Tiwari [39] takes a different approach at the work scheduling methods by assessing the break times for the operators during the shifts. With the objective to reduce the time-integrated workload on the operator, a suitable rest-time model is developed. To calculate the impact on the operator, a computerized heart rate monitor is used to record the variation of the heart rate data. The experimental results indicated that the rest-time had an impact on the physiological and psychological health of the operator. The study concludes that a minimum of 15 mins should be the resting time with more than 45 mins of lunch break and a preferred break time between 13:00-14:00 h during maximum ambient temperatures.

Table 1 presents a summary of papers classified by critical factors and by processing methodology, i.e. single-piece flow and batch processing. This table shows a lack of studies conducted on assessing batch processing and single-piece flow concerning fatigue. This research fills the gap by conducting the study in the manufacturing set-up with the manual and semi-automated assembly line. A discrete-event simulation is developed to define the product flow and the associated operator's fatigue during material handling and assembly operation. As a subsection of the research, an experimentation analysis is conducted with varied job rotation schedules, and results are discussed.

TABLE 1:
LITERATURE REVIEW SUMMARY

	Batch Processing	**Single Piece Flow**
Space	Consumes more space as it includes large equipment to process the batch and also the WIP space [5].	Consumes less space as the parts flow in the assembly line with smaller number of parts in WIP [6].
WIP	More number of parts in WIP because of the batch size [8], [26].	Less number of parts in WIP because of continuous flow [40].
Quality	Difficult to identify the quality flaw, entire batch to be reworked [4].	Easy identification of defect as one part is processed at a time.
Fatigue	Repetitive workload, stacking and restacking work, and static standing position negatively impacts health and comfort.	Job rotation, balanced workload conditions and less musculoskeletal impact due to non-repetitive work pattern.

3. METHODOLOGY

This section presents a simulation framework to evaluate single-piece flow and batch processing, two critical production configurations. What makes this study unique is the incorporation of modeling constructs to represent the operator's fatigue in the simulation model. It has been well documented that single-piece flow is more efficient than batch processing. Nonetheless, from the operator's perspective, single-piece flow may be more challenging. This study would like to uncover any tradeoffs between productivity versus operator's fatigue in these two production configurations. The framework is summarized in Figure 1, and its description is provided below.

- Phase 1: Define the process and operations. In this study, we consider basic manual operations which include assembly, drilling, grinding, and painting. In section 3.1, the system configuration is discussed in detail for both SPF and BP.
- Phase 2: Establishment of time standards. A standard time estimation tool, Basic MOST, is used to split operations into granular tasks. The summation of the individual normal times for the tasks gives the total normal time (in seconds) required for an operator to perform the tasks. Section 3.2 discusses in detail how Basic MOST is applied.
- Phase 3: Personal Fatigue and Delay Calculations. To calculate the standard time of an operation, it is required to know the normal cycle time and the allowance factors. Since the operations are driven by humans, there's an associated fatigue that they develop, which has to be considered while designing the line for a target Takt time. Here, appropriate fatigue allowances are considered. The two main approaches studied here are the Personal Fatigue Delay (PFD) Index and the Strain Index(SI). Section 3.3 discusses the fatigue allowances in detail where various fatigue factors are studied through the

simulation model for both single-piece flow and batch processing. Further in the single-piece flow analysis, job rotation frequency is studied to understand its impact on throughput.

- Phase 4: Discrete-Event Simulation Model: The discrete-event simulation model attempts to represent the operations of a configurable manufacturing assembly operation. Based on the operations and the estimated cycle times including fatigue factors, a FlexSim simulation model is developed to test the hypothesis for both configurations- SPF and BP.
- Phase 5: Experiments and Results. A Design of Experiments is developed where the throughput of both SPF and BP are assessed with various simulation models. These factors include fatigue, job rotation, and production configuration. Chapter 4 discusses these elements in detail.

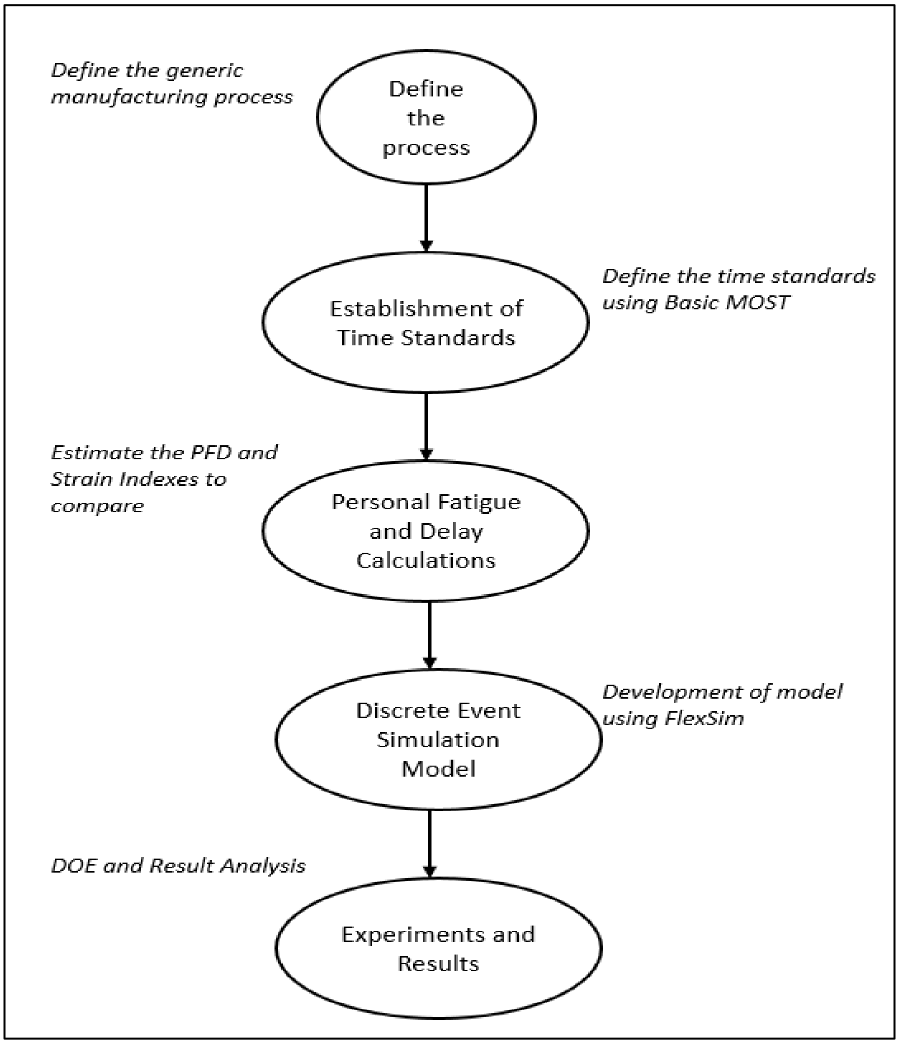

Fig. 1. High-level summary of the approach

3.1 System Configuration

A manufacturing process is presented below as a series of manual operations to produce sheet metal bracket. The manufacturing process comprises six operations with the following flow: 1) assemble the masking tape on the pre-marked location on the bracket to avoid the area getting painted in the last operation, 2) and 3) drilling operation on the each side of the pre-marked drilling locations using a small hand held drilling tool, 4) and 5) grinding operation on the each side of the pre-marked locations to remove the excess materials and smoothen the surface of the job using a small die grinder, 6) painting operation on the pre-marked surface using a small paint brush.

A conveyor system is used to hold work in process inventory. The reader should note that in the case of BP, there is no queue as each job is processed at a time. Each operating table is assumed to be 2' X 6' in size. The material movement between stations is driven through a conveyor system. The manufacturing plant is assumed to run two shifts per day, each with 12 hours per shift. The number of stations is defined based on the cycle time for respective operations to meet a target of 1000 units per hour.

Parameters:

- Target production rate(n): 1000 units/hour
- Cycle time (seconds):
  - Single-piece flow(t_1) = 10.4
  - Batch Process(t_2) = 102
- Single-piece flow:

  # Parts/hour = $3600/t_1$ = 346 units/hour

  # Stations required to produce 1000 units/hour = n/346 = 3

  Each station has six sub-stations = 6×3 = 18 stations

Each sub-station has an operator = 6×3 =18 operators

- Batch Processing:

  # Parts/hour = $3600/t_2$ = 35 units/hour

  No. stations required to produce 1000 units/hour = n/35 = 28 stations

  Each station has an operator, hence the total number of operators = 28

TABLE 2:
DERIVATION OF NUMBER OF STATIONS AND OPERATORS

Single-Piece Flow	
Target	1000
Takt time (secs)	10.4
Number of parts produced per hour	346
Number of stations required to produce 1000 per hour	3
One line has 6 stations, hence total number of operators	18

Batch Processing	
Target	1000
Takt time (secs)	102
Number of parts produced per hour	35
Number of stations required to produce 1000 per hour	28
Each station has an operator, hence total number of operators	28

The summary of the system configuration is shown below in Table 3.

TABLE 3:
CHARACTERISTICS OF THE MODEL

Sl. No.	Nature of production system	BP	SPF
1	Transfer of material	Manual	Conveyor
2	Total manpower	28	18
3	Number of stations	28	18

3.2 Establishment of Time Standards

The time standards are established based on three main factors: estimated normal time, standard deviation to consider human variability, and the fatigue percentage using Equation 1.

Total Standard Time = Normal Time × Human Variability Factor × Fatigue Factor (1)

The description of each component in Equation 1 is provided below.

3.2.1 Normal Time:

Some companies set standard operating times of manual work by using predetermined motion-based time study methods such as Maynard Operation Sequence Technique (MOST). MOST technique establishes baseline processing time standards using pre-defined industry metrics rather than capturing cycle times using stopwatch-based time studies [21]. In this case study, Basic MOST approach is used to analyze the tasks. Basic MOST has different sequence categories for the manual work: General Move Sequence, Controlled Move Sequence, and Tool Use Sequence.

- **General Move Sequence** for the spatial movement of an object freely through the air.

$$NT = (A+B+G+A+B+P+A) \times 10 \times 0.036 \quad (2)$$

- **Controlled Move Sequence** for the movement of an object when it remains in contact with a surface or is attached to another object during the movement.

$$NT = (A+B+G+M+X+I+A) \times 10 \times 0.036 \quad (3)$$

- **Tool Use Sequence** for the use of common hand tools, normally it is a combination of General Move and Controlled Move activities.

$$NT = (A+B+G+A+B+P+A+B+P+A) \times 10 \times 0.036 \quad (4)$$

where:

A=Action distance

B=Body motion

G=Gain control

P=Placement

M=Move Controlled

X=Process Time

I=Alignment

This research categorizes the manufacturing assembly operations into ‘general moves’. Table 4 summarizes the breakdown of this activity. As an example, if the walk to pick up the object takes about 3-4 steps, then index 6 is assigned, and like this, all the indexes are generated to estimate the cycle time for that particular sub step. The MOST technique uses time measurement units (TMU) instead of seconds for measuring time. The time equivalence is 1hr = 100,000 TMU’s and 1 TMU = 0.036 Seconds.

$$TMU = \sum_{i=1}^{n} S \text{ X } 10 \text{ X } 0.036 \tag{5}$$

where, S= Sum of all the process step cycle time

i = Number of process steps

TABLE 4:
CYCLE TIME STUDY FOR ASSEMBLY OPERATION USING BASIC MOST

General Move: A - B - G - A - B - P - A					
Index X 10	**A: Action Distance**	**B: Body Motion**	**G: Gain Control**	**P: Placement**	**Index X 10**
0	<=2 in. <=5 cm.			Hold Toss	0
1	Within reach		Light object light object simo.	Lay aside loose fit	1
3	1 - 2 steps	Bend & arise 50% occ	Blind, collect, interlocked, obstructed, non-simo, disengage, heavy/bulky get, free	Adjustment, light pressure, double placement	3
6	3 - 4 steps	Bend & arise		Care, obstructed, heavy pressure, blind, precision, intermediate moves	6
10	5 - 7 steps	Sit or stand			10
16	8 - 10 steps	Through door climb on/off stand & bend bend & sit			16

For SPF process, the normal time is estimated based on the general move indexes for each operation as shown in Table 5.

TABLE 5:
CYCLE TIME STUDY FOR SPF USING BASIC MOST

Sl No.	Operation Description- Assembly	Frequency	General Move							Normal Time (Seconds)
			A	B	G	A	B	P	A	
1	Pick up the part	1	3	0	3	0	0	0	0	2.2
2	Pick up the sealant	1	1	3	3	0	0	0	0	2.5
3	Apply the sealant on the part	1	0	0	0	3	1	6	0	3.6
4	Button press to index the part	1	1	0	0	1	0	1	3	2.2
										10.4
Sl No.	**Operation Description- Drill1**	**Frequency**	**General Move**							**Normal Time**
			A	B	G	A	B	P	A	
1	Pick up the drilling tool	1	3	0	3	0	0	0	0	2.2
2	Pick up the drill bit	1	1	1	1	0	0	0	0	1.1
3	Insert the drill bit to the tool	1	0	0	0	1	0	6	0	2.5
4	Drill the part position 1	1	0	0	0	3	1	6	0	3.6
5	Button press to index the part	1	0	0	0	1	0	1	1	1.1
										10.4
Sl No.	**Operation Description- Drill2**	**Frequency**	**General Move**							**Normal Time (Seconds)**
			A	B	G	A	B	P	A	
1	Pick up the drilling tool	1	3	0	3	0	0	0	0	2.2
2	Pick up the drill bit	1	1	1	1	0	0	0	0	1.1
3	Insert the drill bit to the tool	1	0	0	0	1	0	6	0	2.5
4	Drill the part position 2	1	0	0	0	3	1	6	0	3.6
5	Button press to index the part	1	0	0	0	1	0	1	1	1.1
										10.4
Sl No.	**Operation Description- Grind1**	**Frequency**	**General Move**							**Normal Time (Seconds)**
			A	B	G	A	B	P	A	
1	Pick up the grinding tool	1	3	1	3	0	0	0	0	2.5
2	Grind the part position 1	1	0	0	0	3	3	6	3	5.4
3	Button press to index the part	1	1	0	0	1	0	1	3	2.2
										10.1
Sl No.	**Operation Description- Grind2**	**Frequency**	**General Move**							**Normal Time (Seconds)**
			A	B	G	A	B	P	A	
1	Pick up the grinding tool	1	3	1	3	0	0	0	0	2.5
2	Grind the part position 1	1	0	0	0	3	3	6	3	5.4
3	Button press to index the part	1	1	0	0	1	0	1	3	2.2
										10.1
Sl No.	**Operation Description- Paint**	**Frequency**	**General Move**							**Normal Time (Seconds)**
			A	B	G	A	B	P	A	
1	Pick up the paint tub/bucket	1	3	1	6	0	0	0	0	3.6
2	Paint the part	1	0	0	0	1	1	6	0	2.9
3	Return the paint tub/bucket to the location	1	0	0	0	1	1	3	0	1.8
4	Button press to index the part	1	1	0	0	1	0	1	3	2.2
										10.4

The summary of the cycle times estimated using Basic MOST for all the stations in the assembly line is represented in Table 6 below.

TABLE 6:
OVERALL CYCLE TIME OF SPF PROCESS

Operation Sequence	Operation	Cycle time (secs)
Station-1	Assembly	10.4
Station-2	Drill 1	10.1
Station-3	Drill 2	10.1
Station-4	Grind 1	10.4
Station-5	Grind 2	10.4
Station-6	Paint	10.4

Similarly, Table 7 represents the normal cycle time estimated using Basic MOST for batch processing operation.

TABLE 7:
OVERALL CYCLE TIME OF BP

Sl No.	Operation Description	Frequency	General Move							Normal Time (Seconds)
			A	B	G	A	B	P	A	
1	Pick up the part and place on the table	1	10	6	3	10	0	6	0	12.6
2	Pick up the sealant	1	6	3	3	0	0	0	0	4.3
3	Apply the sealant on the part	1	0	0	0	3	1	6	0	3.6
4	Pick up the drill bit	1	6	3	3	0	0	0	0	4.3
5	Insert the drill bit to the tool	1	0	0	0	1	0	6	0	2.5
6	Drill the part position 1	1	0	0	0	3	1	6	0	3.6
7	Return the drill bit	1	0	0	0	3	3	3	0	3.2
8	Pick up the drill bit 2	1	6	3	3	0	0	0	0	4.3
9	Insert the drill bit to the tool	1	0	0	0	1	0	6	0	2.5
10	Drill the part position 2	1	0	0	0	3	1	6	0	3.6
11	Return the drill bit	1	0	0	0	3	3	3	0	3.2
12	Pick up the hand grinder 1	1	6	3	3	0	0	0	0	4.3
13	Grind the part position 1	1	0	0	0	3	1	6	0	3.6
14	Return the hand grinder 1	1	0	0	0	3	3	3	0	3.2
15	Pick up the hand grinder 2	1	6	3	3	0	0	0	0	4.3
16	Grind the part position 2	1	0	0	0	3	1	6	0	3.6
17	Return the hand grinder 2	1	0	0	0	3	3	3	0	3.2
18	Pick the paint tub and brush	1	6	3	3	0	0	0	0	4.3
19	Paint the part	1	0	0	0	3	1	6	0	3.6
20	Return the paint tub and brush	1	0	0	0	3	3	3	6	5.4
21	Move the part to finished goods location	1	6	0	3	10	6	6	10	14.8
22	Button press to indicate the process completion	1	0	0	0	3	0	1	6	3.6
										102

3.2.2. Fatigue Factor:

Fatigue factor is associated with the allowance that is given to the operator while the task is being performed. This is comprised of personal, fatigue and delay factors. As an example, restroom breaks, operator stepping aside for a phone call, operator receiving instructions from supervisor, etc. are considered. The details on various types of fatigue factors are discussed in Section 3.3. However, the fatigue factors are multiplied to the normal cycle time to contribute to the calculation of standard process time.

3.2.3 Human Variability:

Work performed by humans is highly stochastic, thus in this category, human variability is considered as a contributing factor to estimate the standard process time. As an example, in case of SPF, the assembly operation is estimated to be performed by the operator in 10.4 seconds. However, since this operation is not automated and involves human element, there is some variation associated always. It is not always possible for an operator to hit the same cycle time every time during the operation. In order to consider that variation in the cycle time, a 20% standard deviation factor is multiplied to the normal time [25]. This processing time is thus assumed Normally Distributed with a 20% deviation.

3.3 Fatigue Models

There are two types of fatigue factor methods considered in the study: Personal Fatigue and Delay (PFD) and Strain Index (SI). These factors are described below.

3.3.1 Personal Fatigue and Delay (PFD):

In a manual manufacturing system, an additional allowance must be considered to the normal operating time so as to recover the loss in production due to the interruptions an operator receives while performing the task:

- Personal: This is the allowance for the operator's personal needs, such as the restroom breaks, attending a phone call, etc.

- Fatigue: This is the allowance given to the operator for getting affected by the working environment, such as the concerns like standing/bending, eye strain, poor lighting, noise, etc.
- Unavoidable Delays: This is allocated to deal with the unavoidable interruptions like machine breakdown, part unavailability, etc.

Neibel [30] discusses the applications of these allowances. An allowance is a multiplier to the normal time. It is always based on the daily production time. An industrial survey is conducted for 42 different plants for various standard operations, and the average allowance for all the plants is 17.7%. The allowances are assigned based on the different subcategories such as personal time, unavoidable delays and fatigue, time for cleaning the workstation, time for oiling the machines, planned and unplanned shutdowns, and tool maintenance time. The respective indexes are added to get the total effort time and is segregated between the machine and operators time.

Table 8 shown below represents the survey summary on the indexes for personal fatigue and delay are based on the standard operations in the plants.

TABLE 8:
TABLE SHOWING PFD ALLOWANCES FOR STANDARD OPERATIONS [21]

Time study allowances for standard operations										
Symbol	**Facility or operation**	**Method**	**Total applied to effort time**	**Total applied to machine time**	**Personal**	**Clean work station**	**Oil machine**	**Shutdown**	**Tool maintainence**	**Unavoidable delays and fatigue**
21	Anneal	Oven	10	-	5	1/2	-	-	-	4 1/2
22	Assembly	Bench	13	-	5	-	-	-	-	8
23	Assembly	Floor	14.5	-	5	-	-	-	-	9 1/2
24	Blacksmith	Drop forge	21	-	7	1	-	-	-	13
25	Brake	Power	15	-	5	1/2	-	-	-	9.5
26	Braze	Electric	15	-	5	1/2	-	-	-	9 1/2
27	Drill	Hand feed	15	-	5	1/2	1/2	1/2	2	6 1/2
28	Drill	Power feed	15	12	5	1/2	1/2	m-2	m-4	-
29	Engrave	Pantograph	18	-	5	1/2	1/2	e-1/2	e-2	e-6 1/2
30	Lathe, English	Over 36 inches	15	15	5	2	1	m-2	m-5	e-7
31	Lathe, Engine		15	15	5	2	1	m-2	m-5	e-7
32	Lathe, Turret		17	15	5	2	1	m-2	m-5	e-9
33	Milling		16	15	5	2	1	m-2	m-5	e-8
34	Grinding	Blanchard	15	15	5	2	1	m-2	m-5	e-7
35	Grinding	Thread	17	15	5	2	1	m-2	m-5	e-9
36	Grinding	External and interna	16	15	5	2	1	m-2	m-5	e-8
37	Punch press	Up to 100 tons	14		5	1/2	1	1/2	-	7
38	Saw	Circular	14		5	1/2	1/2	1/2	1	6 1/2
39	Saw	Do-All	15		5	1/2	1/2	1 1/2	2	5.5
40	Shear	Square	15		5	1/2	1/2	1		8
41	Welder	Spot	17		5	1/2	-	2	3	6 1/2
42	Paint	Spray	17		5	2	-	1	1	8
m: applied to machine time only e: applied to effort time only										

From the table, indexes for the operations such as assembly, drilling, grinding and painting are referred directly for this research. The standard cycle times for the operations based on these indexes are the inputs for simulation to test the hypothesis. Hence, in this case, the estimated standard operating time for the various processes of SPF and BP based on [21] is summarized below in Tables 9 and 10, respectively.

TABLE 9:
TABLE SHOWING STANDARD CYCLE TIME FOR SPF BASED ON PFD

Sl No.	Operation	Normal Cycle Time (secs)	PFD factor	Standard Cycle Times (secs)
1	Assembly	10.4	14.5	11.9
2	Drill-1	10.4	15	12.0
3	Drill-2	10.4	15	12.0
4	Grind-1	10.1	17	11.8
5	Grind-2	10.1	17	11.8
6	Paint	10.4	17	12.2

TABLE 10:
TABLE SHOWING STANDARD CYCLE TIME FOR BP BASED ON PFD

Sl No.	Operation	Normal Cycle Time (secs)	PFD factor	Standard Cycle Times (secs)
1	Overall Operation	102	30	132.6

3.3.2 Strain Index (SI):

SI is another approach for calculating the operator's fatigue and exertion in manufacturing [34]. While analyzing the distal upper extremity disorder, [11] developed the SI approach. It is now a widely used method for assessing the risk associated with the work. The SI is given in Equation 6.

$$SI = (IE \times DE \times EM \times HWP \times SW \times DD) \quad (6)$$

where:

IE = Intensity of exertion

DE = Duration of exertion

EM = Efforts per minute

HWP = Hand/write posture

SW = Speed of work

DD = Duration per day

SI is defined based on six parameters and rated over a scale of 1-5. According to [11], the thresholds defined with regards to the safety at work are: SI ≤ 3 indicates the working environment is safe; $3 \leq SI \geq 7$ indicates a moderate risk; and $SI \geq 7$ indicates a hazardous working condition.

For each parameter described in the table, appropriate indexes should be chosen from the corresponding index table. From the table, it is evident that IE, HWP, and SW are subjective and, DE, EM and DD are driven based on the duration the operator is exposed to fatigue. To calculate the DE, which is represented in percentage, we need to sum the time where the exertion occurs, and then divide it by the total cycle time, and the resultant should be matched to the appropriate range from the table. EM is the number of times the effort applied on each element, which is the sum of efforts for all human based work elements and divide it by the cycle time in minutes and select the appropriate index from Table 11.

TABLE 11:
TABLE SHOWING SI PARAMETERS AND MULTIPLIERS [28]

SI parameters and multipliers						
Rating	**IE***	**DE**	**EM**	**HWP**	**SW**	**DD**
Rating criteria						
1	Light	< 10	< 4	Very good	Very slow	≤ 1
2	Somewhat hard	10-30	4-9	Good	Slow	1-2
3	Hard	30-50	9-15	Fair	Fair	2-4
4	Very hard	50-80	15-20	Bad	Fast	4-8
5	Near maximal	≥ 80	≥ 20	Very bad	Very fast	> 8
Rating	**IE**[1]	**DE**[1]	**EM**[1]	**HWP**[1]	**SW**[1]	**DD**[1]
Multiplier table						
1	1	0.5	0.5	1.0	1.0	0.25
2	3	1.0	1.0	1.0	1.0	0.50
3	6	1.5	1.5	1.5	1.0	0.75
4	9	2.0	2.0	2.0	1.5	1.00
5	13	3.0[†]	3.0	3.0	2.0	1.50

* IE= Intensity of exertion; DE= Duration of exertion; EM= Efforts per minute; HWP= Hand/ wrist posture; SW= Speed of work; DD= Duration per day (h)
[†] If DE is 100%, the multiplier of effort per minute is set to 3.0

To apply the same methodology for the operations chosen in the research, all the 6 parameters are multiplied to get the estimated SI factor for respective operations. Below is the summary of the indexes assigned and fed as an input to the simulation to test the hypothesis.

TABLE 12:
TABLE SHOWING STANDARD CYCLE TIME FOR SPF BASED ON SI

Sl No.	Operation	Normal Cycle Time (secs)	SI factor	Standard Cycle Time (secs)
1	Assembly	10.4	12	11.6
2	Drill-1	10.4	11.3	11.6
3	Drill-2	10.4	11.3	11.6
4	Grind-1	10.1	12.5	11.4
5	Grind-2	10.1	12.5	11.4
6	Paint	10.4	11	11.5

TABLE 13:
TABLE SHOWING STANDARD CYCLE TIME FOR BP BASED ON SI

Sl No.	Operation	Normal Cycle Time (secs)	SI factor	Standard Cycle Time (secs)
1	Overall Operation	102	22.4	124.8

3.3.3 Job Rotation:

Job rotation in this research can only be applied and studied on single-piece flow. It is designed based on the fact that the operator will rotate their jobs after every break, and thereby eliminating the setup or rotation time from the production schedule. System's behavior is studied for various job rotation schedules. Job rotation reduces boredom, absenteeism, and work stress. Gunesoglu [15] conducts a series of observations and categorizes different types of delays as shown in Table 10. For this study, considered job rotation under avoidable delays by scaling the factor to study the impact on throughput for 2, 3, 4, 6, 8, 10, and 12 hours of operational time. The reason for considering job rotation under avoidable delays is to schedule the rotation when operator returns from break. This approach does not only help the reduced set-up or unproductive time, but it also improves the performance of the system. Various job rotation frequencies are evaluated, and the corresponding results are analyzed in detail.

TABLE 14:
AVOIDABLE DELAYS FOR JOB-ROTATION ANALYSIS [15]

Analysis of avoidable delays for job- rotation				
Flow type	**Symbol**	**Number of observation (n)**	***p* (%)**	***f* (%)**
1. Productive activities	G	9815	73	1.0
2. Unavoidable delays	$V_{\delta\gamma}$	2011	15	0.8
3. Personal activities	V_p	1123	8	0.6
(2 + 3)	V	3134	23	0.9
4. Avoidable delays	N	551	4	0.4
Total		13500	100	

Job-rotation factor, R, is calculated as:

$$R= (t\times (n/p))/3600 \tag{7}$$

where:

R= Job rotation factor

t= Takt time in seconds

n= Number of observations

p= Avoidable delay percent

The fatigue factor F is estimated as follows:

$$F = f * (p/R) \tag{8}$$

where

F = Fatigue Factor

f = Frequency of job rotation

p = Avoidable delay percent

R = Job rotation factor.

For example, suppose t=10.4 secs, n=551 and p=4.08 percent, job rotation factor R is 1.59, as computed by Equation 7. The fatigue factors for various rotation models is shown in Table 15, which are calculated by using Equation 8.

TABLE 15:
FATIGUE BASED ON VARIOUS ROTATION INTERVALS

	Rotation Intervals (Hrs)						
Job Rotation Frequency	2	3	4	6	8	10	12
Fatigue (%)	5.1	7.7	10.3	15.4	20.5	25.6	30.8

3.4 Discrete Event Simulation Model

A discrete-event simulation model is developed by using FlexSim software. The purpose of using simulation in this study is to analyze the impact on throughput under various design points. A simulation model is built for each process configuration, i.e. SPF and BP. The overall environment for simulation in both the systems is maintained the same for comparison, except the main driving values such as cycle time and fatigue factors.

3.4.1. Single-Piece Flow Simulation Configuration:

In case of SPF operation, the simulation model includes three assembly lines with six stations each. Each operator performs one task at a time. The tasks are divided into smaller segments and assigned to the operator. In this assembly line operation, each operator has to finish the work and pass the job to the next station. For the SPF environment, cycle time of the operation is estimated to be 61.8 secs. There are three lanes named A, B and C. For the SPF environment, cycle time of the operation is estimated to be 61.8 secs. Below figure represents the process flow for SPF.

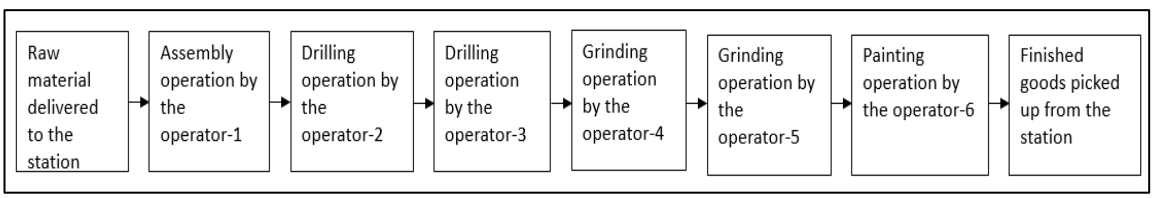

Fig. 2. Process flow of the single-piece flow operation

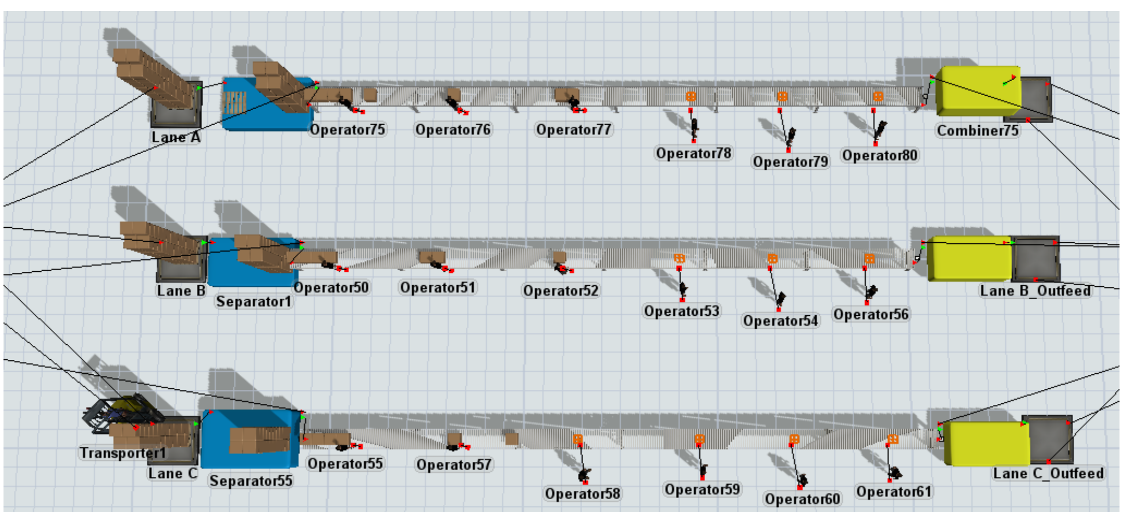

Fig. 3. Layout of single-piece flow operation

3.4.2. Batch Process Configuration:

In batch processing, the worker is assigned to conduct all the tasks from the start to finish on the job. The operator has to switch between the tools to perform respective operations. The estimated cycle time to perform the job is 102 secs. The job will not be moved to the next phase of the manufacturing system until all the tasks are performed by the operators in the defined flow and move it to the finished goods section. This process is repeated for the whole operation time. Each of these individual working stations are referred as tables.

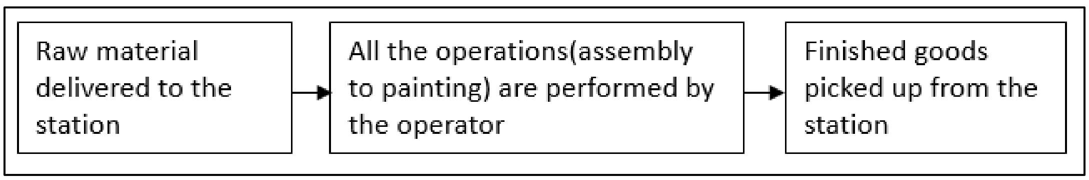

Fig. 4. Process flow of batch processing

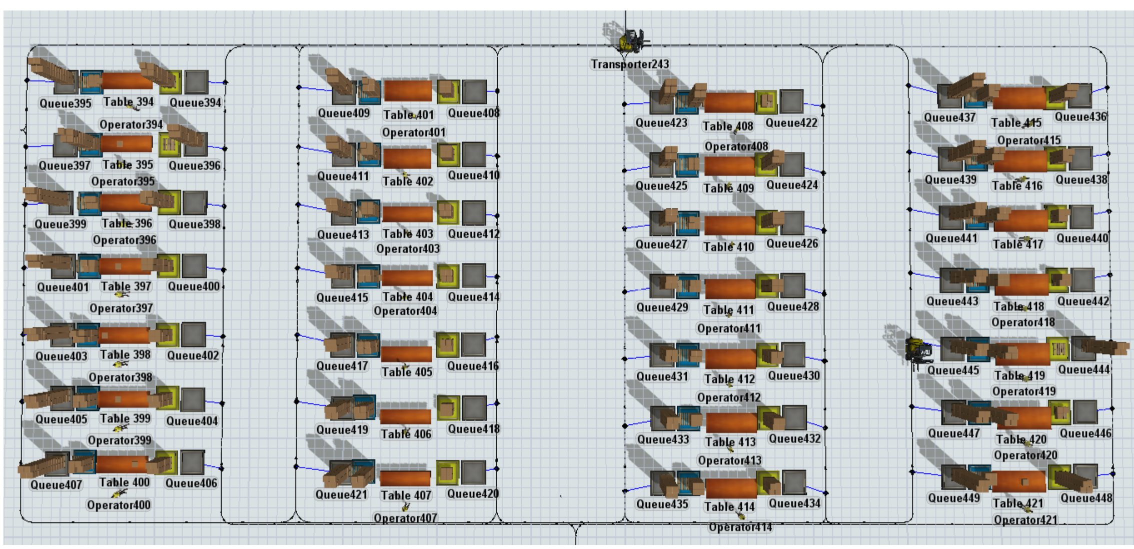

Fig. 5. Layout of batch processing operation

4. DESIGN AND ANALYSIS OF SIMULATION EXPERIMENTS

In this chapter, a detailed analysis of the proposed methodology is discussed. The main elements of this chapter are divided into three categories:

- Design of Simulation Experiments
- Statistical Analysis of Simulation Results
- Operational Expense Analysis

To compare the two manufacturing systems- single-piece flow and batch processing, the simulation experiments are designed based on with fatigue and without-fatigue inputs. Under analysis with fatigue, the response in terms of throughput is assessed based on two different fatigue indexes: Personal Fatigue and Delay, and Strain Index units. Job rotation analysis is considered for single-piece flow. Using Minitab, statistical experimentation is designed, and lastly, the overall operational expense for both the manufacturing systems is studied and compared.

4.1 Design of Simulation Experiments

4.1.1. Simulation runs:

Each simulation is run for 20 simulation days along with 10 simulation days for warm-up period. Simulations were run as independent runs. Common random numbers were not used in these experiments. To maintain the continuous flow of the parts in the system, input and output stations are designed to receive and deliver 50 units per batch.

- Model Verification and validation:

The simulation models are developed to visualize and verify the process based on the input given to the model for various scenarios. Through the software output, we verify the model is running as expected. The model should then be validated to understand if the simulation results replicate the system under study. In this research, we verify and validate the cycle times observed in the static and dynamic environments, 16 and 17 provides the summary of the results.

TABLE 16:
SPF DOE SUMMARY FOR VARIOUS FATIGUE MODELS

Process	**Standard Cycle time (secs)**	**Simulation Cycle time (secs)**
with PFD	71.6	71.6
with SI	69.1	69.1
without fatigue	61.8	62.1

TABLE 17:
BP DOE SUMMARY FOR VARIOUS FATIGUE MODELS

Process	**Standard Cycle time (secs)**	**Simulation Cycle time (secs)**
with PFD	132.6	132.6
with SI	124.8	124.8
without fatigue	102	98.7

4.1.2 Design of Simulation Experiments:

- Factors and Factor Levels: This experiment considers the following factors:
    - Factor-A: Manufacturing process configuration.
        - The levels of Factor A are Single Piece Flow and Batch Processing.
    - Factor-B: Fatigue models.
        - The levels of Factor B are PFD and SI
    - Factor-C: Number of job rotations.
        - The levels of Factor C are the 7 job-rotation frequencies: 2-hour, 3-hour, 4-hour, 6-hour, 8-hour, 10-hour, and 12-hour
- Design Points (Combinations): These designs are unbalanced. To study the effect of fatigue variation on the throughput of the system, each model is studied for with 2 levels: +10% and -10%. Therefore, the following combinations are generated.
- Models based on PFD:

  - With standard PFD of the base model
  - With +10% PFD
  - With -10% PFD
- Models based on SI:
  - With standard SI of the base model
  - With +10% SI
  - With -10% SI
- Model without fatigue: The system is studied without incorporating the fatigue factor. The experimental design is represented in Table 18. The responses of the experiment are measured in terms of throughput, operator and station utilization.
- Simulation Runs: Each of the models are run for 20 replications.

TABLE 18:
SUMMARY OF DESIGN OF SIMULATION EXPERIMENTS

	Fatigue Factor	Statistical Analysis	Response Measure
SPF	With Fatigue	With Base PFD	Throughput with PFD
		With + 10% PFD	
		With - 10% PFD	
		With Base SI	Throughput with SI
		With + 10% SI	
		With - 10% SI	
BP	With Fatigue	With Base PFD	Throughput with PFD
		With + 10% PFD	
		With - 10% PFD	
		With Base SI	Throughput with SI
		With + 10% SI	
		With - 10% SI	

- Base Model

In the base model, both the processes are studied based on the various fatigue inputs: with PFD, with SI, and without fatigue. As explained in below, operator utilization in case of SPF is idle for some time because of the starve/blocked time from the immediate stations, whereas in BP utilization is indicated as 100% because of the independent stations. In the simulation run, each pallet for input and output feed contains 50 parts.

4.2 Statistical Analysis of Simulation Results

4.2.1 Base Models:

- SPF base model with PFD: The base simulation model is developed with the standard cycle time estimated based on the PFD inputs as shown in Table 9.

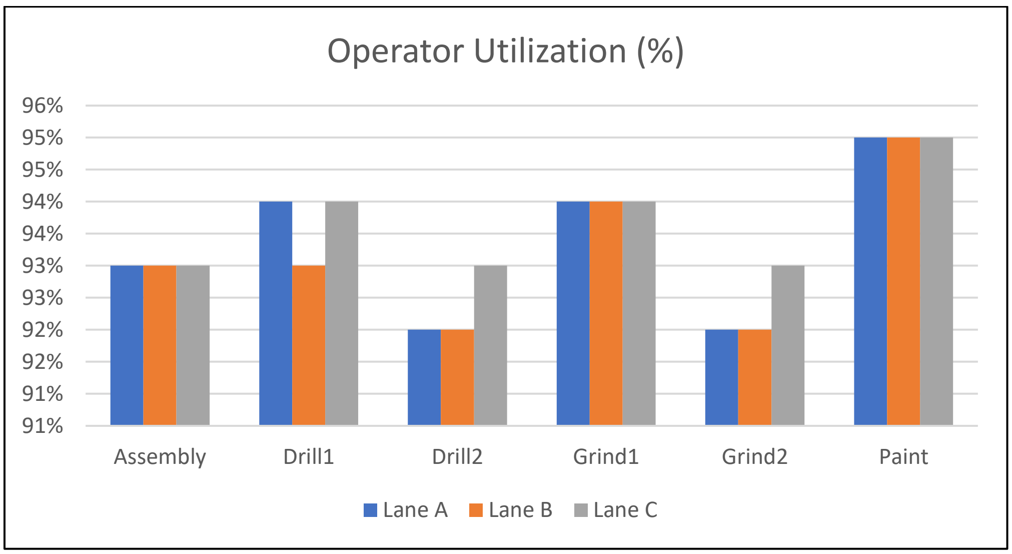

Fig.6. SPF operator utilization with PFD

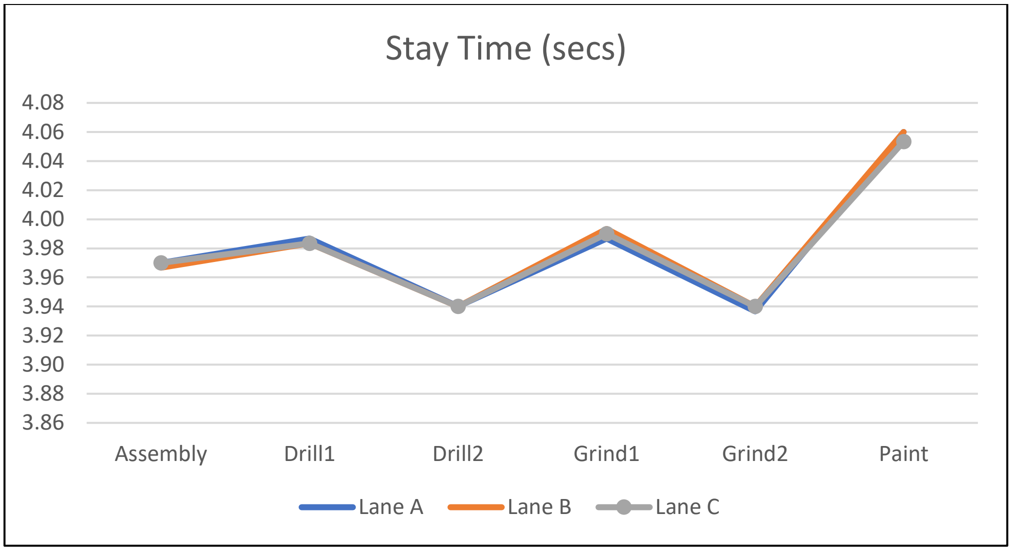

Fig. 7. SPF stay time with PFD

In this model, the throughput per hour is 16.88.

- BP base model with PFD: The base simulation model is developed with the standard cycle time estimated based on the PFD inputs as shown in Table 10. The operator's utilization in case of BP is considered as 100% because of the independent nature of work benches.

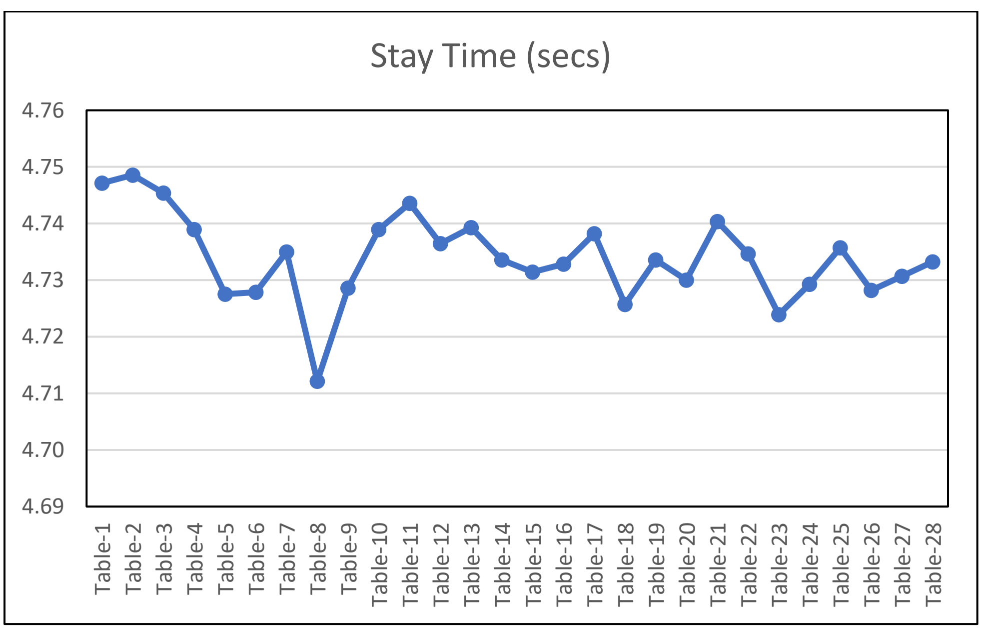

Fig. 8. BP stay time with PFD

In this model, the throughput per hour is 15.16.

Based on the simulation results, it is evident that SPF system's throughput is ~ 10.2% higher than Batch Process. In case of SPF, the cycle time fluctuation between the lanes is symmetrical whereas the batch processing time slightly varies between the individual stations.

- SPF base model with SI: The base simulation model is developed with the standard cycle time estimated based on the SI inputs as shown in Table 12.

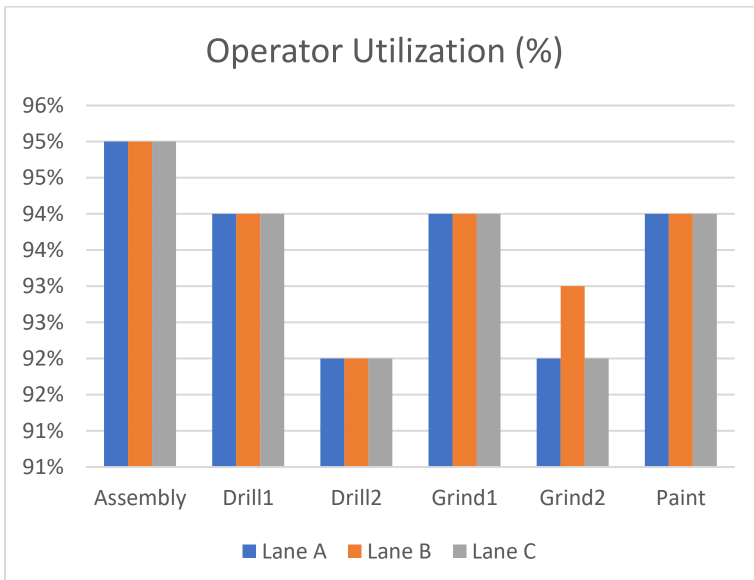

Fig. 9. SPF operator utilization with SI

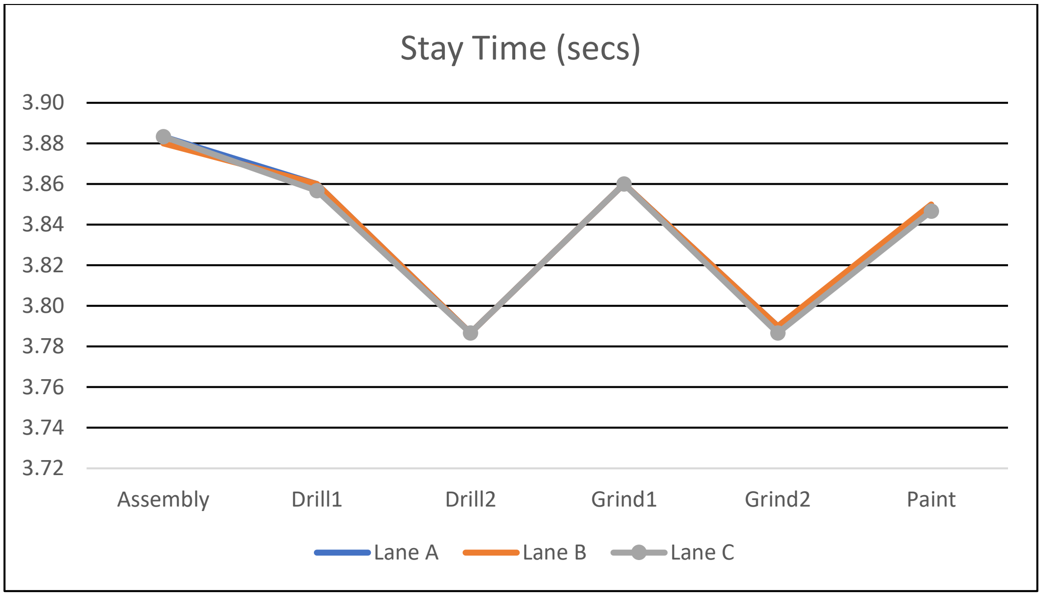

Fig.10. SPF stay time with SI

In this model, the throughput per hour is 17.57.

- BP base model with SI: The base simulation model is developed with the standard cycle time estimated based on the SI inputs as shown in Table 13. The operator's utilization in case of BP is considered as 100% because of the independent nature of workbenches.

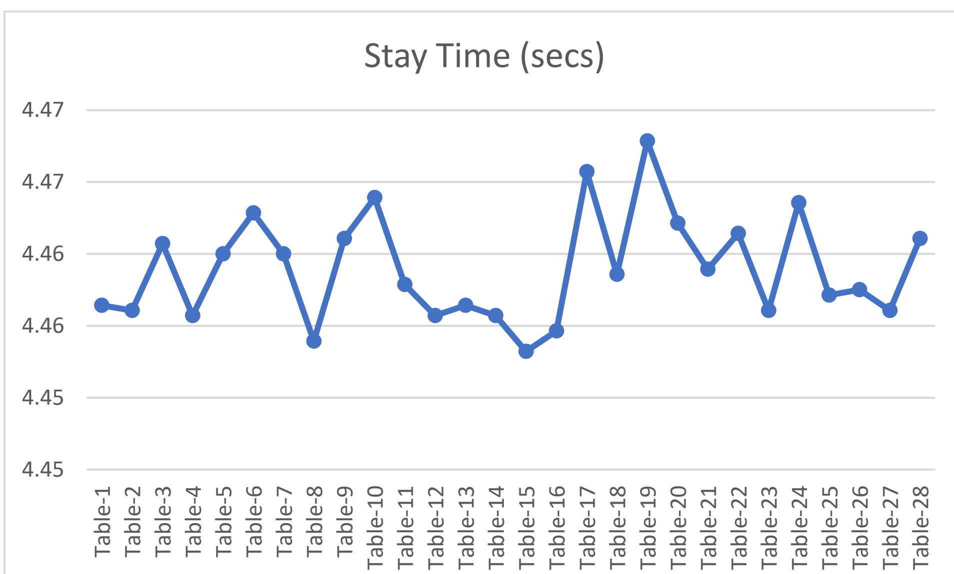

Fig. 11. BP stay time with SI

In this model, the throughput per hour is 16.13.

Based on the simulation results, it is evident that SPF system's throughput is ~ 8.2% higher than Batch Process. The stay time between the stations is more consistent in case of SPF, and for BP, there is slight variation between the stations.

- SPF base model without fatigue:

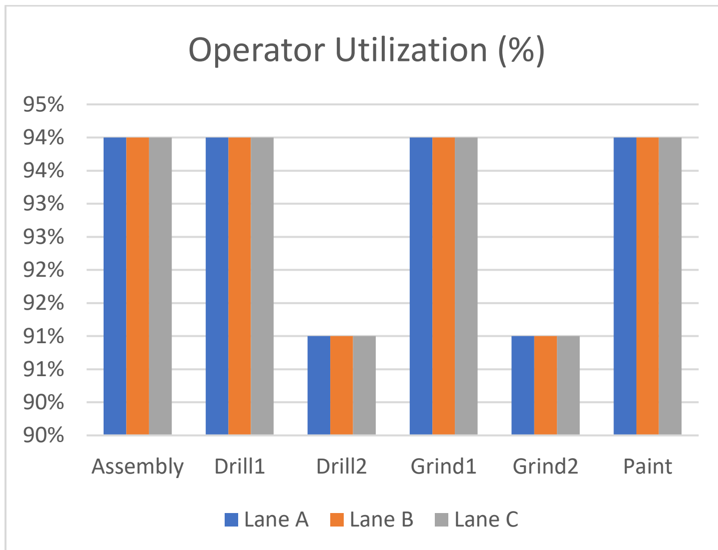

Fig.12. SPF operator utilization without fatigue

Fig. 13. SPF stay time without fatigue

In this model, the throughput per hour is 19.49.

- BP base model without fatigue:

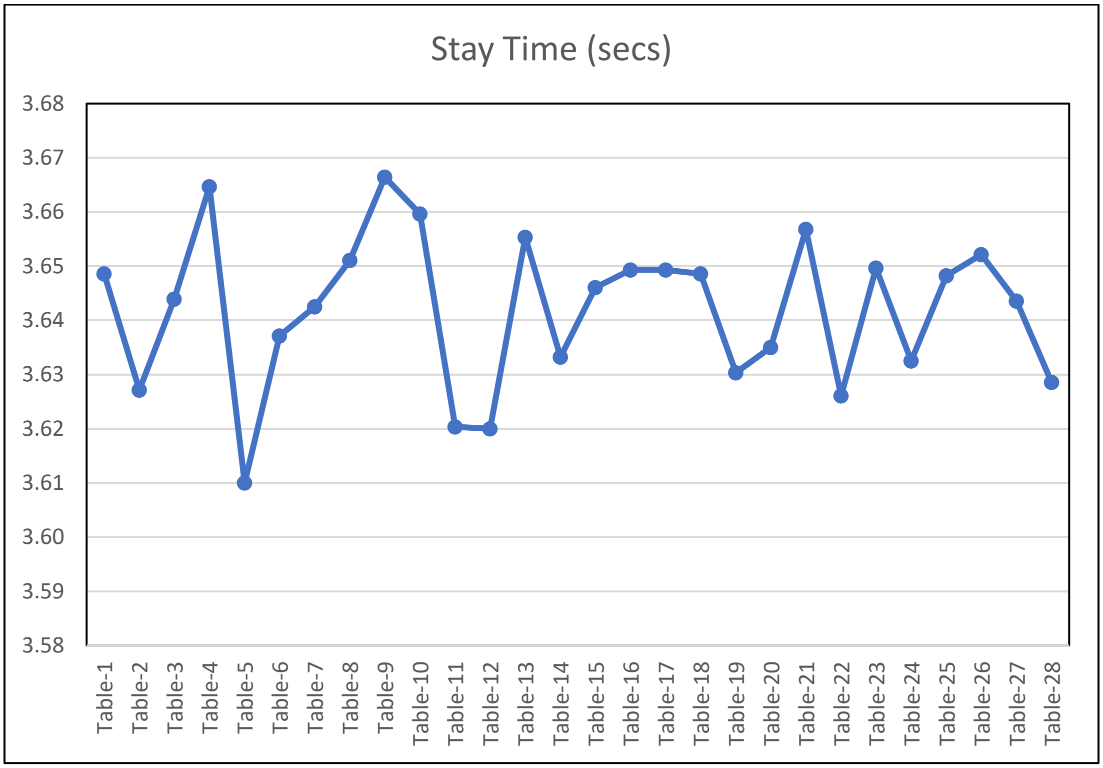

Fig. 14. BP stay time without fatigue

In this model, the throughput per hour is 19.23.

The operator's utilization in case of BP is considered as 100% because of the independent nature of work benches. Based on the simulation results, it is evident that SPF system's throughput is ~ 1.4% higher than Batch Process. The stay time between the stations is more consistent in case of SPF, and for BP, there is slight variation between the stations.

4.2.2 With +/- fatigue factors:

Fatigue plays an important role in the operator's performance, the lesser the fatigue experienced by the operator, the better is the performance. In this system, fatigue factor is varied with +10% and -10% in both PFD and SI values to see the impact on the throughput. Throughputs for both SPF and BP are compared back, and results indicate that with higher fatigue factor, the throughput of the system is reduced. Detailed graphical analysis for each of these cases is shown below;

a. With +10% PFD fatigue factor:

Single-Piece Flow:

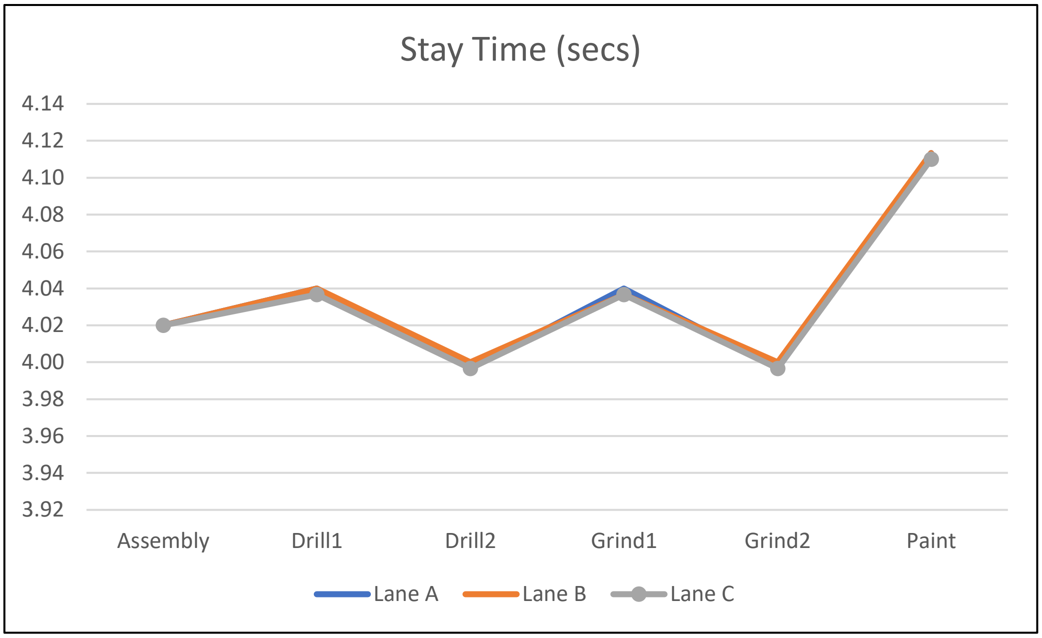

Fig. 15. SPF operator utilization with +10% PFD

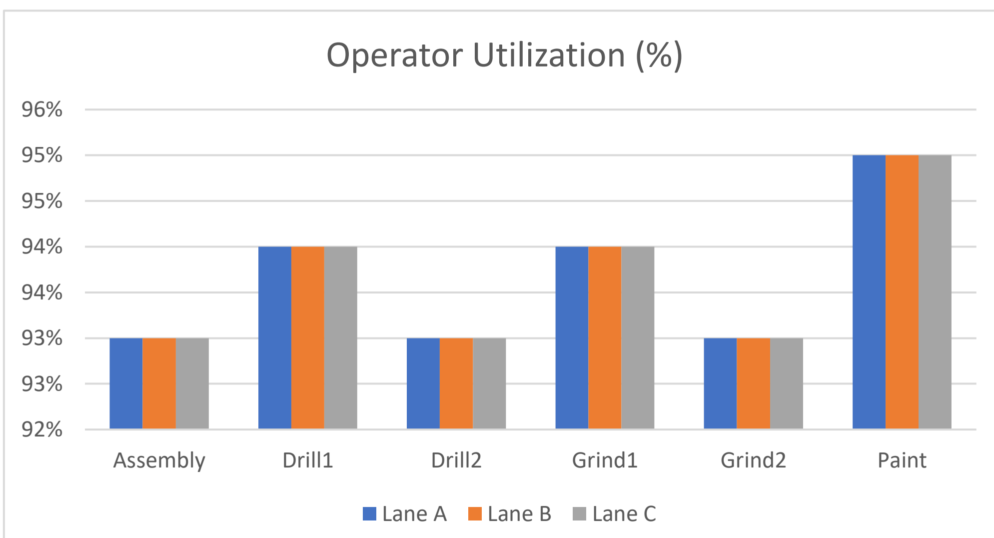

Fig. 16. SPF stay time with +10% PFD

In this model, the throughput per hour is 16.67.

Batch Processing:

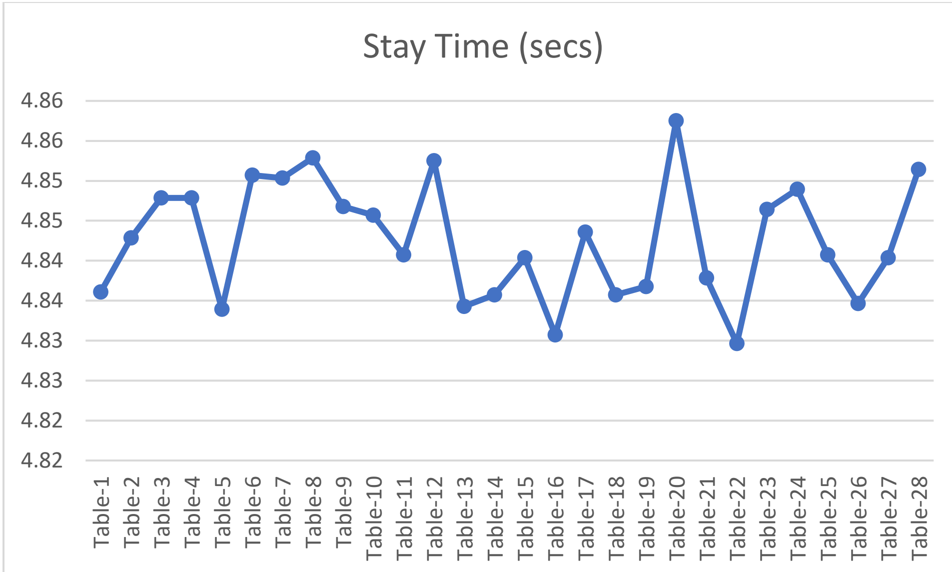

Fig. 17. BP stay time with +10% PFD

In this model, the throughput per hour is 14.81.

The operator's utilization in case of BP is considered as 100% because of the independent nature of workbenches. Based on the simulation results, it is evident that SPF system's throughput is ~ 11.15% higher than Batch Process. The stay time between the stations is more consistent in case of SPF, and for BP, there is slight variation between the stations.

b. With -10% PFD fatigue factor:

Single-Piece Flow:

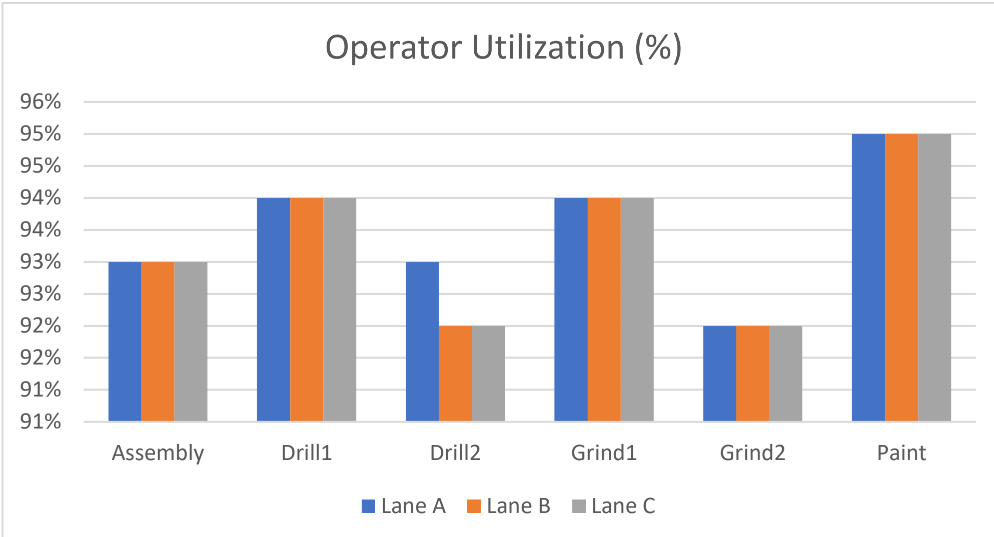

Fig. 18. SPF operator utilization with -10% PFD

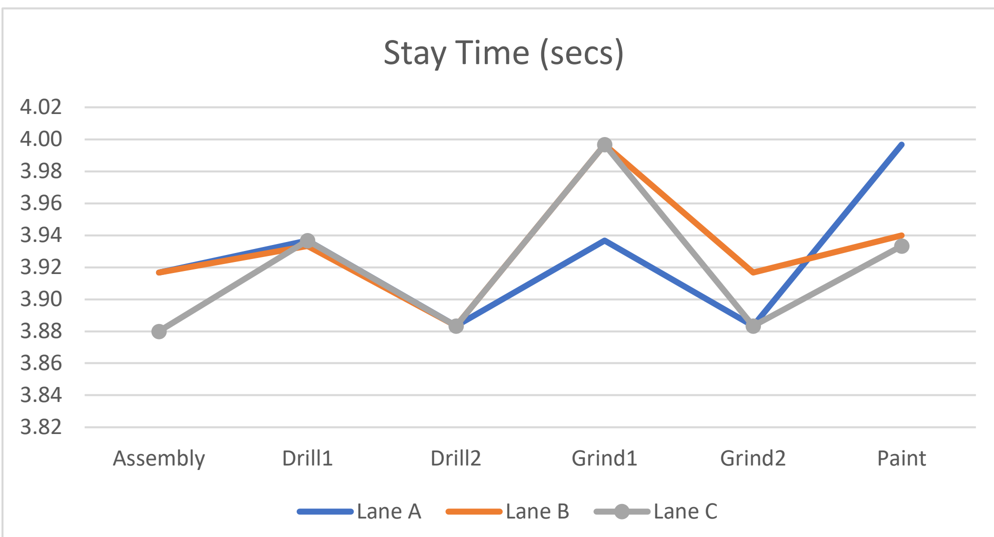

Fig. 19. SPF stay time with -10% PFD

In this model, the throughput per hour is 17.14.

Batch Processing:

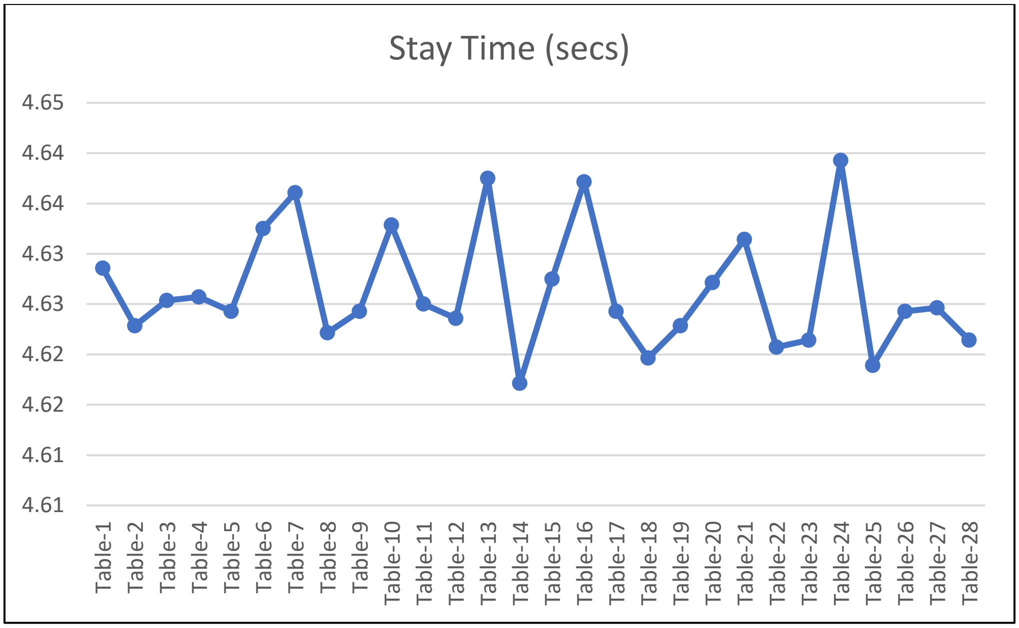

Fig. 20. BP stay time with -10% PFD

In this model, the throughput per hour is 15.83.

The operator's utilization in case of BP is considered as 100% because of the independent nature of workbenches. Based on the simulation results, it is evident that SPF system's throughput is ~ 9.33% higher than Batch Process. The stay time between the stations is more consistent in case of SPF, and for BP, there is slight variation between the stations.

c. With +10% SI fatigue factor:

Single-Piece Flow:

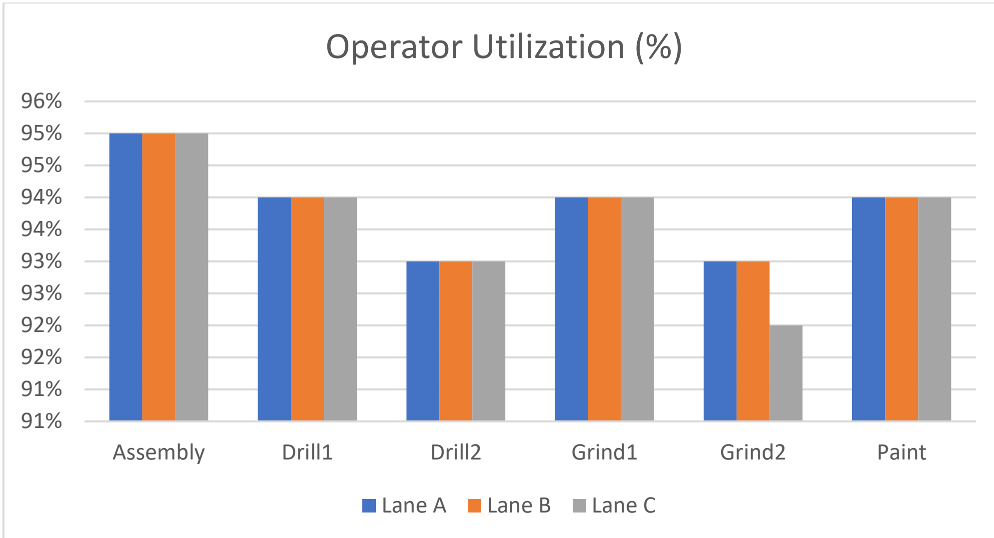

Fig. 21. SPF operator utilization with +10% SI

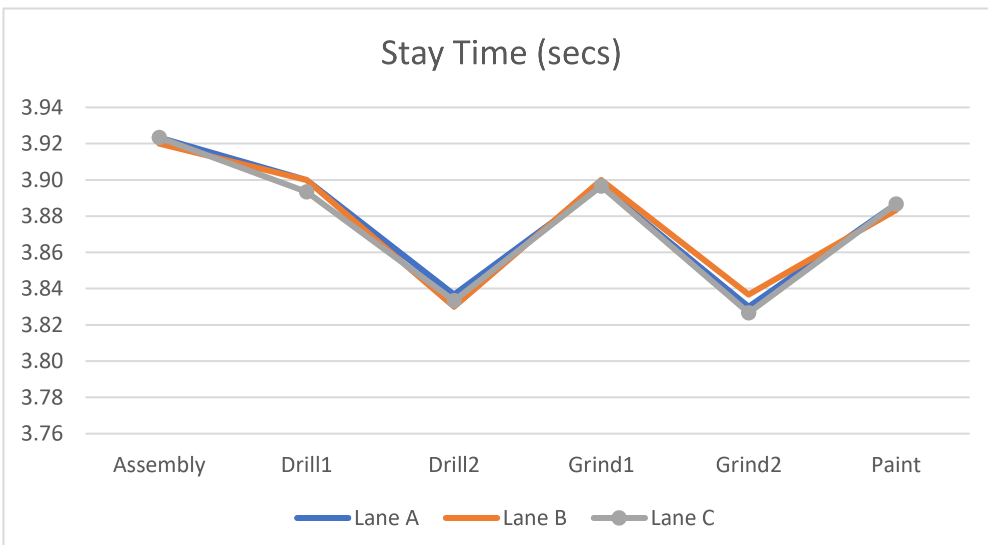

Fig. 22. SPF stay time with +10% SI

In this model, the throughput per hour is 17.39.

Batch Processing:

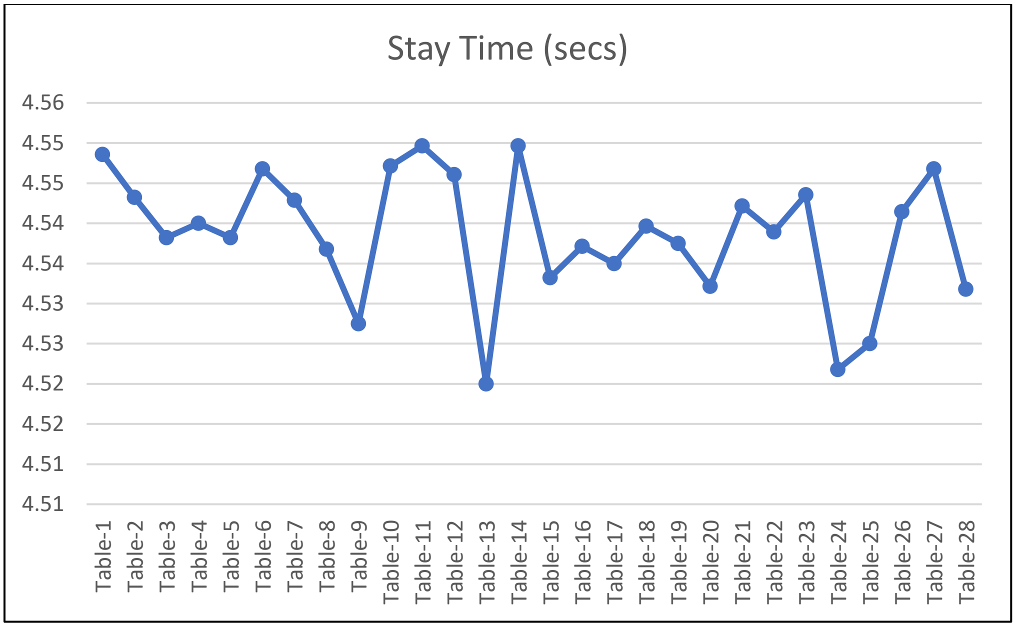

Fig. 23. BP stay time with +10% SI

In this model, the throughput per hour is 15.79.

The operator's utilization in case of BP is considered as 100% because of the independent nature of work benches. Based on the simulation results, it is evident that SPF system's throughput is ~ 9.2% higher than Batch Process. The stay time between the stations is more consistent in case of SPF, and for BP, there is slight variation between the stations.

d. With -10% SI fatigue factor:

Single-Piece Flow:

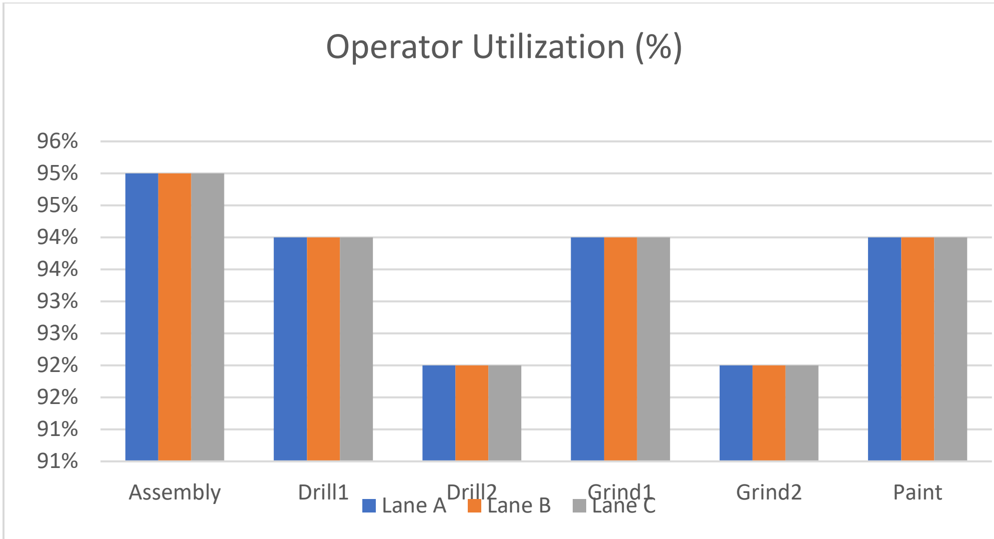

Fig. 24. SPF operator utilization with -10% SI

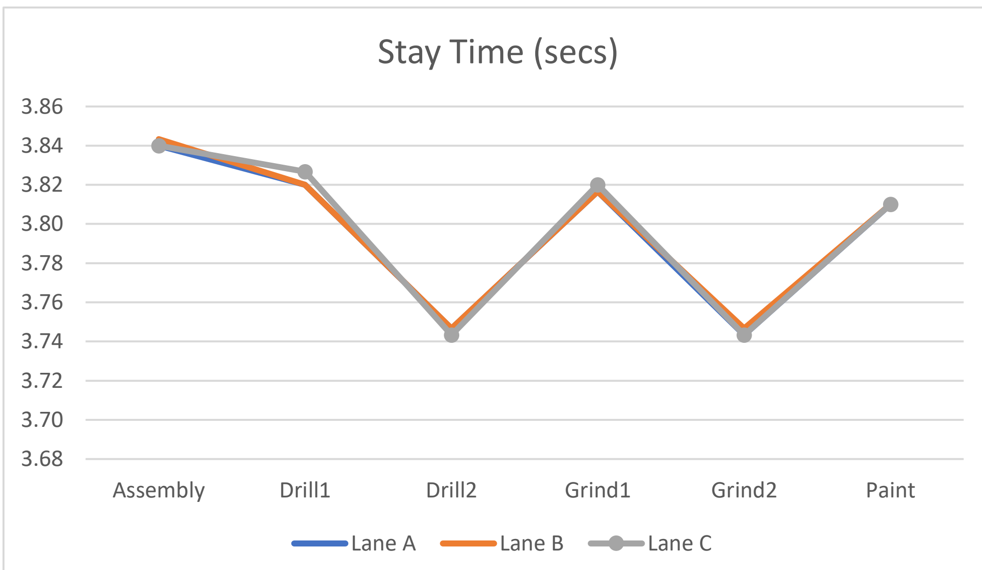

Fig. 25. SPF stay time with -10% SI

In this model, the throughput per hour is 17.74.

Batch Processing:

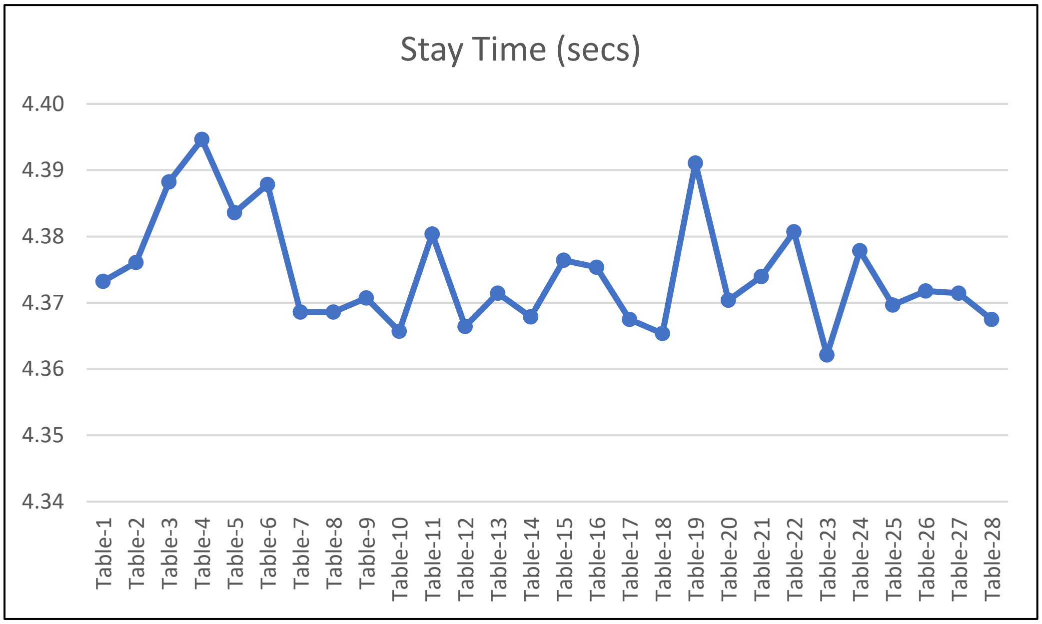

Fig. 26. BP stay time with -10% SI

In this model, the throughput per hour is 16.40.

The operator's utilization in case of BP is considered as 100% because of the independent nature of work benches. Based on the simulation results, it is evident that SPF system's throughput is ~ 7.6% higher than Batch Process. The stay time between the stations is more consistent in case of SPF, and for BP, there is slight variation between the stations.

Result Analysis: The above results indicate the throughput in SPF system is higher than BP in all the different processes.

- Case1: SPF system's throughput is ~ 11.15% higher than BP
- Case2: SPF system's throughput is ~ 9.33% higher than BP
- Case3: SPF system's throughput is ~ 9.2% higher than BP
- Case4: SPF system's throughput is ~7.6 % higher than BP

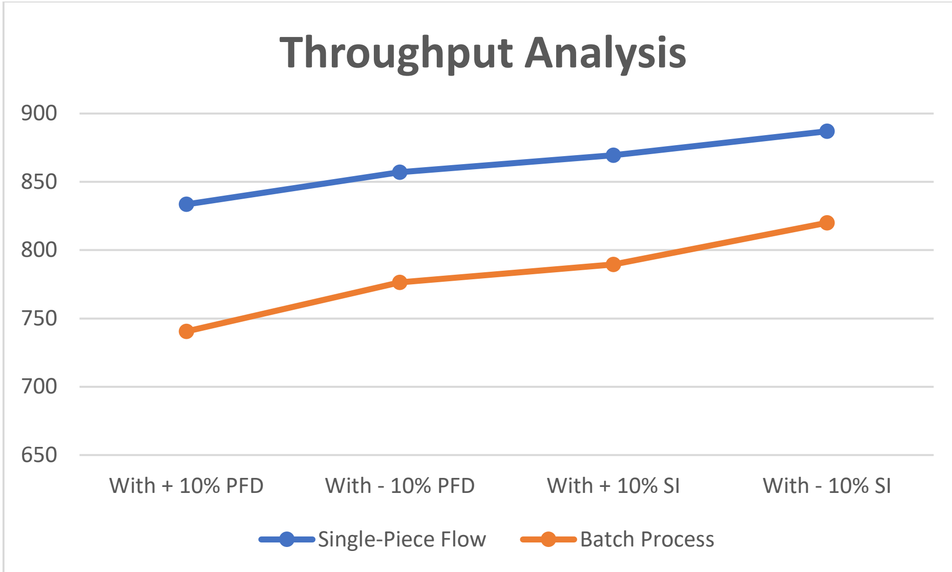

Fig. 27. Throughput analysis of SPF vs BP

4.2.3 Job Rotation:

Job rotation is designed based on scaling the indexes recorded from Gunugslu [15]. The design of experiment is conducted based on the number of hours of rotation that can be incorporated per shift. For the study purpose, job rotation intervals of 2, 3, 4, 6, 8, 10 and 12 hours are designed. In this research, it is considered and proposed that the operator will start with the next job right after finishing the break time so that setup and rotational time are eliminated.

- Throughput analysis with 2-hour job rotation frequency:

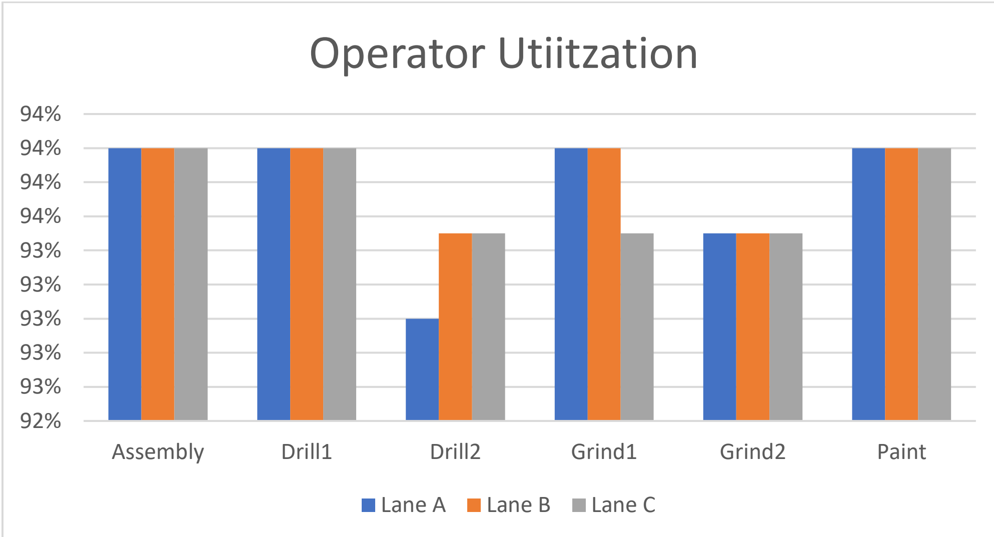

Fig. 28. Operator utilization at 2-hour rotation

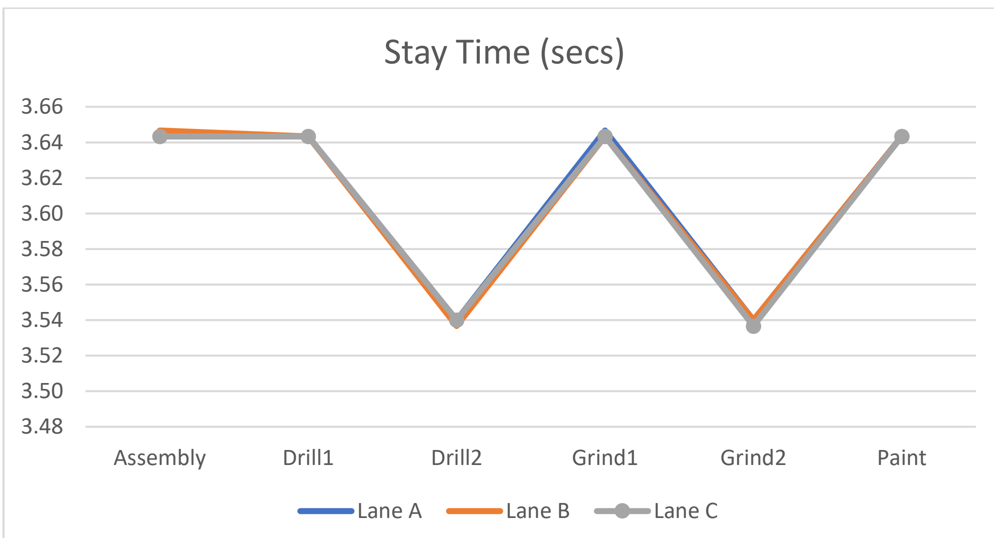

Fig. 29. Stay time at 2-hour rotation

In this model, the throughput per hour is 18.60.

- Throughput analysis with 3-hour job rotation frequency:

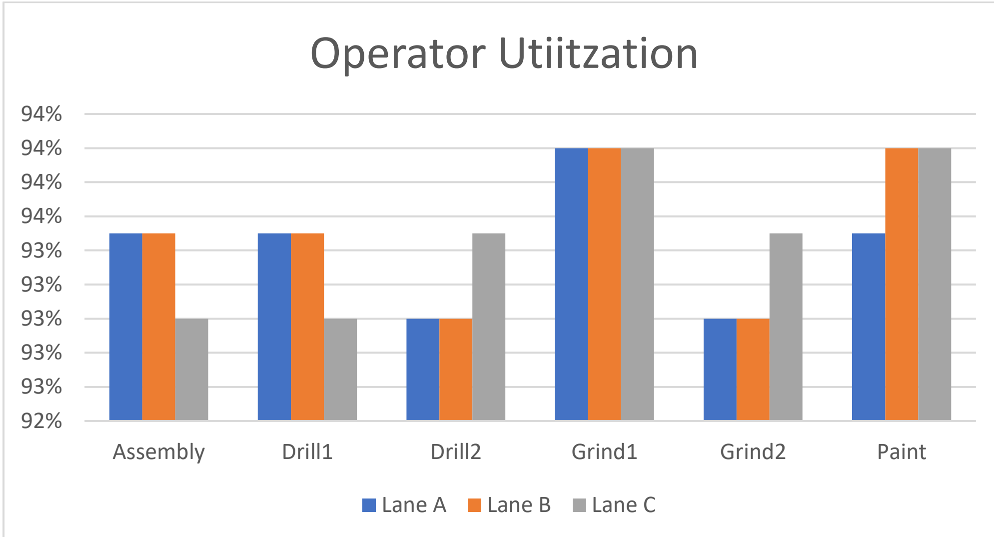

Fig. 30. Operator utilization at 3-hour rotation

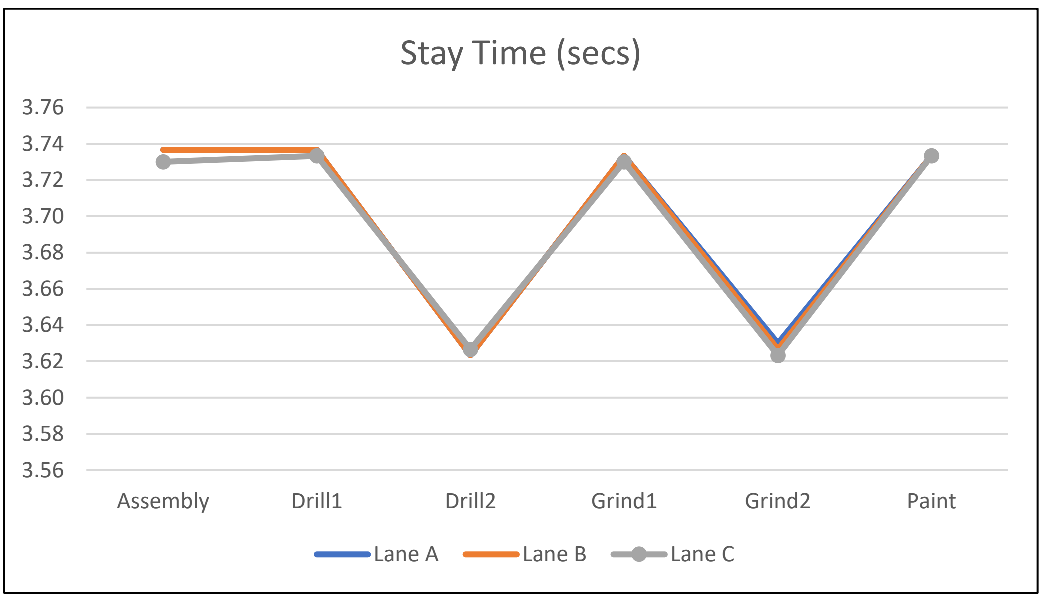

Fig. 31. Stay time at 3-hour rotation

In this model, the throughput per hour is 18.16.

- Throughput analysis with 4-hour job rotation frequency:

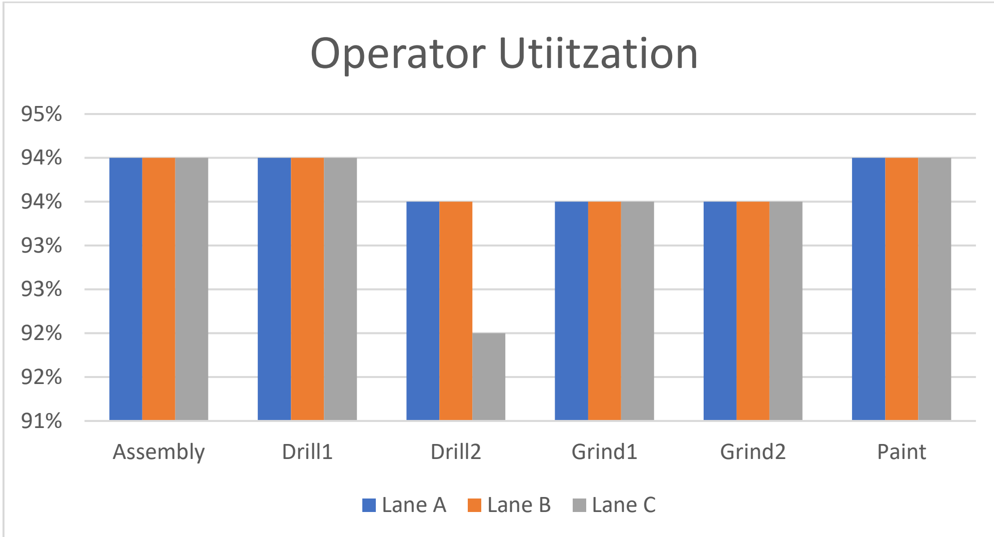

Fig. 32. Operator utilization at 4-hour rotation

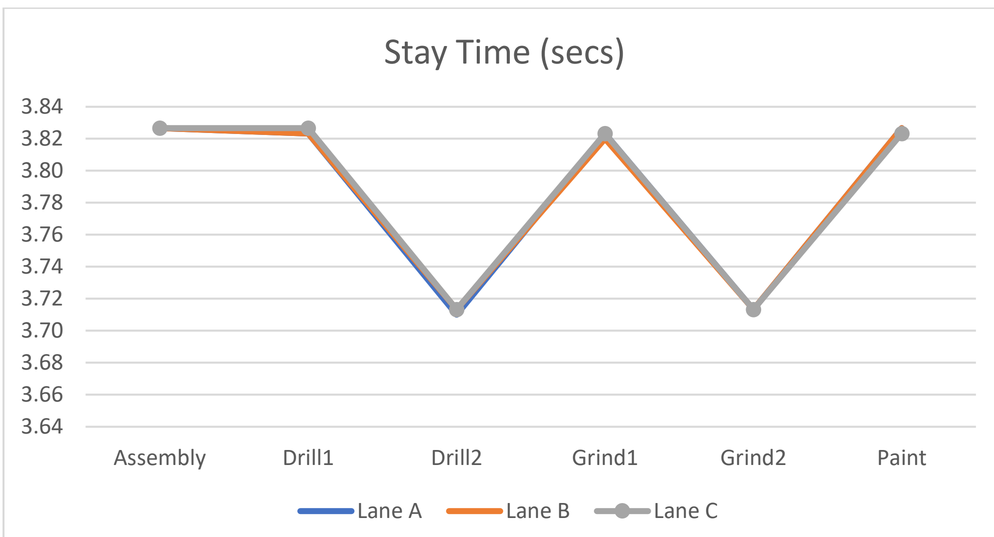

Fig. 33. Stay time at 4-hour rotation

In this model, the throughput per hour is 17.76.

- Throughput analysis with 6-hour job rotation frequency:

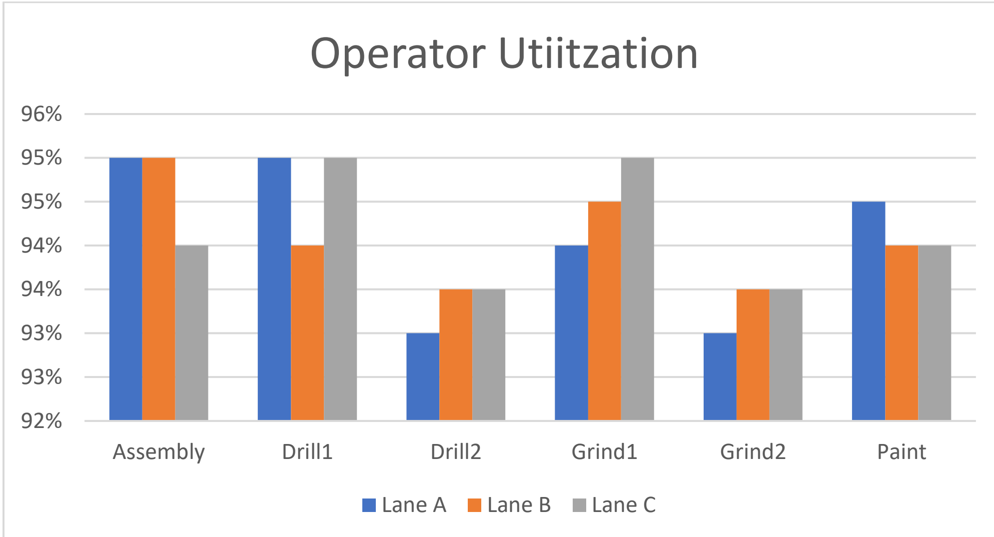

Fig. 34. Operator utilization at 6-hour rotation

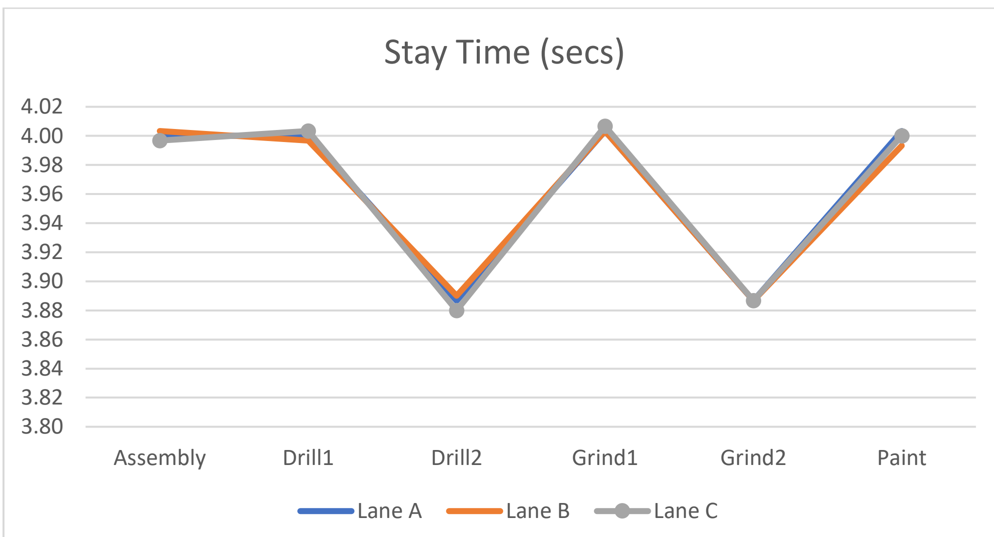

Fig. 35. Stay time at 6-hour rotation

In this model, the throughput per hour is 17.

- Throughput analysis with 8-hour job rotation frequency:

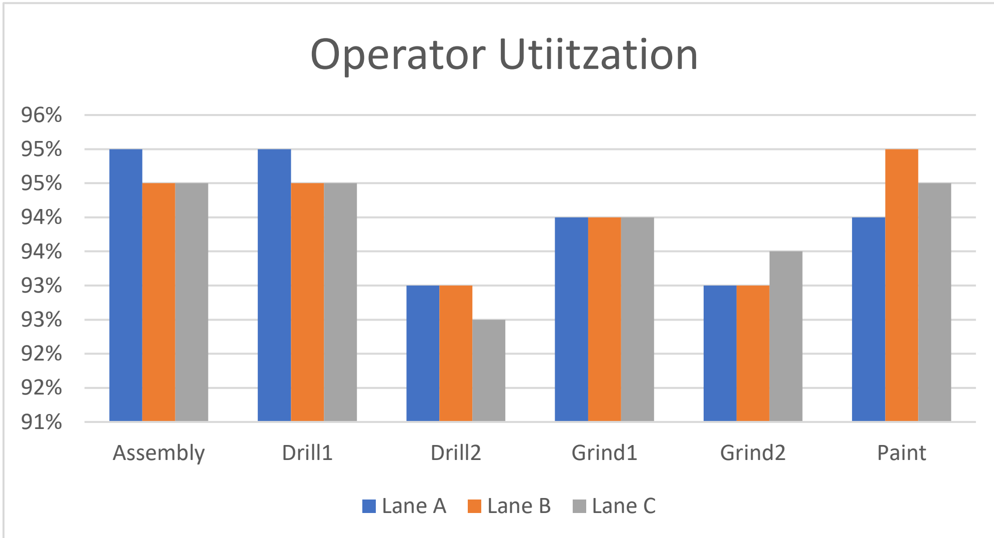

Fig. 36. Operator utilization at 8-hour rotation

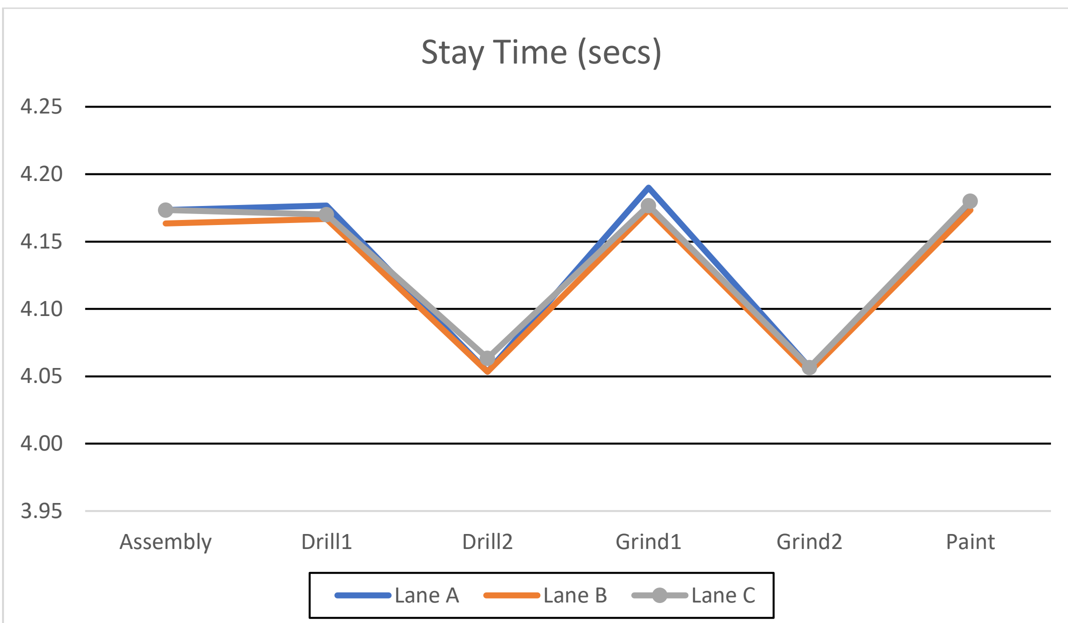

Fig. 37. Stay time at 8-hour rotation

In this model, the throughput per hour is 16.32.

- Throughput analysis with 10-hour job rotation frequency:

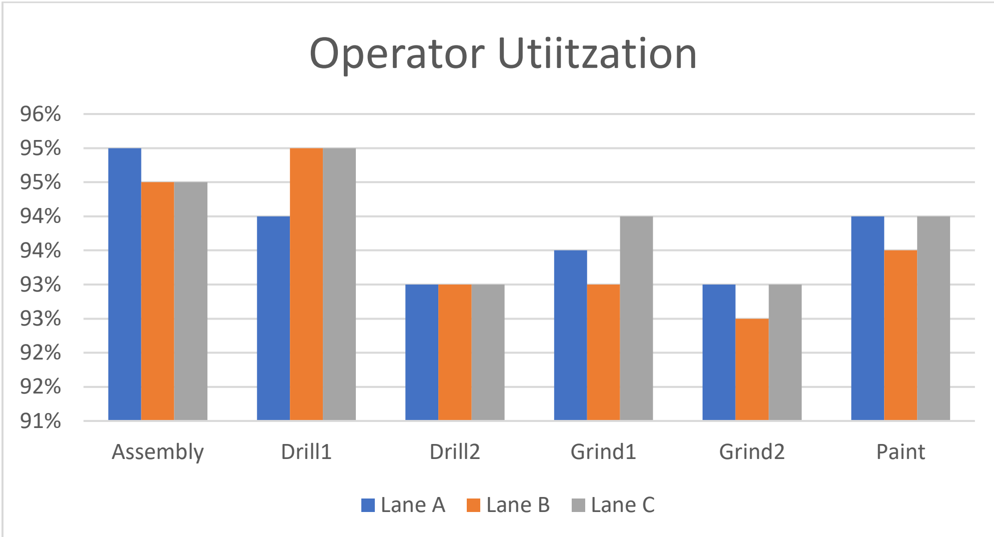

Fig. 38. Operator utilization at 10-hour rotation

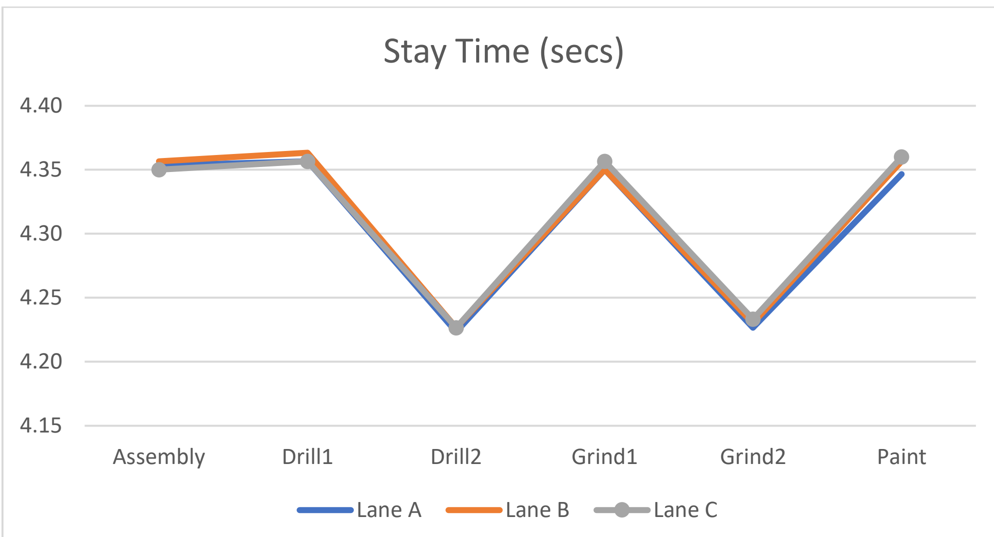

Fig. 39. Stay time at 10-hour rotation

In this model, the throughput per hour is 15.69.

- Throughput analysis with 12-hour job rotation frequency:

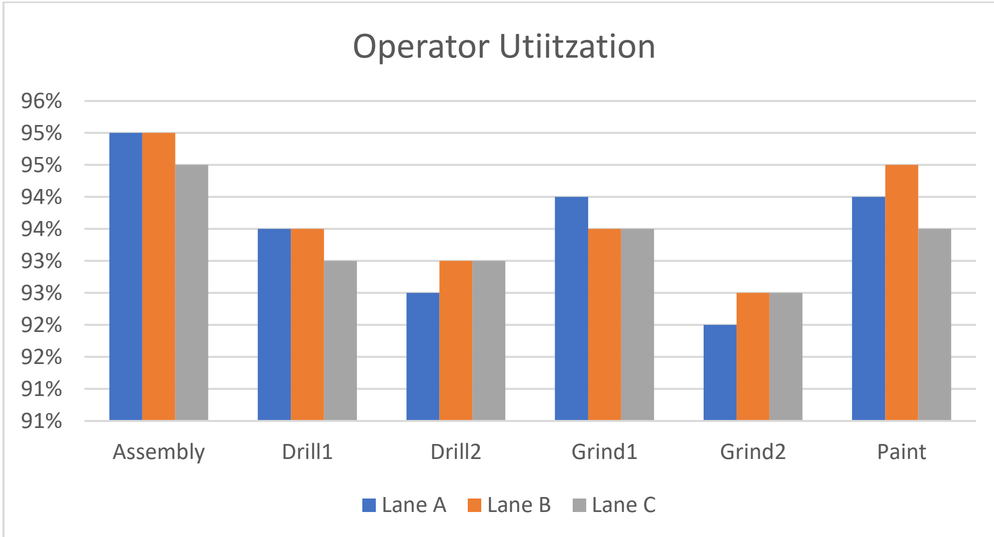

Fig. 40. Operator utilization at 12-hour rotation

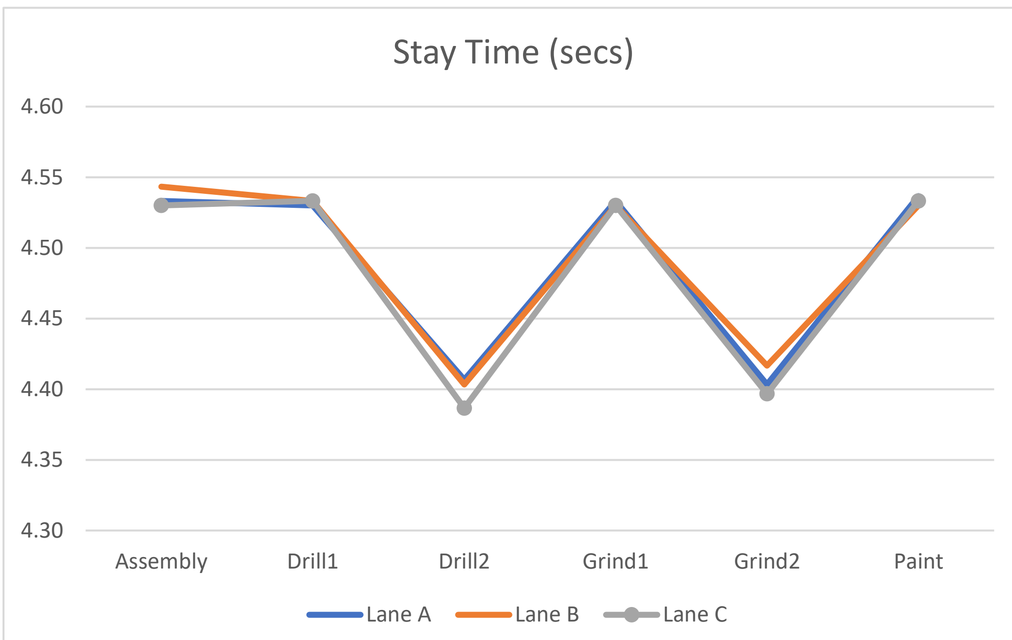

Fig. 41. Stay time at 12-hour rotation

In this model, the throughput per hour is 15.09.

Job rotation is one of the preferred ways to avoid MSDs. In this analysis, we studied the different job rotation frequencies against throughput. Higher the frequency of rotation, less is the fatigue factor, but throughput reduces proportionally. As the job rotation involves a small downtime in moving the operators between the stations, it is proposed through this model that job rotation should be scheduled after the operators return from the break. This not only improves production throughput but also develops the operator's skillsets and promotes team work. The trend indicates that throughput of the system is higher at job rotation frequency of 2hrs and eventually reduces as the frequency increases. The impact on utilization with the job rotation is observed to be higher with the more frequent job rotations. As the operators rotate between the jobs, it reduces the fatigue stress on the operator and they can perform efficiently.

4.2.4 Statistical Analysis and Discussion:

For each scenario, mean, standard deviation, standard error, and 95% confidence interval for the stay time difference between the following five comparisons:

- Batch processing versus single-piece flow without fatigue
- Batch processing versus single-piece flow with PFD
- Batch processing versus single-piece flow with SI
- Overall comparison of batch process versus single-piece flow
- Single-piece flow with varied job rotation frequencies

Table 19 summarizes the results.

TABLE 19:
TWO-SAMPLE T-TEST SUMMARY

Test Type	Fatigue Parameter	Process Type	Mean	StDev	SE Mean	95% CI
Two-Sample T-Test	Without Fatigue	SPF	3.452	0.0989	0.023	(-0.36, 0.21)
		BP	3.527	0.606	0.11	
	With PFD	SPF	3.98	0.0412	0.0097	(-0.76, -0.73)
		BP	4.73	0.0077	0.0015	
	With + 10% PFD	SPF	4.034	0.0398	0.0094	(-0.82, -0.73)
		BP	4.817	0.0921	0.017	
	With - 10% PFD	SPF	3.925	0.0399	0.0094	(-0.71, -0.68)
		BP	4.626	0.0059	0.0011	
	With SI	SPF	3.837	0.0376	0.0089	(-0.63, -0.60)
		BP	4.459	0.0037	0.0007	
	With + 10% SI	SPF	3.878	0.0352	0.0083	(-0.67,-0.64)
		BP	4.539	0.0081	0.0015	
	With - 10% SI	SPF	3.797	0.039	0.0092	(-0.59,- 0.56)
		BP	4.374	0.0084	0.0016	

A two sample T-test is conducted to understand the difference between SPF and BP with respect to stay time without the fatigue effect. The overall comparison of batch process versus single-piece flow is studied in detail with respect to the various fatigue models. The trend of the results indicted a higher mean stay time for the BP in comparison to SPF, and furthermore the models with SI fatigue inputs showed better performance. The differences were observed to be of same magnitude and provided the robust result in assessing the SPF and BP systems. The models with +/-10% fatigue factors indicated the behavior of the system through the mean stay time of the part in the respective stations. In the below section, interval plot and box plots of SPF and BP are discussed. The plots represents that the throughput rate is higher in case of SPF with a P-value of 0.039.

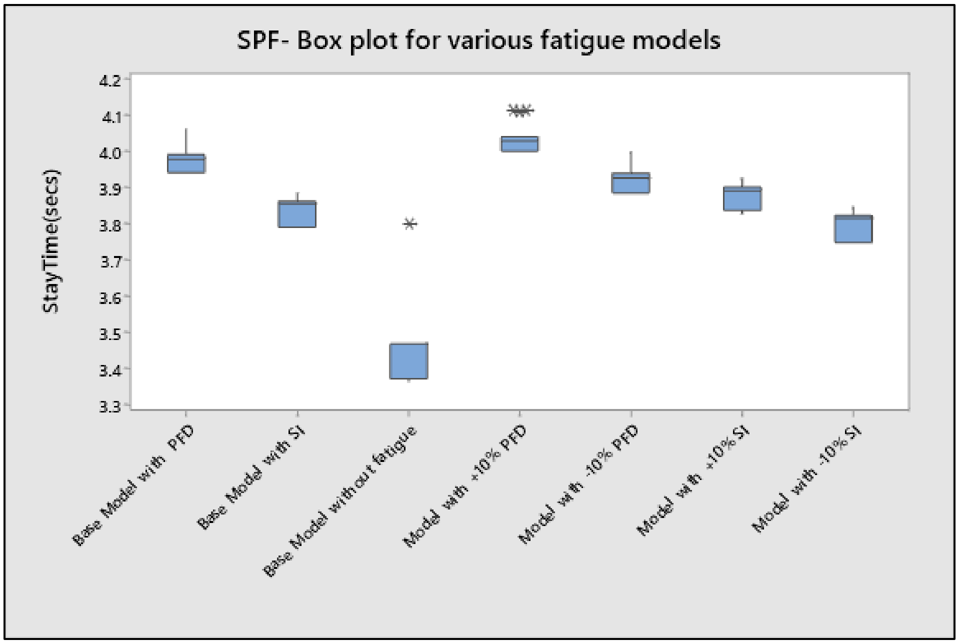

Fig. 42. Box plot of SPF stay time vs various fatigue models

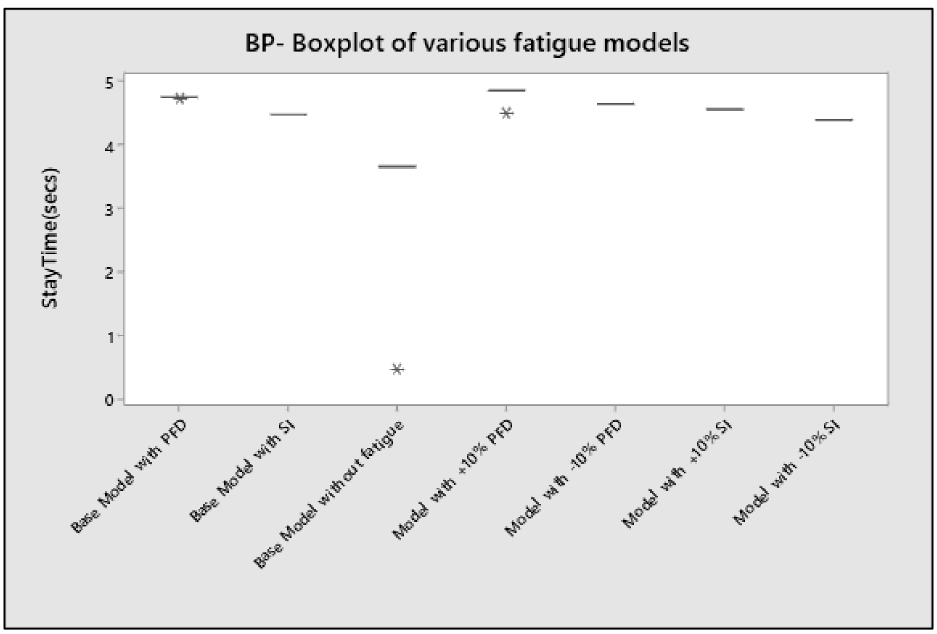

Fig. 43. Box plot of BP stay time vs various fatigue models

With the 12 different models studied to compare the performance of both the systems, it is observed that the SPF system consistently provided higher throughput in comparison to BP. It is observed that within each of these models, it is proved that with the higher fatigue rates, throughput of the system goes down. The stay time of the part processing is lower with the reduced fatigue impact. In this research, two different fatigue estimation methods are used- PFD and SI. It is observed that in all the models studied in detail, throughput is higher in the models based on SI analysis. Also, the throughput and stay time represents that the variation between the fatigue models. Table 20 provides the summary of throughput in each of the scenarios, and the research proposes that the SPF model based on SI system is efficient in comparison to other systems.

TABLE 20:
DOE SUMMARY FOR VARIOUS FATIGUE MODELS

Process	Fatigue Factor	Response Measure	Statistical Analysis	Takt time(secs)	Throughput/Hr	Ratio of takt time w.r.t throughput without fatigue
SPF	With Fatigue	Throughput with PFD	With standard PFD	4.06	844	1.1
			With + 10% PFD	4.1	834	1.1
			With - 10% PFD	4.0	857	1.1
		Throughput with SI	With standard SI	3.9	879	1.0
			With + 10% SI	3.9	870	1.0
			With - 10% SI	3.8	887	1.0
BP	With Fatigue	Throughput with PFD	With standard PFD	4.7	758	1.3
			With + 10% PFD	4.9	741	1.3
			With - 10% PFD	4.6	777	1.3
		Throughput with SI	With standard SI	4.5	807	1.2
			With + 10% SI	4.5	790	1.2
			With - 10% SI	4.4	820	1.2

- Single Piece Flow with Fatigue and Job Rotation:

Single-piece flow is further studied in detail by varying the intervals of job rotation such as designing the model with rotation frequencies of 2 hours, 3 hours, 4 hours, 6 hours, 8 hours, 10 hours and 12 hours during the same working shift. An interval plot is shown below which represents the decline of throughput as the rotational frequency decreases.

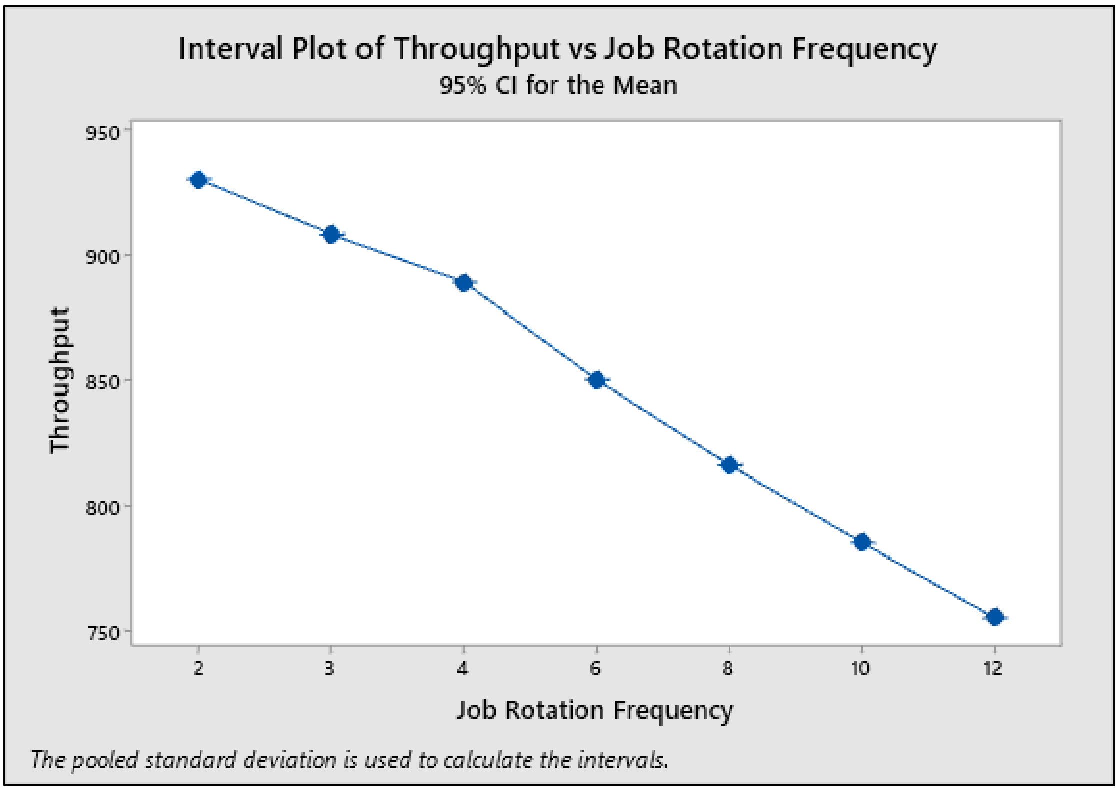

Fig. 44. Interval plot of SPF throughput vs job rotation frequency

The below graph shows the box plot of stay time plotted against each job rotation frequency. If the stay time of the operation is low, the throughput of the system exponentially increases.

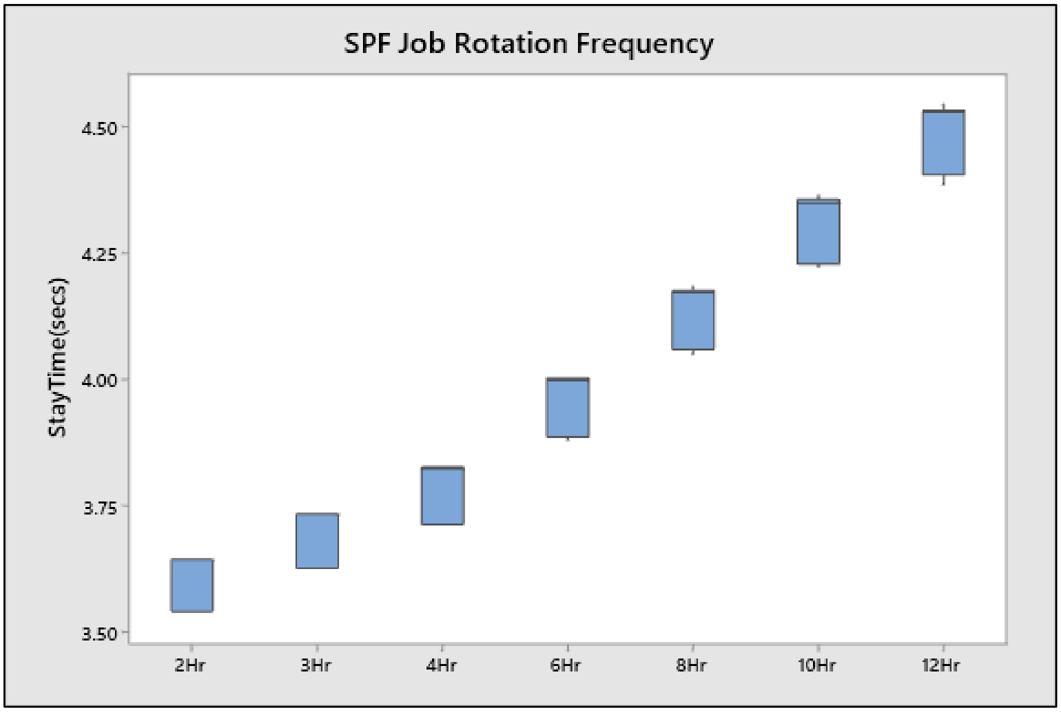

Fig. 45. Box plot of SPF stay time vs job rotation frequency

- Residual and Contour plots:

Regression analysis is conducted to plot the relationship of throughput of the system with respect to takt time and job rotation frequencies. Graphs 55 and 56 indicate that takt time is less for the frequent job rotations scenarios and results in higher throughput. The intensity of throughput variation with respect to the ratio of takt time and job rotation is represented the contour and surface plots. Regression equation and coefficients are detailed below;

$$Z = 142.7 - 39 * X + 897.8 * Y \qquad (9)$$

where,

Z = Throughput,

X = Job Rotation Frequency

Y = Ratio of takt time w.r.t throughput

TABLE 21:
REGRESSION ANALYSIS SUMMARY

Coefficients				
Term	Coef	SE Coef	T-Value	P-Value
Constant	142.70107	480.66617	0.3	0.7813
Job Rotation Frequency	-39	12.66823	-3.08	0.037
Ratio of takt time w.r.t throughput	897.86477	528.10573	1.7	0.0643
Model Summary				
S	R-sq	R-sq(adj)		
3.657	99.79%	99.69%		

From the regression analysis, it is evident that the job rotation frequency has high impact in the proposed model with a P-value of 0.037. Through the model, it is proven that higher frequency of job rotation during the shift breaks are helpful to improve the throughput with an R^2 value of 99.79%. Based on these results, the model provides an opportunity to estimate the throughput of the system based on the number of job rotations available per day and the associated takt time ratio.

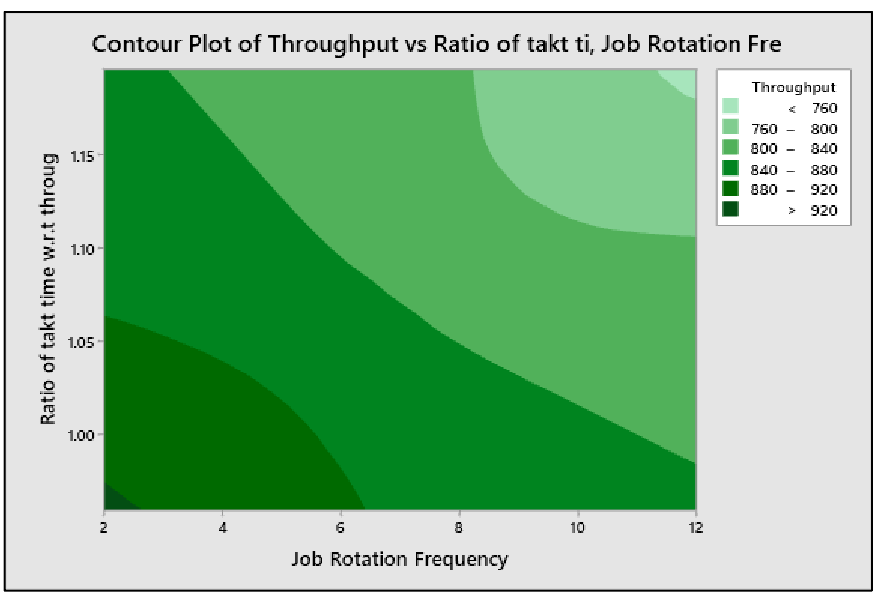

Fig. 46. Contour plot of throughput/hr with ratio of takt time and job rotation

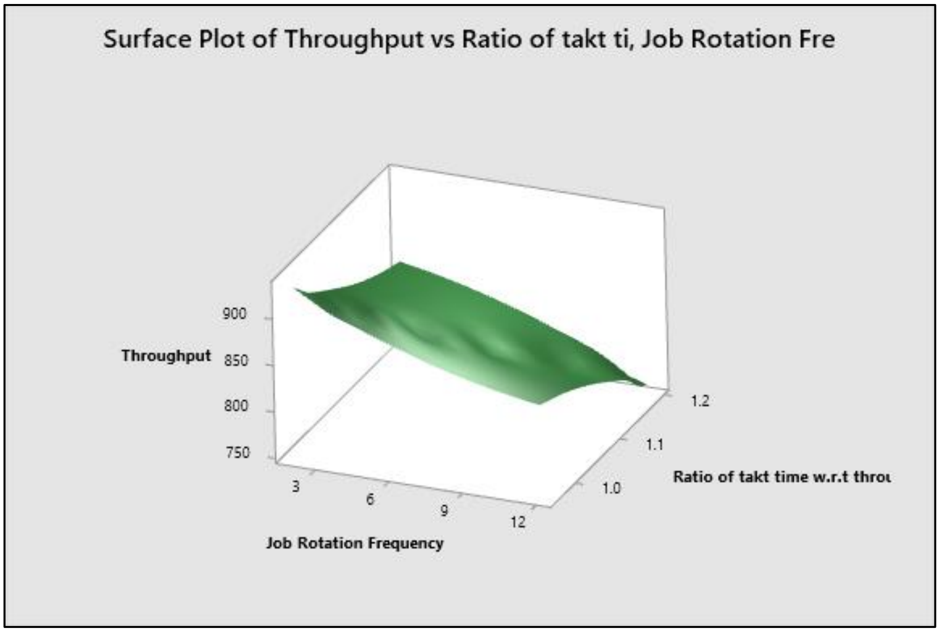

Fig. 47. Surface plot of throughput/hr with ratio of takt time and job rotation

TABLE 22:
SUMMARY OF THROUGHPUT VS JOB ROTATION FREQUENCY

	Rotation Intervals (Hrs)						
Job Rotation Frequency	2	3	4	6	8	10	12
Fatigue (%)	5.1	7.7	10.3	15.4	20.5	25.6	30.8
Throughput	930	908	889	850	816	785	755

Job rotation is analyzed for different levels. With frequent job rotations, higher is the throughput. Fig. 22 indicates the analysis outcome. With varied rotational frequencies, throughput of the SPF system was assessed. As the fatigue level is lower for higher frequency rotation, this research recommends to-include 3 job rotations per shift, with the rotation starting after every break. Though 2-hour job rotation is providing higher throughput, but from the management standpoint this could be very frequent unless the rotation happens along with the break. With the SPF system, the production target can still be achieved with a lesser workforce when compared to batch processing. Also, with the introduction of job rotation program, each operator is cross trained to perform the other tasks in the assembly line, hence operator's skillset is improved.

4.3 Operational Expense Analysis

Based on the system design, single-piece flow requires less workforce in comparison to batch processing. A high-level summary of the cost associated with both the systems are shown below through a generic example considering 40 hours per week per shift, resulting in approximately 35% of the cost difference.

TABLE 23:
SUMMARY OF COST IMPACT BETWEEN SPF AND BP

	Single-Piece-Flow	**Batch Processing**
Labor Cost/Hr	$ 18.84	$ 18.84
Working Hrs/Week	40	40
#Operators/Week	18	28
Cost/Year	$ 705,369.60	$ 1,097,241.60

In this research, several models were studied for both single-piece flow and batch processing manufacturing environments. Based on the simulation, statistical, and operational expense analysis, it is evident that SPF's performance is better than BP system. Furthermore, incorporating the job rotation schedule not only helps in the reduction of MSD, but also increases throughput. Implementing the job rotations during shift break time is ideal and recommended in order to effectively utilize the operating time.

5. CONCLUSION AND FUTURE RESEARCH

5.1 Conclusion

As defined in the objective section 1.2, this research provides a comparison of batch processing and single-piece flow based on fatigue and job rotation factors. Using Basic MOST technique, normal times are estimated within which an operator has to perform the job, and FlexSim software is used to build and assess the model. Various fatigue factors are discussed and analyzed as a response measure. Environments of both the SPF and BP models are kept the same expect the cycle time and associated fatigue factors for each type of operation. The number of stations and operators were carefully calculated, and using PFD and SI indexes, fatigue is measured for each operator performing different operations. Normal distribution of the cycle time is considered in the study to simulate the actual working environments. In SPF, as the takt time is lower compared to the BP, the throughput of the system is higher, and also the job is divided into small tasks with a properly balanced cycle time for each station with the main lines leading to less fatigue accumulation on the operator. In the case of batch processing, the same operator has to perform all the tasks from start to end, and hence fatigue accumulation is high, and the performance factor is affected.

Based on the results of the experimentation, SPF has better performance compared to BP. Further analysis of SPF was carried out to introduce the job-rotation factor in the process. Job rotation elements are referred from the literature and based on the number of observations for avoidable delays, the factors are scaled-down appropriately to fit into the SPF regression model. In this research, it is emphasized that the job rotation schedules are introduced in such a way that the job change happens when the operator comes back from the breaks. High-frequency job rotation schedules may not be efficient from the production standpoint, as it consumes the rotation or setup times out of production hours. Very less frequent rotation can result in MSD concerns. Hence this research proposes to have a 3-hour job rotation that matches 2 short breaks and 1 meal break per shift. This research recommends adopting single-piece flow with 3-hour job rotation per shift.

5.2 Future Direction

Due to limited time, this research focused on comparing the batch and single-piece flow manufacturing systems based on fatigue and job rotation techniques. The future research can be focused on analyzing the various other factors affecting job rotation. This can include opertor's job satisfaction based on the job type such as operator prefers a different role whereas he is enforced to follow another work. The impact of different break time schedules for the operator on the throughput can be assessed to understand if there is an opportunity to improve productivity: this can be varying the number of breaks per shift, to varying the break duration. Another interesting factor to measure would be voice of opeators in assessing the skillset gain through job rotation in single-piece flow versus the same job throughout the shift in batch processing.

The implemention of this new methodology of designing the single-piece flow into a real case study is beneficial. The future study can also compare the different fatigue estimation methods. Also, the study can be further taken into consideration to quantify the quality related issues in job rotation in single-piece flow environment, as well as in batch production. In addition, the future study should focus on the link between the injury rate of batch and single-piece flow, and furthermore extending the same analysis on to various job rotation frequencies. This study can be further taken to assess the economic impact of injuries and opertor's error.

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