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Simulation-Driven Analyses of Performance of PCB Assembly Operations: A Case Study

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Abstract

This paper reports on an investigation of printed circuit board (PCB) assembly operations in the main manufacturing plant of a Canadian company which produces and delivers electronic products used in industrial, commercial, condominium (multi-residential), and other building applications. It delves into the complexities of the plant's PCB assembly processes, which start with a section in which many components are first introduced using surface mount technology, followed by a second section in which other components are inserted into PCB through-holes. Modelling and simulation of these and subsequent sections of the manufacturing facility's PCB assembly operations allow the evaluation of various alternatives that may be considered to improve operating performance. For instance, the advantages and disadvantages of manual versus automated through-hole insertion are weighed. Additionally, the study reveals valuable insights into operator allocation strategies, aiming to optimize production efficiency and reduce processing times.

Keywords: Printed circuit board (PCB); surface mount technology (SMT); assembly line; discrete event simulation; agent-based modelling and simulation

1. Introduction

With the complexity of printed circuit boards (PCBs) in the electronics sector having increased in the last three decades (Noroozi and Mokhtari, 2015), the operation of PCB assembly lines has posed significant challenges for electronic manufacturing companies. In this paper, we report on our observations and analyses of PCB assembly operations in the main manufacturing plant of a Canadian company that manufactures various electronic products and systems used in industrial, commercial, condominium (multi-residential), and other applications falling outside the realm of "consumer electronics".

In the manufacturing facility under study, multiple

PCB models are assembled using a single PCB assembly line having two major sections: (i) a surface mount technology (SMT) section; and (ii) a more traditional "through-hole" (TH) section where leads are inserted into plated through-holes and wave-soldered from the bottom to fill in the holes and interconnect the components. In the SMT section, various electronic components are introduced via component feeders and are attached and connected on the surface of a PCB using batch solder-reflow processes. Licari and Swanson (2011) note that SMT: (1) helps to attain higher packaging densities, higher reliability, and reduced cost than the TH insertion process; and (2) is currently the process most widely used for high-volume, low-cost consumer electronic PCBs.

The various PCBs manufactured in the facility under study, however, generally involve combinations of components requiring the sequential application of both SMT and plated TH insertion processes. Operations managers have pointed out that scheduling and carrying out the production of PCBs on the single two-stage assembly line presents challenges.

We report here on two of the concerns we have addressed in our study:

- Whether the TH component insertion process should be carried out by operators manually or with the use of a machine; and
- Whether it is possible to determine an appropriate combination of numbers of operators at each section of the assembly line.

The remainder of this paper is organized as follows. We provide a brief review of relevant literature in Section 2. In Section 3, we describe the stages/sections of the PCB assembly line under study. We discuss the simulation model in Section 4 and the simulation inputs and some outputs in Section 5. We discuss our simulation results in Section 6, and conclusions and limitations of our study in the final section.

2. Brief review of relevant literature

For over four decades, discrete event simulation (DES) had been the cornerstone of simulation work in the operational research community (Siebers et al., 2010). However, the emergence of agent-based simulation (ABS) has revolutionized the modeling of a complex system's dynamics in various domains. ABS allows each agent to possess unique attributes and behaviours, which collectively shape the system's overall behaviours (Macal and North, 2010; Macal, 2016). ABS has thus gained prominence for its ability to simulate a wide range of domains involving complex systems, offering insights into cumulative impacts arising from agent behaviours and interactions (Heath and Hill, 2010; Macal, 2016). This emergence of ABS and other recent developments in the field of modelling and simulation (M&S) have played a pivotal role in reshaping the application of M&S in various manufacturing fields, including the electronics sector. In this sector, cost-effective development and production of electronic modules are essential to maintain competitiveness in high-wage manufacturing nations, two prominent strategies have emerged: (i) Design for Manufacturing, and (ii) manufacturing optimization. These strategies hinge on the establishment of models that clarify the intricate relationship between process inputs and outputs (Seidel et al., 2023).

Hosseinpour and Hajihosseini (2009), among many others, have reiterated that M&S is a helpful and valuable work tool in manufacturing. We briefly look into some previous research and M&S tools, aimed at optimizing PCB manufacturing processes, considering the electronics sector's pursuit of heightened efficiency, cost reduction, and sustainability. Feldmann et al. (1994) developed a computer-aided PCB assembly process planning tool that enables optimization, simulation, and NC programming for certain process steps.

Günther et al. (1996) developed a computationally efficient heuristic solution procedure aimed at minimizing total operator time, within the context of the component kitting problem in semi-automated PCB assembly. Dengiz and Akbay (2000) developed two simulation models to investigate effects of push and pull systems in PCB manufacturing processes. They found that a proposed pull system can boost daily productivity by 12%. A three-step heuristic approach designed for efficient scheduling of automated PCB assembly, which adapts standard methods from vehicle-routing problems, was developed by Grunow et al. (2004). Dengiz (2009) observed that the integration of the Taguchi method with simulation models underscores its potential in optimizing PCB manufacturing processes. A simulation study comparing PCB assembly lines operating in mixed-model mode versus the traditional batch mode was conducted by Yilmaz et al. (2009). They investigated two alternative material flow systems. Noroozi and Mokhtari (2015), in studying a practical application at a PCB assembly line, developed a mixed integer programming model and incorporated a Monte Carlo simulation into genetic algorithm-based intelligent optimization techniques. Yevsieiev et al. (2023), using GPSS (a process-oriented simulation language for modeling discrete systems), developed a model simulating an automatic SMT production process within the framework of cyber-physical systems. Simulation results allow estimation of production capacity and the loading of each equipment. As well, Tan et al. (2019) developed a DES model to test proposed strategies for preventive and corrective maintenance of an SMT line.

Recent research has also witnessed utilization of ABS in PCB assembly operations. For instance, Matsuda et al. (2016) constructed a "digital eco-factory" for a PCB assembly line using a multi-agent based approach. The digital eco-factory, as a multi-agent system, allows simultaneous examination of environmental performance, productivity and manufacturability.

More recently, digital twin frameworks have been developed for PCB manufacturing, albeit restricted to fully SMT automated process lines (Karanjkar et al., 2018; Seidel et al., 2023).

3. Environmental assessment and PCB assembly operations model

The simulation model presented in this study is grounded in a real-world case study of a Canadian company's PCB assembly area. The model comprises two distinct scenarios developed using the software *AnyLogic Simulation Software* (Anylogic, 2023), both of which aim to replicate the intricate PCB assembly process within the company's facilities.

The PCB assembly area primarily consists of three integral parts: (1) the Surface Mounted Technology (SMT) section, (2) the Through-Hole (TH) section, and (3) the Post Wave and Touch Up (PW) section. The SMT area encompasses various stations, including the PCB loader, Solder Paste Printer, Solder Paste Inspector, three distinct Pick&Place machines, an Operator Control station, a multiple-temperature profile Oven for soldering components to the board, an Auto-Optical Inspector, and a Final Inspection Station where SMT products are manually examined before being placed on carts for further processing.

The TH section involves a series of manual operators who supplement the panels with missing components, a wave solder preparation station, and the Wave Soldering machine, where TH components are fused onto the PCBs using molten metal. Lastly, a rapid final board inspection station is employed.

In the PW section, panels are routed to nine different stations, where they undergo detailed inspections and manual defect resolution. Following this, the panels are cut, if needed, in a certain amount of boards and trimmed before being sent to an additional station known as the Flying Probe (FP), where product resistance is measured before finally progressing to the final assembly stage.

The two distinct scenarios developed in this study serve different analytical purposes. The first one evaluates process flow time for the various production lines, conducts sensitivity analyses, and assesses resource utilization across the three production lines. Furthermore, as a main purpose, it focuses on a specific scenario, the Automated Through Hole (ATH), wherein the manual operators in the TH section are replaced with a dedicated machine (3), the Fuji sFAB-D, which the company already possesses but has not utilized. This allows for a comparison between automated and manual scenarios, enabling a comprehensive evaluation of their outcomes.

The second scenario, involving a different product, assesses how the percentages of operators utilization change as the number of operators varies.

4. Simulation model development

4.1. 1st scenario

The first scenario replicates the three main lines of the PCB assembly area:

1. In the initial section, the simulation models the panel's movement along the SMT section (Figure 1), including the setup of feeders in the pick-and-place machines—an essential step for initiating the line. The flowchart is structured to mimic the real-world case's operational sequence, utilizing data for each delay from the company's records.

Figure 1. 3D view of the SMT section.

2. The second part illustrates the board's progression through the manual through-hole (MTH) section (Figure 2), followed by processing in the wave solder and post-wave and touch-up stages. Here, observational data collected from the actual production line were employed.
3. The third section (ATH) substitutes the four operators from the MTH section, originally used for a specific product, with a single machine and an operator responsible for machine assistance and replenishing feeders and the eight different trays containing components for board assembly. Operations are organized to consider the machine's capacity in relation to component availability and quantity. Additionally, in this specific section of the flowchart (Figure 3), a scenario was included where, at random intervals during the simulation, the machine experiences breakdowns or requires maintenance due to failures. As a result, the line is halted for a specified delay period needed to restore its operations. This approach closely replicates real-world machinery behavior and facilitates a

precautionary analysis.

Figure 2. 3D view of the MTH section.

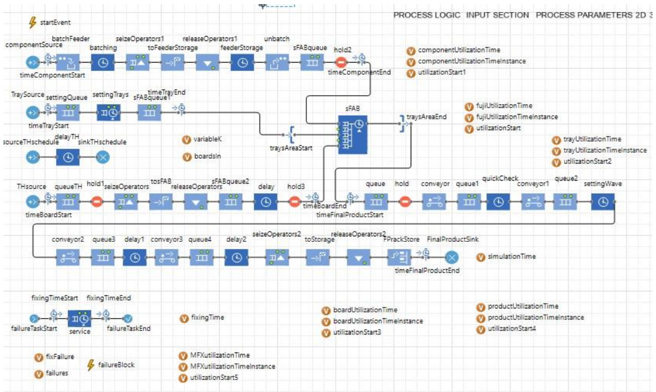


Figure 3. System logic implementation of the automated section.

4.2. 2nd scenario

The second scenario replicates the two main sections of the PCB assembly area considering another product to be processed:

1. First part concerns the set-up of feeders' components and the SMT process. Also, this flowchart, as the first scenario, it is structured to mimic the real-world case's operational sequence, utilizing data for each delay from the company's records.

2. The second one concerns handling process of PCB within the TH and FP sections. All the data utilized were derived from direct field sampling.

5. Input parameters, evaluation criteria and simulation outcomes

5.1. 1st scenario input parameters definition

The SMT section simulates the processing of 200 panels with a total run and setup time of 08:26:40 hours, including 05:40 hours for setting up the 68 pick and place machines. Each panel's processing time is approximately 2 minutes, and it is assumed that the pick and place setup time is about 5 minutes. During the simulation, all times, except for the machine times, can vary using a triangular distribution between minimum, average, and maximum values, allowing for the consideration of time effects on the final simulation duration.

Regarding the TH section, the processing time for each panel per operator is calculated based on an average of 7 seconds for each component to be assembled, varying with the quantity of components needed. In this simulation, 150 components are used per board. The utilization time for the post-wave and touch-up stations is calculated with a target production rate of about 4 panels per hour.

The third section, involving the replacement of the MTH line with a machine, assumes that feeders can hold approximately 5000 components, which would be enough for 33 panels considering 150 parts per board, and regular setup times are planned accordingly. Additionally, the machine contains 8 trays loaded by the operator in parallel with machine processing, taking about 3 seconds for each component. Thus, there is a set time delay for the trays after every 8 boards processed.

5.2. 2nd scenario input parameters variation

A preliminary analysis has been conducted to identify the design characteristics (factors) that may affect the performance measures of both the SMT and TH sections. The analysis indicates that several parameters, such as the number of operator personnel, the quantity of raw materials (such as feeders, components to be mounted, and PCBs) entering the line daily, and the process times associated with assembly cycle activities, may have a substantial impact on the overall performance of the hub. A total of 7 parameters have been found, with two levels allocated to each element. For the SMT section Simulation are used 3 of them, otherwise for the TH Section are employed 4. These results respectively in the generation of 8 scenarios for the first and 16 for the second. That will be examined using the simulation model. A concise depiction of each factor is provided below, and Table 1 presents the corresponding levels given to each factor.

- *operatorsSMT* – the number of operators employed daily in the SMT section.
- *boardArr* – the number of PCBs entering weekly the SMT section.
- *numberOfFeeder* – the average number of feeders entering daily the SMT section.
- *NumberOfSFPcb* – the number of pieces completed in the SMT section (“semi-finished”).
- *ManualOperator* – the number of operators that are employed in the MTH section.
- *NumberOperatorPostWave* – the number of operators that test the installation of parts in the

PW section.
- *NumberFlyingProbe* – the number of operators that test the electronic features in the FP section.

Table 1. Design parameters.

FACTOR	MIN LEVEL	MAX LEVEL
operatorsSMT	2	4
boardArr	19	23
numberOfFeeder	19	23
NumberOfSFPcb	14	16
ManualOperator	2	6
NumberOperatorPostWave	5	9
NumberFlyingProbe	1	2

5.3. 1st scenario evaluation criteria

In the first section related to SMT, the objective is to assess the process flow time for each agent, representing the working time of distinct entities in relation to the total duration. Moreover, the evaluation will extend to variations in total time across minimum, average, and maximum time configurations, with a concurrent identification of potential production line bottlenecks.

In the second section, the emphasis shifts towards the identification of bottlenecks within both the manual insertion line and the post-wave and touch-up stages. The primary aim is to identify specific stages or components contributing to delays and subsequently propose efficiency enhancements to ensure a seamless workflow, meeting production targets effectively.

In the third section, pertaining to the automated production line, the focus remains on assessing process flow times and potential bottlenecks. However, the primary objective shifts towards conducting a comparative analysis between the automated and manual operator models. This comparison will encompass an evaluation of total processing times and machine utilization percentages, highlighting the advantages and efficiency gains associated with the automated production line over the manual operator configuration.

5.4. 2nd scenario evaluation criteria

In the first section pertaining to SMT, the objective is to evaluate the process flow time for each agent. This represents the working time of individual entities in comparison to the total operational duration. Furthermore, this evaluation will encompass the calculation of the utilization rate, contextualized within an hourly time frame.

In the MTH section, the aim remains consistent in assessing the process flow time for each agent, and extending to the PW and FP sections. The primary objective here is to discern the optimal combination of operators to minimize both the in-line duration and the processing time for the PCB.

5.5. 1st scenario outcomes

In the SMT section, an analysis of variance was conducted to understand the variation in processing flow times among different agents. The obtained plot showed in Figure 4, revealed that components requiring the most time were closely linked to the setup of pick and place operations, indicating a potential bottleneck in the assembly line. Furthermore, it was observed that under varying time setups, the total simulation time changed accordingly.

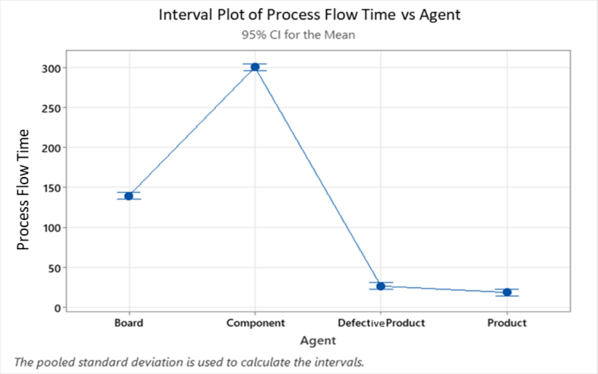


Figure 4. Variation in total utilization time across different agents.

In the TH section, a similar analysis was carried out as in the SMT section, indicating that the bottleneck for this section primarily lies with the panels being processed by manual operators. Main Effects Plot (Figure 5) and Mean Charts (Figure 6) were utilized to emphasize this aspect. The post-wave and touch-up processes are intricately linked to this operation, making panel handling a crucial aspect of workflow optimization.

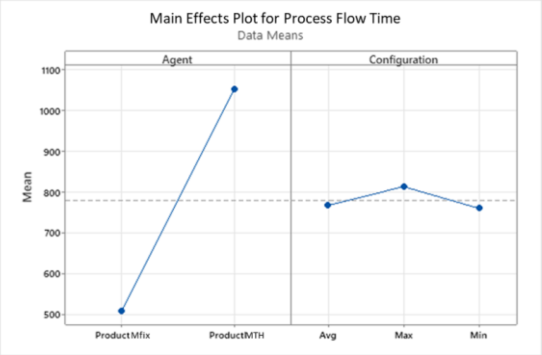


Figure 5. Main effects of different variables on the outcome.

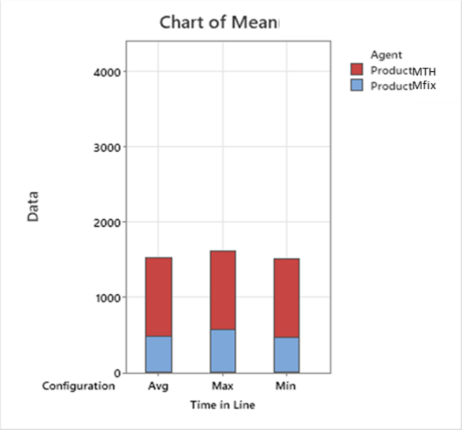


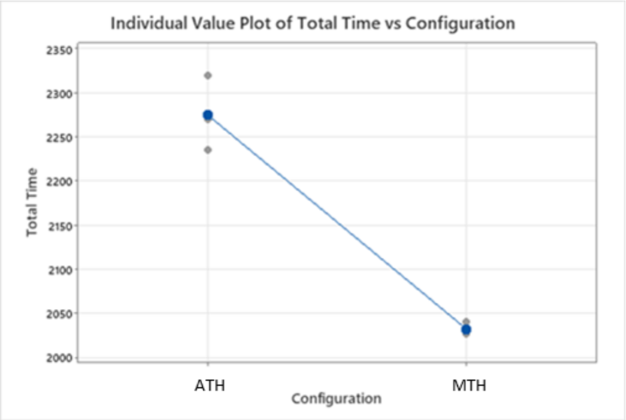
Figure 6. Average utilization time of section (MTH vs Mfix) with respect to the total.

For the automated production line (ATH), the analysis initially followed the same approach as the SMT section. Here, the majority of processing flow time was found to be occupied by the boards being processed. A comparison between the automated and manual insertion sections was also conducted, featuring Individual Value Plots of Total Time versus Configuration (Figure 7a). It became evident that while the total time for simulation was slightly higher in the automated configuration, there were intervals where the machine was not in operation due to setup requirements during the workflow. Conversely, the assumption of continuous manual operator activity was not entirely realistic, as it doesn't align with human behavior. These findings were substantiated by Main Effect Plots (Figure 7b), highlighting that machine utilization as a percentage of total time was notably lower compared to manual operators.

5.6. 2nd scenario outcomes

The combination of factor levels for the design parameters has been utilized to provide multiple operational scenarios for the assembly line.

The simulation results for each section have been evaluated using the Minitab software. The subsequent parts provide a description of the simulation outcomes for each performance measure:



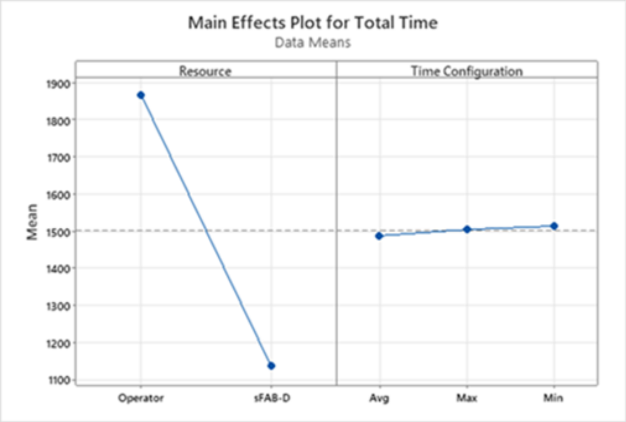


Figure 7a. Individual value plot of total time vs configuration.
Figure 7b. Utilization time of manual (MTH) and automated (ATH) sections with respect to the total time and different time configurations with respect to the total.

1. *TimeTot1Board* and *TimeTot1FP*: the simulation results shows that the average time spent for each PCB, in the SMT section, as well as per semi-finished PCB, in the MTH, PW and FP section, slightly and proportionally decreases to the increase respectively of the number of the operators employed in the SMT section and the number of operators in the MTH, PW and FP section. Moreover, while an increase of the number of operators in the MTH section increase the time spent to process a semi-finished product, an increase of the daily average number of raw materials in both lines has almost no impact to the average time spent. In fact, the process is almost automatic, and time required to process a board is more or less the same. Finally, the simulation results shows that the average time to process one board in the SMT section is 24 min and 149.5 min in the MTH, PW and FP sections. Figure 8 and Figure 9, respectively, depict numerically respectively the simulation results related to *TimeTot1Board* and *TimeTot1FP* performance measures.

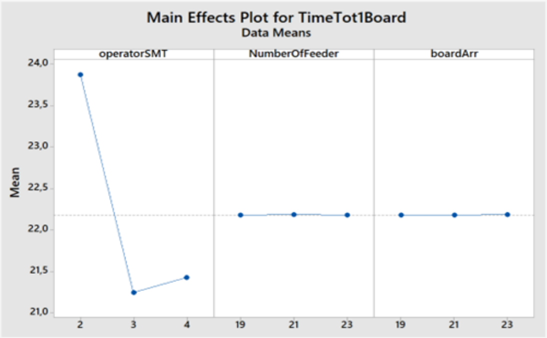


Figure 8. Main Effects Plot – *TimeTot1Board*

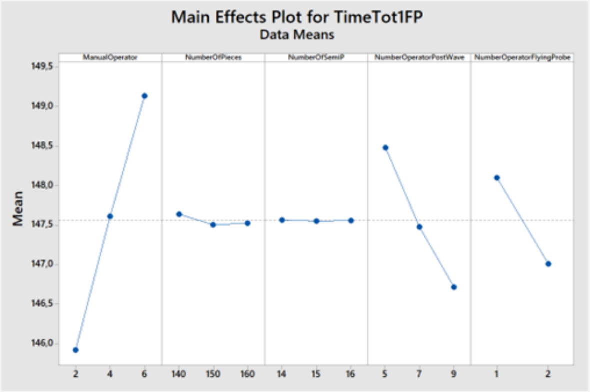


Figure 9. Main Effects Plot – *TimeTot1FP*

2. *TtotOp, Utiliz%*: the simulation results show that the average working time per hour of the operators for SMT section and the average utilization time per hour are strongly affected by the number of operators hired to perform all the activities. In fact, by employing even only one additional operator the average working times drop by 23%, and precisely from 56 minutes to 43 minutes per hour with a consequential decrease of the utilization rate from 93% to 73%.
3. *TtotOpM, %OpM, TtotPW, %OpPW, TOperatorFlyingProbe, %OpFP:* the number of operators allocated to the MTH stations has an impact on both the average working time per product for operators in the MTH section and their utilization rate. It is noteworthy that a reduction in the quantity of operators does not inevitably lead to inefficiency. In reality, this approach has the potential to minimize time inefficiencies, since each operator would sequentially transfer the board to the subsequent station until all components have been installed. The effects of alterations in the availability of raw materials seem to have a negligible influence on this matter. In a similar vein, the number of operators on the PW section has an impact on both the average working time per product and the utilization rate of operators. The circumstances are analogous for operators in the FP section. The capacity to concurrently handle and evaluate several goods implies that augmenting the number of operators at each station has the potential to diminish the overall duration of labor. Figure 10, for the PW section, and Figure 11, for the FP section, report the numerical impact of process time to the assembly cycle.

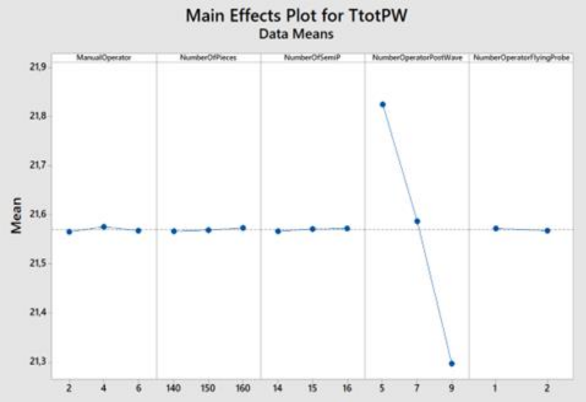


Figure 10. Main Effects Plot – *TtotPW*

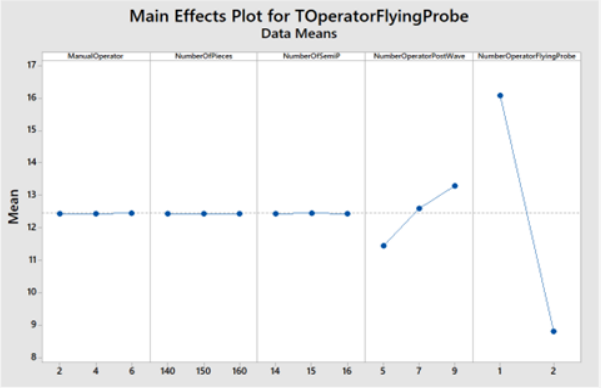


Figure 11. Main Effects Plot – TOperatorFlyingProbe

6. Results and Discussion

In the 1st scenario, the study reveals that the automated assembly line, with its capacity to address failures effectively, emerges as a more reliable choice compared to the manual assembly line. This real-world applicability proves pivotal in minimizing disruptions during production. While simulation-based operator utilization in the manual section may not accurately mirror real-world patterns, the automated line's scalability reduces workforce dependency, rendering it a more sustainable option in the long term. Despite marginally longer processing times observed in simulations, the automated line is recommended for its enhanced reliability and potential for long-term efficiency gains.

In the 2nd scenario, the optimization of production efficiency heavily relies on the critical aspect of effectively allocating operators within the manufacturing process. The scenario suggests that by strategically modifying the quantity of operators, it is possible to attain a harmonious compromise between time and efficiency. In certain situations, the utilization of 3 operators in the SMT section, 2 operators in the MTH section, 9 operators in the PW section and 2 operators in the FP section can enhance the efficiency of the process, resulting in a doubling of the speed. As a consequence, there is an increase in the efficient usage of resources and a clear enhancement in terms of both production time and output.

The ramifications of the aforementioned discoveries are of significant magnitude, as they have the potential to result in cost savings and an enhancement in product quality as a result of the expedited turnaround time. Nevertheless, it is imperative to acknowledge that this analysis was carried out within a defined set of circumstances, and as such, the outcomes may differ depending on other external variables or limitations.

7. Conclusions

Future research endeavors should delve deeper into optimizing automated assembly lines for enhanced efficiency and cost-effectiveness in PCB manufacturing. Exploring advanced failure handling mechanisms and refining operator utilization simulations will be crucial. Additionally, investigating innovative technologies to further reduce processing times while maintaining reliability will pave the way for even more efficient automated production lines.

The efficiency of PCB production is directly impacted by the strategic distribution of operator numbers. Our research findings suggest that ideal combinations of operator numbers can result in a significant reduction of processing times, up to a 50% decrease. Future study should aim to delve deeper into the relationship between operators and machines, while also examining more advanced methods of handling failures and exploring emerging technologies. The optimization of operator usage and the adoption of innovative methodologies may serve as crucial factors in enhancing the efficiency and cost-effectiveness of automated production lines.

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