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Original scientific paper

IMPROVING ELECTRIC MOTOR ASSEMBLY USING ONE PIECE FLOW, ERGONOMICS, AND CELLULAR LAYOUT

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Abstract

Manufacturing organizations continuously strive to improve their performance to survive in the competitive market. This study aims to improve the performance of a production line by utilizing a discrete event simulation model for manufacturing the rotor part of an electric motor. While previous studies have focused primarily on technical factors, this paper addresses the shortage of research on the impact of physical ergonomics on production line performance. By integrating human movements into other improvement methods, this study proposes four strategies: one-piece flow, elimination of unnecessary human motions, their integration, and switching to a Cellular Manufacturing System (CMS). The results demonstrate that the adoption of the one-piece flow among some workstations increases productivity and utilization of resources by about 21 % and 9 %, respectively. However, the elimination of the unnecessary motions resulted in insignificant improvement due machine's automatic nature. Lastly, the study found that converting the production line into a CMS resulted in a significant increase in productivity (32 %), maximum resource utilization (17 %), and a decrease in work in process (40 %).

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Key Words: Assembly Lines, Simulation, Single-Piece Flow, Human Factors, Cellular Manufacturing System, Work in Process

1. INTRODUCTION

Electric motors are considered as an essential unit in various products. A production line of electric motors includes various manufacturing and assembly processes among successive workstations/machines, which are linked together by a transportation mechanism and operated by skilled workers. In general, the production processes can be carried out by manually operated, machinery or computer-controlled machines. The literature is rich in various performance improvement methods for production lines. A review of various improvement methods is presented by [1]. This review identified several methods, e.g. motion and time study, effective utilization of workforce, automation method, process analysis, eliminating non-productive activities, Cellular manufacturing system (CMS), line balancing, Kaizen, bottleneck analysis, and 5S technique. However, the impact of investigating different aspects such as Just-In-Time (JIT) tools, e.g., single piece flow, physical ergonomics (repetitive movements), CMS, and Jidoka (autonomation) on the performance of real production lines were not adequately addressed in the existing studies. Besides, integrating robotic manipulators into a production line has emerged as a solution to reduce cycle times, decrease costs, and increase overall output [2, 3]. The proposition of any of such improvement initiatives should be simulated first for saving resources. Using discrete event simulation (DES), the non-continuous processes can be imitated with different probabilistic natures that perfectly reflect the real working environment [4], after the processes' standardization. Recently in [5] simulated the effect of considering JIT on the production line performance. In addition, the impact of combining two or more improvement methods on the system performance is rarely considered in the relevant literature.

This study addresses a significant gap in research on improving production line performance. While previous research has focused mainly on work-study and time-study methods, little attention has been given to the impact of physical ergonomics and human factors. Additionally, there is a lack of investigation into the effect of integrating these factors with traditional methods. This study aims to fill this gap by investigating the effect of four improvement strategies (ISs) individually and in combination on the performance of a production line, including the adoption of single-piece flow, waste reduction of human movements, a combination of both methods and modifying the production line into a CMS. Real data from a leading manufacturing company in Egypt for the production of home appliances were used to develop a DES model to analyse the different effects of these strategies on production line performance.

2. LITERATURE REVIEW

This section focuses on the main attributes, which formulate the current work. These attributes include the flow of items over the production line, physical ergonomics, and CMS.

2.1 Flow of items over the production line

There are two types of parts flow: single-piece flow and flow in batches. The adoption of the single-piece flow over batch can reduce waste and achieve the concept of lean manufacturing. However, line balancing is mandatory for achieving smooth flow on the line [6]. The literature provides many surveys of the development of line balancing, see e.g. [7, 8]. A classification scheme of line balancing approaches can be found in the work of Boysen et al. [9], who identified the gap between the requirements of real configuration problems and state-of-the-art research. In the work of Pisuchpen and Chansangar [10], a line-balancing methodology is applied to balance a production line for a plastic vision lens to improve its productivity. Caggiano et al. [11] presented a DES model of an assembly line for the production of a Skycar light aircraft. The model was used to accurately simulate the line behaviour in the digital environment and to identify any potential areas for optimization e.g., bottlenecks and low-efficiency workstations. Jitchaiyaphum and Prombanpong [12] integrated line balancing and waste reduction to improve the productivity of the assembly line. In their study, they focused on human errors and developing actions to prevent these errors. As a result, they could improve the line productivity by about 159 %. Wang et al. [13] proposed to balance the disassembly line while achieving multi-objectives using genetic algorithms. Most of these lines adopted the concept of single-piece flow over the assembly line. Relying on Basavaraj [14] the single-piece flow gives better assembly line performance than batch processing for productivity and workers fatigue.

2.2 Motion study and physical ergonomics

Motion study focuses on the way that a worker performs a given task. Verma et al. [15] defined motion study as a technique of analysing the body motions employed when doing a task with the objective of eliminating or reducing ineffective movements. By using motion study and the principles of motion economy, the task can be redesigned to be more effective and less time-consuming. In addition, the main objective of the motion study is job simplification so that the job can be less fatiguing, less time-consuming, and safer. Which satisfies the main target of physical ergonomics at workstations. Generally, the literature on assembly systems ignores the fact that ergonomics can have an impact on productivity and human safety. Battini et al. [16] analysed how ergonomics and assembly system design techniques are closely related. Their research developed a theoretical framework to assess a concurrent engineering approach to designing assembly systems, in conjunction with optimizing the ergonomics of the workplace. Others like Tutsoy and Barkana [17] considered improving human safety using automation. Battini et al. [18] introduced a multi-objective optimization model for solving assembly line balancing to include the ergonomics aspect. Recently, Tanasic et al. [19] investigated the effect of lean tools on assembly line performance. According to Malega et al. [20], workplace self-organization increases the system's flexibility and responsiveness. Kulkarni et al. [21] proposed to improve the winding operation of an electric motor assembly by using a time study. They succeeded to reduce cycle time by about 44 % which leads to an increase in productivity.

2.3 Cellular manufacturing system

Cellular manufacturing is one of the most important applications of group technology in production [22]. According to Bhatnagar and Saddikuti [23], CMS comprises categorizing machines used in the firm's production system into cells dedicated to part families that have similar requirements in terms of tooling, setups, and operations sequences. Kaku et al. [24] proposed a study to analyse the human-task-related performances in converting a conveyor assembly line to CMS. Farsijani et al. [25] presented a mathematical programming model to minimize the total distance between entries, and simulation models for two manufacturing systems, a new cellular manufacturing, and a conventional job shop manufacturing system. A summary of the literature reviewed is presented in Table I.

From the above review, most of the research focuses mainly on methods based on work-study, time study as well as effective utilization cycle time of various stations of the assembly line. Although physical ergonomics can affect the performance of production lines, very few researchers have investigated human considerations. None of them investigates the effect of merging both techniques on the production performance that are addressed within this paper.

Table I: Summary of the literature review.

No.	Authors	ALB*	HWM*	ALB- HWM*	CMS*	Other	Used method
1	[4]	X			X		Arena
2	[6]	X					Algorithm
3	[10]	X				X	Arena
4	[18]	X	X				Mathematical model
5	[23]				X		Mathematical models
6	[24]	X			X		Simulation models
7	[26]	X					Arena
8	[27]	X					Arena
9	[28]	X					Arena and OptQuest
10	[29]	X	X				Tecnomatix
11	[30]	X	X				Simulated annealing
12	[31]	X				X	Automated feeding
13	[32]	X					WITNESS
14	[33]	X				X	Arena

**Notes:* ALB: Assembly Line Balancing; HWM: Human Work Motions; CMS: Cellular Manufacturing System

3. PROBLEM DESCRIPTION

The current study considers the production line of the rotor of an electric motor that is used in a set of home appliances. Fig. 1 shows the rotor which consists of a set of slotted steel laminations pressed together in the form of a cylindrical magnetic path where aluminium or copper bar conductors are embedded in its surface and mounted on a rod. The sequence of manufacturing processes is illustrated in Fig. 2. Two parts: a set of lamination sheets, and a rod are input as raw materials to the rotor manufacturing line. The set of steel laminations is pressed together to form a cylindrical shape. Then, aluminium is injected to fill the grooves and be in direct contact with the steel laminations. The rod raw material is machined by turning, grinding, and knurling, respectively. Afterward, the finished lamination and rods are assembled into rotors, which are further processed by some machining operations as shown in Fig. 2.

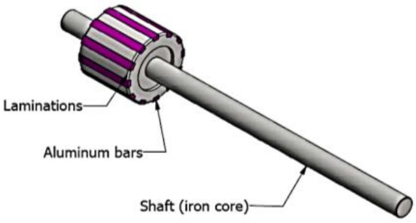

Figure 1: Squirrel-cage rotor for an A.C. induction motor.

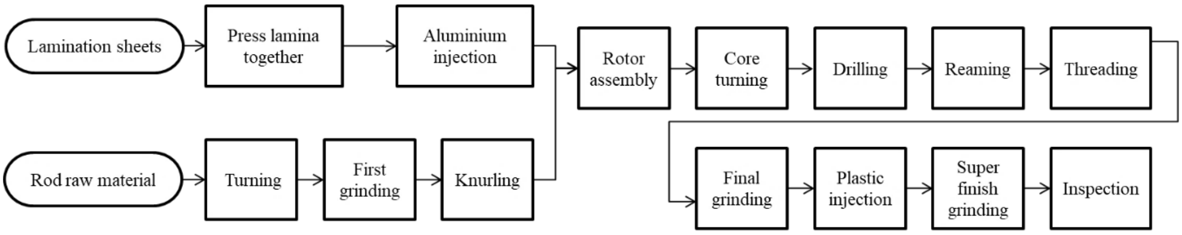

Figure 2: Rotor manufacturing steps.

Fig. 3 shows the current layout of the rotor production line, which includes seven workstations, namely (Pressing, Aluminium injection, Rod turning, Rotor assembly, Drilling, Core turning, and Grinding). In addition, it shows the workflow among these stations which are arranged as a job shop production. The average daily production capacity of the rotor production line is 1480 rotors/day. The line is working two shifts of 8 hours per day including 1.5 hours as a total allowance for lunch, personal, fatigue, delay, and other allowances. A value stream mapping (VSM) is developed to help map out inefficiencies and time wastes as shown in Fig. 4. Data collected during the mapping process includes cycle time, distances travelled, number of machines, and the number of processes. Based on the VSM analysis, the bottleneck stations are the core turning and grinding processes with large cycle times for workstations number 5 and 7, respectively. This means that a lot of time is wasted in the transportation of work in process (WIP) between the seven stations. From a method and time study, the standard time was identified. The main problem is to eliminate the effect of the bottlenecked stations on the overall productivity of the production line and increase its throughput without extra resources.

4. PERFORMANCE IMPROVEMENT METHODOLOGY

In this section, we explain the proposed methodology for performance improvement, which includes two parts. The first part shows the proposed improvement strategies while the second part presents a simulation model for evaluating the impact of the proposed strategies.

4.1 The proposed improvement strategies

Four Improvement Strategies (ISs) were proposed and investigated for productivity improvement, as follows:

IS1 – Adoption of the single-piece flow over batch flow whenever possible: it aims to achieve the single-piece flow over the production line by rearranging the workstations using the line-balancing concept. The distance moved can be reduced, WIP could be reduced, utilization of workstations could be increased, as well as line throughput could be increased. Fig. 5 shows the VSM of the re-arrangement of the production line into four workstations, rather than six workstations as in the original layout. For example, the press machines are relocated close to the aluminium injection machine, which in turn leads to reducing the working space, and time wasted in transportation and moving batches between both stations. Moreover, this will result in achieving synchronous flow. Similarly, the rotor assembly, the core turning, and the drilling workstations are to be combined into one workstation.

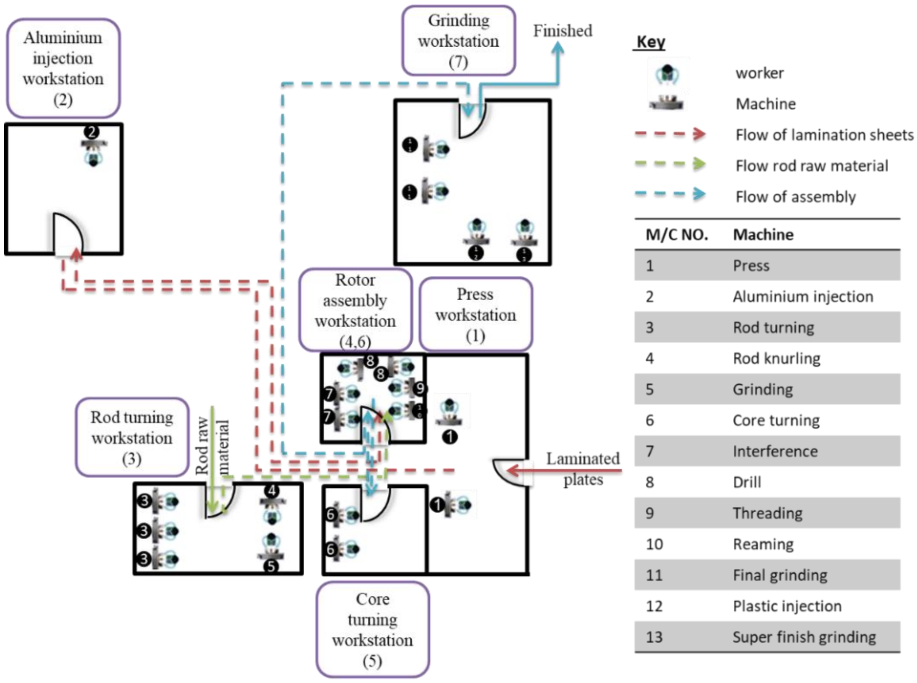

Figure 3: The current layout and workflow of the rotor production line.

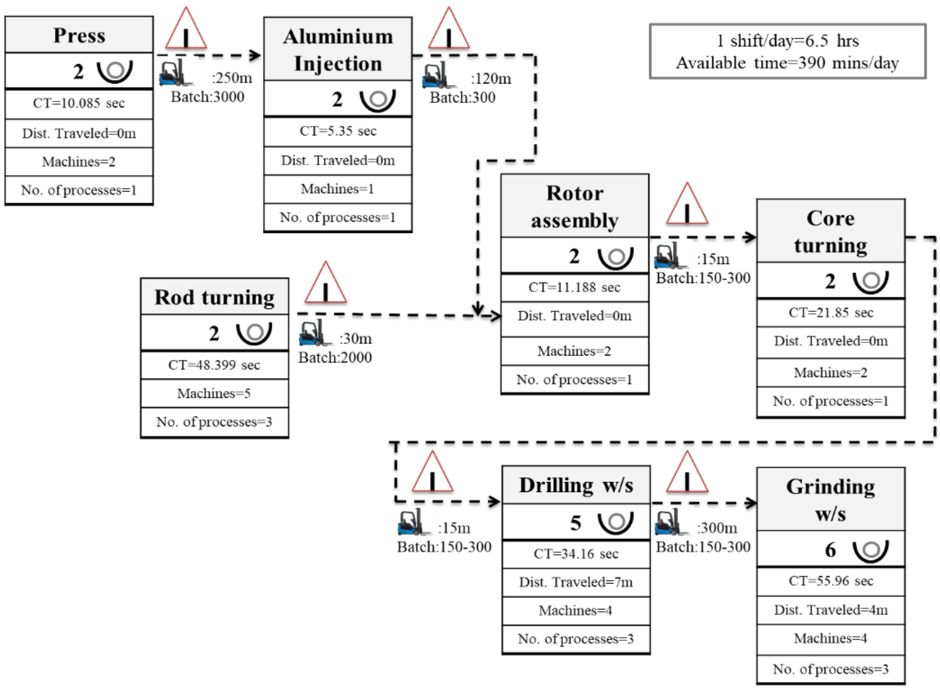

Figure 4: Value stream mapping of workstations of the current line.

IS2 – Reducing human and work motions: it aims to eliminate production wastes such as the unnecessary motion of workers or/and work pieces when performing production tasks and to identify the best sequence of motions to improve line efficiency. Because some processes, e.g., pressing and injection, depend on automatic machines or/and semi-automatic machines, IS2 is applied to processes that only involve workers such as threading, drilling, and final grinding. As an example, Fig. 6 shows the proposed improvement in motion when applying human-work motion analysis as compared with the current motion sequence for the threading processes. In the threading process, the human motion per cycle is reduced from 8 seconds to 5 seconds with a 37.5 % reduction in cycle time. Other processes such as drilling and final grinding are improved by 40 % and 20 % respectively.

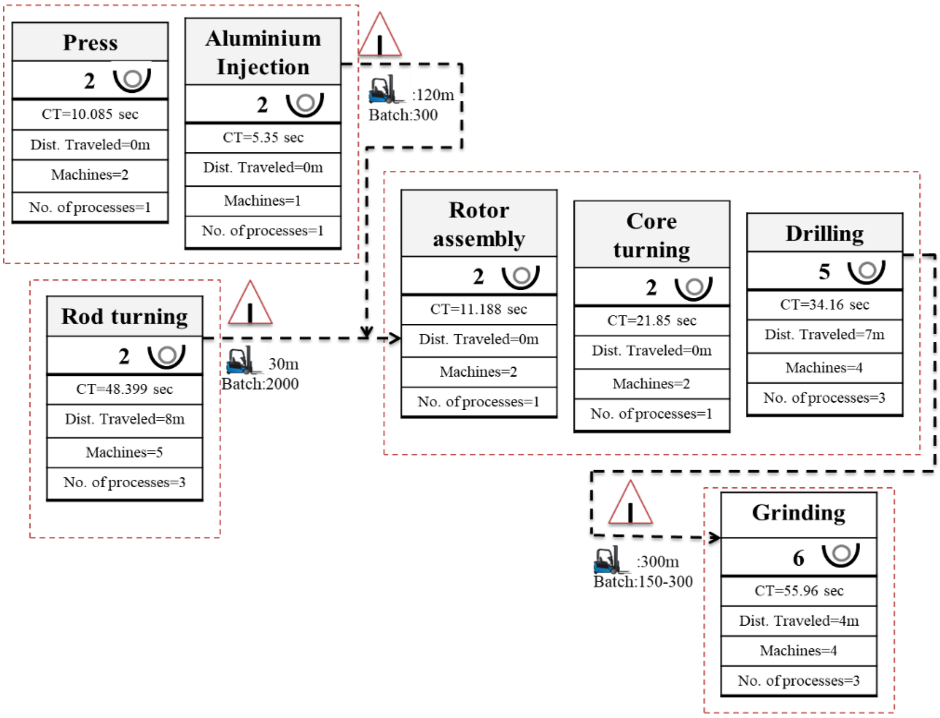

Figure 5: The VSM as proposed by IS1.

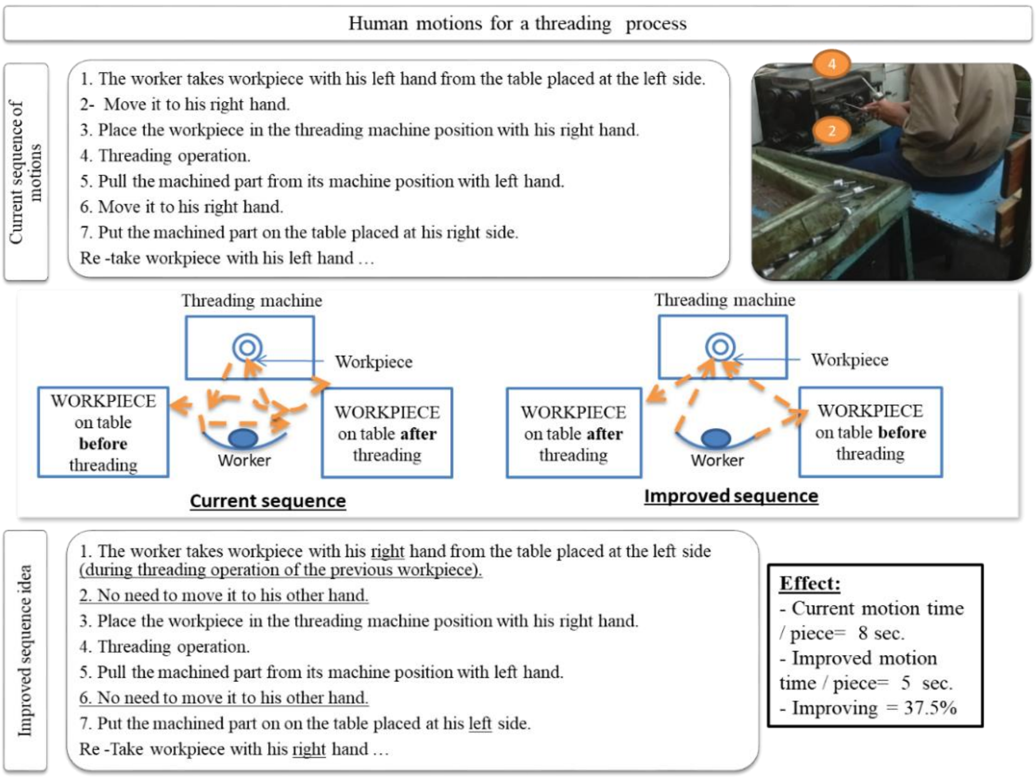

Figure 6: Elimination of unnecessary human motions of the threading process.

IS3 – Combining IS1 and IS2 into an integrated strategy: it simulates the combination of IS1 and IS2 to achieve more improvements in the productivity of the production line.

IS4 – Developing a CMS: it aims at eliminating production wastes and reducing flow times by using CMS. Fig. 7 shows the proposed CM which consists of three cells, in which each cell can perform a part type. The first cell is to produce the laminated part, the second cell is dedicated to producing the base rod, and the last cell is to assemble and manufacture the rotor. In the proposed CMS model, a single-row layout of equal area facilities is considered to locate machines in cells 1 and 2 while multiple rows shape is considered for the layout of machines in cell 3. Parts are moved between cells in batches with the same value as the current line. The machines are located close to one another to reduce the intra-cell movement and route time.

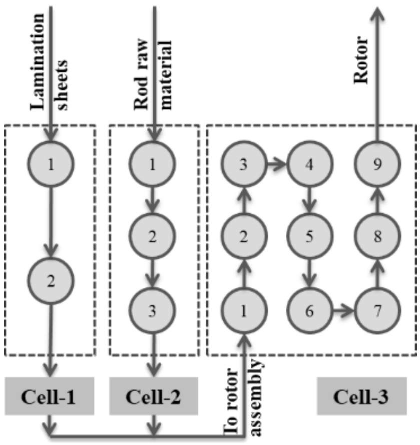

Figure 7: A representation of the proposed CMS layout.

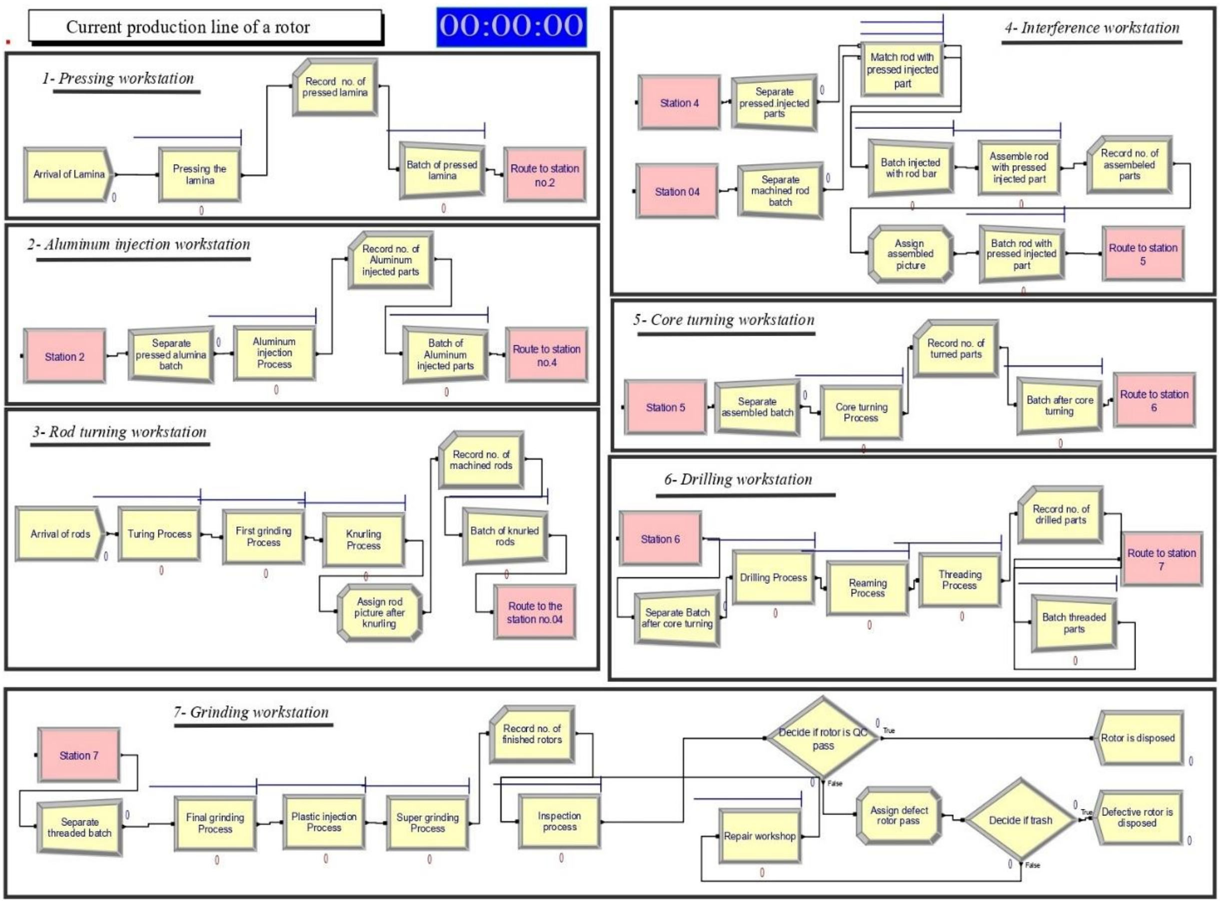

Figure 8: Simulation of the current production line.

4.2 The simulation model

Simulation has proven to be an important tool in analysing innovative manufacturing strategies [11]. The main benefit is the time and cost saving for investigating a specified scenario without consuming resources. The performance of various manufacturing strategies can be investigated using the simulation as a decision-support tool. To evaluate the results of the proposed improvement strategies, a DES model is developed using Arena simulation, following the flow chart in Fig. 2. The simulation model for the current production line is shown in Fig. 8. The simulation model considers three entities, i.e., lamination sheets, the raw material of the rod, and the rotor (final product). This simulation model is adapted to evaluate the suggested improvement strategies. The first step is to determine the probability distributions of different processes by fitting probability distributions to production data using the input analyser module of Arena simulation. The probability density function of the processing time of each workstation are represented in Table II. These formulas can be used to predict the stochastic random variables of the processing time at each specific workstation.

The simulation model has been verified carefully to ensure that the model precisely represents the facility under research. To reduce the error variance, the number of replications is set to 20 replications. The developed model simulates one shift with a replication length of 6.5 hours, warm-up periods of 13 hours, and 20 replications.

Table II: Probability density function of the processing time for each workstation.

Workstation	Activities	Lot size	Distribution of the processing time (sec.)	*P*-value	No. of machines
Pressing	Sheet piercing and blanking.	250	Constant (10)	-	2
Aluminium injection	Inject the lamina that comes from the press.	400	TRIA (5, 5.3, 6)	0.0428	1
Rod turning	Turning the rod to the required dimensions.	1000	Constant (36.513)	-	3
	Grind the rod.		TRIA (8.05, 9.88, 10.9)	> 0.15	1
	Knurling the rod.	20	2 + 2.3 × BETA (0.989, 1.35)	0.0639	1
Interference	Assembly rod with the rotor.	150	10 + WEIB (1.74, 2.42)	> 0.15	2
Core turning	Turning the rotor.	150	19.2 + WEIB (3.02, 2.1)	> 0.15	2
Drilling	Drill the rod to make a hole.		8 + WEIB (3.09, 2.03)	> 0.15	2
	Reaming tip of this hole.		3 + WEIB (1.68, 1.99)	> 0.15	1
	Thread the top of the rod.	150	TRIA (6, 6.68, 10.4)	> 0.15	1
Grinding	Grind the rotor.		18 + 3.48 × BETA (2.05, 1.35)	> 0.15	2
	Plastic injection to make a washer of plastic on the rod.		TRIA (12, 18.3, 20)	> 0.15	1
	Make super finish grinding for the rotor.		17 + ERLA (1.1, 2)	> 0.15	1

5. RESULTS AND DISCUSSIONS

The following sub-sections discuss the results of the four improvement strategies in terms of WIP, resource utilization, and productivity as shown in Tables III, IV, and V.

5.1 The results of IS1

As shown in Table III, single-piece flow can effectively reduce the WIP by 30 %. By checking the resource utilization resulting from IS1 (Table IV), it can be noted that the supper-grinding station has the highest improvement in resource utilization of about 13 %, followed by the inspection station with 11 %, and aluminium injection station with 9 %. In addition, there are many other increases in resource utilization ranging from 1 % to 5 % in other workstations. Given the improved resource utilization in most of the workstations, the line productivity was also improved by about 21 % as can be seen in Table V.

Table III: Improvement percentage of WIP in the four strategies.

	% Improvement in WIP			
	IS1	IS2	IS3	IS4
Rotor	30 %	1 %	30 %	40 %

Note: % Improvement = $\frac{Current\ WIP - WIP\ of\ the\ improvement\ strategy}{Current\ WIP} \times 100$

Table IV: Resource utilization under the current and suggested strategies.

Resource Name	Current strategy	IS1	IS2	IS3	IS4
Aluminium injector	29 %	29 %	29 %	29 %	29 %
Center lathe-01	52 %	52 %	52 %	52 %	52 %
Center lathe-02	42 %	47 %	42 %	47 %	47 %
Drill	21 %	23 %	17 %	19 %	23 %
Drill-reamer	18 %	20 %	18 %	20 %	20 %
Drill-threading	15 %	16 %	9 %	10 %	16 %
Grinding machine	41 %	41 %	41 %	41 %	41 %
Grinding-final	39 %	39 %	33 %	33 %	43 %
Injection machine	61 %	65 %	62 %	64 %	72 %
Inspector	50 %	61 %	51 %	61 %	88 %
Interference machine	49 %	49 %	49 %	49 %	49 %
Knurling machine	13 %	13 %	13 %	13 %	13 %
Press	27 %	27 %	27 %	27 %	27 %
Repair machine	9 %	12 %	10 %	11 %	13 %
Super grinding machine	61 %	74 %	62 %	74 %	82 %
Average Utilization	35 %	38 %	34 %	37 %	41 %

Table V: Percentage improvement in the line productivity under the four strategies.

Key Performance Indicator (KPI)	IS1	IS2	IS3	IS4
Average productivity increase per shift	21 %	1 %	21 %	32 %

Note: % Improvement = $\frac{No.\ of\ produced\ rotors\ under\ strategy\ i - Current\ No.\ of\ produced\ rotors}{Current\ No.\ of\ produced\ rotors} \times 100$

5.2 The results of IS2

As can be seen from Table III, the impact of IS2 on WIP is negligible. This is because of the existence of machine-controlled time with less involvement of human factors. Accordingly, the percentage of improvement in the total cycle time of such stations is very small. Regarding resource utilization, the impact is also small, it can vary from 1 % to 5 % improvements in some workstations, e.g., injection, inspector, repair machine, super grinding, and aluminium injector. On the other hand, the utilization of some resources was decreased after adopting this strategy, e.g., the stations of drilling, threading, and final grinding. This is because of the reduction in the processing time of these operations. In addition, the starving phenomenon in some situations: the operation showed wait for the arrival of the parts. Therefore, not all these reductions lead to productivity improvement because a part of the operation becomes underutilized. The impact of this strategy on the line final productivity is also very small and it contributes about 1 %. This small contribution due to the small reduction in the cycle time that varies from 5 sec. to about 12 sec. in some cases.

5.3 The results of IS3

Combining IS1 and IS2 aligns with the impact of the single-piece flow alone, given the slight impact of IS2 as shown before. It can be noted that the percentage of resource utilization is the summation of that of the single-piece flow and the elimination of unnecessary motions for all workstations. Similarly, there is no impact on productivity above that of the of the single-piece flow alone.

5.4 The results of IS4

As shown in Table III, the amount of WIP was reduced by 40 %, meaning that the impact of IS4 is significant. It can be noted from Table IV that IS4 led to a significant improvement in resource utilization compared to the current layout, where the highest improvement reaches 41 % for the inspection, followed by the supper grinding machine, and the injection machines. The utilization of many other workstations is increased with small percentages varying from 1 % to 5 %. Table V shows that the rotor productivity increased by about 32 %.

Finally, it is found that converting the current production line into a CMS leads to better results in improving the WIP, resource utilization, and line productivity. The single-piece flow provides good results, while the elimination of human movement has the least improvement. These results were obtained because the operator-controlled portion of the service time is small. In other words, most of the machines are automatic or semi-automatic machines. In such production systems, the worker contribution is very limited to a small number of processes, and the machine controls the different process cycles. The elimination of unnecessary motions will be appreciated in situations where manual work dominates machine work.

Based on the results, DES is an effective tool to investigate the proposed improvement initiatives. The results obtained are satisfactory compared to those observed in the literature. For example, the increase in productivity varies from 1.35 % to 9.87 % obtained by Sime et al. [27] for an apparel assembly line, while Mendes et al. [28] increased it to 55 % in the same industry type. In winding operation of an electric motor Kulkarni et al. [21] succeeded to improve cycle time by about 44 %, and reducing human movement by 38.34 %.

7. CONCLUSION

In this paper, four strategies have been proposed and investigated for improving the performance of a real production line. The considered line is dedicated to producing the rotor part of the electric motor in a home manufacturing company located in Egypt. Five discrete event simulation models have been developed using Arena software. The first simulation model was developed to reflect exactly the current production line. In the second simulation model, the implementation of a partially single-piece flow increases the average production capacity from 746 to 900 rotors/shift which is equivalent to an increase of 21 % in productivity. The third model proposes to eliminate unnecessary human movements within workstations; it improves production capacity by only 1 %. The fourth model tries to meet the concept of lean manufacturing, it combines two improvement initiatives: single-piece flow and reduction of excess movements. Such an integrated model cannot significantly affect production performance above the single-piece flow alone. The implementation of the fifth model was performed to convert the production line into a cellular manufacturing system. It provides better production performance; this model has minimized WIP of the assembled rotor and sub-assembled parts. The adoption of such an improvement initiative can improve productivity by 32 %, increase average utilization by 17 % and reduce the WIP by 40 %. As a perspective of this work, the authors suggest implementing this study on a system of manual operations and/or mathematically investigating the impact of using the different lean tools [34] under fuzzy processing time. Further research could extend this paper's findings by exploring how the advancements in automation, control, robotics, autonomous vehicle, and artificial intelligence could enhance the performance of the production line.

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