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Effect of manpower factor on semiautomatic production line completion time: A system dynamics approach

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ABSTRACT

Completion time in a manufacturing sector is the time required to complete a product in sequence process during production operation. In a semiautomatic production line, manpower factors such as fatigue and pressure are two significant influences on completion time. However, it is found that previous studies lack the concern to include manpower factor in completion time. Hence, this paper develops a causal loop diagram and stock flow diagram to simulate the influence of manpower factor on the completion time in a semiautomatic production line. In this research, a well-known audio speaker manufacturer is selected as a case company. As a result, it is found that the preparation time for materials has a great impact on fatigue and pressure as it contributes the highest percentage of deviation from the completion time base run with 72.22%. Finally, a policy regarding completion time improvement is recommended to the management to enhance their production performance.

Keywords**:** Causal loop diagram; stock flow diagram; system dynamics; completion time; semiautomatic production line.

INTRODUCTION

In production sites, product layout, or known as production line, is built up to arrange production activities in sequence to ensure the smoothness of work flow in production activities [1, 2] and generate the best productivity [3]. A fully automatic production line is entirely equipped with machines but need manpower to handle the machine [4]. On the other hand, a semiautomatic production line is the combination between manpower and machines to perform specific task [5-7]. In a semiautomatic production line, the factors that relate to manpower performance are stress [8-10] and fatigue [10-14]. However, it is found that the past studies appear to have more emphasis on fully automatic production lines, while little attention has been given to the semiautomatic production line that is associated with manpower factor as found in [15-18]. The reason is that manpower factor is a qualitative variable that does not have a direct measurement [19]. With this lack of concern, a study that focuses on a semiautomatic production line with the inclusion of manpower factor is further explored to fill the knowledge gap in such areas. It is known that the related activities in production systems are performed within standard completion time [16, 20, 21]. Completion time, or also known as flow time, refers to the time required to complete an item in sequence order [15]. In analysing the completion time problem, a case company with a semiautomatic production line in producing audio speaker products is considered in this research. Figure 1 shows the flow of completion time at a semiautomatic production line of the case company. Before the product is completely assembled and distributed to customers, there are some challenges faced by the company such as manpower factor [22], waiting time for material preparation [23], unstable inventory of materials [24], irregular time of material delivery [25], and machine breakdown [3, 26]. Consequently, those challenges create tardiness or lateness of a job's due date from its completion time [27]. Hence, the occurrence of tardiness contributes to low production rate and customer dissatisfaction [28] and jeopardises the company's good name [29].

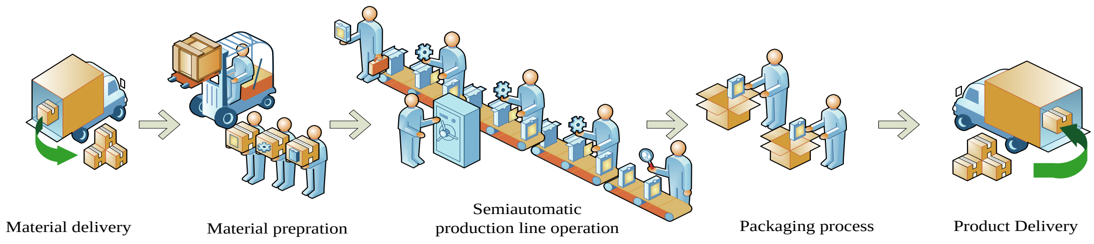


Figure 1. Flow of completion time at a semiautomatic production line of the case company.

Based on the literature review, most of the previous studies on production operation that particularly concerned policy design research have implemented system dynamics (SD) as found in [15, 16, 30-32]. SD refers to the computer simulation method for modelling and simulating a dynamic and complex system with feedback process inclusion [33, 34]. One of the important stages in SD is the development of a casual loop diagram (CLD), which aims to capture the cause and effect of various factors that contribute to the problem [35-37]. However, the number of previous studies related to manpower factor using SD is far from adequate [38] as found in [15, 16, 31, 39]. Hence, this paper developed CLD and stock flow diagram (SFD) for analysing the completion time problem at a semiautomatic production line with the inclusion of manpower factor.

METHODS AND MATERIALS

In this section, the research framework, conceptualisation of the problem, and modelling process based on SD are elaborated in the following subsections.

Research Framework

The research framework based on the SD methodology is divided into five stages as illustrated in Figure 2. The five stages are problem identification, model conceptualisation, model formulation, model testing, and finally, policy formulation and evaluation. Iteration may happen from any step to another step until the structure and behaviour of the model representing the real world state is achieved [19, 35]. In the problem stage, the scopes of the problem and its boundaries are identified. After that, CLD is developed where diverse theories regarding the source of the problem are captured qualitatively. In the next stage, the conceptual diagram is converted to SFD to visualise the linkage of related factors in the problem. Then, model testing is developed through behaviours and structures of the simulated model to produce a meaningful concept in the real environment or actual system [35]. Finally, the developed model is evaluated for improvement purposes once it has been validated in the testing stage [40, 41].

Subsequently, the policy formulation regarding completion time is improved and proposed to the management to enhance their performance.

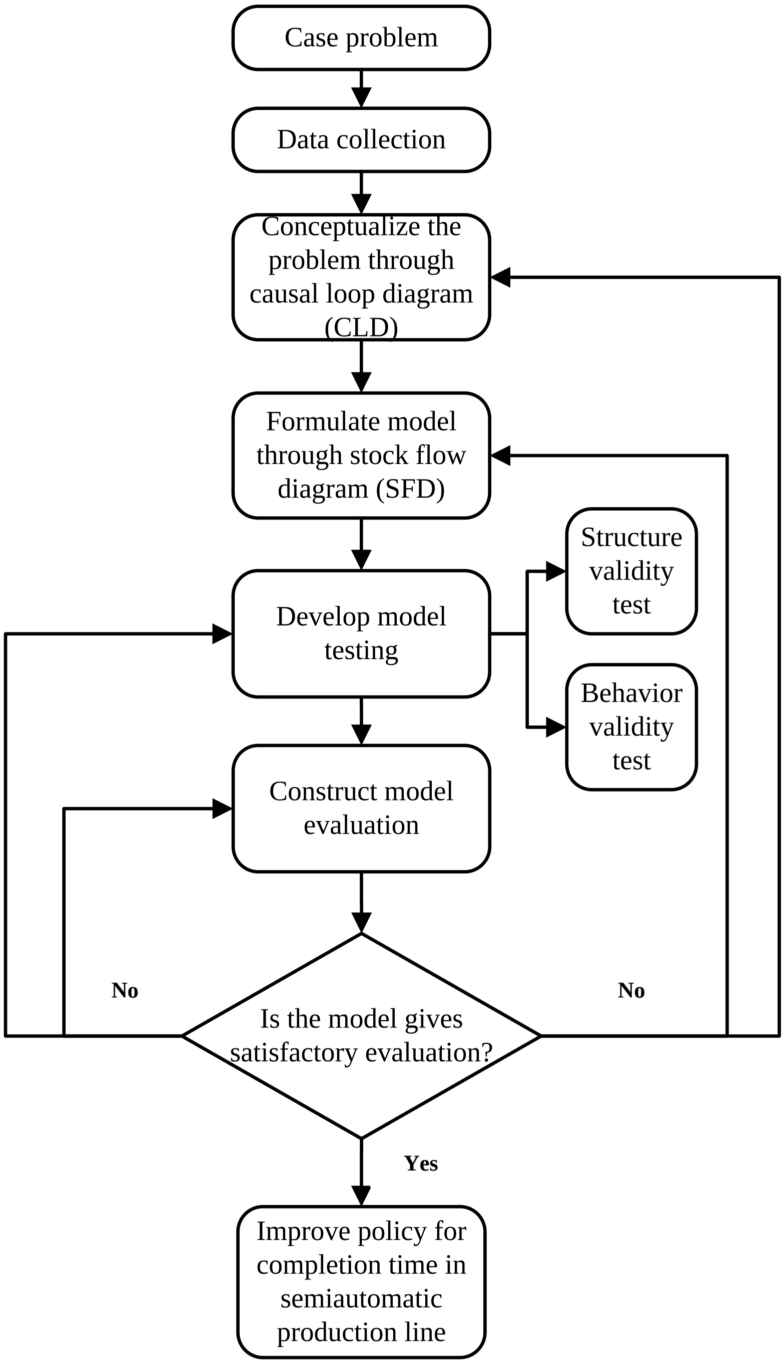


Figure 2. Research framework for simulating completion time.

Data Collection

To analyse the completion time, a well-known company in producing audio speakers is selected. The primary data is obtained through a discussion with Production Planner and Production Control Executive to identify the factors that contribute to the completion time problem. On the other hand, the secondary data is collected from the daily reports of Production Control Department and Production Department. The secondary data needed for analysing the completion time is listed in Table 1. Moreover, the production line operates from 8 a.m. until 5 p.m. or eight hours in one day with one hour for recess time. It is found that the actual completion time is frequently deviated from the production target. Hence, this paper developed CLD and SFD for simulating the production operation with the inclusion of related data and manpower factor towards the completion time problem.

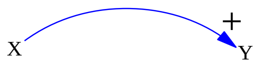
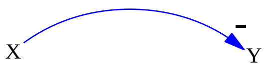
Table 1. List of secondary data needed for analysing completion time.

Secondary data	Unit
Number of manpower, *h*	person
Preparation time for material, *i*	hour
Machine breakdown rate, *j*	1/piece
Material warehouse inventory, *k*	piece
Actual completion time, *l*	hour

Development of Causal Loop Diagram

During the stage of model conceptualisation, CLD is developed to assist the modeller in representing a causal structure [33]. CLD refers to a causal structure tool for conceptualising the cause and effect of the problem by emphasising the feedback structure among the variables in a model [35]. In developing CLD, a curved line with an arrow is created to represent the causal relationship or information feedback that links from one variable to another variable. Every link in the diagram must be labelled with polarity, whether positive (+) or negative (-). Table 2 explains the function of each link polarity. Besides, feedback loop is one of the important processes involved in the development of CLD. There are two types of feedback loop, which are reinforcing loop and feedback loop. A reinforcing loop is a positive (+) feedback system that is normally indicated by R sign [35]. A feedback loop is considered a positive or reinforcing loop if the number of negative (-) link polarity is even in the loop. In contrast, a balancing loop is a negative feedback loop with a negative (-) sign that is normally indicated by B sign. A feedback loop is considered a negative or balancing loop if the number of negative (-) link polarity is odd in the loop.

Table 2. Definition of link polarity.

Symbol	Description
	The (+) sign within an arrow implies that if variable X increases, then variable Y also increases. On the other hand, if variable X decreases, so does Y.
	The (-) sign within an arrow indicates that if variable X increases, then variable Y decreases. If variable X decreases, then variable Y increases.

Development of Stock Flow Diagram

After the CLD is constructed, the diagram is transformed to SFD to simulate the model with richer visual language. In this research, eight hours of working period, *t*, are considered for the production operation. Besides, Eq. (1) shows the formulation of the selected equations to completion time. The related equations are as follows:

Work in process, q =

$$\int_{t_o}^{t} (\text{production start rate}, v - \text{production completion rate}, w) + 0 \quad (1)$$

Units: pieces

Moreover, according to the company representatives, the schedule pressure on manpower is considered stable if the value is equal to 1. However, if the value of schedule pressure is more than 1, it shows that more pressure is imposed on the manpower caused by the production schedule, which is an unhealthy situation for manpower performance. In contrast, if the value of schedule pressure is below than 1, then manpower has less pressure, which is lower than production capacity. Besides, a lookup table for the effects of fatigue on productivity, *f*, is provided based on the input from utilisation, *b*, as illustrated in Figure 3. A lookup table refers to a functional of a non-linear relationship between two variables [19]. In this research, as suggested by [19], a lookup table is developed to represent the effect of fatigue on productivity that is caused by production utilisation since different effects of fatigue are created by different utilisation levels.

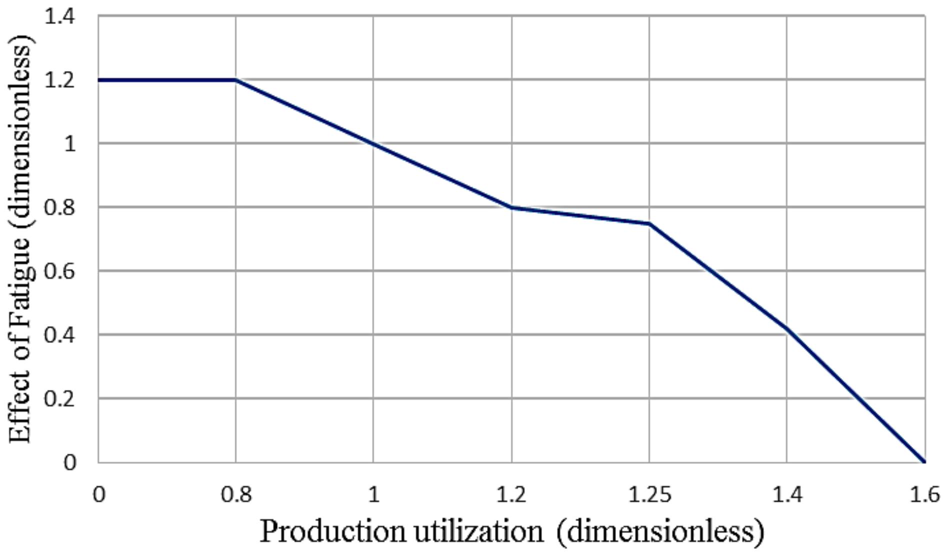


Figure 3. The effect of fatigue on productivity based on input from production utilisation.

Referring to Figure 3, based on the judgment of the company representatives, the effect of fatigue on productivity is presumed to be stable if the value of output is equal or above than 1. However, if the output is below than 1, the effect of fatigue on productivity is an unhealthy situation for manpower performance. In this research, production utilisation is considered as the input for the lookup table.

Model testing

In this stage, the model is tested for its structure and behaviour validity. Table 3 shows the tests that are developed in this research. The selection of test is not restricted since no single test is sufficient and it is always based on the purpose of the research [40, 41].

Table 3. The development of model testing in the integrated model.

Major test	Types of test	Description	Method
Structure validity test	Dimensional consistency	To verify each equation is dimensionally consistent with real world meaning.	Inspect model equations.
Behaviour validity test	Behaviour reproduction	To test whether the model simulated the real pattern behaviour as actual system.	Compare with the historical data. In this research, data of production completion rate, *r*, from a production daily report is considered.

Model Evaluation

Once the structure and behaviour validity have been established, a model evaluation is constructed through an intervention strategy. Intervention refers to the necessary action that must be taken to eliminate or reduce the problem based on the modeller's judgment that has been identified before developing the SD model. The effects of related interventions are observed on the actual production completion rate, schedule pressure, and effect of fatigue on productivity. In this research, the intervention strategies are developed as mentioned in Table 4.

Table 4. The development of intervention strategies.

Type of intervention	Description	Range of parameter changes	Observation output
Intervention 1	Change parameter for the number of manpower, *h*, (the base run is 30 persons)	• Reduce to 29 persons • Increase to 31 persons	• Actual production completion rate, *r* • Effect of fatigue on productivity, *f* • Schedule pressure, *c*
Intervention 2	Change parameter for the preparation time for material, *i*, (the base run is 1 hour)	• Reduce to 0.5 hour • Increase to 2 hours	
Intervention 3	Change parameter for the machine breakdown rate, *j*, (the base run is 0.0013 per pieces)	• Increase to 0.002	

RESULTS AND DISCUSSION

Model Testing

Based on the result of the dimensional consistency test, the model equations are consistent. Besides, for the behaviour reproduction test, the result's pattern from the SFD almost resembles the actual data of production completion rate from the production operation at the case company as shown in Figure 4. Hence, the model is validated to capture the actual structure and behaviour of the semiautomatic production line.

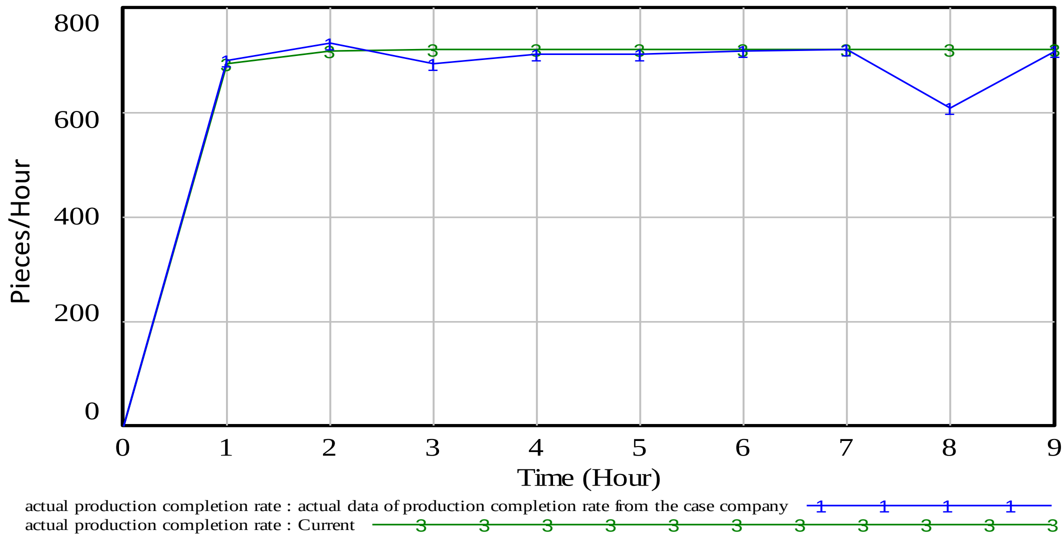


Figure 4. The model passed the behaviour reproduction test.

CLD and SFD of Semiautomatic Production Line Model

Figure 5 presents the overall CLD to explain the influence of manpower on completion time at a semiautomatic production line. In this diagram, three loops are involved, which are material, completion time, and fatigue.

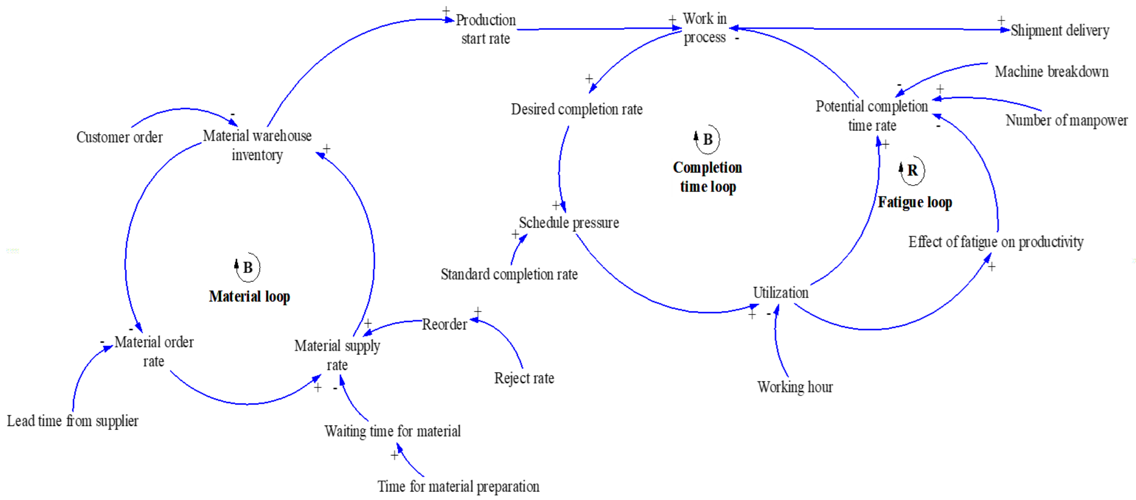


Figure 5. Causal loop diagram of completion time at semiautomatic production line.

Once the CLD is constructed, the diagram is transformed into an SFD. Figure 6 illustrates the development of SFD for completion time at a semiautomatic production line. In the development of the SFD, three stocks are formulated, namely material warehouse inventory, work in process, and finished goods warehouse inventory. As mentioned in Table 4, the intervention strategies are number of manpower, preparation time of material, and machine breakdown rate. The results of the interventions are as follows:

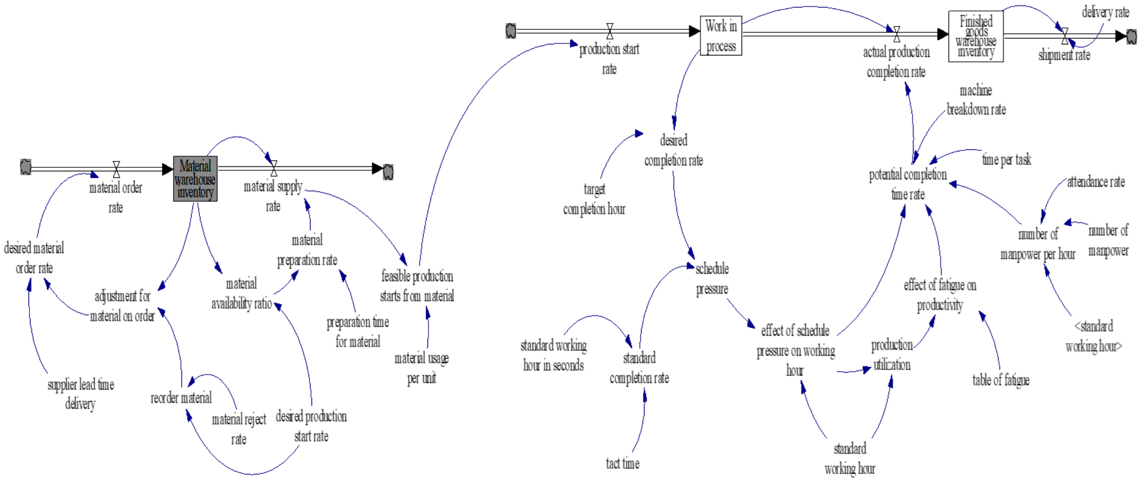
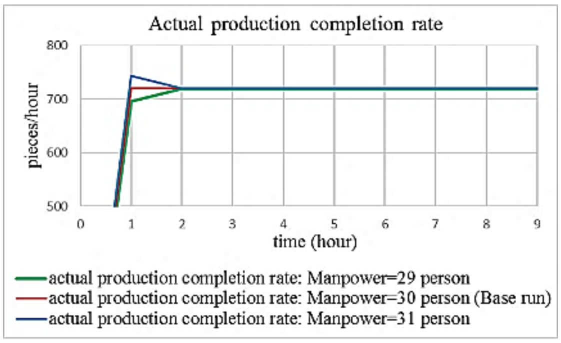


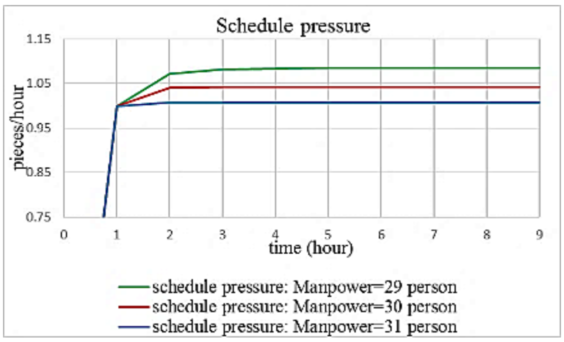
Figure 6. Stock and flow diagram of completion time for semiautomatic production line.

Intervention 1: Number of Manpower Parameter

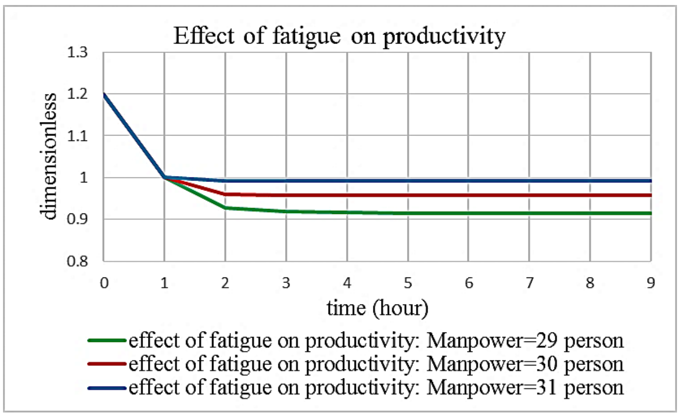
Intervention 1 is conducted by reducing and increasing the number of manpower parameter to 29 and 31 persons, respectively. The intervention results are observed as depicted in Figure 7. Besides, Table 5 presents the completion rate for different numbers of manpower during the working period.



(a)



(b)



(c)

Figure 7. Results of interventions on (a) production completion rate; (b) schedule pressure; (c) effect of fatigue on productivity.

Based on the result of Figure 7(a), the actual production completion rate for 31 persons of manpower recorded the highest value (744 pieces/hour) for the first hour of the working period as compared to 29 persons and 30 persons of manpower (696 pieces/hour and 720 pieces/hour, respectively). However, Figure 7(b) indicates that for 31 persons, the schedule pressure is less than 1, which indicates that it is below the production capacity. Meanwhile, the schedule pressure for 29 persons is more than 1, which shows that it is an unhealthy situation for manpower performance since more tasks are required to be done in producing products at the production line. Hence, the completion rate of the following working hour is similar despite the differing number of manpower. Table 5 shows the completion rate based on the different number of manpower at the production line.

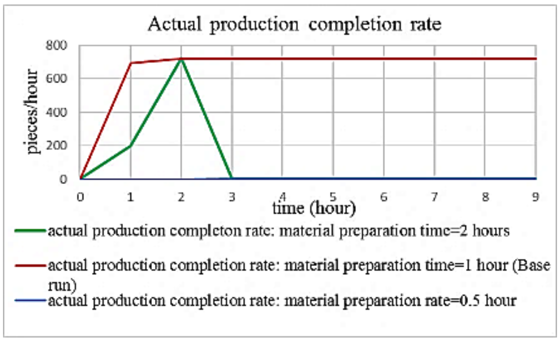
Table 5. Completion rate based on intervention on the number of manpower

Number of manpower, *h* (person)	Completion rate, *r*, (pieces/hour) during t^{th} working period (hour)								
	1	2	3	4	5	6	7	8	9
h = 29	696	720	720	720	720	720	720	720	720
h = 30 (the base run)	720	720	720	720	720	720	720	720	720
h = 31	744	720	720	720	720	720	720	720	720

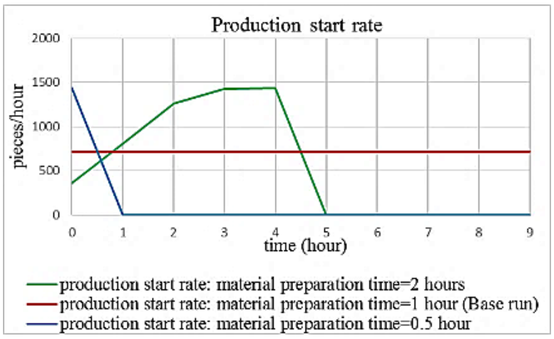
The effect of fatigue on productivity as presented in Figure 7(c) for 29 persons of manpower shows the lowest value (0.967) since more work must be performed by a lesser number of manpower. From the results, it can be induced that a lesser number of manpower creates less effects of fatigue on productivity even though the actual production completion rate is equal for different numbers of manpower. On the other hand, there is no necessity to have more number of manpower (above 30 persons) since it contributes to the additional cost of hiring manpower as compared to the existing number of manpower (30 persons). The result indicates that the ideal number of manpower is 30 persons since the schedule pressure and effect of fatigue are stable. Hence, the number of manpower is a crucial factor on completion time as highlighted by [22] in reducing the process time at the assembly line and [42] in increasing production efficiency at the assembly line.

Intervention 2: Preparation Time of Material

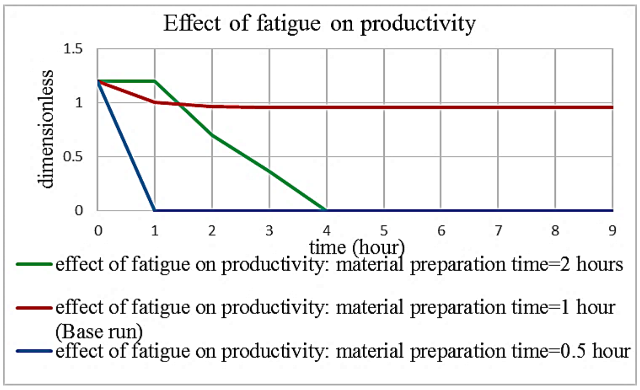
Intervention 2 is conducted by reducing and increasing the preparation time of materials to 0.5 hour and 2 hours, respectively. The intervention results are observed as illustrated in Figure 8. Moreover, Table 6 shows the completion rate for different times of material preparation during the working period. Based on Figure 8(a), no production completion rate is recorded for 0.5 hour of material preparation time due to the high rate of receiving materials at the production line (1430 pieces/hour) during the first working period (Figure 8(b)). On the other hand, the actual production completion rate is recorded to only sustain until the second hour of the working period if the material preparation time is 2 hours due to the high production start rate (1430 pieces/hour) that occurred during the third working period (Figure 8(b)). However, the completion rate for 1 hour of material preparation time shows the stable completion rate for the entire working period (720 pieces/ hour) due to a consistent production start rate (720 pieces/hour). Table 6 shows the completion rate based on intervention on the preparation time of materials.



(a)



(b)



(c)

Figure 8. Results of interventions on (a) actual production completion rate; (b) production start rate; (c) effect of fatigue on productivity.

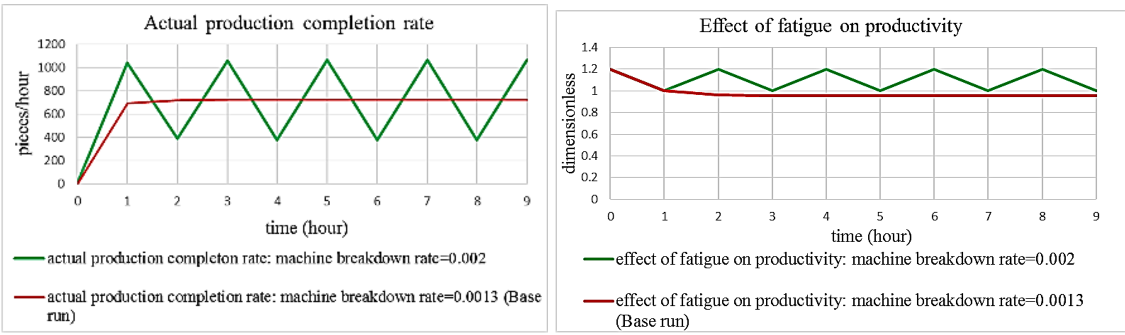
Table 6. Completion rate based on intervention on waiting time for material preparation

The preparation time for material, *i* (hour)	Completion rate, *r*, (pieces/hour) during t^{th} working hour (hour)								
	1	2	3	4	5	6	7	8	9
i = 0.5	0	0	0	0	0	0	0	0	0
i = 1 (the base run)	720	720	720	720	720	720	720	720	720
i = 2	200	720	0	0	0	0	0	0	0

Moreover, the effect of fatigue on productivity as shown in Figure 8(c) drops to 0 (below 1) for both 0.5 hour and 2 hours of the material preparation time during the first and third hours of the working period, respectively, which indicates an unhealthy situation for manpower performance. From the results, it can be induced that the acceleration of material preparation (0.5 hour) contributes to the extreme fatigue to manpower as they are only able to sustain their work in the first hour of the working period. On the other hand, postponement of material preparation (2 hours) contributes to the extreme fatigue of manpower due to high accumulation of material shortage, which occurred during the third hour of working period. Hence, by considering the preparation time of material, it could serve to improve the completion time as emphasised by [15] in reducing material delivery lead-time in enterprise operations and [16] for smoothing material flow in the supply chain system.

Intervention 3: Machine Breakdown Rate

Intervention 3 is conducted by increasing the machine breakdown rate to 0.002. The intervention results are observed as presented in Figure 9. In addition, Table 7 demonstrates the completion rate for different rates of machine breakdown during the working period. Referring to Figure 9(a), when the machine breakdown increased to a higher rate, which is 0.002, the actual production completion rate is unstable (between 1,000 pieces/hour and 400 pieces/hour). Subsequently, the effect of fatigue on productivity (Figure 9(b)) indicates the unbalanced value for the entire working period. On the other hand, if the machine breakdown rate is 0.0013, the completion rate and the effect of fatigue on productivity are stable. Table 7 shows the completion rate based on the intervention of machine breakdown rate. From the results, it can be induced that if the machine breakdown rate occurs higher than 0.0013, the production is still able to operate but with unstable outcomes, hence this leads to the shortage of production output target. Therefore, machine breakdown is crucial to be considered in reducing the completion time as highly recommended by [26] to reduce the lost time in the production line and [43] smoothen the operation of the production line. Based on the three intervention strategies, it is found that the changes on the preparation time for material contributes the highest percentage of deviation from the completion time base run. As indicated by Table 6, if material preparation consumes 2 hours (more than 1 hour of the base run), the completion rate decreases to 72.22%. On the other hand, the changes on the number of manpower and the machine breakdown rate contribute to the deviation of 3.33% and 44.4% from the base run of completion rate, respectively.



(a) (b)

Figure 9. Results of interventions on (a) actual production completion rate; (b) effect of fatigue on productivity.

Table 7. Completion rate based on intervention on machine breakdown rate.

Machine breakdown rate, j (1/pieces)	Completion rate, r, (pieces/hour) during t^{th} working hour (hour)								
	1	2	3	4	5	6	7	8	9
j = 0.0013 (the base run)	720	720	720	720	720	720	720	720	720
j =0.002	1000	400	1000	400	1000	400	1000	400	1000

CONCLUSIONS

This paper developed the CLD and SFD diagrams of SD to explain the influence of the manpower factor on completion time at a semiautomatic production line. Based on the result, changes in the number of manpower, preparation time of material, and machine breakdown rate significantly affect manpower fatigue as indicated by the intervention strategies. It is found that the preparation time for material contributes the highest percentage of deviation from the completion time base run up with 72.22%. Besides, a policy on the preparation time of material is proposed to ideally maintain the time within one hour. Moreover, the acceleration and deceleration of the material preparation time could extremely influence manpower fatigue as they struggle to cope with the production output target due to the bulkiness of the production start rate. For an ideal production completion rate, 5,040 pieces of material should be well prepared within one hour for the semiautomatic production line to produce 720 pieces of audio speakers in one hour with 30 persons of manpower, while the machine breakdown rate should be maintained at 0.0013 to meet the daily target. In a nutshell, CLD and SFD are advantageous guidance to analyse the completion time by including the manpower factor in a holistic picture. Moreover, the top management of the audio speaker manufacturing company is able to identify the factors that contribute to the deferment of standard completion time in the semiautomatic production line and reduce the problems through the development of the intervention strategies. For future work, the development of SFD should consider other factors such as inspection rate, reject rate, and working overtime, and vary the intervention strategy to enhance the performance of the completion time model.

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