Manufacturing Enhancement through Reduction of Cycle Time using Time-Study Statistical Techniques in Automotive Industry

Abdul Rehan Khan Mohammed*, Ahmad Bilal
University of Warwick
Coventry, United Kingdom
*a.mohammed.3@warwick.ac.uk

***Abstract*— Within the complex and competitive automotive manufacturing industry, manufacturing Cycle Time (CT) remains one of the Key Performance Indicators (KPIs). Its reduction is of strategic importance as it contributes to time-to-market shortening, faster bottleneck detection, achieving throughput targets and improving production-resource scheduling. This paper presents a case study on CT analysis for early stage identification of the bottleneck stations and the processes in a manual assembly line that is responsible for increased manufacturing CT. The case study is conducted on an automotive seat manufacturing plant in the UK. For detailed CT analysis, CT of each station is recorded. Results of the case study shows that bottlenecks identification at an early stage can significantly enhance the overall performance of the production line.**

***Keywords*— automotive industry, cycle time and production line**

I. Introduction

In automotive industry, there is a constant pressure to reduce CT and maintain required production takt time. Manufacturing CT can be defined as the time required to complete one cycle of manufacturing operation(s) at a station level to produce a product. Whereas, takt time refers to the frequency of a product that must be produced to meet customers' demand. Takt time can be typically split into CT, waiting time, idle time and starved time. Measuring CT of a manufacturing processes is critical to manufacturers; so as to evaluate job execution rate at a station level. CT of a typical manufacturing process is reliant upon various factors that include: product mix, components used, machinery involved, inventory, scheduling practices and process technology. Due to high complexity and constant change in these factors, its challenging to conduct comprehensive production analysis for CT reduction [1].

Simulation software are extensively used for carrying out comprehensive CT exploration but a number of issues impede their everyday use. For instance, with more than 65 commercial simulation software's available in the market, manufacturers finds it challenging to choose an appropriate software that fits their requirement. Additionally, due to absence of strong simulation standards or languages it becomes difficult for manufacturers to maintain these software's and requires additional simulation specialists for their support [2]. When a model is developed using these simulation software's for CT analysis, it may take from several hours and numerous repetitions to find out optimal solution to reduce CT [3]. The data fed into simulation models is mostly based on assumptions made during the design stage. The actual assembly process time is often different than the predicted by simulation. As a result, time-study statistical techniques are readily adopted by the manufacturers as a complementary solution to simulation software to help in reduction of manufacturing CT [4].

KPIs of a production line can be measured in two ways: online or real-time KPIs and offline KPIs. Online KPIs are used to report the status and performance of a production line. Offline KPIs are used to report the performance of a production line based on historical data. Online KPIs are used by operators as well as managers to make quick judgements on how to improve their current performance by rectifying problems straightaway. Offline reports are typically used by managers to assess the performance, identify problems and make necessary plans to avoid such problems in the future. Offline reports give an opportunity to compare historical data from various perspectives. This paper will be focusing on both online and offline KPI monitoring as the combination of both is significantly beneficial to identify problems and put necessary plans in place to resolve them.

Manufacturing of seats is usually characterized by linear sequence of operations which means the sequence of operations remains the same (typically increasing or decreasing by a known common difference). Due to this linearity, if any operation fails or delays, it effects the whole manufacturing process. The paper is aimed at identifying the stations that are responsible for causing the delays in the seat production, and then drilling down to investigate the processes that are responsible for the delays. Since, the line is characterized as linear sequential, the takt time plays a critical role in measuring the line performance [5], [6]. Takt time is calculated based on the available time divided by the demand (per production order or shift) [7]. Factors such as premature purchasing of raw materials; retrieval and storage of goods; and other cost related issues; which are encountered in producing ahead of demand can be totally eliminated by producing on demand.

Takt time is assigned for the whole production line and its value is decided based on the processes breakdown between each stations. Therefore, measuring and keeping up with the takt time is of great importance within automotive manufacturing industries [8]. Failing to keep up with the takt time results in reduced productivity, increased time-to-market and has negative impact on the overall manufacturing performance. The case study presented in this paper focuses on addressing the challenges faced by Company X in maintaining its takt time during production.

The methodology presented in the paper identifies the root causes of the increased manufacturing CT through step by step drill down approach. It aims to provide the specific process within the processes which is responsible for increased CT. The paper is organized as follows: section II presents literature review, section III gives an overview of the company X, its product process flow, problems with their existing assembly line and the structure of current assembly line data. Section IV describes the methodology adopted to tackle the existing problems in the company X. Section V provides the conclusion.

II. Literature review

In the era of fourth industrial revolution, it is critical for the manufacturers to live up to on-time customers' demands and ensure customers satisfaction. Hence, manufacturers are constantly finding ways to reduce the CT of the manufacturing processes with increased performance and productivity of the whole manufacturing plant, along with maintaining high standards of product quality [9]. In a highly complex automotive industry, reducing CT is of great importance, since it contributes to faster fault detection, time-to-market shortening and realizing throughput targets [10]. There are numerous methods, tools and techniques developed to tackle CT related problems. A few of them are listed below: Sada et al. [11], used a simple spreadsheet technique to decrease CT in a semiconductor fabrication plant. The spread sheet is used to compare the theoretical CT with actual CT for each process involved in the fabrication. This comparison is done to detect the bottleneck process and by doing so the CT is improved by 24%.

Silva et al. [12], adopted statistical analysis to record every moments of parts throughout the IBM's multi-layer ceramics line. The purpose is to find all the meaningful dimensions that can allow to detect and round CT glitches. By implementing statistical analysis, IBM's microelectronic production line saw an improvement of 15% in overall CT. Yih-yi et al. [13], designed an algorithm that is used to find the shortest CT for the production process in semiconductor fabrication industry. The algorithm is based on the where-to-dispatch and what-to-dispatch mechanism. This mechanism is grounded on calculating minimal waiting time and transportation time, by embedding this mechanism it is evidenced to reduce 32.5% waiting time in the current semiconductor manufacturing industry. Chung-Jen et al. [14], proposed an Manufacturing Intelligence (MI) method to exploit the value of production data to reduce CT. The MI is based on neural networks that predicts the Work In Process (WIP) for CT reduction. To verify the method, it is tested in an integrated device manufacturer production line in Taiwan and the result is considerable improvement in CT.

Tamas et al. [15], proposed a dynamic CT setting algorithm to improve CT of an industrial open station conveyor. The algorithm is developed taking into account the complexity of the production process and product variability. Indoor positioning system along with smart wireless sensors were installed to track and record each movement of production to figure out bottlenecks and improve CT. David et al. [16], used ManSim/X manufacturing line simulator to examine the effect on CT by varying the percentage of different products on the semiconductor production line. The results proved that factors such as process complexity, operator availability, production rate and factory shut downs effected the CT. However, these results were limited to the given production line. Dharun et al. [17], worked on reducing CT of a T-shirt manufacturing plant. By employing several lean tools, namely: failure mode effect analysis, time and motion study, kaizen and value stream mapping, the plant overall CT is reduced to 20%.

Lerdlekha [5], adopted standard time analysis to reduce CT in wood product manufacturing industry. By comparing the standard times of assembling and polishing required for the manufacturing of the product with the set takt time, production capacity is increased from 560 units/month to 1200 units/month. Dinesh et al. [18], proposed a vendor rationalization strategy for streamlining the supplies to reduce manufacturing CT in an engineer-to-order Indian company. Kraljic's matrix-based model is implemented which reduced the manufacturing CT of feeder hopper from 43 days to 21 days. Similarly, various research articles discussed the CT related problems and suggested possible solutions to efficiently tackle it [19]–[21].

From the intensive literature review it is apparent that solutions pertaining to CT were resolved either using time-study analysis or developing simulations models. Papers which were based on deploying simulation models for CT reduction mainly discussed about the difficulties in understanding software language, suffered with number of software glitches and consumed ample time for generating, testing and implementing those models. Moreover, most of these articles were specific to a particular production line or manufacturing plant where the case study is carried out. For a seat manufacturing industry that develops highly customized products, developing, training, testing and implementing these simulations models can be time consuming. So, manufacturers are finding complementary solutions that can monitor their production performance before these models are generated. Plus, due to constantly changing customer demands, models developed with the help of simulation software's becomes redundant sooner and requires constant redevelopment.

Likewise, all the aforementioned research papers concluded by mentioning the bottleneck equipment, station or line responsible for the decreased manufacturing productivity and poor performance of the production plant. Bottleneck in manufacturing process perspective is identified by determining maximum CT in the production line. For example, if the maximum CT of a station is greater than the takt time, then the customers' demands are not fulfilled and vice-versa. They failed to mention precisely which process is the reason behind the poor throughput of the equipment, station or production line. Knowing the exact process could have benefitted the production line operators, engineers, supervisors as well as the managers to rethink on that particular process not the whole processes involved.

The purpose of identifying the exact process is critical to improve and enhance manufacturing efforts. For example, within a given station depending on the task distribution, station has to execute several processes. In case of CT related issues, not every process is the reason for poor line performance. So, identifying the specific process becomes vital for the manufacturer to better understand the definite cause and develop a solution to minimize the cause of increased CT. Company X where the case study is performed comprises of sequential assembly lines consisting of various operating stations. Maintaining takt time for sequential assembly lines are crucial for the manufacturers because a delay at any station can stop the whole assembly line leading to reduced productivity and effecting the overall production performance. So it is important to maintain with the takt time assigned to the production process. As a result it becomes increasingly important to specifically mention the exact process causing the CT delays.

III. Case Study

The time-study data analysis presented in this case study is conducted on the data obtained from the company X final assembly line. To scrutinise the cause of poor production line CTs, step by step drill down is performed to specify the precise origin of the cause, i.e., the sub-process within the process. Based on the findings of time-study data, a number of solutions are suggested that can enhance the production performance. In this section, background of the company X, its product process flow and the problem faced by their existing production line is discussed.

A. Company background

The evolution of automotive products towards electrification and autonomy combined with data analytics is driving the development of innovative car components. Seats is one of the most complex components in a car that must integrate complex electronics systems to create safer, more connected and adaptable products built from advanced lightweight and sustainable materials. Company X UK is leading the smart manufacturing initiative for company X globally, which deals with car seat manufacturing. Company X's manufacturing UK employs 200 staff and 2000 workers across three UK plants. It manufactures seats for various cars brands, with its major customer being Jaguar Land Rover (JLR). In company X, every component that is required to manufacture a seat is pre-assembled in sub-assembly lines and final seat is primed in assembly lines within their manufacturing plants. Figure 1, is a block diagram representation of an assembly line with a list of key inputs and output. The inputs to the assembly line are fetched from the sub-assembly lines; and inputs to this sub-assembly lines are the raw materials based on the seat requirements.

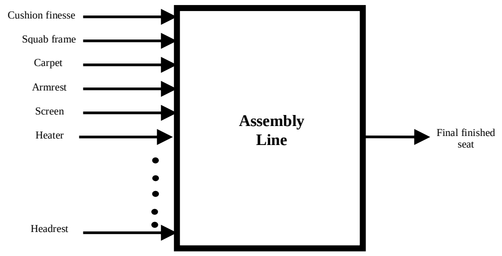


Fig. 1. Snapshot of a assembly line with list of inputs and output

B. Product Process Flow

To produce a seat in this company it has to go through a final assembly line, which consist of thirteen stations excluding those stations which are dedicated for test and inspection operations and further rework. Each station involves human for process undertaking; machines for material handling; conveyors for continuous movement of production operations and buffers to link stations. This assembly line is typically an intermittent line that does not produce identical products due to highly customised and huge variety of seat options. Intermittent assembly lines are primarily know for facilitating quick assembly of comparable parts while leaving the room for customization. Every station in this assembly line has different process to undertake based on the customers requirement.

Due to high complexity involved in manufacturing, the operations carried out at the stations are mostly manual and varies with every seat based on its specifications. Various operations that takes place at different stations are mentioned in table I. Every seat that is manufactured includes various seat features, such as: model number, drive type, model year, country name, carpet type, rear frame type, heater type, articulation type, screen type, speakers type, armrest type, lumbar type, headrest type and foot-well lamp type. In addition, customers can also select the colour of the seat features. Figure 2 represents the layout of the company X, where '*A*' denotes subassemblies, '*B*' denotes final assembly line, '*C*' denotes test and inspection line and '*D*' denotes rework line.

It is necessary to inspect the reasons behind the reduced productivity of seats. As a result, to understand and investigate the bottlenecks and constraints within the final assembly line, time-study data exploration is conducted.

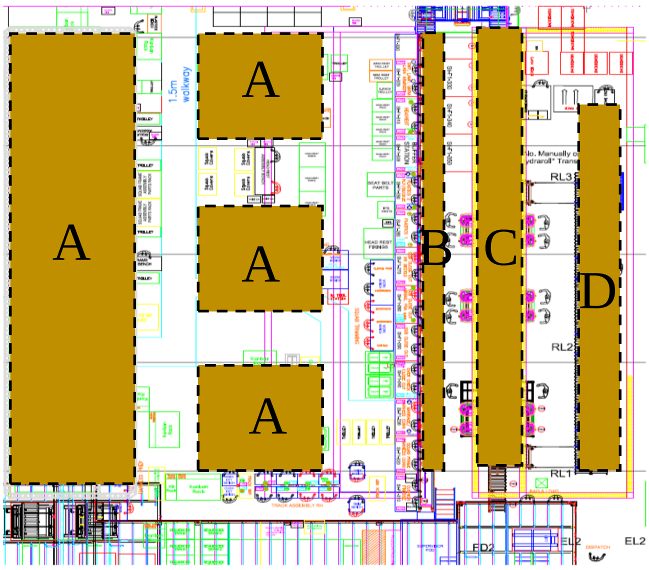


Fig. 2. Company X manufacturing plant layout

TABLE I. Operations carried out at various stations in the final assembly line

Station	Process
1	placing and handling cushion finesse
2	setting up squab frame with cushion finesse
3	fixing marriage bolts on the cushion finesse
4	fixing marriage bolts on the squab trim
5	installing heaters and its connections
6	placing airbags and its components
7	completing the airbag installation
8	mounting the valance fit with its required components
9	completing the valance fixings
10	buffer station
11	fixing headrest, backboard and other necessary components
12	installing switch-pack and foot-well lamp
13	buffer station

C. Problems with the existing assembly line

The major problems faced by this company in the final assembly line are abrupt increase in the station CTs leading to reduced standard Job Per Hour (JPH); reduced productivity; increased blocked and starved time for various stations and poor Overall Equipment Effectiveness (OEE). The JPH for the line at full capacity is set at 98 seats but due to increased CTs, the JPH is reduced to 96 seats. To understand the root causes of reduced JPH, this study aims to analyse CT of the manufacturing processes of all stations.

The required CT data is recorded from the final assembly line starting from 1st July 2018 up to 30th July 2018. The production window (shift hours) is set to 8 hours per day excluding the operators break times. The data collected from the line contains several parameters, for example: average CT of each station, Unique Seat Identifier Number (USIN), seat option, Standard Jobs Per Day (SJPD) and number of Seats In Rework (SIR). A sample of the dataset is shown in table II.

CT data related to station 10 and 13 is not populated because these are buffer stations. Buffer stations are installed to stabilize any fluctuations arising during normal working of assembly line, so data related to buffer stations are not accounted for further data exploration. The takt time of 98.5 seconds is set throughout the production process, implicating that every station should complete its operations within the set takt time. The highlighted red values in table II signposts the stations whose average CT is over the takt time. Station 7 is seen with 4 highlighted values in table II indicating the main reason behind the whole assembly line delays during that production period.

TABLE II. ASSEMBLY LINE MANUFACTURING SAMPLE DATA FOR JULY 2018

Date	Station average CT per day (seconds)											SJPD	SIR
	1	2	3	4	5	6	7	8	9	11	12		
1/10	54.8	86.1	85	91.2	86.2	88	99	91	87.2	82.6	85.5	767	31
2/10	63.6	85.5	85	89.8	91.3	78	91	78.3	86.2	87.3	78	781	04
3/10	87.7	95.3	91	92.3	85.2	84	86	85.2	81.1	74.7	84.4	782	04
4/10	85.6	88	91	91.2	85.5	85	78	85.3	86.1	71.3	74.6	781	05
5/10	59.4	89.1	86	78.2	75.6	78	105	78.9	84.5	89.6	85.8	783	28
6/10	78.7	91.3	82	85.6	74.1	74	105	85.1	85	85.8	76.1	785	08
7/10	78.6	86.5	75	75.6	73.2	86	89	91.5	90.6	86.7	84.6	773	17
8/10	99.3	76.5	83	90.2	78.5	89	86	78.2	90.6	74.8	75.1	771	11
9/10	85.2	86.8	91	79.6	86.8	90	111	87.8	91.2	93.3	91.5	779	13
10/10	88.4	90.2	74	86.1	84.5	91	91	84.5	89.2	91.5	87.1	781	10

In the recorded data timeframe, the assembly line produced 2 seat models (model A and model B) with 3 sub-types/variants (sub-type 1, sub-type 2 and sub-type 3) based on customer specifications. The rate of seat production is setup at 785 seats per day (SJPD-785) with no more than 5 seats in rework (per day). The number of operators required for the whole assembly line is 26 for the final assembly line. Two operators are required per station, each operator dealing with different type of seat, namely, right hand seat and left hand seat. The total number of seats that are manufactured during the given time period is 18850 against set target of 19080 seats; which means that the assembly line is running short of 230 seats during that month.

IV. METHODOLOGY

Once the order is received, according to build to sequence operators starts gathering the required raw material needed to fulfil the order from their warehouse. The raw material then gets pre-assembled in the sub-assembly lines. The pre-assembled parts are fed as inputs to final assembly line (typically in boxes alongside the final assembly line) where the seat gets its complete shape. To investigate the root cause of the increased production takt time, the following methodology (figure 3) is employed. Implementation of the solution is not in the scope of this paper and is considered as the future work.

A. *Data pre-processing*

The raw historical production data from the final assembly line contained numerous parameters including CT data from all the stations, SJPH, SIR, RR and USID. The parameters which are not needed for further data processing are filtered and only CT data of assembly stations is considered. This CT data is abundant with missing data and outliers. In the data pre-processing phase, all the missing data is filtered out, next outlier-detection and replacement scheme is carried out for effective data analysis [22]. This scheme replaces those data points which deviates drastically from the given norm or average value, and subsequently interchanges it with normal data points. Average CT of all the stations at 01/10/2018 instant is shown in table III and during that instant it is noticed that station 7 CT is 99.6 seconds (higher than the set production takt time).

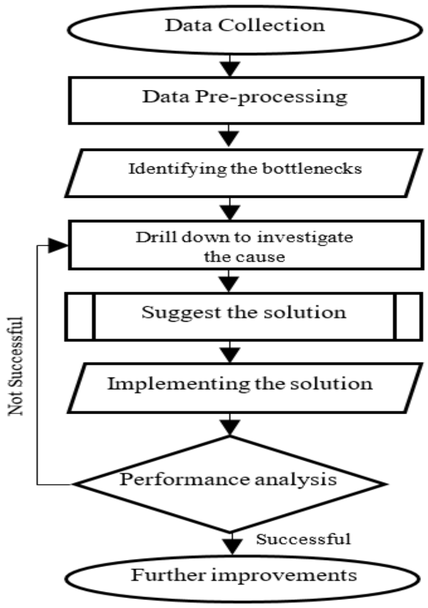


Fig. 3. Methodology implemented in the current assembly line

Figure 4 (a) represents a snapshot of the raw data that is captured from the production line which consists of various missing data redundancies. Figure 4 (b) presents the snapshot of the data after filtering out redundant data using outlier-detection and replacement schemes.

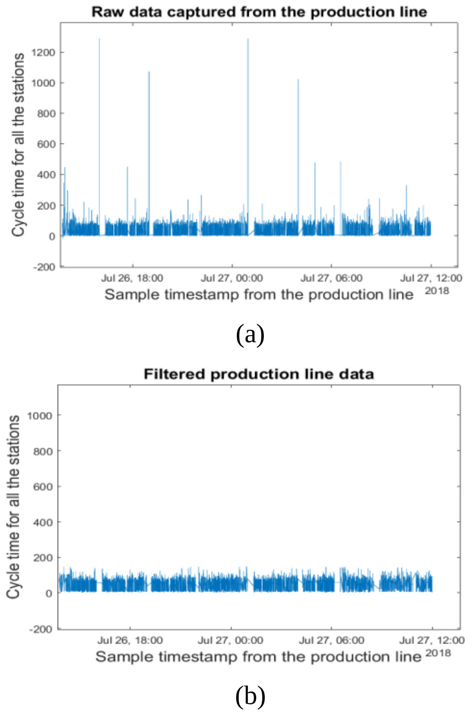


Fig. 4. (a) Snapshot of the raw data captured from the production line. (b) Snapshot of the filtered production line data

University of Warwick

B. Identify the bottlenecks and drill down to investigate the cause

In order to understand the cause of decreased productivity and to target the bottleneck stations, it is important to monitor the performance of these stations individually over a given period of time. Box and whisker plots is used to show the summary of the data distribution, its variability and its central value. These plots are the quickest way to show whether the dataset is symmetric or skewed.

From figure 5, it is evident that station 7 is the root cause for the overall decreased production line performance. The average CT of station 7 during the whole time period of data collection is 99.6 seconds against the set production takt time of 95.5 seconds. Apart from station 7, rest of the stations performed consistently within the takt time assigned to the production line. Next, the 3 evident outliers seen across station 5 is carefully investigated. From the investigation it is realized that operators at the station 5 failed to stop the process recording during the break times. Hence, these outliers are treated as bad data points because they are caused due to human errors and unlikely to appear under normal circumstances. Note that these outliers are eliminated from the further data processing.

Few other inference that is be derived from figure 5 is: station 1 average CT is 57.8 seconds and station 3 average CT is 52.3 seconds which is nearly half of the assembly takt time. This huge CT difference pointed towards exploring the uneven task distribution within the stations. Table III gives an insight into average day CT of every station for 1/10/2018, showing that the task distribution over different stations is non-uniform. For instance, average CT for station 1 is 54.8 seconds followed by station 3 and station 6 with 65.2 seconds and 61.9 seconds, meaning these station had the longest waiting time when compared to all other stations.

Next step is to drill down station 7 to discover which seat model and its variants are the sources of the increased CT. By further time study data analysis, it is obvious that model B with an average CT of 101.67 seconds (4.67 seconds more than the set production takt time) is the reason behind the increased CT (as shown in figure 6 (a)). Whereas, model A with average CT of about 67.32 seconds didn't contribute to any production delays. Now it is apparent that model B in station 7 is the main reason behind increased CT.

In final step, station 7 model B is further investigated to examine which sub-process (sub-type) is responsible for the delays. Figure 6 (b), represents the different model B sub-type processes carried out at station 7. Sub-type 1 process with average CT of about 165.33 seconds is the reason behind the model B to perform poorly, followed by sub-type 2 process with CT of about 99.1 seconds. Whereas, sub-type 3 process averaged CT of about 90. 3 seconds which is the under the production takt time.

TABLE III. AVERAGE STATION CT (SEC) FOR A DAY (01/07/2018)

Station	1	2	3	4	5	6	7	8	9	11	12
Average CT	54.8	86.1	65.2	91.2	86.2	61.9	99.6	90.1	87.2	82.6	85.5

C. Suggest solutions

Sub-type 1, model B at station 7 is the bottleneck in the studied assembly line. It is due to this station that the SJPD, productivity and performance of the overall production line is effected. Based on intensive research on how to reduce CT and the results from data analysis, the author suggests few solutions which can help to improve the current state of the production line. Installing buffer stations well-thought-out the line and considering a change from traditional sequential conveyor line to parallel conveyor line can help the manufacturer to reduce the operations delays. But this change can be costly and will require additional resources for its normal working.

Line balancing is suggested as the best fit solution for the given problem because from the table II it is witnessed that there is a huge unbalanced task distribution between various stations. Rethinking about the current state of tasks distribution between the stations and splitting most frequent interrupted processes can help to reduce the waiting time, blocked time and starved time; thereby increasing the line throughput. By exploring the processes carried out by all the stations in the assembly line, several processes were shifted within the stations for better line balancing. Particularly, the processes undertaken at the station 7 (bottleneck station) of the assembly line is shifted to other stations and few were split within the station itself.

Furthermore, table IV shows the variations in the actual time taken to complete various operations at station 7 with the theoretical time. By comparing theoretical time with the actual time of the processes carried out at station 7 it is obvious that the Company X current assembly line needs line optimization apart from line balancing. If this bottleneck could have been identified at an early stage, it would have significantly enhanced the overall performance of the production line.

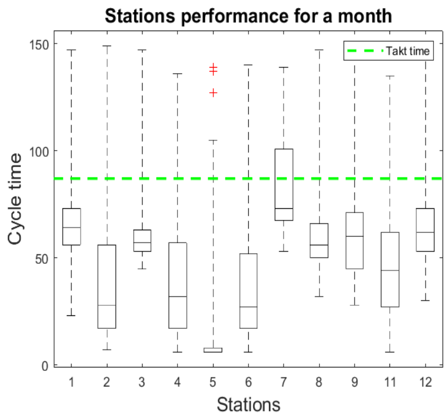
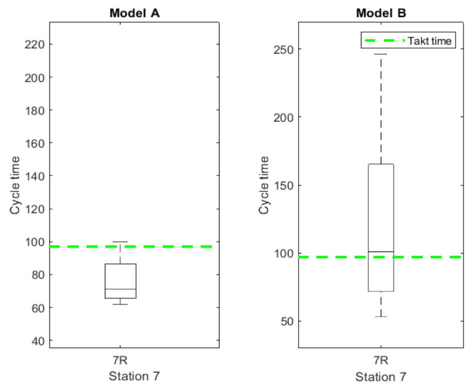
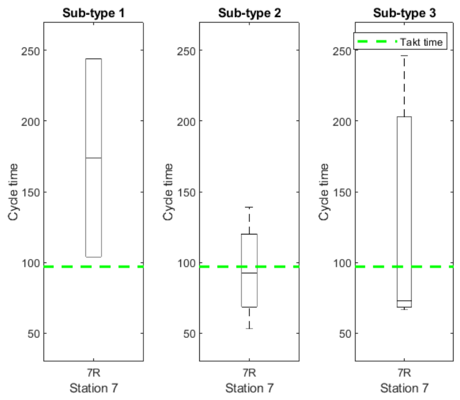


Fig. 5. Box and whiskers plot for stations CT over a given period



(a)



(b)

Fig. 6. (a) Box and whisker plot for station 7 model A and model B. (b) Box and whisker plot for station 7 model B with sub-type1,2 and 3

TABLE IV. AVERAGE PROCESS CT FOR STATION 7 (ACTUAL VS THEORETICAL)

Station 7	Actual time (sec)	Theoretical time (sec)
Main operation		
Completing the airbag installation	103.6	90.5
Type		
Model A	67.5	90.5
Model B	101.3	90.5
Sub-type		
Sub-type 1	165.5	90.5
Sub-type 2	99.6	90.5
Sub-type 3	90.2	90.5

V. CONCLUSION

The study aims to spot the bottlenecks and enhance the production rate of company X seat manufacturing assembly line using time-study data analysis. By performing the time-study data analysis, it is seen that station 7 CT exceeds the takt time. With further drilling down, it is evident that model B with CT of 101.67 seconds and in particular sub-type 1 with CT of 165.33 seconds is the main cause of the delayed production. It is due to sub-type 1, model B at station 7; the company X is able to produce only 18850 seats against set target of 19080 seats that month. Therefore, knowing the root causes behind the decreased production, the author suggests line re-balancing, line optimization and splitting the bottleneck process into sub-process in order to maintain standard takt time and enhance manufacturing process, as the best solution to the tackle CT problem.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support for this work from University of Warwick through the Chancellors international scholarship.

REFERENCES

[1] C. Damasio, F. J. G. Silva, R. M. Gouveia, P. Teresa, and L. P. Ferreira, “Improving manual assembly lines devoted to complex electronic devices by applying Lean tools,” in *28th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2018), June 11-14, 2018, Columbus, OH, USA (FAIM2018), June 11-14, 2018, Columbus, OH, USA*, 2018, vol. 01, pp. 663–671.

[2] J. Vázquez-Herrero and X. López-García, *Recent Advances in Information Systems and Technologies*, vol. 3. 2017.

[3] K. Mustafa and K. Cheng, “Improving Production Changeovers and the Optimization: A Simulation Based Virtual Process Approach and Its Application Perspectives,” in *Procedia Manufacturing*, 2017, vol. 11, pp. 2042–2050.

[4] R. Godina, C. Pimentel, F. J. G. Silva, and J. C. O. Matias, “Improvement of the Statistical Process Control Certainty in an Automotive Manufacturing Unit,” in *Procedia Manufacturing*, 2018, vol. 17, pp. 729–736.

[5] L. Sriratana, “Efficiency improvement of door frame manufacturing process in wood product manufacturing industry,” in *5th International Conference on Industrial Engineering and Applications, ICIEA 2018*, 2018, pp. 189–193.

[6] K. Alvarez, D. Aldas, and J. Reyes, “Towards Lean Manufacturing from Theory of Constraints: A Case Study in Footwear Industry,” in *2017 International Conference on Industrial Engineering, Management Science and Application, ICIMSA 2017*, 2017.

[7] A. R. Rahani and M. Al-Ashraf, “Production flow analysis through Value Stream Mapping: A lean manufacturing process case study,” in *International Symposium on Robotics and Intelligent Sensors 2012 (IRIS 2012)*, 2012, vol. 41, pp. 1727–1734.

[8] K. Venkataraman, B. V. Ramnath, V. M. Kumar, and C. Elanchezhian, “Application of Value Stream Mapping for Reduction of Cycle Time in a Machining Process,” in *3rd International Conference on Materials Processing and Characterisation (ICMPC 2014)*, 2014, vol. 6, pp. 1187–1196.

[9] M. S. Kim and B. Sarkar, “Multi-stage cleaner production process with quality improvement and lead time dependent ordering cost,” *J. Clean. Prod.*, vol. 144, pp. 572–590, 2017.

[10] S. Nallusamy and G. Majumdar, “Enhancement of overall equipment effectiveness using total productive maintenance in a manufacturing industry,” *Int. J. Performability Eng.*, vol. 13, no. 2, pp. 1–16, 2017.

[11] T. Sada, R. A. Yuen, M. Ichikawa, M. Yamada, and K. Kabata, “Simple tool of analysis for cycle time reduction,” *IEEE Int. Symp. Semicond. Manuf. Conf. Proc.*, pp. 79–82, 2001.

[12] B. Silva, F. Hansjorg, and G. Ottmar, “Statistical Analysis of Cycle Times in a Complex Microelectronics Manufacturing Line,” in *IEEE/ISHM 1992 IEMT Symposium-Germany*, 1992, pp. 18–25.

[13] Y. Lee and C.-C. Hsiao, “Cross Area Lot Arrangement – Shortest Inter Cycle Time,” in *ISSM Paper: MC-O-048*, 2007, pp. 1–3.

[14] C. J. Kuo, C. F. Chien, and J. D. Chen, “Manufacturing intelligence to exploit the value of production and tool data to reduce cycle time,” *IEEE Trans. Autom. Sci. Eng.*, vol. 8, no. 1, pp. 103–111, 2011.

[15] T. Ruppert and J. Abonyi, “Industrial internet of things based cycle time control of assembly lines,” in *IEEE International Conference on Future IoT Technologies, Future IoT 2018*, 2018, pp. 1–4.

[16] D. Fronckowiak, A. Peikert, and K. Nishinohara, “Using Discrete Event Simulation to Analyze the Impact of Job Priorities on Cycle Time in Semiconductor Manufacturing,” in *1996 IEEE/SEMI Advanced Semiconductor Manufacturing Conference*, 1996, pp. 151–155.

[17] D. Lingam, S. Ganesh, and K. Ganesh, “Cycle Time Reduction for T-Shirt Manufacturing in a Textile Industry using Lean Tools,” in *IEEE Sponsored 2nd International Conference on Innovations in Information, Embedded and Communication systems*, 2015, pp. 2–7.

[18] D. Seth and S. Rastogi, “Application of vendor rationalization strategy for manufacturing cycle time reduction in engineer to order (ETO) environment,” *J. Manuf. Technol. Manag.*, vol. 1, pp. 1–31, 2018.

[19] W. F. S. Araújo, F. J. G. Silva, R. D. S. G. Campilho, and J. A. Matos, “Manufacturing cushions and suspension mats for vehicle seats: a novel cell concept,” *Int. J. Adv. Manuf. Technol.*, vol. 90, no. 5–8, pp. 1539–1545, 2017.

[20] A. M. Madni, B. Boehm, R. G. Ghanem, and D. Erwin, *Disciplinary Convergence in Systems Engineering Research*. 2018.

[21] A. S. V. Raj, J. Mathew, P. Jose, and G. Sivan, “Optimization of Cycle Time in an Assembly Line Balancing Problem,” in *Global Colloquium in Recent Advancement and Effectual Researches in Engineering, Science and Technology (RAEREST 2016)-Procedia Technology*, 2016, vol. 25, no. 1, pp. 1146–1153.

[22] Y. Wang, L. A. Kung, and T. A. Byrd, “Big data analytics: Understanding its capabilities and potential benefits for healthcare organizations,” *Technol. Forecast. Soc. Change*, vol. 126, pp. 3–13, 2018.