Gradus Vol 3, No 2 (2016) 30-41
ISSN 2064-8014

SIMULATION MODEL FOR IMPROVING PRODUCTION FLOW LINES

Z. Mihály [1], *Z. Lelkes* [2*]

[1] Optasoft Kft., Budapest, Hungary
[2] Department of Information Technology, Faculty of Mechanical Engineering and Automation, Pallasz Athéné University, Kecskemét, Hungary

Keywords:
Factory physics
Throughput
Cycle time
Flow line
Discrete time simulation

Article history:
Received 10 Sept 2016
Revised 22 Okt 2016
Accepted 23 Okt 2016

Abstract

A simulation model for improving production flow lines with multiple products and parallel machines is presented. Superstructure is defined as a graphical representation of production flow line; simulation tool and model are developed. The simulation tool can be used for improving production flow lines.

1 Introduction

Companies make great efforts to diminish their ecological footprint, which is highly connected to supply chains. Thus, researches on environmentally business practices receive more and more attention [14]. One of the main interests is the improvement of production systems, like production of cars, pharmaceutical ingredients or electrical goods.

Discrete manufacturing systems can be classified by several disciplines. Following Govil and Fu [4], the manufacturing systems are: job shops, **flow lines**, flexible manufacturing systems, and assembly systems.

Superstructure is developed for production flow lines. The superstructure consists of all possible solutions and have been widely used for model development, e.g., for modelling and optimizing an ethanol dehydration system [9], or solving mass exchange synthesis problems [16].

The research of manufacturing systems uses divers modelling techniques, e.g., simulation models [15], queueing theory and Petri nets [11]. Some examples from the literature contain investigations into flow line with common buffer [19], complex optimization problems where the flow line is only one element in the model [10] or more complicated systems. Huang and Li examined a two-stage hybrid flow shop with multiple product families [7]. Simulation modelling has a wide range of applications in engineering-aided manufacturing regarding system performance. Modelling apparel assembly cells [1], a Mercedes-Benz production facility [12], or analyzing the performance of a Korean motor factory [2] are only some of the examples.

Hopp and Spearman [6] have introduced the concept of factory physics consisting of useful theories and applications. They investigated flow lines in which there is only one machine per station, one job class, no capacity constraint and which have FIFO (first in, first out) service discipline.

---

[*] Corresponding author
E-mail address: lelkes.zoltan@gamf.kefo.hu

Three main modelling measures are proposed by them:

- Throughput (TH): the number of entities (cars, apples, people, etc...) coming out from the system during a given time
- Cycle time (CT): the average time an entity spends in the system
- Work-in-process (WIP): the number of entities residing in the system at the same time

The higher TH and lower CT the system has, the better the performance will be. These parameters are not independent from each other; Little's law makes connection among them:

$$WIP = TH \times CT \tag{1}$$

According to (1), the optimal value of WIP in a deterministic system is

$$W_0 = T_0 \times r_b \tag{2}$$

where

- Bottleneck rate (r_b): the rate of the station that has the highest utilization
- Raw process time (T_0): the sum of the average process times of every station in the flow line
- W_0 is called the critical WIP level (Hopp and Spearman).

The variability of procedures is measured by the coefficient of variation (CV):

$$CV = \frac{standard\ deviation}{mean} \tag{3}$$

Hopp and Spearman use two so called characteristic functions to analyze the performance. The dependent variables are the TH and the CT, while the independent variable is the WIP level both times. The flow line is modelled as a closed network. It means that the level of WIP is a model parameter [17].

Regarding performance analysis, three important concepts were introduced [6]:

- Best case performance: the best possible performance for a line. It is balanced, and there is no batching.
- Worst case performance: the worst possible performance for a line. All the entities move in one batch.
- Practical worst case (PWC): As the worst case performance is so bad that it is far from practical instances, PWC was introduced to define a realistic worst case. Among these three characteristic cases, PWC is the only one depending on variability, the others are deterministic.

Simulation model for production flow lines is presented. The simulation model is developed for flow improvement. First, the superstructure of production flow line with multiple products and parallel machines is showed. It is followed by the algebraic model. The simulation software is developed on AIMMS modelling language. Last physical experiment of production line is analyzed by the developed model using the same characteristics that are used to evaluate the performance in [5] and [6]. The models use CONWIP (constant work-in-process) control technique, that is to say the WIP level is a constant parameter. Beside Kanban, CONWIP is a widely used technique in lean manufacturing to supervise the WIP level. This control is a characteristic of pull systems and distinguishes them from push systems.

2 Method of examination

2.1 Physical model

In the physical experience, a toy car production has been realized with the assumption of infinite raw material stock at the supplier and stochastic demand (Figure 1). There are three inventories: the inventory of the supplier, the raw materials inventory, and the finished goods inventory

During the transportation, the raw materials need to wait one minute at each transportation unit. More than one of them cannot be transported simultaneously. There are four single machine processes where operations are realized in order to produce the car. The demand is stochastic. There are several roles in the model: 1 customer, 1 production manager, 1 purchaser, 1 supplier, and 4 operators.

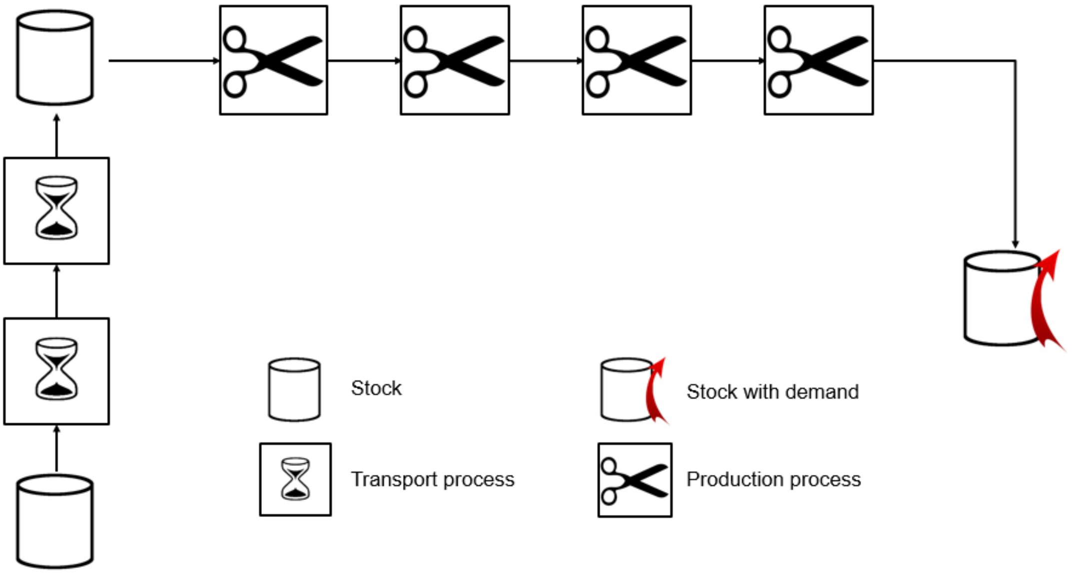


Figure 1. The physical model of experiment

The entire process to produce a toy car takes 4 minutes not taking into account the transport, which needs 2 minutes. The production manager decides about the parts of the operations and people among the four stations at the beginning of the experiment. When an order arrives, the purchaser writes the bill of materials. He gives it to the supplier, who picks the ordered raw materials, and sends it to the production line. The transport takes time, which is modelled with hour glasses. After the purchaser transports the raw material at the beginning of the line, the production of the given car can be started. The production is realized in the stations and the flow is controlled by FIFO. At the end, the customer checks the product's quality. If he finds it right, then the order is fulfilled. If not, then corrections are needed. The flow chart of the discussed process is shown on Figure 2.

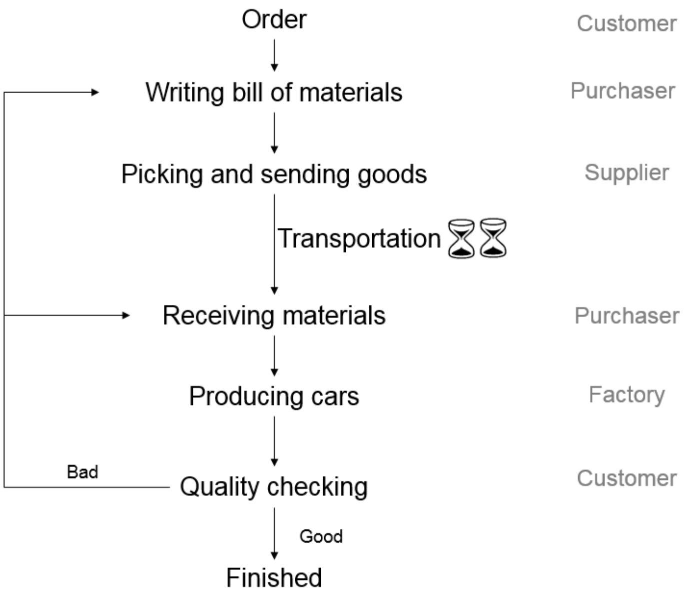


Figure 2. Flow chart of fulfilling an order

2.2 Simulation model

Superstructure

A superstructure is developed for production line with multiple products and processes. The flow line contains buffers (B_i) with infinite capacities. The stations (P_i) have machine groups $\left(P_i^j\right)$ with multiple machines. These machine groups can have different process time distributions$\left(\chi_i^j\right)$. The distribution can be exponential, normal, log-normal or deterministic. In the case of normal distribution, if the stochastic variable takes a negative value then the process time will be zero since it can only be nonnegative. More than one product can be modelled, which can have different process time distribution parameters at machines; χ_i^j is calculated from them. Figure 3 shows the superstructure.

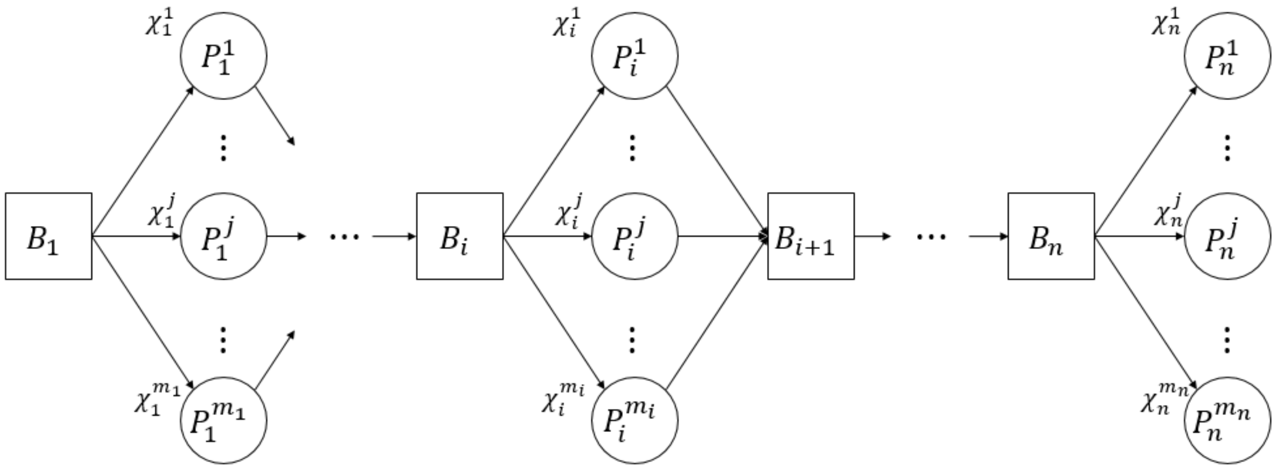


Figure 3. The superstructure of the flow line

Model

The main parameters in the developed model are:

- Ord_i: the ordinal number of the i-th process

- $Proc_j$: the j-th machine group belongs to this process type
- M_j: the number of machines at the j-th machine group
- $Dist_j$: the process time distribution type of the j-th machine group
- w_k: the weight factor of the k-th product
- $Mean_j^k$: the process time mean of the k-th product at the j-th machine group
- Var_j^k: the process time variance of the k-th product at the j-th machine group
- w: the WIP level

The calculated variables are:

- $Time_e$: the time of the e-th event
- MG_e: the e-th event regards this machine group
- SFP_e: the e-th event regards this semi-finished product
- $IsDone_e$: shows if the e-th event is done
- CT_w: the mean cycle team when the WIP level equals to w
- TH_w: the mean throughput when the WIP level equals to w
- $Mean_j$: the process time mean of the j-th machine group
- Var_j: the process time variance of the j-th machine group
- O_j: the number of occupied machines at the j-th machine grouping
- L_j: the length of the waiting line of the j-th machine
- IT_s: the input time of the s-th semi-finished product
- OT_s: the output time of the s-th semi-finished product
- $IsFinished_s$: shows if the s-th semi-finished product is finished
- $WaitingO_s$: the ordinal number of the s-th semi-finished product in the waiting line
- $StartUp_s$: indicates if the s-th semi-finished product is manufactured during the start-up period
- MG_s: the machine group in which the s-th semi-finished product resides
- $Time$: the actual time on the simulation clock
- $MaxErr$: the maximal permitted value of the relative error
- CT_{act}: the actual CT estimation
- CT_{prev}: the CT estimation when the previous semi-finished product was finished
- TH_{act}: the actual TH estimation
- TH_{prev}: the TH estimation when the previous semi-finished product was finished

The main functions and constraints are:

- $Mean_j = \sum_k \left(w_k \times Mean_j^k\right) \quad \forall j$ (4)
- $Var_j = \sum_k \left(w_k \times Var_j^k\right) \quad \forall j$ (5)
- $O_j \leq M_j \quad \forall j$ (6)
- $\sum_k w_k = 1$ (7)
- $IT_s \leq OT_s \quad \forall s$ (8)
- $\sum_s (1 - IsFinished_s) = w$ (9)
- $\frac{|TH_{act} - TH_{prev}|}{TH_{prev}} \leq MaxErr \land \frac{|CT_{act} - CT_{prev}|}{CT_{prev}} \leq MaxErr \Rightarrow The\ simulation\ can\ be\ finished$ (10)
- $Time_e = Time + observed\ process\ time \quad \forall e$ (11)

<u>Algorithm</u>

The simulation model is a discrete time simulation program with next-event time advance mechanism. Comparing with fixed-increment time advance method, it is more complicated, but more efficient regarding computational effort [18]. Figure 4 shows the mechanics of next-event time advance simulation method.

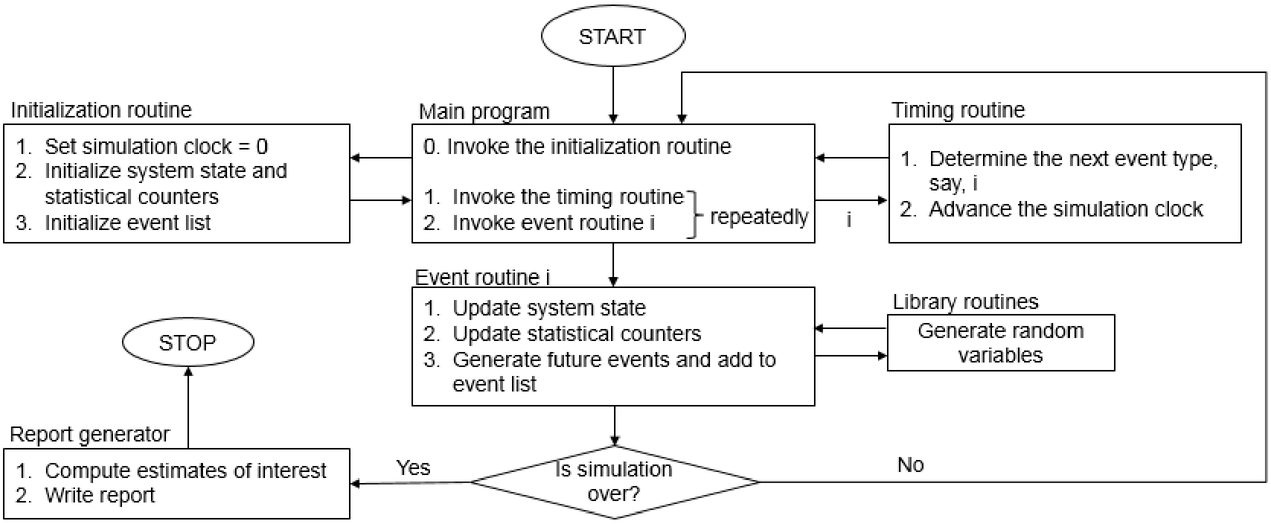


Figure 4. Flow chart of next-event time advance simulation method [8]

After starting the simulation, the main program invokes the initialization routine. It sets the simulation clock to 0, initialize the system state, the statistical counters and the event list. Afterwards, the main program gets back the control, and calls the timing routine. It determines the next event, its type, and advances the simulation clock to the time of this event. Its type is given back to the main program, which invokes the appropriate event routine. It updates the system state, the statistical counters, and generates future events, which will be added to the event list. During these tasks, it might be needed to generate random observations from probability distributions, which is done by several library routines. After every event, it is checked if the simulation can be terminated. If yes then the report generator is invoked from the main program. It computes the estimates of interest, writes report, and the program finishes the calculation after that. If not, then the main program gets back the control, and calls the timing routine. The service discipline is FIFO at all station. The entity always goes to a free machine with the shortest expected process time.

The simulation program is implemented in AIMMS modelling language [13]. It has already been used in other studies with success. E.g., [3] used it on supply chain optimization with homogenous product transport constraints. The simulation program can be easily extended in this environment. AIMMS is linked to the most modern solvers, which can be easily integrated. Furthermore, it has an advanced graphical user interface, which can be used for simplifying analysis.

The program carries out simulation series in a given WIP interval in order to determine the characteristic functions. There is one entity in the first process, and WIP – 1 before that in the initial system state. (WIP is the actual value of the model parameter.) Two condition have to be met in order to terminate the simulation. The first one is to reach the end of the start-up period. After that, the system comes to its normal operating point; it is filled up fully with entities. The second condition is that the relative error of TH and CT should be lower than the limit of tolerance. If the level of tolerance was too low then the calculations would take too much time. However, if it was too high, the results would be too noisy or unusable.

3 Computational results

The simulation tool is used to investigate the deteriorating effect of variability in 3.1. The deterministic and the stochastic version of the same system is compared to each other there. The result of experiment (physical model) is presented in 3.2. The line is evaluated regarding possibilities to improve it.

3.1 The deteriorating effect of variability

If there is no variability the TH and the CT is calculated in the best case as follows:

$$TH = min\left(\frac{w}{T_0}, r_b\right) \quad (12)$$

$$CT = max\left(T_0, \frac{w}{r_b}\right) \quad (13)$$

Where w denotes the WIP level [5]. However, the characteristic functions of the system changes if variance appears. The deterministic and the stochastic version of the same system are compared on Figure 5. The results of the latter case were gathered with the simulation tool. At CV = 0.6, the maximal decrease and the maximal increase of CT occurred at the critical WIP level. The TH is decreased by 31%, while the maximal increase of CT is 44% on W_0 compared to the deterministic case.

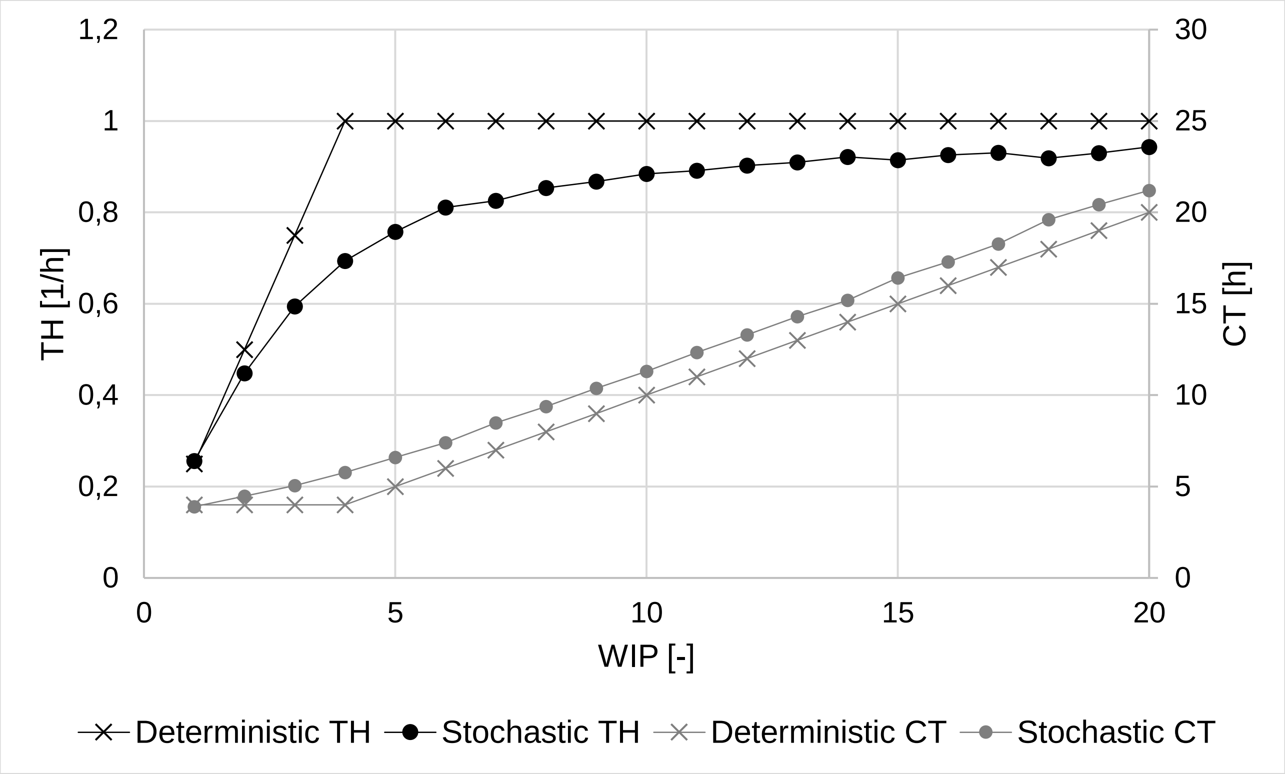


Figure 5. The deteriorating effect of variability on systems with CV=0.6

3.2 Improving flow lines

The simulation tool is used for improving the realistic production flow line used in the physical experiment. The system contains five processes: transportation (including 2 levels) and 4 production steps. The data of the processes is shown on Table 1 (SD stands for standard deviation). As the first process has the highest mean process time, it is the bottleneck; the others are non-bottleneck processes. The performance improvement is examined using the TH and CT change on the W_0 of the physical model assuming the variance 0.

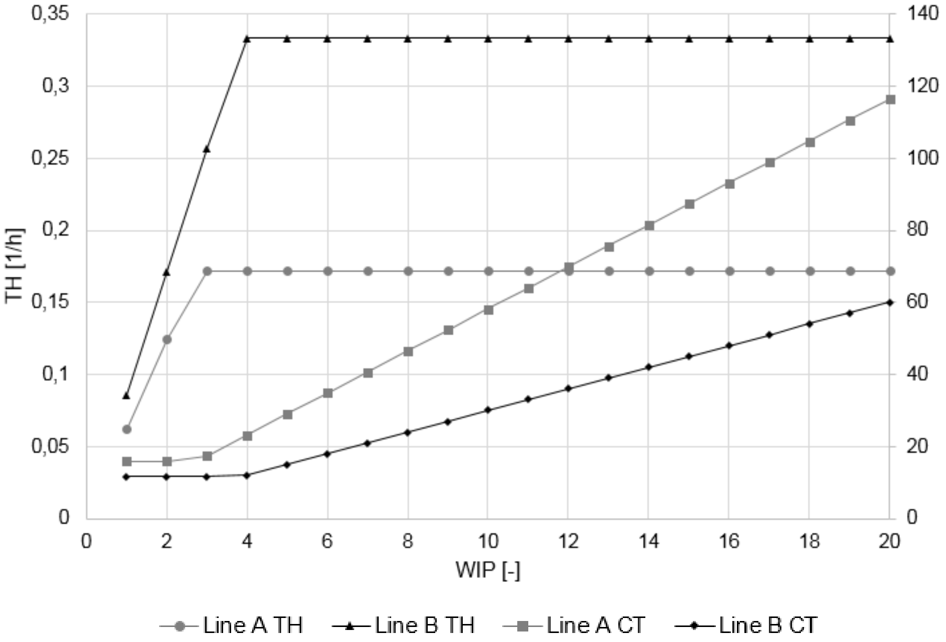
Table 1. The characteristics of the physical model

Process	*Mean [min]*	*SD [min]*	*CV [-]*

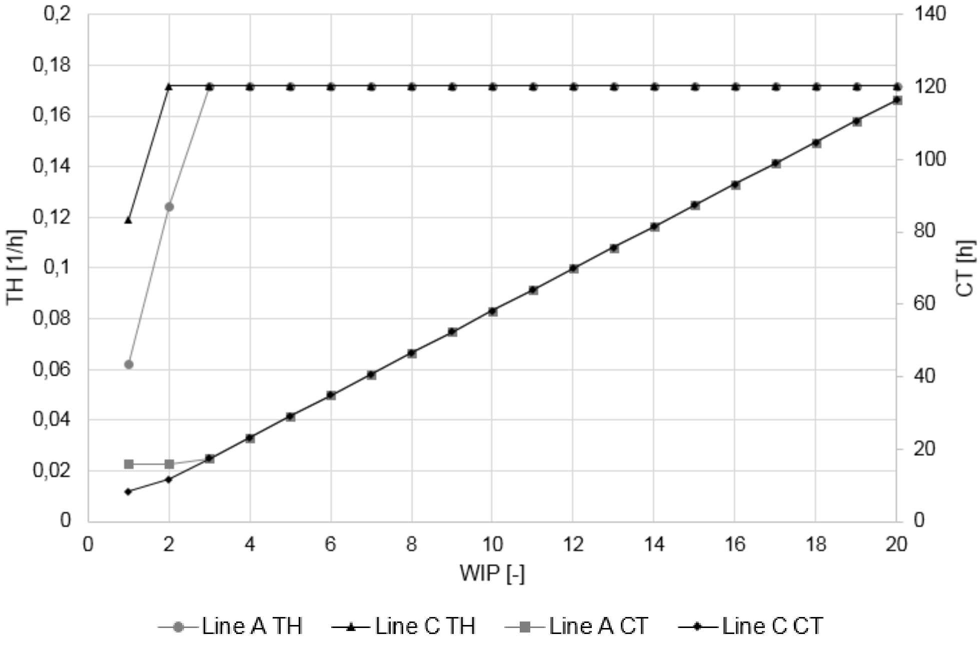
Process 1	5.82	0.49	2.86
Process 2	2.71	0.18	0.49
Process 3	2.50	0.28	0.71
Process 4	3.00	0.23	0.69
Process 5	2.00	0.23	0.46

Table 2 shows all the data regarding the development experiments. Line A is the original experiment assuming it a deterministic system. Line B and C are its improved versions. Line B has a lower bottleneck mean process time while in Line C, non-bottleneck mean process times are decreased so the speed of the chosen processes are increased. Line D is the original experiment, but as stochastic system. Line E, F, G and H are its modified variants. Line E has lower bottleneck mean process time, Line F has better non-bottleneck mean process times. In Line G, the bottleneck's production time variability is decreased while in Line H non-bottleneck processes' production time variances are diminished.

Based on equation (12) and (13) it can be seen, that production the line can be improved by increasing production speed of processes. Using these equations the effects of different developments on deterministic flow lines can be calculated as in 3.1. Improving the bottleneck's production time (see Line B) from 5.82 to 1.45 (the new speed is 4 times higher) increases TH by 50% while diminishes CT by 33% (see Figure 6/a) on the critical WIP level of Line A. Improving the non-bottleneck processes production times (see Line C), that is Process 2 from 2.71 to 0.68, Process 3 from 2.50 to 0.63, Process 4 from 3 to 0.75 and Process 5 from 2.00 to 0.50, does not change the TH and the CT on the critical WIP level of Line A (see Figure 6/b) but at lower WIP both TH and CT improved.



a) Improving Line A to Line B



b) Improving Line A to Line C

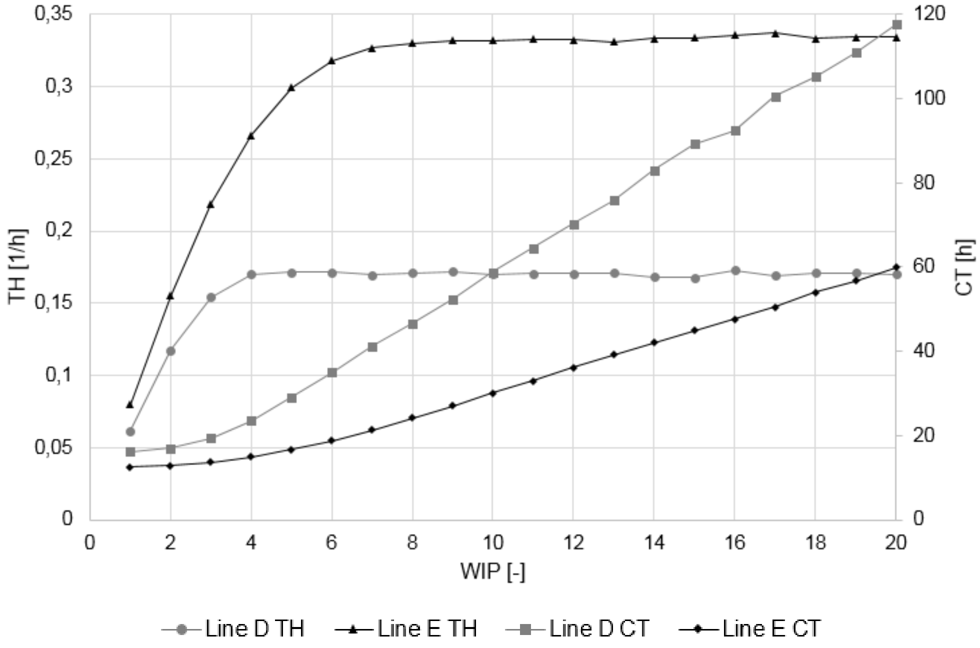
Figure 6. Improvement of the deterministic flow line

Table 2. Model parameters regarding improvement experiments

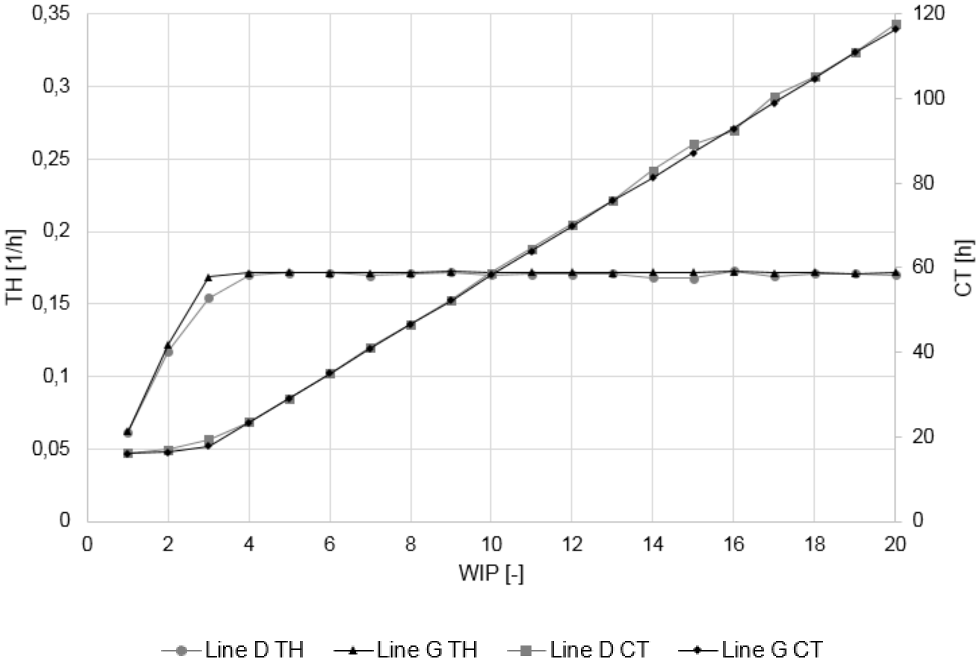
	Line A	*Line B*	*Line C*	*Line D*	*Line E*	*Line F*	*Line G*	*Line H*
Mean1	5.82	1.45	5.82	5.82	1.45	5.82	5.82	5.82
Mean2	2.71	2.71	0.68	2.71	2.71	0.68	2.71	2.71
Mean3	2.50	2.50	0.63	2.50	2.50	0.63	2.50	2.50
Mean4	3.00	3.00	0.75	3.00	3.00	0.75	3.00	3.00
Mean5	2.00	2.00	0.50	2.00	2.00	0.50	2.00	2.00
SD1	0.00	0.00	0.00	2.86	2.86	2.86	0.71	2.86
SD2	0.00	0.00	0.00	0.49	0.49	0.49	0.49	0.12
SD3	0.00	0.00	0.00	0.71	0.71	0.71	0.71	0.18
SD4	0.00	0.00	0.00	0.69	0.69	0.69	0.69	0.17
SD5	0.00	0.00	0.00	0.46	0.46	0.46	0.46	0.12

Stochastic models cannot be evaluated by those equations; the results are produced by the simulation tool. Four possibilities of development are investigated regarding the stochastic model of the physical experiment (see Line D): the bottleneck station, that is to say Process 1, can be improved with reducing either mean process time, which increases its speed, or process time variance. These two possibilities can be used for the non-bottleneck stations, too.

At first, the bottleneck is evaluated. If its mean process time is diminished from 5.82 to 1.45 (see Line E) then TH gets higher by 42% and CT lower by 30% on W_0 comparing to Line A (Figure 7/a). On the other hand, if the bottleneck's process time standard deviation is reduced from 2.86 to 0.71 (see Line G) then TH increase by 9% and CT decrease by 8% (Figure 7/b). It can be concluded that improvement of mean has a more visible effect than of variability.



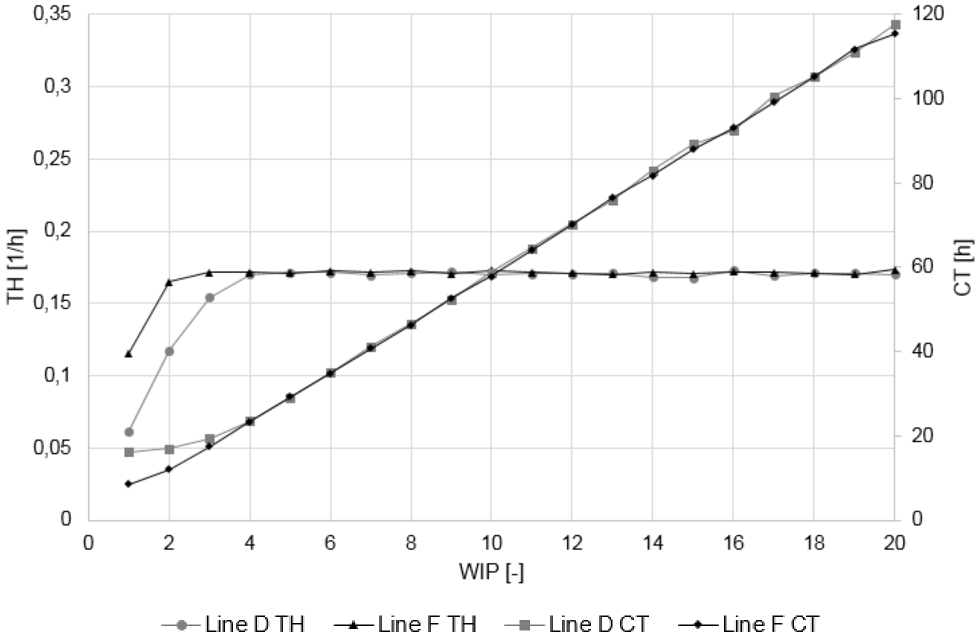
a) Improving Line D to Line E



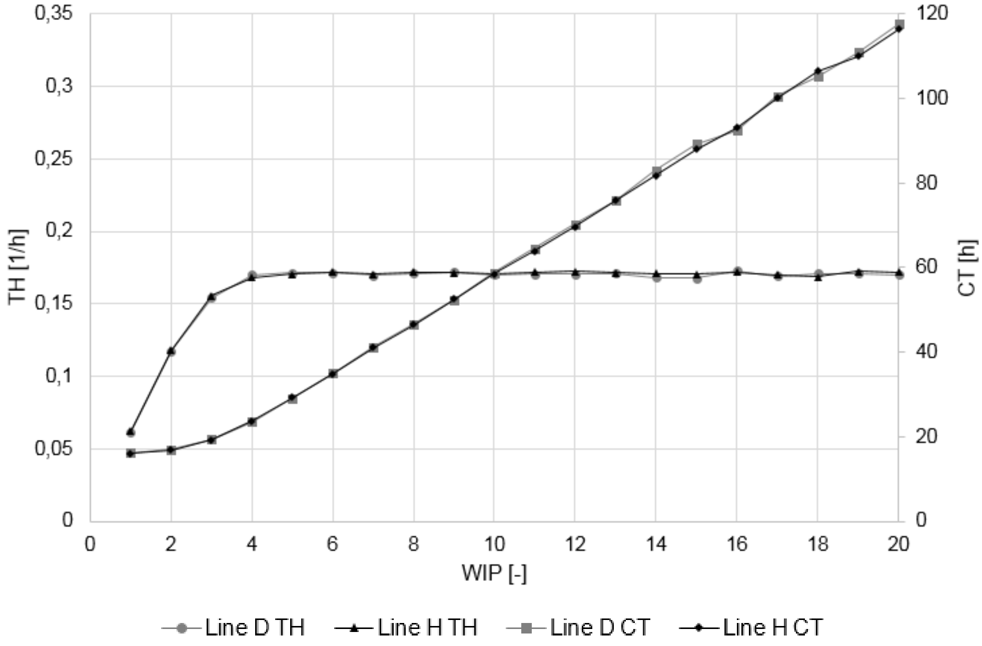
b) Improving Line D to Line G

Figure 7. Improvement of the bottleneck process

In this paragraph, the effect of improving non-bottleneck procedures is discussed. Reducing their mean process times (see Line F), from 2.71 to 0.68 for Process 2, from 2.50 to 0.63 for Process 3, from 3.00 to 0.75 for Process 4 and from 2.00 to 0.50 for Process 5, results in increasing the TH by 11% and decreasing CT by 10% (Figure 8/a). Diminishing the standard deviations of process times (see Line H), that is from 0.49 to 0.12 in Process 2, from 0.71 to 0.18 in Process 3, from 0.69 to 0.17 in Process 4 and from 0.46 to 0.12 in Process 5, changes both the TH and the CT by 1% on the critical WIP level of Line A. The mean has greater influence regarding non-bottleneck processes as well. The data referring to performance improvement on the critical WIP level is summed up in Table 3.



a) Improving Line D to Line F



b) Improving Line D to Line H

Figure 8. Improvement of the non-bottleneck processes

Table 3. The increase of TH and the decrease of CT on the critical WIP level

TH	*Mean*	*Variance*
Bottleneck	42%	9%
Non-bottleneck	11%	1%

CT	*Mean*	*Variance*
Bottleneck	30%	8%
Non-bottleneck	10%	1%

4 Conclusion

A superstructure and a simulation model for production flow lines with multiple products and parallel machines are presented. A simulation software tool is developed and used to improve flow line. Physical model result is presented and investigated regarding improvement. The improvement of non-bottleneck standard deviations has the least effect. It improves both the TH and the CT by 1% on the critical WIP level. Reducing bottleneck variance or non-bottleneck means by 75% has a better outcome (8-11% difference in TH and CT). The advance of bottleneck mean has the greatest consequence: the TH increases by 42%, the CT decreases by 30% on the critical WIP level. Based on the results the developed simulation model can be used for improvement design of production flow lines.

References

[1] J. T. Black and B. J. Schroer, "Simulation of an apparel assembly cell with walking workers and decouplers", *Journal of Manufacturing Systems*, vol. 12, no. 2, pp. 170-180, 1993.

[2] K. Cho, I. Moon and W. Yun, "System analysis of a multi-product, small-lot-sized production by simulation: A Korean motor factory case", *Computers & Industrial Engineering*, vol. 30, no. 3, pp. 347-356, Jul. 1996.

[3] T. Farkas, Z. Valentinyi, E. Rév and Z. Lelkes, "Supply chain optimization with homogenous product transport constraints", *Computer Aided Chemical Engineering*, vol. 25, pp. 205-210, 2008.

[4] M. K. Govil and M. C. Fu, “Queueing theory in manufacturing: A survey”, *Journal of Manufacturing Systems*, vol. 18, no. 3, pp. 214-240, 1999.

[5] W. J. Hopp, *Supply Chain Science*, Long Grove, Illinois: Waveland Pr Inc, 2011.

[6] W. J. Hopp and M. L. Spearman, *Factory Physics*, New York, New York: McGraw-Hill Education, 2000.

[7] W. Huang and S. Li, "A two-stage hybrid flowshop with uniform machines and setup times", *Mathematical and Computer Modelling,* vol. 27, no. 2, pp. 27-45, Jan. 1998.

[8] A. M. Law, W. D. Kelton, *Simulation Modeling and Analysis*, 3rd ed. New York, New York: McGraw-Hill Education, 2000.

[9] Z. Lelkes, Z. Szitkai, E. Rev and Z. Fonyo, ”Rigorous MINLP model for ethanol dehydration system”, *Computers and Chemical Engineering*, vol. 24, pp. 1331-1336, 2000.

[10] J. Olhager and B. Rapp, "Balancing capacity and lot sizes", *European Journal of Operational Research*, vol. 19, no 3, pp. 337-344, Mar. 1985.

[11] H. T. Papadopoulos and C. Heavey, “Queueing theory in manufacturing systems analysis and design: A classification of models for production and transfer lines”, *European Journal of Operational Research*, vol. 92, no. 1, pp. 1-27, Jul. 1996.

[12] Y. H. Park, J. E. Matson and D. M. Miller, "Simulation and analysis of the Mercedes-Benz all activity vehicle (AAV) production facility", *Proceedings of the 1998 Winter Simulation Conference*, pp. 921-926, Dec. 1998

[13] M. Roelofs and J. Bisschop, *AIMMS The user's guide*, AP Haarlem, The Netherlands: AIMMS B.V., 2016.

[14] J. Sarkis, "A strategic decision framework for green supply chain management", *Journal of Cleaner Production*, vol. 11, no. 4, pp. 397-409, Jun. 2003

[15] J. S. Smith, "Survey on the use of simulation for manufacturing system design and operation", *Journal of Manufacturing Systems*, vol. 22, no. 2, pp. 157-171, 2003.

[16] Z. Szitkai, Z. Lelkes, E. Rev and Z. Fonyo, “Solution of MEN Synthesis Problems Using MINLP: Formulations of the Kremser Equation”, *Computer Aided Chemical Engineering*, Vol. 9, pp. 1109-1114, 2001.

[17] W. Whitt, "Open and closed models for networks of queues", *AT&T Bell Laboratories Technical Journal*, vol. 63, no. 9, pp. 1911-1979, Nov. 1984.

[18] W. L. Winston, *Operations Research: Applications and Algorithms*, Boston, Massachusetts: Cengage Learning, 2003.

[19] H. Yamashita and S. Suzuki, "An approximation method for line production rate of a serial production line with a common buffer", *Computers & Operations Research*, vol. 15, no. 5, pp. 395-402, 1988.