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A Simulation Study on Improving Throughput in a Crankshaft Line Considering Limited Budget

Guan Wang [1], Shou Song [1], Yang Woo Shin[2], Dug Hee Moon[1†]

[1]Department of Industrial and Systems Engineering, Changwon National Univ.
20 Changwondaehak-Ro, Changwon, Gyeongnam 641-773, Korea
{ wgcan1, songshou } @hotmail.com, dhmoon@changwon.ac.kr[†]
[2]Department of Statistics, Changwon National University
20 Changwondaehak-Ro, Changwon, Gyeongnam 641-773, Korea
ywshin@changwon.ac.kr

Abstract In this paper, we discussed a simulation study for improving the throughput of a crankshaft manufacturing line in an automotive factory, where there is the limitation of budget for purchasing new machines. Although this problem is a kind of knapsack problem, it is not easy to calculate the throughput by mathematical analysis, and therefore simulation model was developed using ARENA®. To determine the investment plan, we used two methods, arrow assignment rule and all enumeration method.

1. Introduction

The major components that make up an engine are popularly called the 5C's, namely, camshafts, crankshafts, cylinder blocks, cylinder heads, and connecting rods. These major components are machined and assembled in their respective manufacturing sub-lines, and the completed components are transferred to the final engine assembly line. A final engine assembly line then consists of a series of assembly operations.

A crankshaft is the part of engine that changes the reciprocating linear piston motion into the rotation motion (see Figure 1). To produce a crankshaft, various machining processes such as milling, drilling, turning, rolling, grinding, finishing, burnishing, and measuring processes are required. Although the process-flow of a crankshaft line is different among automotive factories, the typical layout concept is the flow-line having multiple parallel machines.

In general, the production lines of the components of an engine are highly automated. However, there are many reasons which could cause the breakdown in a process, and they are machine failure, changing tools, repair parts, set-up change, and so on. Some of these events occur with deterministic interval, but others occur with stochastic interval. Thus, buffers are installed between two successive operations to prevent the starvation and blockage. The uncertainty of the breakdown influences the performance of the line, and it is also the main

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reason why most automotive factories implement a computer simulation to verify the layout design.

Figure 1: Example of crankshaft.

There have been some researches that dealt with the performance of a simulation for verifying the design of a production line in an automotive factory. Most of these prior studies focused on the individual shop (e.g., body shop, paint shop, engine shop, transmission shop and general assembly shop) because exploring the whole system was too complicated. Ulgen *et al.* (1994) discussed the use of discrete-event simulation in the design and operation of body and paint shops, and they classified the use of simulation in the body shop into two aspects. The first classification was based on the stage of development of the system and the second was based on the nature of the problem investigated.

Jayaraman and Agarwal (1996) addressed a general concept when the simulation technique is applied to the engine plant, and Jayaraman and Gunal (1997) presented a simulation study in a testing area of an engine plant. The simulation studies regarding the engine block line are suggested by Choi et al. (2002), Kumar and Houshyar (2002). In Moon et al. (2003), they considered the tool change time for specialized machines those do not equip ATC (Automatic Tool Changer) in an engine block line. Dunbar III et al. (2009) described the simulation study of alternatives for transmission plant assembly line. Xu et al. (2012) presented a case study that integrates a simulation study with Analytic Hierarchy Process (AHP), and the integrated model was applied to the design of a transmission case line in a Korean automotive factory. The process-flow of the engine block line is similar to that of the crankshaft line or transmission case line.

The crankshaft line considered in this paper is an existing system. The factory has a plan to increase their production capacity within the limited budget to meet the increasing demand. The configuration of the crankshaft line is explained in section 2. The process model of the line in section 3 enables us to find the bottleneck points and have an insight into the problems existing within the system. The simulation model is explained in section 4, which is followed by the result of the experiments in section 5. The comparison between the old system and the new system suggests ways on how to further improve the throughput.

2. Configurations

The layout concept of the crankshaft line considered in this paper is a typical flow line. All operations are connected serially, but some operations are designed with a parallel system having two or three identical machines. The purpose of installing parallel operations is to enhance the ease of machining or to reduce the risk of the breakdown of a line. Figure 2 shows the concept of crankshaft line considered in this paper. OP-30, OP-40, OP-60, OP-90 and OP-150 are parallel lines. Thus, a part can choose only one of two or three machines to finish the operation and then it goes to the next operation.

Only one type of crankshaft is produced in this line, and the target of annual production quantity is 120,000 units. The annual working days are 261 days (21.75 days per month) and the working hours are 10 hours per one day including the two hours of overtime.

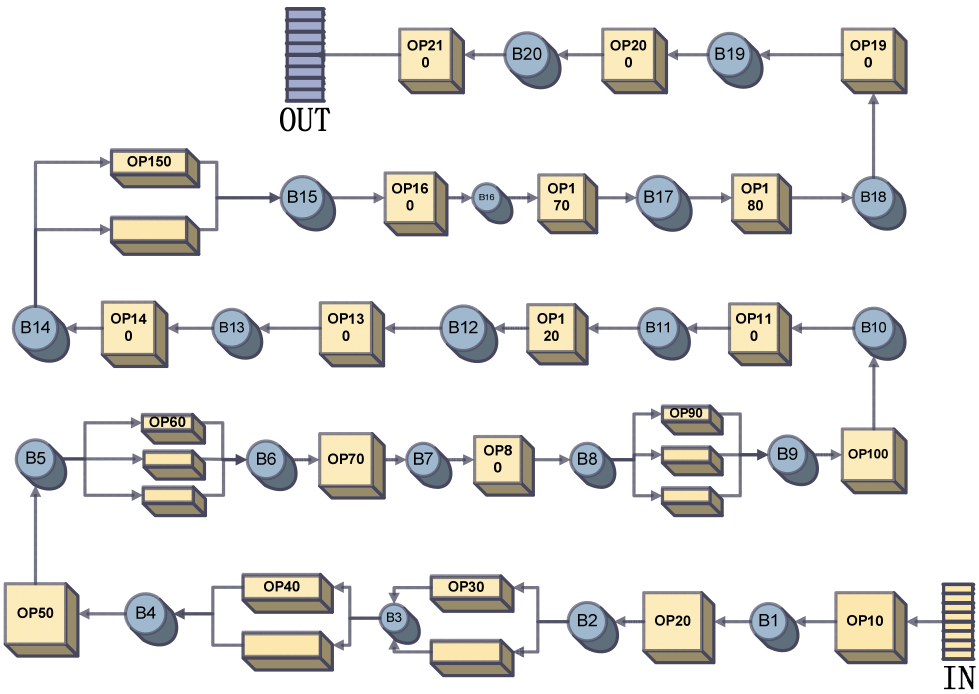


Figure 2: Processes of crankshaft.

2.1 Configuration of the System

• *Operations and Cycle Times*
Operations are designed considering the types of processes and the target tact time. If we assume that there is no failure, no tool change, no starvation and no

blocking, the ideal target tack time is calculated as 261*10*3600/120,000 = 78.3 seconds. Table 1 shows the details of operations including number of machines and operation cycle time. The longest average cycle time of an operation is 80 seconds at OP-150 when we consider that there are two machines in OP-150. Thus, this factory has to reduce the cycle times of some operations to meet the target production quantity.

At each operation, we assume that operation cycle time is deterministic because most of the machines are automated. Loading and unloading times are included in the operation cycle time. In some operations, there are multiple parallel machines for one operation because the tasks are complex, and it is difficult to separate them into two operations.

Furthermore, an operation is composed of more than one processes, for example there are 16 drilling and milling processes in OP-60. Thus, 16 types of tools and their life cycle should be considered for modeling.

Table 1: Descriptions of operations.

OP No	Operations	Number of Machine	Cycle Time (sec.)
OP-10	Mass Centering	1	50
OP-20	Rear Turning	1	46
OP-30	Rough JR/Pin Milling	2	140
OP-40	Journal Grooving	2	152
OP-50	Pin Grooving & Milling	1	50
OP-60	Oil Hole Drilling	3	195
OP-70	Middle Washing	1	48
OP-80	Deep Rolling	1	51
OP-90	Re-centering & Hole Drilling	3	198
OP-100	Trust Turn & Rolling	1	48
OP-110	Journal Head Grinding	1	75
OP-120	Orbital Pin Grinding	1	52
OP-130	Front Angular Grinding	1	47
OP-140	Rear Angular Grinding	1	54
OP-150	CPS Hole Boring	2	160
OP-160	Final Balancing	1	48
OP-170	Deburring	1	48
OP-180	Lapping	1	50
OP-190	Final Washing	1	48
OP-200	Final Measuring	1	50
OP-210	Sprocket Assembly	1	51

• *Buffer*

Various types of conveyor are used in the line for transportation and storage. Specially, a part should be loaded on a jig for transportation. Thus, the buffer capacity shown in Table 2, means the maximum number of jigs in a conveyor.

Table 2: Buffer capacity.

Buffer	Capacity	Buffer	Capacity	Buffer	Capacity	Buffer	Capacity
B1	20	B6	23	B11	34	B16	1
B2	17	B7	15	B12	20	B17	23
B3	2	B8	17	B13	17	B18	39
B4	17	B9	17	B14	20	B19	16
B5	20	B10	20	B15	20	B20	17

• *Down Times*

Two kinds of downtimes are considered, namely, machine failure and tool exchange. The failure distributions are obtained from the historical data. The mean values of the MTTF (Mean Time to Failure) and the MTTR (Mean Time to Repair) of the machine failure are listed in Table 3. The distribution functions of MTTF and MTTR are assumed as Exponential distributions, respectively.

Table 3: Input data of MTTF and MTTR.

OP No	MTTF (min.)	MTTR (min.)	Down Time Percentage	OP No	MTTF (min.)	MTTR (min.)	Down Time Percentage
OP-10	2,619.2	42.9	1.61%	OP-120	1,852.2	49.3	2.59%
OP-20	3,284.3	43.3	1.30%	OP-130	2,179.6	38.8	1.75%
OP-30	2,896.8	61.1	2.07%	OP-140	2,178.8	39.6	1.79%
OP-40	2,903.4	54.4	1.84%	OP-150	6,607.4	47.8	0.72%
OP-50	1,849.6	51.9	2.73%	OP-160	2,619.6	42.5	1.60%
OP-60	3,948.1	45.0	1.13%	OP-170	2,167.1	51.3	2.31%
OP-70	1,825.6	75.9	3.99%	OP-180	2,173.3	45.1	2.03%
OP-80	4,394.9	41.9	0.95%	OP-190	2,613.6	48.5	1.82%
OP-90	5,631.9	72.6	1.27%	OP-200	3,302.0	25.6	0.77%
OP-100	2,161.7	56.7	2.56%	OP-210	4,374.7	62.1	1.40%
OP-110	1,850.9	50.6	2.66%				

In a machining process, tool change (or tip change) is required at every predetermined number of parts, and the number is used for MCBF (Mean Count between Failures). As for tool exchange, if there is more than one tool in a machine, a different MCBF is implemented to each tool independently. Most of machining centers equip ATC (Automatic Tool Changer) and many tools are inserted in tool magazine. Table 4 show the tool change interval and time of OP-90, where there are 13 tools in magazine. Tool change time is the sum of the time for opening (and closing) door, the time for exchange tool and the time for in-line gauging. Opening and in-line gauging times are constant, but exchange tool time is variable with respect to the number of tools to be changed.

- Opening and closing door = 0.33 minutes.
- Exchange tool = 0.67 minutes/tool

- In-line gauging = 3 minutes

Since the tools having same MCBF are changed at the same time (for example, T04 and T14 should be changed in every 200 cycles), and the tool change time is calculated as 0.33+0.67*2+3=4.67 minutes. After producing 6,600 parts, six tools (T04, T14, T01, T08, T09 and T02) should be changed at the same time, and the tool change time is 0.33+0.67*6+3=7.35 minutes.

Table 4: Input data of tool changes (OP-90).

Tool No	Tool Type	MCBF	Tool No	Tool Type	MCBF
T04	TAP	200	T07	DRILL	500
T14	TAP	200	T02	INSERT TIP	660
T01	DRILL	330	T06	INSERT TIP	990
T08	REAMER	330	T11	INSERT TIP	1,350
T09	DRILL	330	T03	INSERT TIP	1,800
T12	ENDMILL	450	T10	TAP	2,000
T13	DRILL	500	T05	TAP	2,000

• *Defectives*
Inspection for finding defectives are conducted in four operations, i.e., OP-20, OP-50, OP-120 and OP-210, and the defect rates are 0.23%, 0.17%, 0.26% and 1.14%, respectively. We assume that there is no repair or rework for the defectives.

2.2 Objective of Study

To increase the throughput, the company prepare for some budget to invest. Generally, three types of strategies are applied to increase throughput, and they are buying additional machines, installing additional buffers and replacing tools with longer life cycle. However, in this paper we only consider the strategy of buying new machines. The total budget available is $1,050,000 and the prices of new machines are listed in Table 5. Then, the mathematical model can be defined as follows, where x_i denotes the number of additional machines in operation i, $\phi(x_1,..,x_N)$ denotes the throughput of the system, C_i is the price of machine i and B is the total budget.

$$\max\ \Pi = \phi(x_1,..,x_N) \quad (1)$$

$$s.t.\ \sum_{i=1}^{N} C_i x_i \le B \quad (2)$$

$$x_i : \text{integer} \ \ for\ i = 1,..,N.$$

Table 5: Prices of Machines ($1,000).

OP No	Price	OP No	Price	OP No	Price	OP No	Price
OP-10	1,180	OP-70	120	OP-130	476	OP-190	370
OP-20	230	OP-80	1,010	OP-140	476	OP-200	350
OP-30	952	OP-90	357	OP-150	417	OP-210	390
OP-40	1,012	OP-100	270	OP-160	726		
OP-50	962	OP-110	833	OP-170	350		
OP-60	357	OP-120	1,190	OP-180	500		

3. Solution procedure

3.1 Simulation

Simulation model is useful for estimating the value of $\phi(x_1,..,x_N)$, because it is not easy to calculate it by mathematical model. Thus, simulation models were developed with ARENA® (See Kelton et al. (2002)) .The simulation run time was set to 14,641 minutes including 1,331 minutes of warm up time. Then, the data gathering time was 13,310 minutes, and the time is the operation time per one month in practice.

The experimental results of ten replications are explained in Table 6. The error obtained from simulation to the historical data in practice is 1.3%, and we conclude that the simulation model is reasonably valid. Figure 3 shows the percentages of busy, idle (starvation), blockage and failure of each operation.

Table 6: Simulation Result (As-Is).

	Real	Simulation		Error
		Mean	95% C.I.	
Throughput	8,795	8,683	±147.5	1.3%

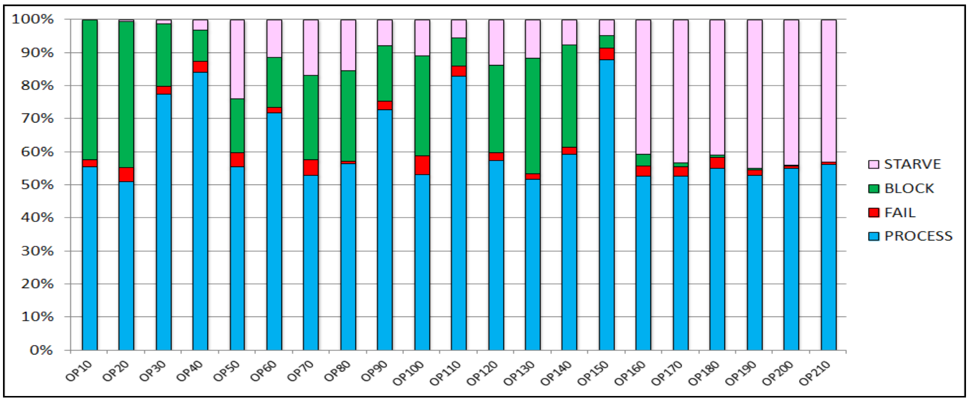


Figure 3: State of operations (As-Is)

3.2 Bottleneck Search

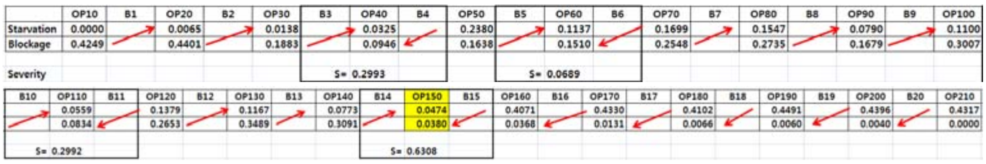
The next step is to find which machine should be added to the existing system (As-Is) under the limit of total budget for investing. There have been a few algorithms to find the bottleneck in a flow line, and two of them are "Arrow Assignment Rule" explained in Li and Meerkov (2009), and "Active Period Method" suggested by Lawrence and Buss (1994). However in this paper, we compared Arrow Assignment Rule and all enumeration method.

3.2.1 Arrow Assignment Rule

Let's denote BL_i and ST_i as the blocking probability of machine i (m_i) and the starving probability of m_i in steady state, respectively. If $BL_i > ST_{i+1}$, assign the arrow pointing from m_i to m_{i+1}. If $BL_i < ST_{i+1}$, assign the arrow pointing from m_{i+1} to m_i. In case that there are multiple machines with no emanating arrows, the one with the largest severity (S_i) is primary, where the severity of each is defined by

$$S_i = |ST_{i+1} - BL_i| + |ST_i + BL_{i-1}|,\ i = 1,.., N-1\,. \tag{3}$$

From the result shown in Fig. 3, we obtained the candidates of bottleneck as shown in Fig.4. There were four candidates (OP-40, OP-60, OP-110, and OP-150) and the primary bottleneck was OP-150.



	OP10	B1	OP20	B2	OP30	B3	OP40	B4	OP50	B5	OP60	B6	OP70	B7	OP80	B8	OP90	B9	OP100
Starvation	0.0000		0.0065		0.0138		0.0325		0.2380		0.1137		0.1699		0.1547		0.0790		0.1100
Blockage	0.4249		0.4401		0.1883		0.0946		0.1638		0.1510		0.2548		0.2735		0.1679		0.3007
Severity							S= 0.2993				S= 0.0689								

B10	OP110	B11	OP120	B12	OP130	B13	OP140	B14	OP150	B15	OP160	B16	OP170	B17	OP180	B18	OP190	B19	OP200	B20	OP210
	0.0559		0.1379		0.1167		0.0773		0.0474		0.4071		0.4330		0.4102		0.4491		0.4396		0.4317
	0.0834		0.2653		0.3489		0.3091		0.0380		0.0368		0.0131		0.0066		0.0060		0.0040		0.0000
	S= 0.2992								S= 0.6308												

Figure 4: Candidates of bottleneck (As-Is)

One new machine is added to OP-150 because the price of machine is $417,000 and it is less than the total budget $1,050,000. After that, the simulation model was modified and the new throughput obtained by simulation was 8,997. The increment was 314 units (3.6%).

In the second round, three candidates, i.e., OP-110, OP-40 and OP-90, were selected for bottleneck. However, the machine prices of OP-110 and OP-40 are higher than the available budget, $633,000. Thus, we determine an additional machine in OP-90, and the throughput obtained from new simulation was 9,076, and the remaining budget was $276,000.

In the third round, although there are two candidates, OP-110 and OP-40, and they could not be alternatives because of the price. Finally we checked new candidates whose price is less than the remaining budget and they were OP-20, OP-70, and

OP-100. Simulation experiments were conducted for each candidate and OP-20 was the best among them. Thus the best investment plan was add one machine for each of OP-20, OP-90 and OP-150, and the final throughput increased to 9,247 (6.5% of increment) and the total investment cost is $1,004,000.

3.2.2 All Enumeration

To determine the best investment plan, we found all alternatives which satisfied the constraint in equation (2). There were 367 alternatives and the simulation results are shown in Table 7. The best plan was to add one machine for each of OP-70, OP-150 and OP-200, respectively. The investment plan obtained from Arrow Assignment Rule was the second-best. The company wants to reduce the investment cost as small as possible if the increment target of throughput is achieved. Thus, if the target is set to 6%, Plan 3 (OP-150 and OP-170) is the best because the efficiency of investment cost is the highest.

Table 7: Simulation Results (all enumeration).

Rank	Investment ($1,000)	Plan	Through-put	Increment		Efficiency[1)]
				Quantity	Percent	
1	887	OP-70,OP-150,OP-200	9,265	582	6.7%	0.656
2	1,004	OP-20, OP-90, OP-150	9,247	564	6.5%	0.561
3	767	OP-150, OP-170	9,223	540	6.2%	0.704
4	774	OP-60, OP-150	9,211	528	6.1%	0.682
5	767	OP-20, OP-70, OP-150	9,191	508	5.9%	0.662
6	669	OP-100, OP-150	9,187	504	5.8%	0.753

[1)] Efficiency of Investment = Increased Quantity/Investment Cost

4. Conclusions

In this paper, we discussed a simulation study for improving the throughput of a crankshaft manufacturing line in an automotive factory, where there is the limitation of budget for purchasing new machines. Although this problem is a kind of knapsack problem, it is not easy to calculate the throughput by mathematical analysis, and therefore simulation model was developed using ARENA®.

To determine the investment plan, we used two methods, arrow assignment rule and all enumeration method. The arrow assignment rule is slightly modified to consider the budget limitation for buying new machines. The investment plan obtained from arrow assignment rule was compared to the result of all enumerations (367 cases). The best plan of arrow assignment rule was the second-best plan of all enumeration method. It means that the arrow assignment rule does not guarantee the optimality.

For further research, the more efficient search algorithm of investment plan can be developed. Furthermore, we can extend the strategies of improving throughput by considering buffer increase within the space available and by selecting new tools having long life cycle and high speed. However, we note that companies prefer investing cost to the general purpose machine for the sustainability of manufacturing system. Thus we can consider giving different priorities to the machines to optimize the investment plan.

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