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<Original Research Paper>

A Simulation Based Study on Increasing Production Capacity in a Crankshaft Line Considering Limited Budget and Space

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예산과 공간 제약하에서 크랭크샤프트 생산라인의 생산능력 증대를 위한 시뮬레이션 기반의 연구

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In this paper, we discussed a problem for improving the throughput of a crankshaft manufacturing line in an automotive factory in which the budget for purchasing new machines and installing additional buffers is limited. We also considered the constraint of available space for both of machine and buffer. Although this problem seems like a kind of buffer allocation problem, it is different from buffer allocation problem because additional machines are also considered. Thus, it is not easy to calculate the throughput by mathematical model, and therefore simulation model was developed using ARENA® for estimating throughput. To determine the investment plan, a modified Arrow Assignment Rule under some constraints was suggested and it was applied to the real case.

Keywords: Production Capacity, Crankshaft Line, Limited Budget and Space, Modified Arrow Assignment Rule, Simulation

1. Introduction

The major components that make up an engine are popularly called the 5C's, namely, camshaft, crankshaft, cylinder block, cylinder head, and connecting rod. 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 (Xu *et al*., 2012).

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

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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, buffer is installed between two successive operations to reduce the effects of starvation and blockage. The uncertainty of the breakdown influences the performance of the line, and it is also the main reason why most automotive factories implement a computer simulation to verify the layout design.

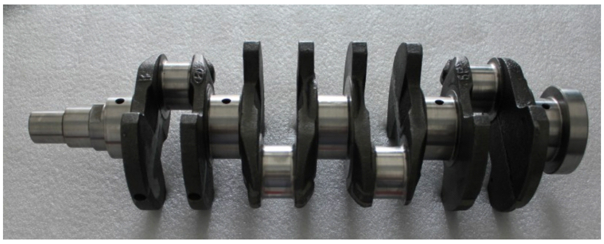


Figure 1. Example of crankshaft

There have been some researches using simulation that dealt with the design problem of a production line in an automotive factory. Since the whole system was too complicated, most of the studies in literature focused on the individual shop such as body shop, paint shop, engine shop, transmission shop and general assembly shop. Ulgen *et al*. (1994) discussed how to 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 have been suggested by Choi *et al*. (2002), Kumar and Houshyar (2002). In Moon *et al*. (2003), they considered the tool change times for specialized machines not equipping 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*. (2010) compared three different types of layouts in automotive engine block lines and Moon *et al*. (2012) analyzed the effect of failure distribution in automotive engine 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 operated by a Korean automotive company. The factory has a plan to increase the production capacity within the limited budget to meet the increasing demand, and thus, it is necessary to find where is the bottleneck for growing up throughput.

There have been some researches which deal how to find bottlenecks in manufacturing systems for improving the performances of systems (see Li and Meerkov, 2009; Lawrence and Buss, 1994; Kwon and Lim, 2013; Li *et al*., 2011). Most of the papers have focused on developing the detecting methods for bottlenecks.

Another area related to this paper is buffer allocation problem. There have been many researches dealing with the optimal buffer allocation problem. Powell (1994) studied the buffer allocation problem for unbalanced lines with three machines. Rules of thumb for the optimal sequential placement of buffer space were developed. Seong *et al*. (1995) used gradient search algorithm when the objective function is to maximize net profit. So (1997) presented a study on the optimal buffer allocation problem of minimizing the average work in process subject to a minimum required throughput and a constraint on the total buffer space. Gershwin and Schor (2000) suggested primal-dual problem considering optimal buffer space allocation in a serial line. A primal problem minimized total buffer space subject to a production rate constraint, and a dual problem maximized production rate subject to a total buffer space constraint. However, they did not consider the profit including cost. Huang *et al*. (2002) consider a flow shop-type production system and use a dynamic programming approach to maximize its production rate or minimized its work in process under a certain buffer allocation strategy. Chan and Ng (2002) compared buffer allocation strategies for maximized the production rate in serial production line. Amiri and Mohtashami (2012) presented a multi-objective formulation of the buffer allocation problem in a serial line in which unreliable machines, finite buffer and exponential service time were assumed. They developed a meta-model for estimating production rate based on discrete event simulation, and used genetic algorithm combined to line search method to solve the multi-objective model, maximizing production rate and minimizing buffer size, and determining the optimal (or near optimal) size of each buffer storage.

In this paper, we combine the simulation study for analysing manufacturing system and the bottleneck search method to determine investment plan considering the limitation of budget and available spaces for machines and buffers. The configuration of the crankshaft line and the mathematical model for optimizing investment plan under the limits of budget and available space are described in section 2. In section 3,

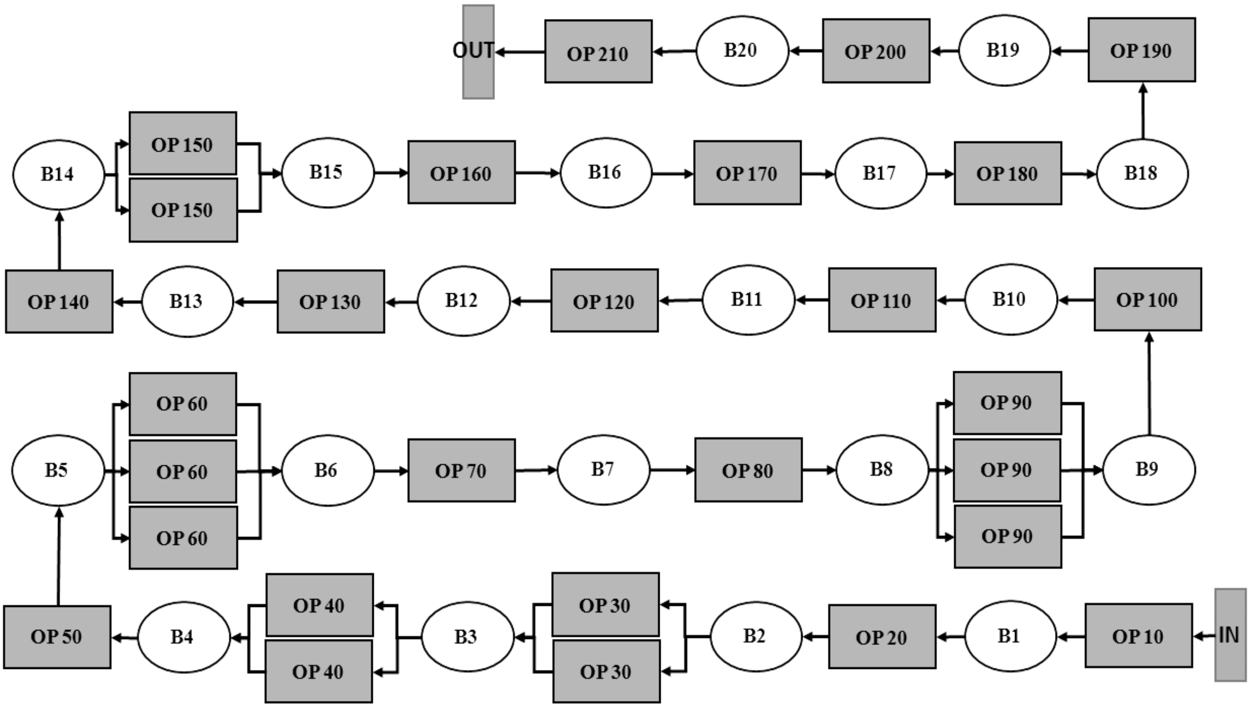


Figure 2. Processes of crankshaft manufacturing

Table 1. Descriptions of operations

OP No	Processes	Number of Machines(As-Is)	Cycle Time (sec.)	Machine Price ($1,000)	Extra Available Spaces
OP-10	Mass Centering	1	50	1,180	0
OP-20	Rear Turning	1	46	230	0
OP-30	Rough JR/Pin Milling	2	140	952	1
OP-40	Journal Grooving	2	152	1,012	1
OP-50	Pin Grooving and Milling	1	50	962	0
OP-60	Oil Hole Drilling	3	195	357	2
OP-70	Middle Washing	1	48	120	0
OP-80	Deep Rolling	1	51	1,010	0
OP-90	Re-centering and Hole Drilling	3	198	357	2
OP-100	Trust Turn and Rolling	1	48	270	1
OP-110	Journal Head Grinding	1	75	833	1
OP-120	Orbital Pin Grinding	1	52	1,190	1
OP-130	Front Angular Grinding	1	47	476	1
OP-140	Rear Angular Grinding	1	54	476	1
OP-150	CPS Hole Boring	2	160	417	2
OP-160	Final Balancing	1	48	726	0
OP-170	Deburring	1	48	350	0
OP-180	Lapping	1	50	500	0
OP-190	Final Washing	1	48	370	0
OP-200	Final Measuring	1	50	350	0
OP-210	Sprocket Assembly	1	51	390	0

simulation model is introduced and modified arrow assign rule for finding the best investment plan is suggested. The result of case study and its optimality are explained in section 4, and conclusion and further study are discussed in section 5.

2. Configurations and Objective

The layout concept of the crankshaft line considered in this paper is a typical flow line as shown in <Figure 2>. In order to enhance the ease of machining or to reduce the risk of the breakdown of a line, some operations have two or three identical machines in parallel where a part chooses only one of machines and then it goes to the next operation after operation. Here, OP-30, OP-40, OP-60, OP-90 and OP-150 consist of multiple identical machines in parallel.

We assume that 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 day including the two hours of overtime.

2.1 Configurations of the System

- Operations and Cycle Times

Operations are designed considering the types of processes and the target tact time. If there are no failure, no tool change, no starvation and no blocking, the ideal target tack time is $261\times10\times3600/120{,}000 = 78.3$ 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 assume 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 process, for example there are 16 drilling and milling processes in OP-60, and 16 types of tools and their life cycles should be considered for modeling.

This factory has been built with some extra machine spaces and buffer spaces in some operations that give a possibility of making a plan to increase the throughput almost twice. <Table 1> lists the existing number of machines, extra available space, cycle time and machine price for each operation.

Table 2. Buffer capacity

Buffer	Existing Capacity(As-Is)	Extra Capacity
B1	20	10
B2	17	13
B3	2	0
B4	17	0
B5	20	10
B6	23	7
B7	15	15
B8	17	13
B9	17	0
B10	20	10
B11	34	0
B12	20	10
B13	17	13
B14	20	10
B15	20	10
B16	1	0
B17	23	7
B18	39	0
B19	16	14
B20	17	13
Total	375	155

- Buffers

Various types of conveyor are used in the line for transportation and storage. A part should be loaded on a jig for transportation. Thus, the buffer capacity listed in <Table 2>, means the maximum number of jigs to be installed in a conveyor between two successive operations. In B3, B4, B9, B11, B16 and B18, there is no available space for additional buffer. The price of additional one buffer (jig) is \$200, and the total investment cost for all additional buffers is \$200×155 = \$31,000.

- Down Times

Two kinds of downtimes, machine failure and tool exchange are considered. The failure distributions are obtained from the historical data. 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 failure time and repair time are assumed to be exponential, and time dependent failure is assumed.

Tool change (or tip change) is assumed to be operation dependent failure. That is, tool change (or tip change) is required at every predetermined number of parts, and the number is defined as MCBF (Mean Count between Failures). If there are two or more tools in a machine, the MCBF's of tools are independent and may be different from each other. Most of machining centers equip ATC (Automatic Tool Changer) and many tools are inserted in tool magazine. <Table 4> lists the tool types and MCBF of OP-90, where 14 tools are in ATC. 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 which are given as

- ◦ Time for opening and closing door = 0.33 minutes,
- ◦ Time for in-line gauging = 3 minutes.

The time for exchange tools depends on the number of tools to be changed and it is given as

- ◦ Time for exchange tool = 0.67 minutes/tool.

Table 3. Input data of MTTF and MTTR

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

Since the tools having same MCBF should be changed at the same time, for example, T04 and T14 should be changed in every 200 cycles, the tool changing time is 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.

- Defectives

Inspections for finding defectives are conducted in four operations 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.

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

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

2.2 Objective of Study

The major concern of a company is to increase throughput within a limited budget. Generally, three types of strategies are usually applied to increase throughput, and they are buying additional machines, installing additional buffers and replacing tools with longer life cycles. However, in this paper we only consider the strategy of buying new machines and adding buffers. The total budget available is \$1,050,000 and the prices of new machines and additional buffer are addressed in section 2.1.

The mathematical model is defined as follows:

$$\max \Pi = \Phi(x_1, x_2, \cdots, x_N, y_1, y_2, \cdots, y_{N-1}) \tag{1}$$

$$\text{s.t.} \sum_{i=1}^{N} C_i x_i + \sum_{i=1}^{N-1} D_i y_i \le B, \tag{2}$$

x_i : integer and $0 \le x_i \le f_i$ for $i = 1, \cdots, N$,

y_i : integer and $0 \le y_i \le g_i$ for $i = 1, \cdots, N-1$, where x_i and f_i are the number of additional machines and its upper bound in operation *i*, respectively. y_i and g_i are the number of additional buffer and its upper bound between operations *i* and *i*+1. Furthermore, Φ is the throughput of the system, C_i is the price of machine I, D_i is the cost of additional one buffer and B is the total budget available.

3. Solution Procedure

3.1 Simulation Model

It is well known to be very difficult to derive analytical solution (i.e., approximation of queueing network) for the flow line with multiple unreliable machines, finite buffers, nonhomogeneous service times and the two types of failures. Note that both of time dependent failure and operation dependent failure are included in the model and the failure distribution functions are nonhomogeneous.

Simulation is known as useful tool for estimating the value of throughput (Φ), WIP (Work In Process), starving probabilities and blocking probabilities at once. Simulation models were developed with ARENA® (See Kelton *et al*. (2002)). To validate the simulation model developed, simulation run time was set to 146,410 minutes including 13,310 minutes of warm up time, and the number of replications was set to 100. Then, the data gathering time was 133,100 minutes, and it was the 10 months in practice.

Table 5. Simulation result (As-Is)

	Real	Simulation		Error
		Mean	95% C.I.	
Throughput	87,950	87,984	±171.7	0.04%

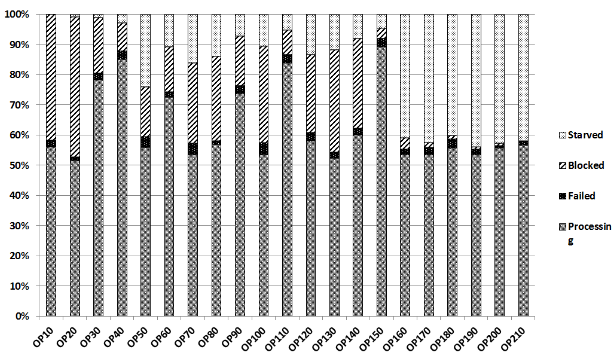


Figure 3. States of operations (As-Is)

The experimental results of 100 replications are presented in <Table 5>. The error obtained from simulation to the historical data in practice is 0.04%, and we conclude that the simulation model is reasonably valid. The ratio of confidence interval to mean was 171.7÷87,984×100 = 0.2%. <Figure 3> shows the portions of busy, idle (starvation), blockage and failure at each operation.

3.2 Modified Arrow Assignment Rule

The next step is to find which machine and buffer should be added to the existing system (As-Is) under the budget constraint. If there are no constraints of budget, the possible number of investment plans (combinations) is $\prod_{i=1}^{N}(f_i+1)\times\prod_{i=1}^{N-1}(g_i+1)$ and that is about 3.61×10^{18} in this problem. If the additional assignment strategy of buffer is assumed to be just zero or full capacity, the number of investment plans is reduced to 5.66×10^{7}.

To solve the integer problem, various meta-heuristic algorithms such as genetic algorithm (GA), tabu search, gradient search and etc. can be used. In order to use GA, the fitness value, namely throughput (Φ), should be estimated for each chromosome. When the number of chromosomes in the first generation is set to 100, we need 100 simulation experiments. If the number of the different chromosomes in the second generation is reduced to 70, we need additionally 70 simulation experiments. This process is repeated until the convergence is obtained. Furthermore, repair process is required for each crossover to consider the limited budget.

Similar situation is happened when various search algorithms are applied to this problem. Unfortunately, no meta-heuristic algorithms guarantee the global optimality, and it is the reason that why we need faster heuristic algorithm.

There are some algorithms to find the bottleneck in a flow line, e.g., 'Arrow Assignment Rule' (Li and Meerkov, 2009), and 'Active Period Method' (Lawrence and Buss, 1994; Kwon and Lim, 2013) and a method using autoregressive moving average (ARMA) model (Li *et al*., 2011). In Arrow Assignment Rule, they considered a serial line having only one machine in each stage which has one type of time dependent failure, because they used mathematical approximation model for estimating throughput, WIP, blocking probabilities and starving probabilities.

In this paper, we adopt the concept of Arrow Assignment Rule for finding bottleneck and modify it with the considerations of limited budget and extra spaces for machines and buffers. We also introduce the concept of investment efficiency as in equation (6) to find the priority of investment.

Denote by BL_i and ST_i the blocking probability of machine *i* (m_i) and the starving probability of m_i in steady state, respectively and define the severity (S_i) of m_i by

$$S_i = |ST_{i+1} - BL_i| + |ST_i - BL_{i-1}|, \text{ for } i = 2, \cdots, N-1, \quad (3)$$
$$S_1 = |ST_2 - BL_1|, \quad (4)$$
$$S_N = |ST_N - BL_{N-1}|. \quad (5)$$

If $BL_i \geq ST_{i+1}$, 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.

The following notations are used to explain the heuristic search rule. "Available" means that both of available space for machine (or buffer) and available investment cost are available. "Up" and "Down" means upstream and downstream, respectively. Efficiency is calculated by

$$Efficiency = \frac{Amount\ of\ throughput\ Icreased}{Investment\ \mathrm{cost}}. \quad (6)$$

- *TP* : throughput,
- *BN* : set of bottleneck machines,
- *COM* : machine candidate,
- *COB* : buffer candidate,
- *e(COM)* : efficiency of machine *COM*
- *e(COB)* : efficiency of buffer *COB*
- *p_BN_m* : primary bottleneck machine having the largest S_i in *BN*,
- *s_BN_m* : set of secondary bottleneck machines having smaller S_i than *p_BN_m* in *BN*,
- *s_BN_m_avl* : subset of available machines in *s_BN_m*,
- *s_BN_m** : machine having the largest S_i in *s_BN_m_avl*,
- *p_BN_b* : primary bottleneck buffer, where

$$p\_BN\_b = \begin{cases} Up\ buffer\ of\ p\_BN\_m, & \text{if } ST_i \geq BL_i \\ Down\ buffer of\ p\_BN\_m, & \text{if } ST_i < BL_i \end{cases}$$

- *s_BN_b* : set of secondary bottleneck buffer related to each machine *i* in *s_BN_m*, where

$$s\_BN\_b_i = \begin{cases} Up\ buffer\ of\ s\_BN\_m_i, & \text{if } ST_i \geq BL_i \\ Down\ buffer of\ s\_BN\_m_i, & \text{if } ST_i < BL_i \end{cases}$$

- *s_BN_b_avl* : subset of available buffers in *s_BN_b*,
- *s_BN_b** : the buffer related to the machine having the largest S_i in *s_BN_m*,
- $BN\_Side = \begin{cases} Up\ side\ of\ p\_BN\_m, & \text{if } ST_i \geq BL_i \\ Down\ side\ of\ p\_BN\_m, & \text{if } ST_i < BL_i \end{cases}$
- *BN_side_m* : set of machines on *BN_side*, which are not included in *BN*,
- *BN_side_m_avl* : subset of available machines in *BN_side_m*,
- *BN_side_m** : machine having the largest S_i in *BN_side_m_avl*,
- *BN_side_b* : set of buffers on *BN_side* which are neither *p_BN_b* nor the buffers in *s_BN_b*,
- *BN_side_b_avl* : subset of available buffers in *BN_side_b*,
- *BN_side_b** : the buffer related to the machine having the largest severity in *BN_side_m*,
- $non\,BN\,Side = \begin{cases} Up\ side\ of\ p\_BN\_m, & \text{if } ST_i \geq BL_i \\ Down\ side\ of\ p\_BN\_m, & \text{if } ST_i < BL_i \end{cases}$
- *non BN_side_m* : set of machines on *non BN_side*, which are not included in *BN*,
- *non BN_side_m_avl* : subset of available buffers in *non BN_side_m*,
- *non BN_side_m** : machine having the largest S_i in *non BN_side_m_avl*,
- *non BN_side_b* : set of buffers on *non BN_side* which are neither *p_BN_b* nor buffers in *s_BN_b*,
- *non BN_side_b_avl* : subset of available buffers in *non BN_side_b*,
- *non BN_side_b** : the buffer related to the machine having the largest S_i in *non BN_side_m*,

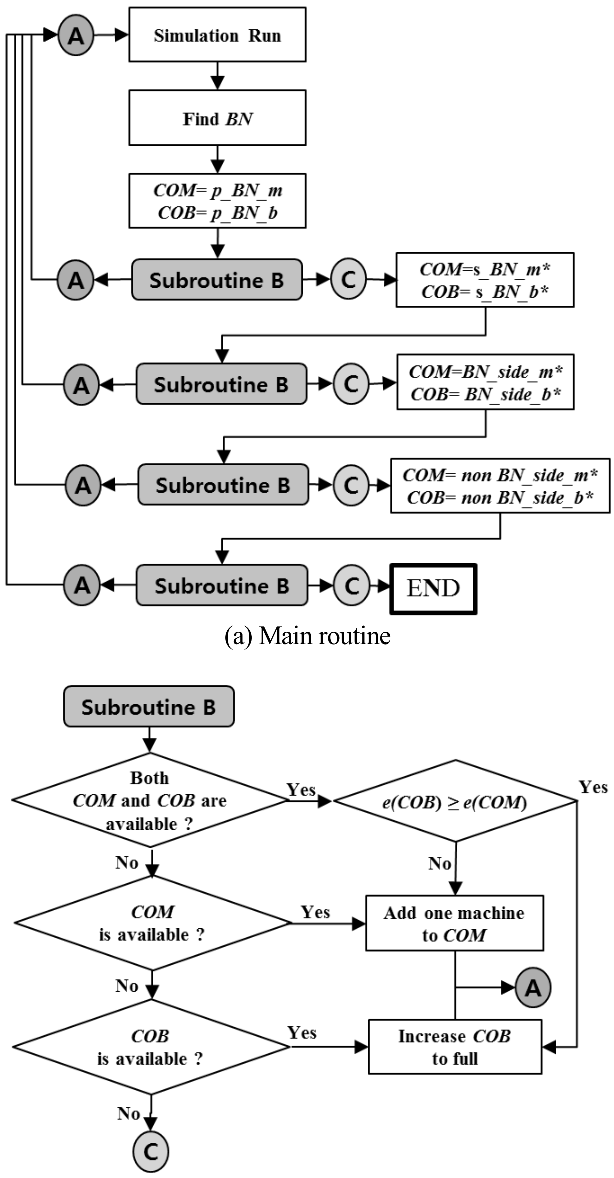
<Figure 4> explains the processes of search algorithm. The algorithm consists with a main routine and a subroutine B.

4. Case Study and Validation

4.1 Case Study

We carried out 100 replications of simulation run with the As-Is problem and the average throughput is 87,894. The set of bottleneck machines *BN* = {OP-40, OP-60, OP-110, OP-150} is obtained as shown in <Figure 5>. Among the operations in *BN*, S_i of OP-150 is the largest (S_{OP150} = 0.625), and thus *p_BN_m* is OP-150 and *s_BN_m* are OP-40, OP-60 and OP-110. Furthermore, *p_BN_b* is B14, because $ST_{OP150} > BL_{OP150}$, and *s_BN_b* are B4, B6 and B11 with respect to OP-40, OP-60 and OP-110. The upstream side of OP150 (*p_BN_m*) is *BN side*, and the downstream side of OP-150 is *non BN side*.

In the first round, the machine candidate (*COM*) is OP-150, because there are two extra available spaces, and the price of machine is $417,000 that is less than the total budget $1,050,000. The buffer candidate (*COB*) is B14, because 10 extra buffers are allowed and the cost of extra buffers is $2,000. Then, two simulation experiments are carried out for the two cases (adding a machine to OP-150 and adding 10 buffers to B14) independently, and new simulation results including throughput, WIP, starving probabilities and blocking probabilities are obtained. The throughput after adding one machine in OP-150 is 91,571 and the throughput in the case of increasing the buffer B14 to full is 88,714. However, the investment efficiency of the former is 8.6 and it is lower than 356 of the later. Thus B14 is selected to increased to full in the first round. The remaining budget is $1,048,000.



(a) Main routine

(b) Subroutine B

Figure 4. Flow chart of algorithm suggested

In the second round, the elements in *BN*, *p_BN_m* and *p_BN_b* are the same as the first round except that *COB* (B14) becomes unavailable. Thus, one new machine is added to OP-150. The new throughput is 91,687 and the increment is 2973 units (3.35%). However, WIP decreases from 178.53 to 99.73.

In the third round, three operations (OP-40, OP-90 and OP-110) are included in *BN*, and OP-110 becomes *p_BN_m* and *COM*. But the machine price of OP-110 is higher than the remaining budget, $631,000, it is unavailable. Thus, we increase the size of *COB* (B10) which is *p_BN_b* to full, and the throughput obtained from new simulation is 91,953, WIP is 98.49, and the remaining budget is $629,000.

In the fourth round, OP-110 is still *p_BN_m*, B10 is *p_BN_b*, OP-40 and OP-90 are elements of *s_BN_m*, and *s_BN_b* contains B4 and B8. However, both of *COM* and *COB* are unavailable since the remaining budget is not enough for adding a machine in OP-110 and B10 is already full. For the secondary bottlenecks, machine prices of OP-40 ($1,012,000) is over the remaining budget and there is no available space in B4. Thus, they are not in *s_BN_m_avl* and *s_BN_b_avl*., respectively and OP-90 becomes new *COM* and B8 becomes new *COB*. After simulations, *e(COB)* is 9.77 and *e(COM)* is 5.51. The next decision is to increase B8 to the full and then the new throughput is 92,121 and WIP is 99.63.

In the fifth round, OP-110 becomes *p_BN_m*. OP-40 and OP-90 are included in *s_BN_m*. *s_BN_b* contains B4 and B8. By the logic, an additional machine is added to OP-90. Then, the throughput is increased to 92,551 and WIP is 105.12. The remaining budget is $269,400.

	OP10	B1	OP20	B2	OP30A	B3	OP40A	B4
Starvation	0.0%		0.8%		1.1%		3.0%	
Blockage	41.7%		46.4%		18.4%		9.1%	
MC Price							$1,012	
Severity							0.303	
	OP50	B5	OP60A	B6	OP70	B7	OP80	B8
Starvation	24.0%		10.8%		16.2%		13.9%	
Blockage	16.5%		14.8%		26.4%		28.0%	
MC Price			$357					
Severity			0.071					
	OP90A	B9	OP100	B10	OP110	B11	OP120	B12
Starvation	7.2%		10.6%		5.2%		13.4%	
Blockage	16.4%		31.8%		8.3%		25.7%	
MC Price					$833			
Severity					0.318			
	OP130	B13	OP140	B14	OP150A	B15	OP160	B16
Starvation	11.9%		8.0%		4.6%		40.8%	
Blockage	33.8%		29.8%		3.4%		3.9%	
MC Price					$417			
Severity					0.625			
	OP170	B17	OP180	B18	OP190	B19	OP200	B20
Starvation	42.4%		40.2%		43.8%		42.6%	
Blockage	1.6%		1.0%		1.0%		0.9%	
MC Price								
Severity								
	OP210							
Starvation	41.8%							
Blockage	0.0%							
MC Price								
Severity								

Figure 5. Candidates of bottleneck (As-Is)

The searching process is repeated until the remaining budget is consumed completely. In the sixth round, there is no available machine in *p_BN_m*, *s_BN_m*, *BN_side_m*, and *non BN_side_m*, and no buffers are available in *p_BN_b*, *s_BN_b*. Thus, we should check up *BN_side* first, and B2 is selected as a *COB* and we increase the capacity of B2 to maximum, because the severity of OP-20 is largest. Then the throughput becomes 92,611. Similarly, B6, B1, B5 and B7 are selected sequentially for *COB* in *BN_side* and their capacities are increased to the upper bounds. After that, B19, B17, B15, B12, B13 and B20 are selected in sequence for *COB* in *BN_side* and their capacities are increased to the upper bounds. Then the final throughput increases to 94,017 and WIP is 136.59. The total investment cost is $805,000 and the remaining budget is $245,000. The number of simulation experiments including As-Is analysis is 19 and the average simulation run time for each experiment is about 15 minutes.

Table 6. Summary of solution processes

	Plan	TP	WIP	Remaining Budget
R0	As-Is	87,984	178.5	$1,050,000
R1	**B14**	88,714	178.5	$1,048,000
R2	B14 **OP-150**	91,687	99.7	$631,000
R3	B14 OP-150 **B10**	91,953	98.5	$629,000
R4	B14 OP-150 B10 **B8**	92,121	99.6	$626,400
R5	B14 OP-150 B10 B8 **OP-90**	92,551	105.2	$269,400
R6 ~ R16	B14 OP-150 B10 B8 OP-90 **B2 B6 B1 B5 B7 B19 B17 B15 B12 B13 B20**	94,017	136.6	$245,000

4.2 Validation for Optimality

To validate the solution procedure suggested, the best solution obtained from section 4.1 is compared with the feasible solutions obtained from all enumerations. However the number of all enumerations is too much big when we assume that the increment size of buffer is set to one. Thus, we inevitably assume that all available buffers are full, and search for the feasible investment plans for machines. Then the number of feasible plans is 30. If we assume that the capacities of some buffers remain without increasing, then the number of feasible plans must be greater than 30. <Table 7> lists the simulation results for all enumerations with the decreasing order of throughput, and scenario 1 is the best and it is the same to the investment plan that we obtained from our heuristic method.

5. 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 and installing additional buffers. In each operation and buffer, limited space is predetermined and it restricts the number of additional machines and buffers.

Although this problem seems like a buffer allocation problem, it is not easy to calculate the objective function (throughput) by mathematical model. Therefore, simulation model was developed using ARENA® and the values of throughput, starving probabilities, blocking probabilities and WIP were obtained by simulation experiments.

To determine the investment plan, we modified arrow assignment rule for considering parallel machines, the budget limitation and the space limitations of machines and buffers. Then, the best solution by the modified arrow assignment rule was compared to the subset of all enumerations (30 cases), and the two results were same. Although the modified arrow assignment rule does not guarantee the optimality, we obtained the best solution in the case study. Furthermore, the number of simulation experiments was reduced to 19.

The limitation of this paper is that we inevitably assumed that the buffer increment is nothing or full. However, this assumption can be relaxed such that the buffer increment is set to one. In this case, we can use the algorithm suggested with the slight modification of buffer increment size, but the number of simulation experiments will be increased drastically. For further research, the objective function can be changed to minimizing cost which includes investment cost and WIP cost. In this case the target throughput becomes new constraint.

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Table 7. Simulation results (all enumerations)

scenario	Invest ($1,000)	Plan (Machine)	Throughput		Increment		Efficiency[1)]
			Mean	95% C.I.	Quantity	Percent	
1	805	OP-90 OP-150	94,017	±149.2	6,033	6.86%	7.49
2	924	OP-130 OP-150	93,613	±154.1	5,629	6.40%	6.09
3	924	OP140 OP-150	93,555	±143.6	5,571	6.33%	6.03
4	718	OP-100 OP-150	93,349	±132.9	5,365	6.10%	7.47
5	865	OP-150 OP-150	93,334	±153.8	5,350	6.08%	6.18
6	805	OP-60 OP-150	93,329	±146.4	5,345	6.07%	6.64
7	448	OP-150	93,114	±139.3	5,130	5.83%	11.45
8	983	OP-130 OP-140	91,769	±174.3	3,785	4.30%	3.85
9	864	OP-60 OP-140	91,494	±140.8	3,510	3.99%	4.06
10	864	OP-90 OP-140	91,492	±149.2	3,508	3.99%	4.06
11	777	OP-100 OP-140	91,391	±138.7	3,407	3.87%	4.38
12	864	OP-90 OP-130	91,330	±157.9	3,346	3.80%	3.87
13	1,043	OP-40	91,245	±163.3	3,261	3.71%	3.13
14	864	OP-60 OP-130	91,230	±155.3	3,246	3.69%	3.76
15	777	OP-100 OP-130	91,222	±153.1	3,238	3.68%	4.17
16	507	OP-130	91,175	±143.4	3,191	3.63%	6.29
17	1,015	OP-60 OP-90 OP-100	91,159	±145.2	3,175	3.61%	3.13
18	1,015	OP-90 OP-90 OP-100	91,137	±153.6	3,153	3.58%	3.11
19	658	OP-90 OP-100	91,116	±139.8	3,132	3.56%	4.76
20	507	OP-140	91,109	±138.6	3,125	3.55%	6.16
21	1,015	OP-60 OP-60 OP-100	91,079	±151.7	3,095	3.52%	3.05
22	864	OP-110	91,038	±118.7	3,054	3.47%	3.53
23	745	OP-60 OP-60	90,760	±144.9	2,776	3.16%	3.73
24	658	OP-60 OP-100	90,739	±135.2	2,755	3.13%	4.19
25	745	OP-60 OP-90	90,735	±145.0	2,751	3.13%	3.69
26	388	OP-60	90,694	±151.3	2,710	3.08%	6.98
27	745	OP-90 OP-90	90,576	±128.8	2,592	2.95%	3.48
28	301	OP-100	90,575	±130.7	2,591	2.94%	8.61
29	983	OP-30	90,330	±112.6	2,346	2.67%	2.39
30	388	OP-90	90,208	±126.4	2,224	2.53%	5.73

[1)] Calculated by Equation (6).

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