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자동차 엔진공장의 크랭크샤프트 라인설계를 위한 시뮬레이션 사례연구

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A Case Study of Simulation for the Design of Crankshaft Line in an Automotive Engine Shop

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ABSTRACT

The major components of an engine are the cylinder block, cylinder head, crankshaft, connecting rod, and camshaft, which are more popularly known as the 5 C's. Thus, the engine shop usually consists of six sub-lines, including five machining lines and one assembly line. The flow line is the typical concept of the layout when the engineer designs the engine shop. This paper introduces a simulation study regarding the new crankshaft machining line in a Korean automotive factory. The major factors for designing the machining line are considered, and their effects on the system performance are evaluated with a three-dimensional (3D) simulation model that is developed with QUEST®. The initial layout is analyzed using the simulation model, and we suggest some ideas for improvement.

Key words : 3D simulation, Automotive, Crankshaft line, Design

요 약

자동차 엔진을 구성하는 주요부품은 실린더블록, 실린더헤드, 크랭크샤프트, 커넥팅로드, 캠샤프트 등으로 구성되는데 이들의 영문명을 따서 5C라고 부른다. 따라서 일반적으로 엔진공장은 5C를 생산하는 라인과, 엔진 조립라인을 포함하는 6개의 라인으로 구성이 된다. 엔진공장은 소품종대량생산의 특성을 가지기 때문에 장비의 배치형태는 흐름라인의 형태를 따른다. 본 논문에서는 국내 자동차 회사 엔진공장의 크랭크샤프트라인 설계를 위한 시뮬레이션 사례를 소개한다. 크랭크샤프트 라인은 기계가공을 중심으로 하는 라인이다. 따라서 라인설계에 영향을 미치는 요인들에 대해 소개하고, 라인 효율에 미치는 영향을 QUEST®라는 3차원 시뮬레이션 도구를 이용하여 분석하였다. 기술팀에서 제시한 초기배치안에 대해 시뮬레이션 모델을 구축한 후 실험을 통하여 시스템 효율을 개선시키기 위한 방법을 제시하였다.

주요어 : 3D 시뮬레이션, 자동차, 크랭크샤프트라인, 설계

1. INTRODUCTION

The major sub-assemblies that make up an engine are popularly called the 5 C's, namely, camshafts, crankshafts, cylinder blocks, cylinder heads, and connecting rods. Each of these sub-assemblies is composed of hundreds of parts. These major sub-assemblies are machined and assembled in their respective production systems, and the completed sub-assemblies are delivered 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 an engine that translates the reciprocating linear piston motion into the rotation motion (see Fig. 1). To produce a crankshaft, various machining processes (turning, milling, drilling, rolling, grinding, finishing and burnishing) and measuring pro-

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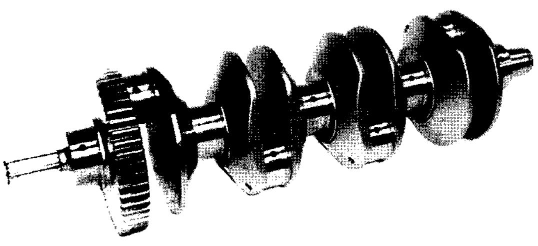

Fig. 1. Example of crankshaft

cesses are required. Although the process-flow of a crankshaft line is different among automotive factories, the layout concept typically used is the flow-line considering the concept of mass production.

The manufacturing lines of the sub-assemblies of an engine are either highly automated or semi-automated. However, there are various reasons of breakdown, for example, 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 breakdown of the whole line due to the breakdown of a particular operation. 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.

In the past, there were some research works that dealt with the performance of a simulation for the verification of the design of a manufacturing line in an automotive factory. Ulgen et al. (1994) discussed the use of discrete-event simulation in the design and operation of body and paint shops in North American Vehicle Assembly Plants. 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. Four categories were observed in this classification, namely, the conceptual design phase, the detailed design phase, the launching phase, and the fully operational phase. The second classification was based on the nature of the problem investigated. Four categories were also observed in this classification. These were equipment and layout design issues, issues related to variation management, product-mix sequencing issues, and other operational issues.

Jayaraman and Agarwal (1996) addressed a general concept when the simulation technique is applied to the engine plant. Furthermore, 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, Kumar and Houshyar (2002), as well as by Moon, Sung and Choi (2003).

From the end of 1990's, digital manufacturing technology has been widely implemented in industries. In the automotive industries, the development of digital manufacturing technology enables to shorten the developing period of a new car. Digital manufacturing links the product development, the production planning and the facility planning using various computer solutions. The core technologies of digital manufacturing are digital mock-up (DMU) and 3D simulation. Wöhlke and Schiller (2005) called the procedure using the two technologies as the digital planning validation (DPV). 3D simulation consists of 3D mechanical simulation like robot simulation, and 3D system simulation (discrete event simulation).

Relative to 2D system simulation, 3D system simulation has the merit of the additional information regarding the validity of the layout design with respect to the utilization of space (not area). Moon et al. (2003, 2005 and 2006) applied 3D simulation to the designs of the engine block machining line, the PBS (Painted Body Storage) and the body shop in the Korean automotive factories respectively.

The crankshaft line considered in this paper is an existing system and various machining processes are included in the line. The factory has a plan to build a new engine shop, but it is still going to use the existing crankshaft line with some modifications. Thus, there are many constraints for designing the new system. Figure 2 shows the initial design of the new crankshaft line. The length of the line is 87 m and the width is 18 m.

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.

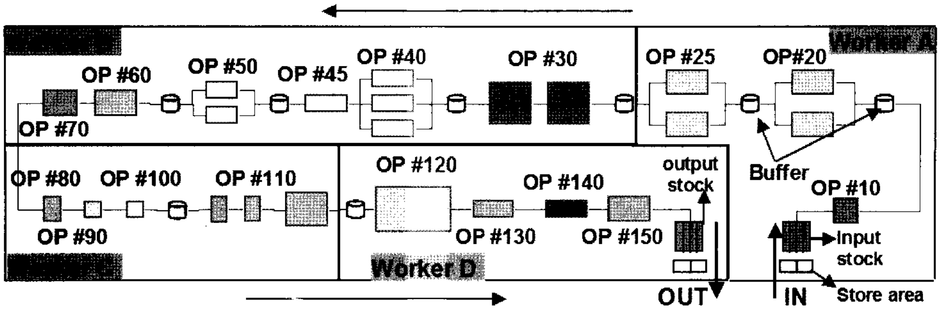

Fig. 2. The initial layout of the crankshaft line

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. CONFIGURATION OF THE SYSTEM

The layout concept of the crankshaft line considered in this paper is a typical flow line (see Fig. 2). Most of the operations are connected serially, but some operations are designed with a partially parallel system. The purpose of installing parallel operations is to reduce the risk of the breakdown of a line. Figure 2 shows the concept of crankshaft line considered in this paper. OP #20, OP #25, OP #40, and OP #50 are parallel operations. Thus, a part can choose only one of the two or three machines to finish the operation and then go on to the next operation. One operation consists of several machines.

2.1 Characteristic of the system

- **Operation and cycle time**

Operations are designed by the type of process and by the time required to finish the process. At each operation, each part is processed during a constant period of time (which is called the 'operation cycle time') because most of the machines are automated. Loading time and unloading time are included in the operation cycle time. However, the transportation time between two consecutive operations is not included in the operation cycle time because there is at least one stock in each operation, and the part is moved to the next operation during the processing time. There are multiple parallel machines for one operation because the tasks are complex, and it is difficult to separate them into two operations.

- **Buffer**

A single lane conveyor (not a closed loop conveyor but a magazine type conveyor) is used as the buffer, and the length of the conveyor determines the capacity of each buffer. In the existing crankshaft line, the capacity of each buffer is the same at 20. The operating logic being followed is the FILO (first in, last out), because one conveyor is used as the buffer. To pick out the oldest part first from the buffer (it means FIFO), two conveyors are necessary. The factory determined to use only one conveyor as the buffer considering the space available and investment cost.

- **Gantry loader**

A gantry loader and a conveyor are widely used as a transportation equipment in the flow line. Although the cost of a gantry loader is expensive, it is preferred over the conveyor because of its features such as the ability to produce less noise and to acquire a good position. In the design of a gantry loader, the number of gantry loader installed and the covering area for each gantry loader are very important. Thus, the effects of gantry loader on the performance measure of the system should be investigated by reviewing the utilizations of them.

■ Worker

There are three kinds of workers in the automotive production line: the production worker, the support worker, and the administrative worker. In the crankshaft line, there are only support workers who are responsible for machine operations, loading and unloading of parts, in-line-gauging, and basic preventive maintenance. Four workers are allocated in the whole crankshaft line, and the working areas of these four workers are shown in Figure 2. The walking speed of the worker is 60 cm/sec. The effect when the number of workers is reduced from four to three was evaluated in the what-if simulation.

2.2 Performance measures

In automotive factories, the major performance measure is the job-per-hour (JPH), and it refers to the number of products produced in an hour. The value of the JPH is the throughput target, and it is determined in the early stage of engineering by the top manager considering the market. Process planning and capacity planning are also conducted to meet the target JPH. The value of the JPH set by the top manager in this factory is 50.

The following are the secondary measures related to the simulation study:

- Utilization of each gantry loader
- Utilization of each buffer
- Utilization of each worker

3. PROCESS MODELING

The process model is used to understand the system and analyze the static aspect of the processes. It facilitates human understanding and communication by documenting the system considered. It is also helpful in gaining insights on how to improve the system during the phases of definition and analysis.

■ Operations and cycle times

An operation is composed of more than one processes, for example there are five drilling processes in OP45. There are 17 operations in the line, and the number of machines in each operation and the cycle time are listed in Table 1.

■ In-line gauging

The in-line gauging refers to a kind of inspection process after finishing an operation. The worker inspects a part for every 50 pieces and the gauging time is five minutes. There are 13 operations requires for in-line gauging as shown in Table 1.

■ Down times

There are three kinds of downtimes, namely, machine failure, minor breakdown, and tool exchange. The downtime distributions are obtained from the historical data. The mean values of the MCBF (mean count between failure: it means the sum of operating cycles of a machine divided by the total number of failures) and the MTTR (mean time to repair) of the machine failure and minor breakdown are listed in Table 2. Exponential distributions are used for the MCBF and MTTR. In a machining process, tool should be changed at every predetermined number of parts, and the predetermined number is used for MCBF. Thus, if two or more tools are used in a machine, different MCBF are independently implemented to each tool.

Table 1. Configuration of operation

Operation	Op10	Op20	Op25	Op30	Op40
Number of machines	1	2	2	2	3
In-line gauging	yes	yes	yes	yes	no
Cycle time	44	89	89	89	165
Operation	Op45	Op50	Op60	Op70	Op80
Number of machines	1	2	1	1	1
In-line gauging	yes	yes	yes	yes	yes
Cycle time	55	55	44	44	44
Operation	Op90	Op100	Op110	Op120	Op130
Number of machines	1	1	3	1	1
In-line gauging	yes	yes	yes	yes	no
Cycle time	44	44	133	44	44
Operation	Op140	Op150			
Number of machines	1	1			
In-line gauging	no	no			
Cycle time	44	44			

Table 2. Failure distributions

Operation	Machine Failure		Minor Break	
	MCBF (units)	MTTR (min)	MCBF (units)	MTTR (min)
Op10	43,507.5	47.5	83.3	5.4
Op20	38,673.3	208.9	500.0	7.5
Op25	26,773.8	100.0	500.0	7.5
Op30	174,030.0	20.0	500.0	7.5
Op40	29,005.0	74.2	500.0	7.5
Op45	174,030.0	20.0	500.0	7.5
Op50	21,753.8	148.8	500.0	7.5
Op60	34,806.0	157.0	500.0	7.5
Op70	29,005.0	54.2	500.0	7.5
Op80	21,753.8	81.3	500.0	7.5
Op90	29,005.0	114.2	500.0	7.5
Op100	24,861.4	97.1	500.0	7.5
Op110	19,336.7	80.2	500.0	7.5
Op120	9,159.5	68.7	500.0	7.5
Op130	174,030.0	70.0	500.0	7.5
Op140	17,4030.0	70.0	500.0	7.5
Op150	58,010.0	61.7	500.0	7.5

■ Input and output

There are two stocks, the input stock and the output stock. Each stock has four magazines, and 20 parts can be stored in each magazine. Therefore, the capacity of a stock is 80.

When a raw material arrives at the storage area (it means that a part is generated from the source), a worker picks up the raw material and transports it to the input stock. The handling time is six seconds. Then the gantry loader transports the raw material from the input stock to OP #10. When a part finishes OP #150, a gantry loader picks up the finished part and transports it to the output stock. Then a worker inspects the part and transports it to the output storage area. The mean process time including both inspection and transportation is 41 seconds. Figure 3 shows the structure of the input /output stock.

■ Gantry loader

There are 11 gantry loaders including a gantry loader connecting the input stock and OP #10, and a gantry loader connecting the OP #150 and the output stock.

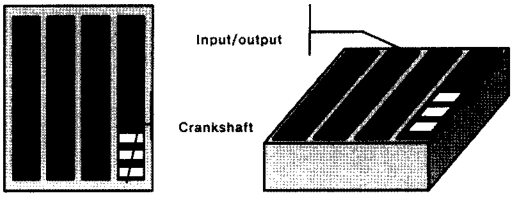

Fig. 3. Structure of input/output stock

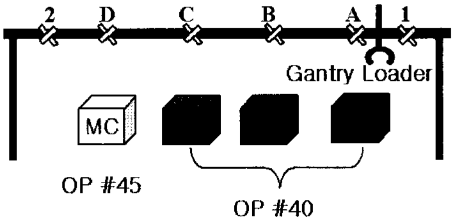

Fig. 4. Structure of the gantry loader of OP #40 and OP #45

The speed of gantry loader is 2 m/sec and the acceleration speed is 2.5 m/sec^2.

Figure 4 shows the layout of Op #40 and OP #45. Three machines in OP #40 and one machine in OP #45 are operated by one gantry loader. In this figure, the points 1 and 2 are pickup and release point respectively. The points A, B, C and D denote the stopping positions of the gantry loader for transporting a part.

4. SIMULATION MODELING

The dynamic analysis can be performed using simulation techniques that permit the determination of the current and future behaviour of the process. In this work, a discrete event simulation is used. Three -dimensional (3D) simulation models are developed with QUEST®. Some equipments are drawn in Factory CAD®.

There are many principles of logic used in this crankshaft line model such as the operating logic of the buffer, that of in-line gauging, that of the workers, and finally, the operating logic of the gantry loader. All of these are programmed with the Simulation Control Language (SCL) that is supported by QUEST®. The logic of the gantry loader is somewhat complex. Figure 5 shows the basic control logic of the gantry loader.

In the simulation model, the shortage of the part (raw material) should not occur because a large amount of part is continuously supplied in practice. In QUEST®, the object that creates part (raw material) is called as 'source'. Two logics are generally used for creating part in the 'source'. One is the logic of push system in which the part is created by a given distribution function. This logic is used when the part arrives independently from the outside of the system. In this case, the shortage of raw material occurs when the inter arrival time is too long. Sometimes, the inventory level at the 'source' increases tremendously when the worker is too much busy or the Op #10 (or the next operations) is broken down for a long time. However, the demerit of 3D simulation model is the speed of running when there are so many 3D objectives including parts. Thus, large inventory of the part in the 'source' should be prevented in the simulation model, and it is difficult to control the inventory level by the logic of push system.

The other method is to use the logic of pull system suggested by Toyota Production System. It means that a new part is created when the part previously created is transported to the input stock by a worker. This logic enables to control the inventory level of part in the 'buffer' which is connected to 'source'. However, the shortage of the part still occurs in the input stock when the worker is busy and the transportation is delayed. To prevent both of shortage and excessive inventory, the logic in Figure 6 is linked to the 'buffer'. Furthermore, we permit calling the worker only when the inventory level of input stock is less than 40. The number was determined by the experiences of factory. Figure 7 is a snapshot of the completed simulation model.

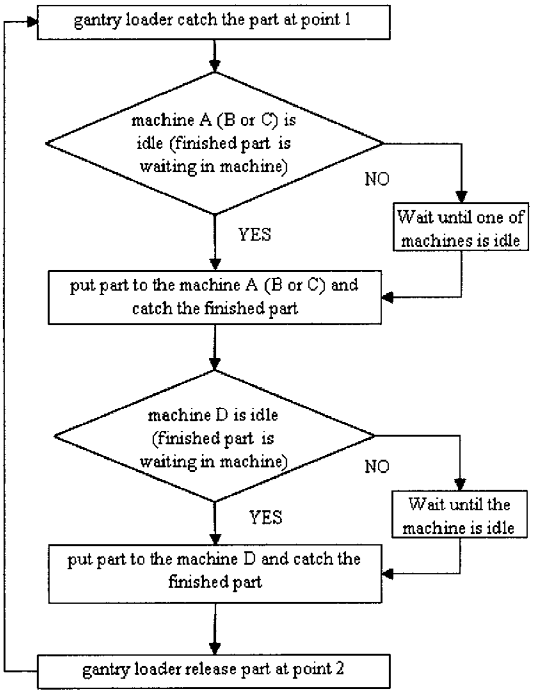

Fig. 5. Control logic of the gantry loader

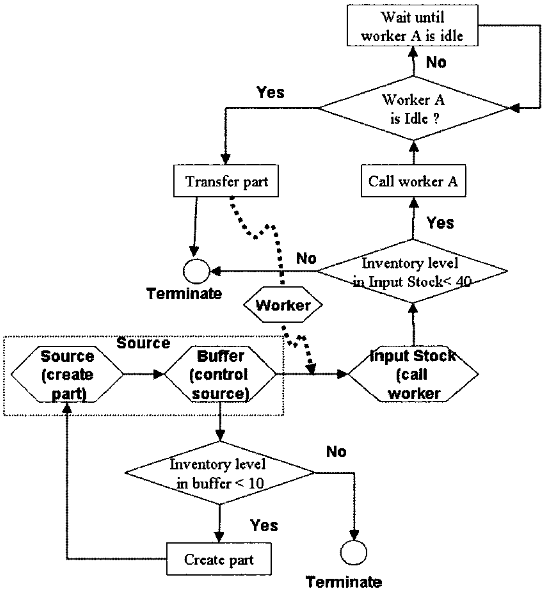

Fig. 6. Control logic of supplying raw material

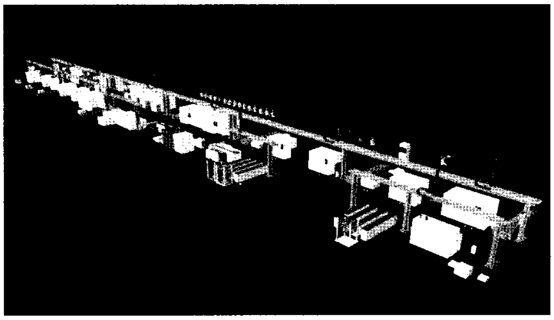

Fig. 7. Snapshot of the simulation model

5. EXPERIMENTS AND RESULTS

The simulation run time was set to one year, and the warm-up period was set to five days. For each scenario, five replications were conducted. As-is analysis was carried out to investigate the performance of the initial layout of the crankshaft line. With the result obtained from the as-is analysis, some improvements were suggested and were then verified in a what-if simulation.

5.1 As-is analysis

The constraints of the crankshaft line are machine failure, minor breakdown, tool exchange, in-line gauging, and so on. Therefore, we investigate which constraint has the most impact on the performance of the system by adding a new constraint one by one. Table 3 shows the scenarios of the experiments and their resulting throughputs.

For the first five scenarios, we know that 'tool exchange' is the most effective constraint, and 'minor breakdown' is the second. From scenario 6 to scenario 9, the constraints are added one by one until all constraints are included. In the experiments, the resulting throughput was 51.4 JPH. This value satisfied the target JPH when all the constraints are included.

Figure 8 shows the utilization of the machines in scenario 9. The total downtime rate including machine failure, minor breakdown, and tool exchange is high in OP #10, OP #20, and OP #25. This is due to the fact that the machines in OP #10 ~ OP #25 are specialized machines and have no tool magazines. Thus, the tool exchange time is greater than that of other machines. To overcome this problem, new machines that have automatic tool magazines should be replaced, or better tools that have a longer tool life should be used. However, it is difficult to adopt both alternatives because of practical limitations.

The utilization of the buffers in scenario 9 is shown in Table 4. It is clear that the utilization of all buffers is not high enough to install all buffers. The highest utilization rate is 79.31% for the buffer between OP #10 and OP #20. The reason for such a high utilization rate is the frequent breakdown of OP #20. Therefore, one way to improve the design is to reduce the buffers having low utilization.

The next concern is the utilization of workers. The utilizations of the workers A and D are obviously higher than those of the other two workers (see Table 5). The reasons are the very high workloads at the input and output stocks, and the frequent machine failures of

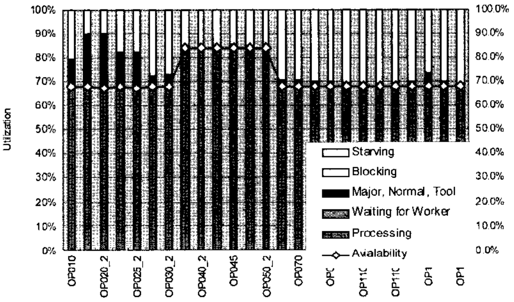

Fig. 8. Machine utilizations of scenario 9

Table 3. Scenario of the As-is analysis

No.	Minor break	Machine failure	Tool exchange	Scrap	In-line gauging	JPH
1	X	X	X	X	X	65.52
2	X	X	X	O	X	65.18
3	O	X	X	X	X	63.62
4	X	O	X	X	X	63.93
5	X	X	O	X	X	56.93
6	O	O	X	X	X	62.09
7	O	O	O	X	X	55.57
8	O	O	O	O	X	55.28
9	O	O	O	O	O	51.40

Table 4. Utilizations of buffers in scenario 9

No.	Buffer Name	Average Load (pcs)	Capacity (pcs)	Utilization (%)
1	010-020	15.861	20	79.31%
2	020-025	3.817	20	19.09%
3	025-030	1.839	20	9.20%
4	030-040	7.215	20	36.08%
5	045-050	1.451	20	7.26%
6	050-060	0.898	20	4.50%
7	100-110	0.477	20	2.39%
8	110-120	0.522	23	2.27%

Table 5. Utilization of workers in scenario 9

Worker	State			Utilization
	Idle	Busy		
		Processing	Empty Travel	
A	11.81%	80.21%	7.98%	88.19%
B	47.98%	47.75%	4.27%	52.02%
C	47.75%	48.23%	4.02%	52.25%
D	32.03%	63.85%	4.12%	67.97%

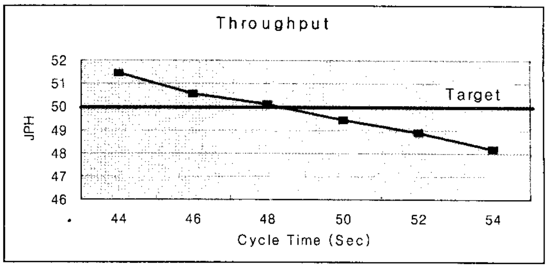

Fig. 9. Change of throughput in scenario 10

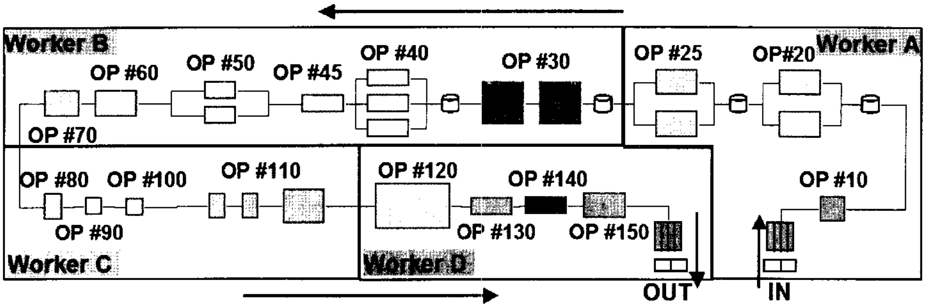

Fig. 10. Layout of scenario 11

the Op #20 and Op #25. This means that the number of workers, as well as ways on how to enhance the working area should be considered in order to improve the performance of the system.

5.2 What-if analysis

From the 'As-is' analysis, we obtained the following observations:

1. The cycle time of some operations can be increased without decreasing the throughput. The purpose of this experiment is to investigate the possibility of reducing the number of machines (scenario 10).
2. There are some buffers that can be eliminated without decreasing the throughput (scenario 11).
3. The layout of the crankshaft line is a kind of U-line suggested in the Toyota Production System. One of the important management strategies in the U-line system is that a worker is made responsible for both input and output. Thus, the work areas of the workers are changed (scenario 12).
4. The number of workers can be reduced from four to three without decreasing the throughput (scenarios 13-1 and 13-2)

■ Scenario 10: Increasing the cycle time

The average operation cycle time was increased from 44 seconds to 46 seconds and then to 48 seconds gradually. It means that the cycle time of OP #110 is increased from 133 seconds to 139 seconds and then to 145 seconds because there are 3 machines in OP #110. From this experiment, the operation cycle time could be increased from 44 seconds to 48 seconds. Unfortunately, the number of machines could not be reduced. Figure 9 shows the result of throughput when the cycle time has been changed.

■ Scenario 11: Eliminating the buffer

The utilizations of the five buffers in Table 4 were less than ten percent. Although the last four buffers in Table 4 are eliminated, the throughput was 50.8 JPH. Thus, we concluded that four buffers could be eliminated without loss in the throughput. Figure 10 shows the new layout.

Furthermore, additional one buffer which is located between Op #25 and Op #30 is eliminated, because it is the buffer showing the next low utilization. Then, the JPH of this new layout was 49.1. It means that even

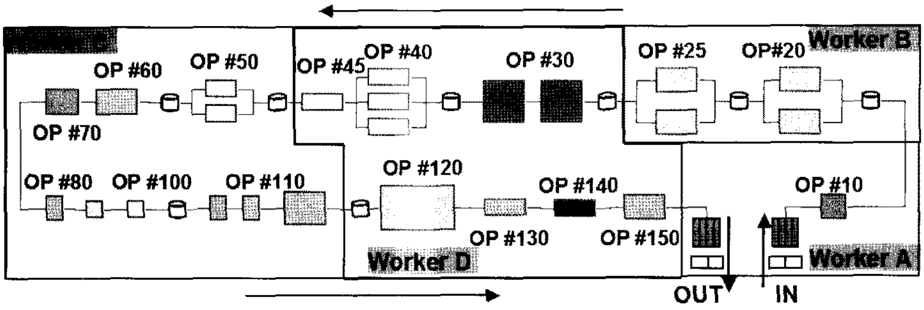

Fig. 11. Layout of scenario 12

though utilization of the buffer between Op #25 and Op #30 is a little low, it is better to keep it in the production line.

Table 6. Utilization of workers of scenario 12

Worker	State			Utilization
	Idle	Busy		
		Processing	Empty Travel	
A	4.66%	56.04%	39.31%	95.34%
B	46.78%	51.27%	1.96%	53.22%
C	66.03%	31.95%	2.02%	33.97%
D	32.02%	63.36%	4.62%	67.98%

■ Scenario 12: Worker re-allocation

The concept of new allocation is based on the rule which is suggested by Toyota Production System. The rule is that one worker is responsible for both of the input and output operations. Thus the work areas were changed from the scenario 9, and the new layout is shown in Figure 11. As a result, the throughput was decreased from 51.4 JPH to 43.1JPH. The reason for this is that the workload of worker A is too much high because the distance between input stock and the output stock is 12 m and it takes 20 seconds for moving. Worker A frequently moved between the two stocks and it increased the percentages of empty travel. Thus, it became the new constraint of the system's performance. Table 6 shows the workloads of the workers when new allocation is implemented.

■ Scenario 13: Reducing one worker

In scenario 13, the number of workers is reduced from four to three under the assumption that four buffers are eliminated (scenario 11). Although there are many alternatives of allocating workers being considered, two alternatives are introduced in this paper (we call them as the scenario 13-1 and 13-2 respectively).

Figure 12 and 13 show the new layouts of scenario 13-1 and 13-2. The concept of the worker assignment in Figure 11 is that a worker handles successive operations. On the contrary, the concept of the worker assignment in Figure 12 is that a worker can handle operations located across the aisle.

The utilizations of the workers in these two new layouts (13-1 and 13-2) are showed in the Table 7. The utilizations of workers of scenario 13-1 are balanced better than those of scenario 13-2. The workload of worker C in scenario 13-2 is a little bit higher than that of worker B. However, it is meaningless to allocate an operation belong to the worker C (for example, OP #45 or OP #120) to the worker B, because any of the two operations does not satisfy the reasonable workload of the worker B. It means that the utilization of worker B increases almost to 100% and the worker B becomes the bottleneck of the system. Thus, with the viewpoint of utilization, scenario 13-1 is better than scenario 13-2.

The values of JPH of these two new layouts (13-1 and 13-2) were 48.94 and 49.57 respectively. The p-value of F-test for evaluating the difference of variances was 0.1566. Thus, it is difficult to say that

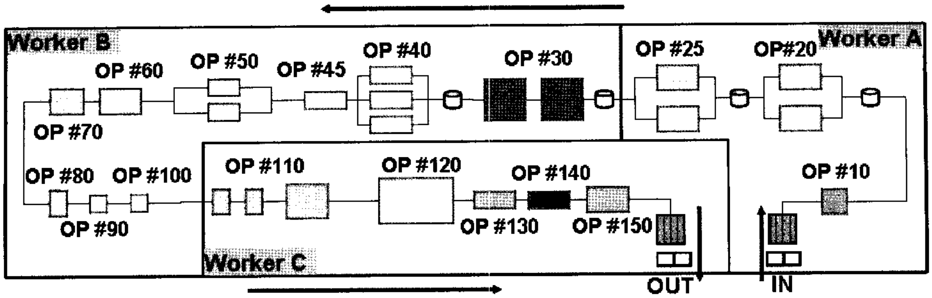

Fig. 12. Layout of scenario 13-1

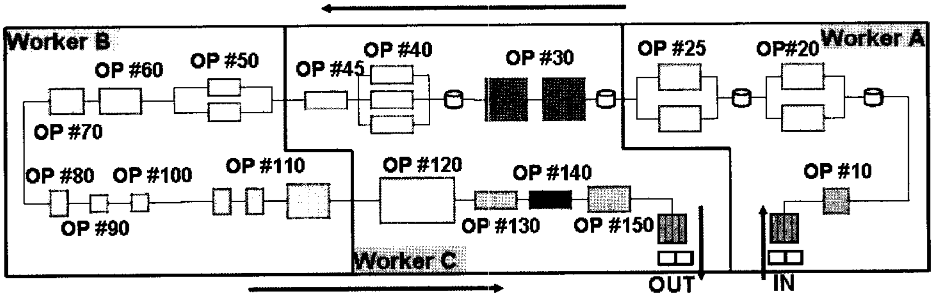

Fig. 13. Layout of scenario 13-2

Table 7. Worker utilizations of scenario 13-1 and 13-2

Worker	Scenario 13-1		Scenario 13-2	
	Mean	Std.	Mean	Std.
A	84.30%	0.59%	85.50%	0.49%
B	84.78%	0.53%	79.01%	0.94%
C	82.68%	1.20%	88.94%	1.68%

Table 8. Throughputs of scenario 13-1 and 13-2

Throughput (JPH)	Scenario 13-1	Scenario 13-2
Mean	48.94	49.57
Std.	0.09	0.21

the variances of the two scenarios are different with the 95% confidence level. The p-value of t-test for testing the difference between means was 0.0019. Thus, we concluded that the throughput of scenario 13-2 was higher than that of scenario 13-1. Although the throughput of scenario 13-2 was better, scenario 13-1 should be selected for the final design because the workloads of the workers were well balanced if there were no additional actions to balance the workloads.

In the 'What-if' analysis, we came to a conclusion that four buffers could be eliminated without the loss of throughput. The target throughput was achieved when the cycle time of operation was increased from 44 seconds to 48 seconds. However, it was impossible to reduce even one machine in the parallel operations. The result of scenario 12 indicated that it was difficult to assign both input and output operations to one worker, although it was beneficial for the management of the flow line. To assign both tasks to one worker, the distance between input stock and the output stock should be decreased, and additional automatic inspection equipment should be installed. Finally we tested the possibility of reducing one worker. Two alternate layouts (scenarios 13-1 and 13-2) were suggested and both of them could not meet the target throughput. In practice the factory preferred the scenario 13-2 with installing a new inspection device in the output stock.

5. CONCLUSION

If a design error of the production line is found at the mass-production stage, a considerable amount of costs and time is required to solve the problem. Therefore, the simulation should be implemented earlier. The computer simulation made it possible to verify the interaction among the components of the system, i.e., resources, buffers, transporters, and workers. The 3D simulation was also useful for checking the space constraints and the working areas of the workers.

In this paper, we explained the configuration of the crankshaft line in a Korean automotive factory, and the procedure of simulation study. From the 'As-is' analysis, we proved that the initial layout satisfies the throughput target. The 'What-if' analysis was then carried out to save on investment and operating costs. As a result, four buffers can be eliminated without the loss of throughput. The number of workers can be reduced from four to three.

For further research, the product mix strategy should be considered, because the operation cycle time is changed when two or more models are machined in this line. The crankshaft line is one of the sub-lines in an engine shop. Thus, this simulation study should be extended to the whole engine shop, and the efficient 3D simulation modelling technique to develop a large system should be studied.

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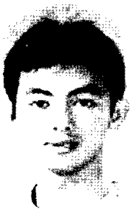

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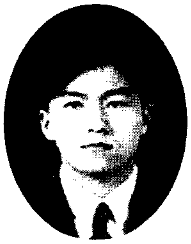

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