Comparison of the Two Layout Structures in Automotive Body Shops Considering Failure Distributions

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There are many challenges in manufacturing system for new factory construction. Although factories produce same product, the layout of each factory may be different. The body shop in an automotive factory is a typical flow line with assembly, but the layout concept of the line varies among factories. In this paper, two types of layouts in the body shops of automotive factories, one for layered build and the other for modular build, are compared using simulation study. The simulation experiments indicate that the modular build layout is better than the layered build layout with respect to production rate. The effects of various failure distributions on the throughputs are also investigated, and some insights are suggested regarding the layout concept.

Keywords: Body shop, Layout structure, Performance, Failure distribution

1. Introduction

Developing new manufacturing system designs in automotive factories involves several challenges. First, the overall concept of the layout pattern should be determined, and then various types of machines and material-handling equipment are selected. At the same time, welding points should be assigned to the welding robots taking the line balancing into consideration. All these jobs are processed in sequence and many iterative jobs are needed to determine the final design.

The function of body shop is to assemble various parts produced in press shop using welding processes. Generally, the body shop is divided into 15~20 sub-assembly lines (see Moon et al., 2006). Each sub-line represents a welding area covering numerous welding operations in different stations. Of course, one or more sub-lines can be outsourced in order to improve the performance of the factory. The decoupled sub-
lines are connected with the power-and-free conveyor or with an electric monorail system (EMS). The function of the conveyor (or EMS) is the transportation of the sub-assembly to the next sub-line and also the preparation of buffer space preparing for any unexpected breakdowns of the two consecutive sub-lines. Each sub-line is a fully automated serial line with no buffer between operations and all operations in sub-line are synchronized. It means that although the real cycle times (welding times) are different among operations, the transportations to the next operation in a sub-line are occurred at the same time, and thus, this type of line is called as a transfer line. <Figure 1> shows the example of sub-line of body shop.

![Figure 1. Example of sub-line in body shop](image1)

The layout structure of an automotive body shop is characterized by the following two factors. The one is different engineering methods. Moon et al. (2012b) addressed that there are two types of construction methods, one is layered build method and the other is modular build method as shown in <Figure 2>. In a layered build method, some parts such as the inner panel and the outer panel of side body are assembled one by one in a same sub-line (see <Figure 2(a)>). However, in a modular build method, those parts (e.g., inner panel and outer panel) are pre-assembled as a sub-assembly in other sub-line, and it is assembled to the main body in another sub-line (see <Figure 2(b)>). It is difficult to conclude which method is better because there are both merits and demerits in each other. Some people say that the layered build method is better with respect to the accessibility of robot gun, and the method guarantees the better quality of welded body. However, it has the weakness of increasing welding points and the over load in main body sub-line. It is known that many of Japanese automotive companies adopt modular build method, but GM (General Motors) has changed from modular build to layered build. The second is the habit of system design. Although two companies adapt same engineering concept, the layout concepts are different each other. It means that although two companies adopt modular build method, there are differences in detail layouts such as number of sub-lines and allocating welding points.

There are two approaches for evaluating the performance of manufacturing system design, and they are mathematical analysis and simulation modeling. Simulation has been widely used for analyzing the real manufacturing systems of automotives. Ulgen et al. (1994), Spieckermann et al. (2000), Kahan et al. (2009) have studied about body shop using simulation. Moon et al. (2006) described the design process in an automotive body shop and explained simulation study. Kibria and McLean (2007) developed an automotive final assembly simulation model to enable interoperability testing. Tahar and Adham (2010) presented the development of manufacturing system design, operation, and maintenance based on simulation. The model was being developed at two different levels: the supply chain and the assembly plant. Cohen (2013) considered a problem how to divide the assem-
Table 1. Main topics of literatures related to body shop

<table>
<thead>
<tr>
<th>Literature</th>
<th>Layout concept comparison</th>
<th>Design processes</th>
<th>Workload re-allocation</th>
<th>Buffer allocation</th>
<th>Relationship with other shop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ulgen et al. (1994)</td>
<td></td>
<td></td>
<td></td>
<td>O</td>
<td></td>
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<tr>
<td>Spieckermann et al. (2000)</td>
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<td>Kahan et al. (2009)</td>
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<td>Moon et al. (2006)</td>
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<tr>
<td>Kibria and McLean (2007)</td>
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<td>Tahar and Adham (2010)</td>
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<td>O</td>
<td></td>
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<tr>
<td>Cohen (2013)</td>
<td></td>
<td></td>
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<td>O</td>
<td></td>
</tr>
<tr>
<td>This paper</td>
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</tr>
</tbody>
</table>

bly lines into segments, and develop a framework for assessing the impact of line segmentation. <Table 1> compares the major concerns of literatures related to body shop.

Queueing theory is the most popular mathematical method, but it has limitation for analysis due to the complexity of system structure. Earlier works related to the queueing analysis are addressed well in Gershwin (1994), Liberopoulos et al. (2006), Curry and Feldman (2009) and Li and Meerkov (2009). There have been two types of approaches for analyzing the complex manufacturing system such as body shop which consists of transfer line and assembly line. The first is the decomposition method suggested by Gershwin (1994) and the other is the aggregation method by Li and Meerkov (2009). However, they still assumed that service process is Poisson process or machines are reliable without failure, and the objectives are limited to the throughput in general. Furthermore, they did not consider the characteristic of automated transfer line in which a failure of one machine results in the stop of whole line. On the other hands, Dhouib et al. (2009) presented a paper for evaluating the performance of approximate analytical approaches dealing with non-homogeneous automated transfer line. Recently, Li et al. (2009) suggested further research areas related to the manufacturing system design using queueing network theory, and Liu and Li (2010) suggested an algorithm for analyzing split and merge system.

In practice, the first consideration for manufacturing system design is to determine the layout concept. There are many factors being considered such as throughput (or production rate), WIP (work in process), maintainability and repairability for failure, investment and so on. Especially, the downtime distribution of machine which are cause by failure and tool change influences on the throughput and WIP, and the variance of downtime is more critical than the mean value. Xu et al. (2010) compared the performances of layout concepts in automotive engine machining lines and Moon et al. (2012a) investigated the effects of distribution functions of TTF (Time to Failure or uptime) and TTR (Time to Repair or downtime) on the system performances such as throughput, WIP and lead time. In their paper, eight types of distribution functions for both TTF and TTR which have different first, second and third moments were selected.

The first objective of this paper is to compare the throughputs of the two different layout concepts (we will use production rates as a performance measure) in automotive body shops. The second objective is to investigated the effects of distribution functions of TTF (Time to Failure) and TTR (Time to Repair) on the system performance. The intension of second objective is to check the possibility of replacing the complex failure distribution function with the function easy to handle mathematically such as Hyper-exponential distribution function. In chapter 2, two layout concepts and their manufacturing contexts are defined. The failure distributions of TTF and TTR are defined in chapter 3, and it is followed by simulation experiments. Finally, the analysis of simulation experiments and conclusion are addressed in chapter 5.

2. System Contexts

2.1 Layout structures of systems

<Figure 3> shows an example of body shop layout in an automotive factory which is explained in Moon et al. (2006). The dashed area is the front sub-assembly lines in automotive body shop which assemble the basic structure of main body, especially with respect to the side body, and it is the scope of this paper. This layout structure is a kind of modular build type and more detail layout is in <Figure 4(b)>: The layout concepts of front sub-assembly lines are different among manufacturers with respect to the welding methods as shown in <Figure 2>. On the contrary, the layout concepts of latter assembly lines are similar among the manufacturers of automotives. <Figure
Comparison of the Two Layout Structures in Automotive Body Shops Considering Failure Distributions

Figure 3. Example of body shop layout (Moon et al., 2006)

Figure 4. Two layout structures of front sub-assembly lines

Figure 5. Two assumed layout models

2.2 Assumed layout system models

To compare the performances of layout structure, two types of assumed layout models are defined as shown in Figure 5(a) and Figure 5(b), respectively (see Moon et al., 2012b). The following assumptions are used for defining the system.

1. The total numbers of welding operations (workloads) are same and they are assumed to be 36.
2. Each sub-assembly line has six operations, and there is no buffer in each sub-line. However, in Figure 5(b), the Side_CPL_LH line and the Side_CPL_RH line are assumed to have only three operations for balancing total workloads.
3. There are buffers (usually electric monorail system) between two sub-assembly lines, and the total amounts of buffers are assumed as 30 in both models. The locations of buffers in Figure 5(a) are five and those of Figure 5(b) are six. Thus, we assume that the buffer sizes in all location are six and five, respectively.
The cycle times of all welding operations are known and constant as one minute because a body shop is a highly automated manufacturing system.

There is only one type of time dependent failure for all operations and the distribution of TTF and TTR are known and same.

There is no starvation for the first operations and there is no blocking in the final operations.

3. Failure Distributions

One of the main objectives of this study is to evaluate the effect of failure distribution in two different layout structures. Although there are many causes of machine breakdown in real world systems, only a single mode of failure is considered. Eight kinds of failure distributions are determined as in Table 2 and Table 3 (See Moon et al., 2012a). The value of MTTF is set to 240 minutes and that of MTTR is set to 10 minutes. Then the average percentage of downtime of each machine is 4% and the theoretical efficiency of each machine is 96% without considering blockage and starvation.

$$e = \frac{MTTF}{MTTF + MTTR} = 0.96$$

The distribution function of TTR is fixed as EXPO (10) which means exponential distribution with the mean of 10 minutes. To evaluate the effect of failure distribution on performance, the eight kinds of distribution functions of TTF are determined as shown in Table 2, where LOGN means lognormal distribution, WEIB means Weibull distribution and H_EXPO denotes hyper-exponential distribution.

Let $X$ be the random variable with the first three moments $E(X^k) = m_k$, $k = 1, 2, 3$. The squared coefficient of variation of $X$ is $CV^2 = \frac{m_2}{m_1^2} - 1$. It is known that the mean queue length depends only on the arrival rate and the first two moments of service time in the M/G/1 queueing system, whereas it depends on the arrival time distribution and service rate in the G/M/c queueing system (Gross and Harris, 1985). It is also reported that the influence of higher moments on the processing time distribution in production lines is moderate (Powell and Pyke, 1994; Lau, 1987). However, the data collected by the field supervisors usually does not include any information concerning the third or any higher moment.

For analyzing the effects of failure distribution, we consider two kinds of distribution which are presented for matching the moments of non negative random variables such as hyper-exponential distribution of order 2 and Coxian distribution with Erlang node. The hyper-exponential distribution of order 2, which is denoted by $H_2 (p; \gamma_1, \gamma_2)$ or simply $H_2$, has the probability density function as in equation (2).

$$f(t) = p \gamma_1 e^{-\gamma_1 t} + (1-p) \gamma_2 e^{-\gamma_2 t}, \quad t \geq 0. \quad (2)$$

The parameters $p$, $\gamma_1$ and $\gamma_2$ can be determined by the first two moments $m_1$ and $CV^2 \geq 1$ of $X$ as follows,

$$p = \frac{1}{2} \left( 1 + \sqrt{\frac{CV^2 - 1}{CV^2 + 1}} \right), \quad \gamma_1 = \frac{2p}{m_1}, \quad \gamma_2 = \frac{2(1-p)}{m_1}. \quad (3)$$

The $H_2$ distribution can also be used for fitting the three moments of nonnegative random variables satisfying $CV^2 \geq 1$ and

$$H = \frac{m_1 m_2}{1.5 m_2^2} > 1. \quad (4)$$

In this case, the distribution $H_2 (p; \gamma_1, \gamma_2)$ with the pre-assigned moments $m_k$, $k = 1, 2, 3$ is uniquely determined by the parameters (Whitt, 1982).

$$\gamma_1 = \frac{1}{2} \left( a_1 + \sqrt{a_1^2 - 4a_2} \right), \quad \gamma_2 = \frac{1}{2} \left( a_1 - \sqrt{a_1^2 - 4a_2} \right), \quad p = \frac{\gamma_1 (1 - \gamma_2 m_1)}{\gamma_1 - \gamma_2}, \quad (5)$$

where

$$a_2 = \frac{6m_1^2 - 3m_2}{1.5m_2^2 - m_1 m_2}, \quad a_1 = \frac{1}{m_1} \left( 1 + \frac{1}{2} m_2 a_2 \right) \quad (6)$$

Let $E_k(\mu)$ denote the Erlang distribution of order $k$ (ERLA) with the parameter $\mu$. The first two moments of $X$ with $\frac{1}{k} \leq CV^2 \leq \frac{k^2 + 4}{4k}$ for $k \geq 1$, can be fitted by the mixture of two Erlang distributions (denoted by $E_{1,k}(p; \mu)$) with probability density function (Tijms, 1994).

$$f(t) = p \mu e^{-\mu t} + (1-p) p_k \mu^{k-1} \frac{1}{(k-1)!} e^{-\mu t}, \quad t > 0 \quad (7)$$

where

$$p = \frac{2kCV^2 + (k-2) - \sqrt{k^2 + 4 - 4kCV^2}}{2(k-1)(1 + CV^2)}, \quad (8)$$

$$\mu = \frac{p + k(1-p)}{m_1}$$
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### Table 2. Moments and parameters of TTF distributions

<table>
<thead>
<tr>
<th>Dist</th>
<th>Group</th>
<th>Case</th>
<th>Moments</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>m₁</td>
<td>CV²</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>α</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>p</td>
</tr>
</tbody>
</table>

#### Group 1
- Case 1: WEIB1
  - m₁ = 240
  - CV² = 0.5
  - m₃ = 4.01874 × 10⁷
  - α = 1.4355226
  - β = 194.830404

#### Group 2
- Case 2: M_ERLA
  - m₁ = 240
  - CV² = 0.5
  - m₃ = 4.14703 × 10⁷
  - p = 0.80153
  - k = 2
  - μ = 120

- Case 3: ERLA
  - m₁ = 240
  - CV² = 0.5
  - m₃ = 8.29440 × 10⁷
  - μ = 240

#### Group 3
- Case 4: EXPO
  - m₁ = 240
  - CV² = 2
  - m₃ = 1.00538 × 10⁸
  - p = 0.720905
  - γ₁ = 117.8500
  - γ₂ = 475.7757

- Case 5: LOGN
  - m₁ = 240
  - CV² = 2
  - m₃ = 6.000.0
  - μ = 240
  - σ = 240

### Table 3. Moments and parameters of TTR distributions

<table>
<thead>
<tr>
<th>Dist</th>
<th>Group</th>
<th>Case</th>
<th>Moments</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>m₁</td>
<td>CV²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>α</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>p</td>
</tr>
</tbody>
</table>

#### Group 1
- Case 1: WEIB1
  - m₁ = 10
  - CV² = 0.5
  - m₃ = 2,907.1
  - α = 1.4355
  - β = 11.01321

#### Group 2
- Case 2: M_ERLA
  - m₁ = 10
  - CV² = 0.5
  - m₃ = 2,907.1
  - p = 0.80153
  - k = 2
  - μ = 5

#### Group 3
- Case 3: ERLA
  - m₁ = 10
  - CV² = 2
  - m₃ = 16,420.3
  - p = 0.720905
  - γ₃ = 8.1179335
  - γ₁ = 0.203649
  - γ₂ = 0.050444

- Case 4: H_EXPO1
  - m₁ = 10
  - CV² = 2
  - m₃ = 16,420.3
  - p = 0.658728
  - 1/γ₃ = 0.203649
  - 1/γ₂ = 0.050444

- Case 5: H_EXPO2
  - m₁ = 10
  - CV² = 2
  - m₃ = 18,000.0
  - p = 0.788675
  - 1/γ₃ = 0.157735
  - 1/γ₂ = 0.042265

### 4. Simulation Experiments and Results

The simulation models are developed with Arena™. The followings are determined as the performance measures for gathering statistics in simulation experiments. At first, production rate means the rate of production quantity during the unit time (one minute) and it is the most important performance measure in manufacturing system design. We also assumed that a part would be supplied to the first machine whenever it becomes idle and there is no blocking at the last machine.

The performance measure, production rate, is defined as follows, and it means the rate of production quantity during the unit time. Note that the cycle times of all operations are assumed to be same as one time unit in this model.

\[
\text{production rate} = \frac{\text{production quantity} \times \text{longest cycle time of operations}}{\text{total production time}}
\]

The simulation run time is set to 1,100,000 minutes and the warm-up period is set to 100,000 minutes. For each scenario,
150 replications are conducted and the average values of statistics are listed.

4.1 Variation in TTF

<Table 4> shows the average production rates and 95% confidence intervals obtained from the experiments when the distributions of TTF are changed following to <Table 2> under the assumption that the distribution function of TTF was fixed as EXPO(10). <Figure 6> shows the behavior of production rates in all scenarios. Within each case, it is obvious that the production rate of modular build type is better than that of layered build type. The second observation is that the production rate increases as the increase of the total buffer size of the system. On the contrary, the production rate has a decreasing tendency as the increase of the variance of TTF. Another interesting observation is that the gap between modular build and layered build increases as the increase of buffer size from 30, 60 and 120, but the gap begins to decrease when the buffer size increases more than a certain value. Thus the gap becomes to be very small when infinite buffer is assumed. Note that the maximum production rate of the system depends on the maximum number of stations in sublines because no buffers are allowed in a subline and infinite buffer are allowed between sublines. Then the upper bound of production rate is 0.96 = 0.7828.

Lau and Martin (1987), Powell and Pyke (1994), and Manitz (2008) have reported that the influence of higher moments (above the second) of the processing time distribution on the throughput in production lines is moderate, and thus they used only the first and second moments for their analyses. However, in this paper we assume that the process time is constant, but the failure is probabilistic. Note that the $m_1$ and $CV^2$ of cases 1, 2 and 3 are same, but the $m_3$ of case 3 is greater than that of case 1 (or case 2). Thus we conduct a two tail t-test and calculate p-values as shown in <Table 5>. The upper triangle of each type in <Table 5> represents the layer build layout and the lower triangle represents the modular build layout. Note that null hypothesis ($H_0$) is that two sample means are same. The production rates of most cases seem to be different statistically with the 95% of confidence when the total buffer size is set to 30. However the throughputs in same groups (shaded area in <Table 5>) are difficult to say different when the buffer size is set to infinite. Thus, we conclude that we do not have to spend time for finding exact distribution if we know mean and variance of failure data when buffer size is very big.

4.2 Variation in TTR

<Table 6> shows the average production rates and 95% confidence intervals obtained from the experiments when the distributions of TTR are changed following to <Table 3> under the assumption that the distribution function of TTF was fixed as EXPO (240). <Figure 7> shows the behavior of production rates for all scenarios. For all cases, it is obvious that the production rate of modular build type is better than that of layered build type. Other observations are similar to those in section 4.1. A new finding is that the effect of variance in TTR is more crucial than that of TTF. It means that the amount of decrement in production rate becomes greater when the variance becomes bigger.

<table>
<thead>
<tr>
<th>Throughput</th>
<th>Distribution</th>
<th>Total number of buffer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Layered</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Group 1</td>
<td>Case 1</td>
<td>WEIB1</td>
</tr>
<tr>
<td></td>
<td>Case 2</td>
<td>M_ERLA</td>
</tr>
<tr>
<td></td>
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<td>ERLA</td>
</tr>
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<td>Case 4</td>
<td>EXPO</td>
</tr>
<tr>
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<td>Case 5</td>
<td>LOGN</td>
</tr>
<tr>
<td>Group 3</td>
<td>Case 6</td>
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<tr>
<td></td>
<td>Case 7</td>
<td>H_EXPO1</td>
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<td>Case 8</td>
<td>H_EXPO2</td>
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</table>
Figure 6. Comparison of production rates for TTF

Table 5. Results of t-test (p-value) for TTF

<table>
<thead>
<tr>
<th>Modular</th>
<th>Layered</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td>Case 1</td>
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<td></td>
<td>Case 8</td>
<td>0.0000</td>
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(b) Total buffer size = Infinite

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<th>Group 2</th>
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<tr>
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<td>Case 8</td>
<td>0.0000</td>
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Figure 7. Total flow time in the system for TTR

Table 6. Production rates of experiments (TTR)

<table>
<thead>
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<th>Distribution</th>
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<th>Modular</th>
<th>Layered</th>
<th>Modular</th>
<th>Layered</th>
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<td>0.4483</td>
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<td>WEIB2</td>
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<td>Case 7</td>
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<Table 7> lists the p-values of t-tests under the null hypothesis (Ho) which assumes that two sample means are same. However, in infinite buffer case, the production rates in same groups (shaded area in <Table 7>) are different especially in Group 3. From this result we can conclude that although the first three moments are the same, the production rate depends on the type of distribution function.

Generally, it is known that the second moment of distribution influences on the performance measures of system. Thus, if the variances of TTF or TTR become bigger, then the production rates become smaller. When we set CV² = 0.5 (cases 1, 2 and 3) for TTR, the production rates are always better than the cases of TTF. However, in the cases of CV² = 2.0 (cases 6, 7 and 8), the production rates of TTR are smaller than those of TTF. It means that the effect of the variance of TTR is more significant than the variance of TTF.

5. Conclusions

In this paper, we discussed the performance of layout structures which are widely used in the body shops in automotive factories. The assembly methods of a car using welding processes are divided into two, the one is layered build type and the other is modular build type. The first motive of this research is which method is superior with respect to production rate. The second motive is to analyze the effects of failure distribution functions on the production rate. In manufacturing design problems, queueing network theory and computer simulation are generally used for estimating performance measures such as throughput (production rate), WIP and etc. When an assembly system is analyzed with queueing theory, one of the difficulties lies in the failure distribution, because the Markov property is not satisfied under the general distribution function of failure. This is the reason that most of researches assumed exponential failure distribution or approximation method considering the first two moments. If there is no severe difference in production rate among different distributions, we can replace the real distribution to the distribution easy to handle such as exponential, hyper-exponential or mixed-Erlang. Thus, we select eight types of distribution of which first moments are all the same and some of them have same second or third moments.

From the results of simulation experiments, we found some observations having useful meanings. The first is that the modular build layout is better than the layered build layout with respect to production rate for all experiments. We presume that this phenomenon is due to the following two reasons. Although the total buffer capacities are same, the number of buffer locations is six in the modular build layout, but it is five in the layered build layout. In the layered build layout, there are three stages which consist with six operations (transfer line), but there are two stages with six operations and one stage with three operations in modular build layout.

The second observation is that the gap of production rate between two layout structures is increased as the increase of total buffer at a certain point, and then it begins to decrease. Thus, the gap becomes very small when infinite buffers are assumed. The third observation is that the effect of the variance of TTR is more significant than the variance of TTF. Finally, we can conclude that although the first three moments are the same, the production rate depends on the type of distribution function. These observations are applied when we determine layout concept in automated assembly shops such as electrical appliances.

For further research, we will optimize the buffer assignment with respect to the total cost which includes investment cost and WIP cost. Furthermore, we can compare the robustness of two layout structures with respect to the mixed model production.

References


Liberopoulos, G., Papadopoulos, C. T., Tan, B., Smith, J. M., and


