Coordinating Differential Customer Lead Times in Relation to the Manufacturing Constraints

Henny.P.G. van Ooijen

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Graduate School of Industrial Engineering and Management Science
Eindhoven University of Technology
P.O.Box 513, Paviljoen F1
NL-5600 MB Eindhoven
The Netherlands

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ABSTRACT

In many make-to-order production situations differential customer lead times often result in differential flow rates (number of operations performed per period). The practice today is that decisions regarding the customer lead times often are taken by the Sales department without considering the impact this may have for manufacturing. This may lead to a capacity problem for manufacturing through which many orders will not be delivered in time. This latter may lead to dissatisfied customers which may be lost for the company. In this paper we derive a method which makes it possible, taking into account manufacturing lead time constraints, to work with differential customer lead times. By means of a simulation study this method has been tested for a production situation where only two different flow rates are required. It turns out that up to a required waiting time reduction for one of the products of about 60% it is possible, using our method, to obtain the desired waiting time reduction in a controlled way.
1. Introduction.

In many make-to-order production situations customers (may) have different lead time requirements even for the same kind of products. For instance Harrison et.al [ ] notice that many high level managers at National Semiconductor Corporation endorse the concept of planning lead times differentiated by order priority status. With that, they mean establishing shorter planning lead times for production lots associated with major (OEM) customers and other urgent orders. Since the service aspect becomes more and more important as a competitive weapon, it is for the Sales department, amongst others, important to have some flexibility with respect to the lead times they can agree upon with the customers. For most production situations today this flexibility is created by Sales itself without taking into account manufacturing. As a result most of the customer requirements regarding the lead time are accepted by Sales without knowing the possible implications this has for manufacturing. Therefore it is not surprising to see that most of the accepted orders are not delivered in time. This is due to production constraints that, in general, do not fit with all the different lead time requirements that Sales arranged with the customers. Customers will be dissatisfied with the service of the company with respect to the delivery reliability and may not return.

Not only accepting the different lead time requirements customers have, but also acting to these requirements is important. This means that Sales has to know what can be arranged with the customers without creating an impossible task for manufacturing. We need to coordinate the different customer lead time requirements (Sales) and the manufacturing possibilities (manufacturing). Stated otherwise: sales need to have flexibility in arranging lead times to customers, however this flexibility need to be determined together with manufacturing.

In this paper we will consider job shop like production situations, that is production situations with a functional lay-out and a job shop routing structure, were products are made to order. The job shop routing structure implies that from each work center (a group of similar machines) work
orders can flow to a number of other work centers. In such production situations throughput time control is a very important issue because of the interaction between throughput time, capacity utilization and batch sizes. A generally accepted way to control the average work order throughput times is to control the work load in the shop, which is known as input/output planning (see Bechte [ ], Bertrand and Wortmann [ ] and Kingsman and Tatsiopoulos [ ]). These techniques are based on the calculation of a norm for the (remaining) work load in the shop given a certain required average throughput time. By controlling the (remaining) work load in the shop according to this norm, it is guaranteed that the average throughput time equals the average throughput time norm.

However, in this way we only control the average throughput time and thus the average flow rate (number of operations performed per period) for all work orders released to the shop. In case customers have different, product independent, lead time requirements, this often only can be achieved by having different flow rates at the work centers. This means that we would like to have different (controlled) flow rates for different (categories) of products. In other words, we would like to group products into categories and use a priority procedure such that at the work centers work orders for products in different categories have different controlled throughput times. In section 2 we will derive a method for generating different flow rates for work orders for different (categories of) products for make-to-order production situations where some form of work load control is used and all products have the same average routing length. This method will be checked by a simulation study that will be described in section 3. Next, in section 4, we present and discuss the experimental results. Finally, in section 5, we summarize our findings in a conclusion.


Suppose we have a number of categories of products, in the remainder of this article called products, and that for each product a different (known) average waiting time has to be realized.
Clearly, to realize different waiting times the decision-maker must be told at what speed the various work orders are expected to get through the work centers. An obvious way to communicate this to the shop floor is to assign operation due dates to the operations in the routing of a work order, based on the waiting time norms (allowances) to be realized. Thus, where there are two products, for work orders which belong to the fast category we assign operation due dates which imply that there is only a little allowance for waiting, whereas for work orders which belong to the slow category we assign operation due dates which imply a large allowance for waiting. Now the question is whether such a simple heuristic, in combination with a due date related sequencing rule, indeed 'forces' the individual work orders to flow at rates implied by these due dates. As has been demonstrated by Kanet and Hayya [ ], operation due dates are very effective in this respect; they realize a small variance in work order lateness. Therefore we will use the operation due date sequencing rule.

Of course using operation due dates for setting flow rate norms (via waiting time norms) implicitly assumes that the real flow rates are in accordance with the flow rate norms used for setting operation due dates. In other words we require realistic due dates. However, we may expect that not every combination of flow rates can be realized. For instance, suppose we have a single machine shop and two products (A and B) and that both products have equal production characteristics: they have a Poisson arrival pattern with an arrival rate of one order per hour, and a negative exponential processing time with a mean value of 27 min. Suppose further that the orders are sequenced according to the operation due dates, where the due dates are independent of the processing times. Then we know from queueing theory (Kleinrock [ ]) that the expected waiting time averaged over the orders for both products is 243 min.

Now suppose that we want different flow rates for orders for product A and for orders for product B. In this case it will be impossible to realize at the same time an average waiting time of 50 min for orders for product A and an average waiting time of 300 min for orders for product B. This can be shown as follows. The average waiting time over all orders is given by general
queueing formulae and the weighted sum of the average of the waiting times of orders for both products equals this given average overall waiting time. Thus, for the present,

\[ \frac{1}{2}W_A + \frac{1}{2}W_B = W_T \]

where \( W_A \) is the average waiting time for orders for product A, \( W_B \) is the average waiting time for orders for product B and \( W_T \) is the average overall waiting time. Evidently the values \( W_A = 50 \), \( W_B = 300 \) and \( W_T = 243 \) do not fit the above equation. Other values such as \( W_A = 200 \), \( W_B = 286 \) and \( W_T = 243 \), however, would fit.

The above restriction on the flow rates (waiting times) can be stated in more general terms. Consider a production department with \( M \) work centers. Suppose we have \( K \) different products with the following relative shop arrival rates of the order streams:

\[ \frac{\lambda_i}{\lambda} \quad i=1,\ldots,K \]

where \( \lambda_i \) is the average number of arrivals of orders for product \( i \) per unit of time, and \( \lambda \) is the total average number of arrivals of orders per unit of time. Furthermore suppose that the work load in the shop is controlled, using a work load control method, such that the actual average waiting time for work center \( m \) equals \( W_m \). Then, actual values for the average waiting times of orders for the different products obey the equation:

\[ \lambda_1 W_{m,1} + \lambda_2 W_{m,2} + \ldots + \lambda_K W_{m,K} = \lambda W_m \quad m=1,\ldots,M \quad (1) \]

where \( W_{m,k} \) is the actual average waiting time for product \( k \) at work center \( m \), \( m=1,\ldots,M \) and \( W_m \) is the actual average overall waiting time at work center \( m \), \( m=1,\ldots,M \).

If we want the actual waiting times to be equal to the allowances, or to be in accordance with the required flow rates, it is clear that the same relationship must exist between the allowances used in the process of setting operation due dates. Thus, if \( A \) denotes the allowance we must demand that

\[ \lambda_1 A_{m,1} + \lambda_2 A_{m,2} + \ldots + \lambda_K A_{m,K} = \lambda A_m \quad m=1,\ldots,M \quad (2) \]

Now the remaining question is the following: suppose (i) we control the work load in the
production department (using some form of work load control, see Plossl and Welch [1979], Bertrand and Wortmann [1981], Bechte [1982] and Kingsman and Tatsiopoulos [1983]) such that \( W_m = A_m \) for \( m = 1, \ldots, M \) (see Eilon and Chowdhury [1976]); and (ii) we use operation due date sequencing with due dates based on waiting time allowances which obey equation (2). Is then the actual average waiting time per product equal to the waiting time allowance, or will there be a difference? And if there is a difference, how large is it, and how can it be explained and controlled?

If the actual waiting times turn out to be equal to the allowances, then we have found a practical method of working with different predictable flow rates. Using equation (2) sales now know which lead times they can promise to the customers without creating a (capacity) problem for manufacturing. Therefore, deliveries will be more reliable and customers may be more satisfied with the service of the company.

Previous research.

Bertrand and van Ooijen [ ] and Ooijen [ ] tested the above described method for different utilization rates and different ratios of the arrival rates. They introduced the normalized waiting time to account for the effect that there is a lower bound \( > 0 \) for the minimum waiting time that can be achieved. This minimum waiting time \( W_{\text{min}} \) is obtained if orders for the product with the highest flow rate have absolute priority over orders for the other products. Therefore the maximum waiting time reduction that can be achieved equals \( W_{\text{fcfs}} - W_{\text{min}} \). Using this maximum reduction the results from the simulations were adapted by comparing the actual waiting time reduction to the maximum reduction that can be obtained. This they called the normalized waiting time reduction:
$100 \times \frac{W_{fcs} - W_a}{W_{fcs} - W_{min}}$

where

$W_a = \text{actual waiting time}$

$W_{fcs} = \text{overall First Come First Serve waiting time}$

$W_{min} = \text{the minimum waiting time that can be achieved using absolute priorities.}$

From the earlier mentioned previous research, based on two products, it can be concluded that to attain a normalized waiting time reduction of $x\% \ (0 \leq x \leq 60)$ for one of the products, we must decrease the waiting time allowance for this product by $x\%$ and increase the waiting time allowance for the other product such that equation 2 holds. Then using the operation due date sequencing rule it is guaranteed that the reduction will be obtained and, moreover, that it will be obtained in a controlled way (small variance in waiting time) at the order level. The results seemed to be rather insensitive to the overall capacity utilization rate of the shop and to the relative arrival rates of the orders for the two different products. It was also observed that, when using different flow rates using the earlier described method, there always is a difference between the normative flow rates (based on the waiting time allowances used) and the actual flow rates.

Based on the results of the previous research we propose a modification of the use of the earlier described method. It appeared that a reduction of the waiting time allowance of $x\%$ did not result in a decrease of the actual waiting time with $x\%$. For practical purposes however it is important to know which waiting time allowance reduction is necessary to get a certain decrease of actual waiting time. Suppose we have two (categories) of products. From the previous research we know that if we use $W_1 = \alpha W \ (0.4 < \alpha < 1.0)$ to set the operation due dates for orders for product 1, this will lead to a normalized waiting time reduction which approximately equals the waiting time allowance reduction $((1-\alpha)\%)$. So we have:
\[
\frac{W - W_{1a}}{W - W_{\text{min}}} = \frac{W - W_{1}}{W} = \frac{W - \alpha W}{W} = 1 - \alpha
\]

where

- \( W \): First Come First Serve waiting time
- \( W_{1a} \): actual waiting time for product 1
- \( W_{\text{min}} \): Head Of the Line priority waiting time for product 1 (in this case product 1 has always priority over product 2) (see Kleinrock [ ])

This gives that the actual waiting times equals

\[ W_{1a} = \alpha W + (1 - \alpha) W_{\text{min}}. \]

If we want \( W_{1a} \) want to be equal to \( \beta W \) then we have to choose \( \alpha \) such that

\[ \alpha(W - W_{\text{min}}) + W_{\text{min}} = \beta W \]

or

\[ \alpha = \frac{\beta W - W_{\text{min}}}{W - W_{\text{min}}} \tag{3} \]

Now we hypothesize that:

if we have two products and we want to have an average actual waiting time for work orders for product 1 equal to \( \beta W \) (0.4 < \( \beta < 1 \)), where \( W \) is the overall average waiting time, we have to use \( W_{1} = \alpha W \), with \( \alpha \) given by equation (3), in the process of setting operation due dates; using an allowance for product 2 such that equation (2) holds, and the operation due date sequencing rule will result in the required average actual waiting time for orders for product 1.

In the following sections we will investigate this hypothesis. Since it will be difficult, if not impossible, to use mathematical methods (we deal with a kind of closed queueing network in
which a dynamic priority rule is used) we used computer simulation to study this problem. This simulation study will be discussed in the next section. In the later sections we will discuss the results of this study.

3. The simulation study.

The production model used in our simulation study is a pure job shop (Conway et al. [1967]). Although the pure job shop is not the kind of production situation often encountered in practice, it is very useful to give insight into the value of the method proposed in section 2. With respect to the waiting time, the most interesting work centers are those with a high utilization rate. In general these will be a subset of all work centers and in this study we have chosen a subset of size five. Order routings are determined upon arrival. The routings are generated such that each work center has an equal probability of being selected as the first work center. After the first operation the probabilities for the order of either leaving the shop or going to another work center are 0.2. At each work center processing times are generated from a negative exponential probability density function with a mean value of 1 time unit. Set-up times and transportation times are considered to be zero.

For a number of products in this shop we aim to give the work orders for these products a high flow rate, whereas for the other products we aim to give the work orders a low flow rate. Therefore we distinguish only two (categories of) products: product 1, the fast product (high flow rate) and product 2, the slow product (low flow rate). Each product has its own random number generator for the determination of the order routings. Per product a different random number generator is used for the generation of the processing times.

The shop is loaded using a very simple work load control method based on the total number of orders in the shop: as soon as a job leaves the shop another job is released. Although this seems to be rather artificial it is not uncommon for most production situations to have some knowledge
of future (planned) orders. This knowledge may be used, and often is used, to pull some orders forward and release them earlier than planned. In this way it is possible to keep the total number of orders on the shop floor more or less constant.

Simulations were performed for three average shop utilization rates: ≈85%, ≈90% and ≈95%. For each utilization rate we used two ratios of the arrival rates (orders for product 1 have the high flow rate):

\[ \lambda_1 = \lambda_2; \lambda_1 = \frac{1}{3} \lambda_2 \]

For each combination of utilization rate and ratio of arrival rates we gradually reduced the desired waiting time reduction for orders for product 1 from A (the overall average waiting time allowance) to 0.4 * A in steps of 0.2 * A. We used 0.4 * A as a lower bound since from earlier research it could be concluded that up to a waiting time reduction of ≈60%, in which case the waiting time allowance equals 0.4 * A, there is an approximately one-to-one relation between the waiting time allowance reduction and the normalized actual waiting time reduction. Beyond a reduction of the waiting time allowance of 60% this relation was no longer linear. The corresponding waiting time allowances for product 1 were calculated by using equation (3). Next we used equation (2) to determine realistic waiting time allowances for orders for product 2.

4. Experimental results and discussion.

In all the simulations done the work centers have identical characteristics (such as utilization rate, average routing length, etc.), so we can omit the work center subscript.

Since we need to know the First Come First Serve waiting time and the Head of the Line priority waiting time, we first did a number of simulations using these sequencing rules. These waiting times can be found in Table 1. To get a utilization rate of ≈85% the number of orders on the shop floor was kept equal to 23. For a utilization rate of ≈90% the number of orders was kept equal to 36 and for a utilization rate of ≈95% we kept the number of orders equal to 76. Using
the waiting times from Table 1 and equation (2) and (6) we calculated the waiting time allowances to be used in the simulations we performed to test the hypothesis stated in section 2. For instance: to obtain a waiting time reduction of 40% in case we have a utilization rate of 90% and the arrival rate of product 2 is four times the arrival rate of product 1, the waiting time allowance for product 1 was set equal to \((1-0.4)*35.16-5.10)/(35.16-5.10)=0.5321\). The corresponding realistic waiting time allowance for product 2, using equation (2), then equals \((5-0.5321)/4=1.1170\).

<table>
<thead>
<tr>
<th>util=85%</th>
<th>util=90%</th>
<th>util=95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\lambda_1=\lambda_2)</td>
<td>(\lambda_1=\frac{1}{4}\lambda_2)</td>
<td>(\lambda_1=\frac{1}{4}\lambda_2)</td>
</tr>
<tr>
<td>(W_{\text{fes}})</td>
<td>22.09</td>
<td>22.06</td>
</tr>
<tr>
<td>(W_{\text{min}})</td>
<td>6.42</td>
<td>4.70</td>
</tr>
</tbody>
</table>

Table 1. The First Come First Serve and the Head of the Line waiting time for three utilization rates (util) and two ratios of the relative arrival rates \(\lambda_1=\frac{1}{4}\lambda_2\) implies that the average number of arrivals of work orders for product 2, the 'slow' product, equals four time the average arrival of work orders for product 1, the 'fast' product).

The results obtained from the simulations are listed in Tables 1, 2 and 3.

Discussion.

From the Tables 2, 3, and 4 we may conclude that the average actual waiting times for work orders for product 1 do not much differ from the waiting time allowances given to work orders for product 1. This means that using the reduction parameter determined by equation (3), to get an
average actual waiting time of $\beta W$ $(0.4<\beta<1)$, in the process of setting the due dates, in combination with the operation due date sequencing rule indeed results in an average actual waiting time that is approximately equal to $\beta W$.

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>1.0</th>
<th>0.8</th>
<th>0.6</th>
<th>0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_1=\lambda_2$</td>
<td>ALLOW</td>
<td>22.09</td>
<td>17.67</td>
<td>13.25</td>
</tr>
<tr>
<td></td>
<td>ACTU</td>
<td>21.98</td>
<td>17.00</td>
<td>12.45</td>
</tr>
<tr>
<td>$\lambda_1=\sqrt{\lambda_2}$</td>
<td>ALLOW</td>
<td>22.06</td>
<td>17.65</td>
<td>13.24</td>
</tr>
<tr>
<td></td>
<td>ACTU</td>
<td>21.96</td>
<td>17.49</td>
<td>13.23</td>
</tr>
</tbody>
</table>

Table 2. Waiting time allowances and average actual waiting times for work orders for product 1, the fast product, for a utilization rate of $\approx85\%$; $\beta$ is the reduction parameter used in equation (3). ALLOW=waiting time allowance; ACTU=average actual waiting time.

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>1.0</th>
<th>0.8</th>
<th>0.6</th>
<th>0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_1=\lambda_2$</td>
<td>ALLOW</td>
<td>35.13</td>
<td>28.10</td>
<td>21.08</td>
</tr>
<tr>
<td></td>
<td>ACTU</td>
<td>34.96</td>
<td>27.46</td>
<td>20.33</td>
</tr>
<tr>
<td>$\lambda_1=\sqrt{\lambda_2}$</td>
<td>ALLOW</td>
<td>35.16</td>
<td>28.13</td>
<td>21.09</td>
</tr>
<tr>
<td></td>
<td>ACTU</td>
<td>35.01</td>
<td>28.08</td>
<td>21.37</td>
</tr>
</tbody>
</table>

Table 3. Waiting time allowances and average actual waiting times for work orders for product 1, the fast product, for a utilization rate of $\approx90\%$; $\beta$ is the reduction
parameter used in equation (3). \( \text{ACTU} = \text{waiting time allowance}; \text{ACTU} = \text{average actual waiting time.} \\

<table>
<thead>
<tr>
<th>\beta</th>
<th>\text{ALLOW}</th>
<th>\text{ACTU}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>75.12</td>
<td>75.03</td>
</tr>
<tr>
<td>0.8</td>
<td>60.10</td>
<td>59.90</td>
</tr>
<tr>
<td>0.6</td>
<td>45.07</td>
<td>45.28</td>
</tr>
<tr>
<td>0.4</td>
<td>30.05</td>
<td>31.54</td>
</tr>
</tbody>
</table>

Table 4. Waiting time allowances and average actual waiting times for work orders for product 1, the fast product, for a utilization rate of \( \approx 95\%; \ \beta \) is the reduction parameter used in equation (3). \( \text{ALLOW} = \text{waiting time allowance}; \text{ACTU} = \text{average actual waiting time.} \\

Comparing the different Tables we can conclude that there is a (very) slight influence of the utilization rate on the performance of our method. For instance for a utilization rate of 85%, \( \beta = 0.8 \) and \( \lambda_1 = \lambda_2 \) we expect an average actual waiting time of 17.67. However we get an average actual waiting time of 17.00, which implies that in this case we get more reduction in waiting time than wanted. For a utilization rate of 95%, all other parameters being equal, we expect an average actual waiting time of 60.10 and we get 59.90, which is very close to what we wanted. This utilization rate effect on the performance of our method is stronger the higher the waiting time reduction must be. Concerning the influence of the ratio of the arrival rates it seems to be that the more orders for product 2 we have, the less the average actual waiting time reduction is for orders for product 1.
Although we did not an ANOVA study yet, we think that we may generalize our conclusions from our simulation study. This because we are only interested in relative differences (percentages) and we used common random numbers in our simulation study. Therefore we also used simulations to determine the First Come First Serve and the Head of the Line waiting time, instead of calculating them using closed queueing network theory.

Therefore, for practical purposes, in case where we have two products, we can state that two obtain an average actual waiting time for orders for product 1 equal to $\beta W$ ($0.4 < \beta < 1$), we must use a waiting time allowance for orders for product 1 given by equation 3 and use the operation due date sequencing rule.

Now if we know the average lead time that customers for product 1 would like to agree upon we can calculate the necessary waiting time reduction by subtracting the total (expected) processing time from the lead times and dividing this by the overall waiting time allowance. By using equation (3) we now can calculate which waiting time allowance must be given to orders for product 1 to obtain the desired waiting time reduction. By using equation (2) we can calculate what this means for the waiting time allowance, and thus the lead time, for customers for product 2.

For example:

suppose that in the earlier given example for orders for product A a lead time is requested of 150 time units; subtracting the average processing time of 27 time units give a required waiting time of 123 time units so $\beta = 0.5062$. Now suppose $W_{\text{min}}$ equals 50 min. then we must use $W_1 = \alpha W$ in the process of setting the due dates, with $\alpha$ equal to 

\[(0.5062 \times 243 - 50)/(243 - 50) = 0.3783.\]

Using $\alpha W$ as waiting time allowance for product 1 will result in a average actual waiting time for product 1 of $\beta W$. For product 2 we then get an average actual waiting time of $(2-\beta) \times 243 = 1.4938 \times 243 = 362.99$, since balance equation (1) holds. Balance equation (3) gives us the realistic allowance which has to be given to orders for product 2, which in this example is $(2 \times 243 - 0.3783 \times 243) = 394.07$. 

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5. Conclusions.

Based on earlier research we have derived a method which makes it possible to create different predictable flow rates for production orders of different products. This method has been tested via the simulation of a job shop with two different products. We used only two products with two different flow rates since this is a situation encountered in many practical settings: repair orders vs. normal orders, rush orders vs. normal orders, engineering orders vs. normal orders etc. The results of the simulation study showed that using equation (3) to determine the waiting time allowance that must be given to the fast product if customers for this product require a certain lead time reduction, indeed leads to the required lead time. However this only holds for lead time reductions that require a waiting time reductions that does not exceed 60% of the overall average waiting time allowance.

Using balance equation (2) Sales has an instrument with which it easily can be determined if certain customer lead time requirements do not lead to manufacturing problems. For instance if a certain lead time reduction for orders for product 1 leads to longer lead time for orders for product 2 which are not acceptable for customers of product 2, then accepting orders for product 1 with the desired lead time reduction will lead to problems. Customers for product 2 may be lost directly, which is the case if they decide not to order, or they may be lost in second instant if they are not satisfied with the resulting lead time.

In case we also would like to satisfy customers for product 2, Sales needs to agree upon another lead time for orders for product 1 or we must increase the capacity. Another possibility is to offer a discount to customer for product 2 if they are willing to accept a longer lead time. This discount, or the cost for the necessary increase in capacity, could be passed on the customers for product 1. This latter is not so unrealistic since to our experience customers are willing to pay for increased service, which in this case is given by accepting shorter lead times.
We may conclude that we have an instrument with which it is possible to coordinate manufacturing constraints and differential customer lead time requirements. The consequences of certain lead time agreements can immediately be determined which is important for the service experienced by the customer; not only in accepting their lead times but also in acting to these agreements. Moreover it can be used to determine the financial impact of certain decisions regarding the lead times.

Although this study has been restricted to two products with equal production characteristics, we think that the results from this study are more general applicable. This we base on the fact that in earlier research ([ ]), using different average routing length or more products and thus more different flow rates, the results for the normalized waiting time were comparable to the results of the study with two products and equal average routing length ([ ]).

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References.


