Emergence of non-predictable dynamics caused by shared resources in production networks

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Abstract

This paper discusses the usage of shared resources in the context of production networks. A simulation study investigates different scenarios of priority concepts for three companies within a small-scale production network including a shared resource. Throughput times of jobs are analyzed by means of statistical distributions as well as symbolic dynamics and time series analysis. It is shown that the collaborative usage of resources induces non-trivial dynamics that are hard to predict. This leads to the conclusion that further research is needed to analyze the possibilities and risks of resource sharing as well as to develop appropriate methods to enable a reasonable usage for manufacturing companies.

1. Introduction

Nowadays, the continuing trend towards mass customization leads to short product lifecycles [1]. Companies are forced to manufacture specialized products in small-scale series. In addition, emerging markets in developing countries cause a high competitive pressure. Quick product changes and the requirement of resource efficiency cause that companies can only purchase production resources if they are able to utilize them to an acceptable degree. However, since quick capacity adjustments are often not possible, production systems are generally designed to be robust in capacity [2]. In this regard, scalability and changeability are concepts to achieve this objective [3], [4]. Nevertheless, designing the production system with over-capacity violates the goal of resource-efficiency [5]. In this context, the usage of shared resources is a promising approach to achieve higher flexibility and efficiency [6]. There are two predominant models of resource sharing: Companies with temporal over-capacity offer their idle resources to other companies or several companies jointly invest in a certain resource which would not be fully utilized by or too expensive for a single company. Basically, every production resource can constitute a shared resource, e.g. a specialized machine, a raw material warehouse or a whole production line. Types of usage range from long-term and regulated joint ventures to often short-term and market-dependent outsourcing.

On the one hand, shared resources decrease the amount of fixed costs and increase responsiveness. On the other hand, shared resources carry the risk of planning uncertainty. As a consequence, the decision about using shared resources has to be made as a trade-off between resource-efficiency and planning security. Although concepts such as information sharing [7], cooperation [8], or outsourcing [9] have been investigated and discussed earlier, the situation will be different in the near future. In the light of increasing scarcity of resources and the need for resource-efficiency, companies will no longer be able to choose whether they want to share resources or not, but which model of sharing to select. In addition, new technologies like cyber-physical production systems offer new possibilities for real-time monitoring via the internet [10]. Regarding these new conditions, the topic of shared resources in manufacturing has to be revisited with a focus on the impact of sharing on the dynamics and performance of manufacturing processes. Moreover, new sharing concepts have to be developed in order to assure
suitable information processing, fair assignment of capacities as well as efficient process control.

The joint usage of shared resources induces cross-company interdependencies in production networks. Occupying a shared resource impacts on the other accessing companies as well as their production processes and material flows, which again impacts on other shared resources. This can lead to dynamical effects and feedback loops in production networks. Hence, in spite of applying suitable prediction methods (see for example [11] for a comparison of several different methods or [12] for an automated system to select and configure suitable prediction methods), key performance indicators like throughput times may be hard to predict. In this context, the predictability of a time sequence can be determined in terms of entropies after transformation into symbol sequences [13], [14].

The paper at hand studies the mentioned dynamical effects within a simulation study of a small-scale production network including a shared resource. In this context, the effects of different priority concepts for resource sharing are regarded. The results of the simulation study show that resource sharing in combination with certain priority concepts can induce different dynamical interdependencies which are difficult to predict. The paper is structured as follows: Section 2 introduces different priority concepts for resource sharing. Section 3 details the results of a simulation study of a small-scale production network including a shared resource. After a description of the simulation configuration, the applied methods for data analysis are described. Subsequently, the simulation results are analyzed and discussed. Section 4 concludes the paper and gives an outlook on further research topics regarding resource sharing and its implications.

2. Priority concepts for resource sharing

Resource sharing can be conducted according to two different models: offering over-capacity to other companies or using a resource jointly with other companies. Depending on the proportion of ownership of a shared resource, different priority concepts for capacities can be applied. Table 1 shows examples of priority concepts for resource sharing.

<table>
<thead>
<tr>
<th>Type of priority</th>
<th>Proportion of ownership</th>
<th>Size of fixed time slots</th>
<th>Job-priority in queue</th>
<th>Rights within dynamical auction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Majority owner</td>
<td>Equal proportions</td>
<td>Large time slots (high throughput)</td>
<td>High job-priorities (rush orders)</td>
<td>More rights within auction</td>
</tr>
<tr>
<td>Minority owner</td>
<td>Equal proportions</td>
<td>Small time slots (low throughput)</td>
<td>Low job-priorities (no rush orders)</td>
<td>Fair auction</td>
</tr>
</tbody>
</table>

Depending on the proportion of ownership, a company can be either a majority owner, a minority owner or equal proportions of ownership can be assigned. According to this proportion, different priority concepts are possible. For example, fixed time slots of different sizes can be assigned. Here, majority owners could receive large time slots meaning a high throughput, whereas minority owners could receive small time slots leading to lower throughput. Another concept can concern the job-priorities in a queue. In this case, jobs of majority owners can be assigned high priority for example by allowing a certain amount of rush orders with highest priority. In contrast, jobs of minority owners are assigned a lower priority, which leads to longer waiting times in the queue. In addition to these two priority-concepts for resource sharing, further concepts like different rights within dynamical auctions can be possible. In this paper, the first two mentioned concepts of the size of fixed time slots and the job-priority within a queue are considered.

3. Simulation study

This section addresses a simulation study of a small-scale production network including a shared resource. After a description of the simulation configuration, the applied methods for data analysis are described. Subsequently, the simulation results of three different scenarios are analyzed.

3.1. Simulation configuration

A discrete event simulation has been developed to investigate the dynamical behavior of the integration of a shared resource, which is accessed by a number of manufacturing companies. The simulation model consists of three manufacturing companies. Each company receives orders and processes these orders on privately owned and controlled work systems. In the final manufacturing step, the orders of all three companies are routed to a commonly used shared resource (SR), which does the final processing of the orders. The SR is modeled as an M/M/1 queuing system: Orders arrive from the three companies at the SR with exponentially distributed inter-arrival times and arrival rate \( \lambda = 0.3 \). Processing time at the SR is also exponentially distributed with service rate \( \mu = 1 \). The queue is served in FIFO order by a single server if not stated otherwise. To ensure the comparability of simulation runs across different scenarios, a fixed random number seed has been used for all scenarios, so that inter-arrival times and processing times of individual orders correspond throughout the whole simulation study. Fig. 1 shows a sketch of the simulation model.

In order to investigate the different priority concepts presented in Section 2, three scenarios were created: In Scenario 1, the basic scenario, all orders coming from the three companies have equal priority and fixed time slots are used to schedule the work of the different companies at the SR. The SR is assigned to each company in turn and exclusively processes orders of this company in FIFO order during the scheduled time slot. Upon reassignment of the SR to another company, orders in process are finished and not preempted. All companies receive an equal proportion of processing time. The size of the assigned time slot has been gradually increased in order to find out which time slot size is feasible. Scenario 2 simulates a priority concept, in which one
company (Company 3) takes a dominating position and can use the SR for a longer time period compared to the other companies. Companies 1 and 2 are granted 4 time units for processing, while Company 3 is granted between 100 and 150 percent of this time (between 4 and 6 time units). Scenario 3 simulates a job-priority, where Company 3 is allowed to release priority orders, which directly move to the front of the queue when they are released to the SR. However, these priority orders do not preempt the order already being processed. Every order leaving Company 3 is randomly marked as a priority order with probability \( p \). To determine the influence of \( p \) on the dynamical behavior, sub-scenarios for values of \( p \) between 0 and 1 have been evaluated.

3.2. Applied methods for data analysis

In order to analyze the performance of the shared resource as well as the three companies of the production network, key performance indicators have to be defined. On this account, throughput times (sum of waiting and processing times in the production systems of the considered company and the shared resource) are considered. The throughput time of the \( n \)-th job of company \( c \) is

\[
y_{c,n} \in \mathbb{R}^+, \quad c \in \{1, 2, 3\}; \quad n \in \{1, \ldots, N\}
\]

Methods for data analysis used in this paper can be categorized as statistical methods and methods from nonlinear time series analysis. The statistical distributions of throughput times per company are characterized by the minimum \( y_{c,\text{min}} \), mean \( \overline{y}_c \) and maximum values \( y_{c,\text{max}} \) as well as by the standard deviations \( \sigma_c \). Moreover, the mean value \( \overline{y}_c \) and standard deviation \( \sigma_c \) over all companies are computed. In order to visualize the distributions, box plots are shown.

In addition to the statistical distributions, the predictability of the throughput times of the different companies’ jobs is analyzed by means of nonlinear time series analysis. On this account, entropies of the time series after transforming into symbol sequences are calculated. In information theory, entropy measures the amount of information contained in an output signal of a source [15]. A high entropy and hence much information within an observed signal implies high uncertainty and low predictability. In this context, the maximum entropy is reached for a signal of uniform distribution, e.g. a white noise process, because, in this case, all events have equal probability. In this paper, the regarded signals are symbol sequences derived from the time series of throughput times according to concepts of symbolic dynamics [16]. For this purpose, the time series of length \( N \) are transformed into symbol sequences of \( N \) discrete elements of an alphabet \( \mathbf{A}^3 = \{1, 2, 3\} \) different symbols. A transformation into one of three different symbols \( (\mathbf{A} = \{0, 1, 2\}) \) is applied:

\[
f(y_{c,n}) = \begin{cases} 0 & \text{when } y_{c,n} \leq \overline{y} \\ 1 & \text{when } \overline{y} < y_{c,n} \leq \overline{y} + 2\sigma_c \\ 2 & \text{when } y_{c,n} > \overline{y} + 2\sigma_c \\ \end{cases}
\]

Low throughput time values are transformed into 0, medium-sized values into 1 and high values into 2. Two possible approaches to compute the entropy of the source signal are by using entropies of blocks of \( B \) subsequent symbols or by using conditional block-entropies [15]. In this paper, the first approach of using (unconditional) block-entropies is applied. Referring to the analogy of an alphabet, these blocks \( w \in \mathbf{A}^B \) can be interpreted as words of length \( B \).

For an alphabet containing \( S \) different symbols, the number of possible words of length \( B \) is \( S^B \). Each possible word is uniquely encoded as an integer value between 1 and \( S^B \). For an exemplary illustration of transforming a time series into \( S = 3 \) different symbols as well as encoding symbol blocks of length \( B = 2 \) as integers between 1 and \( S^B = 3^2 = 9 \), see Fig. 2.

In order to calculate the entropy of the symbol sequence after encoding blocks of length \( B \) as integers, the relative frequencies \( p(w) \) of the \( S^B \) possible blocks are determined through a histogram. The Shannon block-entropy for successive blocks of length \( B \) is computed as

\[
H \text{ }_B = -\sum_{w \in \mathbf{A}^B} p(w) \log_2 p(w).
\]

Using the block-entropies, the Shannon entropy of the...
complete source can be computed as (see [15])
\[
H = \lim_{B \to \infty} \frac{H_B}{B} \in [0, 1].
\] (4)

Since the maximum block-entropy for blocks of length \(B\) is obtained for a uniform distribution of the relative frequencies \(p(w) = \frac{1}{S}\), it follows that
\[
H_B = -\sum_{w=1}^{S} p(w) \log_2 p(w) = -\frac{1}{S} \sum_{w=1}^{S} B \log_2 S = B. \] (5)

Hence, the division by the maximum entropy in equation (4) can be regarded as normalization to [0,1]. In this paper, the number of symbols contained in the alphabet is \(S=3\). The applied block size is \(B=8\). Thus, the source entropy is computed by the approximation
\[
H = \frac{H_B}{8}. \] (6)

In this way, a good compromise between a sufficient convergence and the exponentially increasing computational effort is achieved.

3.3. Analysis of Scenario 1: No priority

This subsection analyzes the results of the first simulation scenario. All three companies have equal priority. The SR subsequently assigns fixed time slots of equal size to the jobs of the three companies. By varying the size of the time slots from 1 to 20, eleven simulation runs are conducted. Fig. 3a) shows the box plots as well as the mean values and the standard deviations of the three companies’ throughput time distributions for each simulation run. There are no considerable differences between the throughput time distributions of the three companies. On average, the mean and median values increase moderately with increasing time slots which are offered at the SR. This result is more obvious for the first two companies than for the third. The average minimum, mean and maximum values as well as the average standard deviations are almost equal for Companies 1 and 2, while Company 3 has higher values (see Table 2), which can be explained as a result of the randomness of the simulation input.

Table 2. Average minimum, mean and maximum values as well as average standard deviations per company \(c\) for the three scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\bar{c})</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>(\bar{y}_{\min})</td>
<td>0.08</td>
<td>0.09</td>
<td>0.13</td>
</tr>
<tr>
<td>(\bar{y}_{\max})</td>
<td>21.38</td>
<td>22.54</td>
<td>31.13</td>
</tr>
<tr>
<td>(\bar{y}_w)</td>
<td>65.9</td>
<td>70.3</td>
<td>91.26</td>
</tr>
<tr>
<td>(\bar{\sigma}_{\max})</td>
<td>14.15</td>
<td>15.09</td>
<td>19.37</td>
</tr>
</tbody>
</table>

Fig. 4a) shows the entropies of the three companies’ symbol sequences of throughput times transformed according to equation (2) with the thresholds specified in Table 3. The entropies and hence the predictability of the three companies’ throughput times show similar evolutions. Starting at low entropies of approximately 0.15 for a time slot size of 1, the entropies increase approximately to 0.4 for a time slot size of 14 and remain almost static for higher time slot sizes. Summing up, for Scenario 1, on average, lower throughput time values as well as a higher predictability of the throughput times are reached for small sizes of fixed time slots at the SR. This result is due to possible idle times of the SR if jobs do not exhaust the whole time slot.

Table 3. Mean values and standard deviations over all three companies for the three scenarios as well as thresholds for transforming the throughput times into symbol sequences.

<table>
<thead>
<tr>
<th>Statistical values and thresholds</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\bar{\tau}) (first threshold)</td>
<td>25.02</td>
<td>23.97</td>
<td>9.14</td>
</tr>
<tr>
<td>(\bar{\tau} + 2\sigma) (second threshold)</td>
<td>62.04</td>
<td>67.21</td>
<td>28.7</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>18.51</td>
<td>21.62</td>
<td>9.78</td>
</tr>
</tbody>
</table>

3.4. Analysis of Scenario 2: Time slot sizes

This subsection analyzes the results of the second simulation scenario. According to the description in Section 2, Companies 1 and 2 are assigned fixed time slots of size 4, while Company 3 is assigned fixed time slots of gradually increasing size between 4 and 6 over eleven simulation runs. For increasing time slot size of Company 3, the box plots of the throughput time distributions (Fig 3b) show increasing values for Companies 1 and 2 and decreasing values for Company 3, on average, with a few fluctuations. For a time slot size of 4.4 and higher, the mean throughput time of Company 3 is always lower than those of the other two companies. Moreover, for increasing time slots of Company 3, the boxes containing the throughput time values between the 25th and 75th percentiles, and thus the distributions, get wider for Companies 1 and 2 and narrower for Company 3. These results were expected and are due to larger time slots of Company 3 and hence more possible throughput per time slot compared to Companies 1 and 2. A probable reason for the result that, on average, the values of Company 2 are higher than those of Company 1 (see Table 2) is again the randomness of the simulation input.

Considering the entropies (see Fig 4b)) of the symbol sequences of throughput times transformed according to equation (2) and the thresholds in Table 3, on average, Company 3 has smaller values than Companies 1 and 2. As a result, the throughput times of Company 3 are better predictable. Starting approximately at 0.2 for each company for equal time slots of size 4, the entropies increase moderately until time slot size 4.4 for Company 3. For higher time slot sizes, the entropy of Company 3 decreases almost to 0.1 for a time slot size of 6 for Company 3, while the entropy of Company 1 increases approximately to 0.3. The entropy of Company 2 shows an increase to 0.4 and a rapid subsequent decrease to 0.2. A reason for the rapid decrease may be overall
high throughput times of jobs of Company 2 on average for the later simulation runs. Altogether, on average, the predictability of the throughput times of Company 3 increases with increasing time slot size, while the predictability of the throughput times of the other two companies is lower and shows a moderate decrease.

3.5. Analysis of Scenario 3: Job-priorities

This subsection analyzes the results of the third simulation scenario regarding different job-priorities and hence possibilities of priority orders of Company 3. The probabilities of priority orders are varied between 0 and 1 over eleven simulation runs. The box plots of the throughput time distributions (Fig. 3c)) show clear results. For increasing job-priority for Company 3, the mean values as well as the maximum values and standard deviations of Companies 1 and 2 increase monotonically. Moreover, the boxes get wider and hence the distribution. By contrast, the mean values of the throughput times of Company 3 decrease monotonically and the boxes get narrower. The maximum values for Company 3 remain almost the same except for the last simulation run, for which every order of Company 3 is a priority order. Here, the maximum value of the throughput times is lower. The standard deviations for Company 3 almost stagnate until a job-priority of 0.4 and decrease for higher job-priorities. Overall, Companies 1 and 2 show almost equal average mean values, maximum values and standard deviations, which are all significantly higher than those of Company 3 (see Table 2). These results were expected since with increasing job-priority, the waiting times of jobs of Company 3 in the queue decrease compared to the jobs of the other two companies.

Fig. 4c) illustrates the entropy evolutions of the symbol sequences of throughput times transformed with respect to equation (2) and Table 3. Starting at a common entropy value about 0.25 for the first simulation run (no job-priority), the entropies of Companies 1 and 2 increase in a similar way to approximately 0.4. The entropy for Company 3 increases until a value of 0.37 for a job-priority of 0.4. In the range of job-priorities for Company 3 from 0 to 0.4, the entropies of Company 3 are higher than those of the other two companies and hence the throughput times are harder to predict. This
result surprises at first glance. However, it can be explained in the following way: On the one hand, a low probability of priority orders indeed leads to decreasing average throughput times compared to the case without priority orders. But on the other hand, the standard deviations and the dynamics of the symbol sequences increase. Thus, the predictability decreases. For higher job-priorities, the entropy of Company 3 decreases monotonically and is consistently lower than those of the other two companies. In the extreme case of job-priority 1, every order of Company 3 is a priority order. Here, the entropy of the symbol sequence for Company 3 almost vanishes to zero.

The only remaining uncertainty can be assigned to the fact that priority orders do not preempt the orders already being processed. Overall, the results of this simulation scenario show relatively clear and expected results regarding the statistical distributions of the throughput times. However, analyzing the entropies leads to non-trivial results regarding the predictability of the throughput times.

4. Conclusion and outlook

This paper considered the usage of shared resources in the context of production networks. Different priority concepts for resource sharing were discussed. Within a simulation study, different priority concepts for three companies within a small-scale production network including a shared resource were investigated. In order to analyze the dynamical evolution of throughput times, statistical throughput time distributions as well as entropies of transformed symbol sequences were computed and discussed. The results of the simulation study showed non-trivial dynamics of the different companies’ throughput times. Hence, it can be concluded that the collaborative usage of shared resources induces dynamics that are hard to predict. Thus, further research is needed to analyze the possibilities and risks of resource sharing as well as to develop appropriate methods to enable a reasonable usage for manufacturing companies.

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References