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Family Based Dispatching in Manufacturing Networks

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ABSTRACT

Intrinsic to family based dispatching is the grouping of similar types of jobs in front of a machine for joint processing. Machine flow times may be improved in this way, as less time is spent on set-ups. Our observations in practice, however, suggest that family based dispatching may result in a bulky arrival pattern for successor manufacturing stages, thereby causing additional delay. So far, literature seems to neglect this effect. To explore this issue we develop queueing theoretical approximations of flow times for a simple two-stage shop. It appears that the optimal batch size for the shop is typically smaller than the optimal batch size for the batch machine. Furthermore, we propose extensions to existing dispatching rules by using information on successor stages. Existing and new extended rules are tested by an extensive simulation study. In line with the queueing theoretical analysis the outcomes indicate that exhaustive rules – assuming batch size to be equal to family queue length – are clearly outperformed by non-exhaustive rules – allowing for smaller batches. Moreover, results show that the inclusion of local information on successor stages in rule decision making improves shop flow times.

KEY WORDS

Family based dispatching, Manufacturing Networks, Group Technology, Simulation, Queueing Analysis.

*Family Based Dispatching in Manufacturing Networks***1 INTRODUCTION**

In a globalising world manufacturers are under constant pressure to cut costs, while improving delivery speed, product quality, flexibility and delivery reliability at the same time (Richards 1996). Group Technology (GT) provides one of the answers to meet these challenges. It suggests exploiting similarities in product and process design to meet the diversity of customer demand in an economic way. Family based dispatching rules supports the GT concept. Jobs sharing similar requirements with respect to machine set-up, are grouped into families and jointly dispatched. Since set-up frequencies are reduced the flow time performance of the specific (batch) machine might be improved.

In this article we study the application of family based dispatching rules in multi-stage manufacturing networks, as they are reflected in, for example, job shops or flow shops. Our research is motivated by a case study concerning the manufacturing of centrifugal pumps (Nomden and Slomp 2006, Bokhorst et al. 2008). In deciding on what to produce next on a machine, the operators apply family based dispatching rules. Hence the time spent on set-ups is reduced. However, at the same time, the operators observe that family based dispatching may cause bulky arrivals at successor stages. As a net effect, flow time for the respective stages could significantly be increased. In order to mitigate this effect, operators adapt batch size taking into account the local status of the successor manufacturing stages. More generally, this practice suggests that possible benefits of family based dispatching should be assessed in a shop-wide context.

Surprisingly, influences of successor stages on batch forming at a batch machine and consequences on the overall shop performance receive no attention in literature. Partly this may be explained by the shop configuration studied. Several authors study a single machine shop (for example, Wemmerlov 1992, Nomden et al. 2008), thereby neglecting influences of other machines. Other authors study the use of family based dispatching rules within flow

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shops or job shops (Frazier 1996, Shambu 1996). However, the rules studied within these contexts focus on batch machine operation only. Moreover, their performance evaluation does not isolate effects on follow-up stages.

Starting from the above observations we distil (i) a need for a better understanding of the way family based dispatching rules influence overall shop performance, and (ii) a potential for improving current (use of) rules. We address both issues starting from an incremental approach. Firstly, we use queueing theory to analyse the effects follow-up stages may have on the perceived benefits of family based dispatching. More in particular, we study influence of a fixed batch size at the batch machine on overall shop performance. Next, we propose extensions to existing dispatching rules. Basically, the extended rules relate their choice of batch size and job family to both local information on the batch stage and follow-up stages. Finally, the potential of existing and extended rules is evaluated by a simulation study.

In order to exclude other influencing factors we chose to study a simple two-stage flow shop. The first stage concerns a batch machine, whereas the second stage represents the remainder shop. The latter stage is made up of one or multiple machines in parallel, each being dedicated to a subset of job families. The shop performance is studied varying work loads, set-up to run-time ratios and number of job families.

The paper is structured as follows. In Section 2, we review existing rules for family based dispatching and the shop configurations being studied. A control framework is used as a generic format to describe the existing and extended rules for family based dispatching. In Section 4, we use queueing theory to explore effects successor stages may have on the perceived benefits of family based dispatching. Next, we propose extensions to existing dispatching rules that use local information on successor manufacturing stages (Section 5). The potential of existing and extended rules for use in manufacturing networks is evaluated by a simulation study (Sections 6, 7). Finally, main conclusions are summarized in Section 8.

*Family Based Dispatching in Manufacturing Networks***2 LITERATURE REVIEW**

Family based dispatching rules received significant attention in literature. This is not surprising given their direct relevance for practice, thereby building on the simple intuition that job similarities may be exploited for reducing machine set-up frequencies. Our literature review starts from a framework for characterizing family based dispatching rules, as proposed by Mosier et al. (1984). We focus on rules adopting the minimization of mean flow time as an objective. See Mosier et al. (1984), Mahmoodi and Dooley (1991), and Ponnambalam et al. (1999) for rules addressing due date related criterions.

Mosier et al. typify family based dispatching rules by distinguishing between three ordered decisions:

- (a) Switching moment: When to select an other family of jobs for servicing.
- (b) Family type selection: Which of the families to process next – assuming the decision in (a) has been made.
- (c) Job sequencing: Which job is to be selected from the chosen family.

Two alternative ways for determining a new switching moment (a) are mentioned in literature, following from the notion of rules being exhaustive or not (Mahmoodi and Dooley 1991). Exhaustive rules assume switching to another family only if all jobs within the current family, including arrivals during the processing, have been processed. Alternatively, non-exhaustive rules do not apply a suchlike restriction.

Existing non-exhaustive rules rely on time fences or local information on the batch stage in deciding on a next switching moment. The AVE rule proposed by Mosier et al. (1984) suggests a choice of family if batch size equals the queue length observed at the previous switching moment. Alternatively, the ECON rule (Mosier et al. 1984, Ruben et al. 1993) allows for a switching decision after each job being completed. Furthermore, Russell

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2
3 and Philipoom (1991) suggest switching when either a specified amount of time has elapsed
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5 or the family is exhausted. Remarkably, simulation studies on a large variety of shop
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7 environments suggest that exhaustive rules generally perform better than non-exhaustive
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9 rules (Lockwood 2000). However, in our recent work (Van der Zee 2010), we show how the
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11 proposed MASP_AD and MASP_HY rules may outperform exhaustive rules for single
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13 machine environments. In deciding on a next switching moment, these rules rely on local
14
15 information on the batch stage, i.e. family set-up times, job processing times, and family
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17 queue lengths. Simulation results indicate significant performance gains for these rules in
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19 case of moderate and high variances of processing and set-up times.
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27 A basic rule, often used as a benchmark in *family priority setting* (b), is the so-called FCFAM
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29 rule (Flynn 1987). This rule shows similarities with the well-known First Come First Serve
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31 rule (FCFS). It prioritizes families by considering the earliest entry moment of the jobs
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33 available in queue for a family. Most definitions for family priority setting can be related to
34
35 the concept of the weighted shortest processing time rule (WSPT), also see Nomden et al.
36
37 (2008) and Nomden and Van der Zee (2008) for overviews. This well-known dispatching rule
38
39 sequences jobs by considering the work load for a job relative to its weight, see, for example,
40
41 Pinedo (1995). For family based dispatching this concept is extrapolated. Alternative rules
42
43 differ on the way batch work load is determined, and subsequently weighted.
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48 Current research on family based dispatching rules mainly uses local information for
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50 priority determination. The rules suggested by Kannan and Ghosh (1996), Mahmoodi and
51
52 Martin (1997), and Nomden et al. (2008) are exceptions. These authors suggest extending the
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54 WSPT scheme by including information on future arrivals. We found, however, no rules in
55
56 literature that include information on successor manufacturing stages.
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Family based dispatching rules typically rely on conventional dispatching rules for *sequencing of individual jobs within a family* (c). Examples include First Come First Serve (FCFS), Shortest Processing Time (SPT), Earliest Due Date (EDD) etc.. See Blackstone et al. (1982) and Chang et al. (1996) for overviews.

From this literature review three observations might be drawn:

- Performance evaluation: *Structural insights on the flow time performance of rules are lacking.*
- Use of information on successor stages: *Current rules neglect local information on successor stages in decision making.* This suggests a potential for their improvement.
- Rule testing: *Promising new non-exhaustive rules* (Van der Zee 2010) *have only been tested for single machine environments.* Their usefulness for manufacturing networks is yet to be explored.

In this article we address the need for a better understanding of family based dispatching rules by:

- Developing queueing theoretical approximations of shop flow times to explore the way successor manufacturing stages influence perceived benefits of family based dispatching. More in particular, we are interested in the question whether a tailoring of batch size – as allowed for by non-exhaustive rules – would contribute to overall system performance.
- Extending existing family based dispatching rules by including shop floor information on successor manufacturing stages.
- Evaluating existing and extended rules for family based dispatching for their flow time performance in alternative manufacturing network configurations using simulation.

3 SHOP DESCRIPTION AND DECISION FRAMEWORK

In this section we describe shop characteristics, and consider a decision framework for its control. The decision framework is meant to facilitate the discussion on rule construction. An overview of the notation and the rules introduced in this section, can be found in the Appendix and Van der Zee et al. (2011a) respectively.

3.1 Shop description

We consider a two-stage shop, see Figure 1. The first stage concerns a batch machine (B), whereas the second stage is made up of parallel machines $m \in S$. Buffers are used to store incoming jobs and to decouple both stages. For all buffers unlimited storage capacity is assumed. We associate each job with a single product. Each job belongs to a certain family $j \in J$. A job family requires a specific, sequence dependent, machine set-up at the batch machine. This so-called major set-up is associated with a set-up time $s_{j_0, j}$. The length of the set-up time is determined by the current set-up – for family j_0 – and the required set-up for family j . Obviously, $s_{j_0, j} = 0$ for $j = j_0$. Job related, so-called minor set-ups, are assumed to be included in job processing times ($p_{i, j, 1}$) for the batch machine, with i identifying individual jobs being available within a family j . Parallel machines $m \in S$ are assumed to be identical with respect to processing times ($p_{i, j, 2}$). However, each machine $m \in S$ is dedicated to a subset of job families ($J_m \subset J$). For simplicity reasons we assume subsets (J_m) to be non-overlapping.

[Insert Figure 1 about here]

*Family Based Dispatching in Manufacturing Networks***3.2 Decision framework**

In this section we define a decision framework. The framework builds on the notion that family based dispatching rules may be characterized according to three ordered decisions, cf. Mosier et al. (1984). Also see Section 2. Here we will discuss main implementation issues, using existing rules as vehicles for discussion. Before doing so, we will consider the scope of the framework, as defined by the shop configuration, and the objective.

3.2.1 Scope

The shop control concerns both stages of the shop, cf. Figure 1. For reasons of simplicity and clarity of understanding we assume a First Come First Serve policy (FCFS) for the second stage. Hence, shop control boils down to making dispatching decisions (including release) for the first (batch) stage. As an objective we consider the minimisation of mean flow time per job in the long run. Given N processed jobs, mean flow time per job (\bar{T}) is defined as:

$$\bar{T} = \frac{\sum_{j \in J} \sum_{i=1,2,\dots} ft_{i,j}}{N}$$

with [1]

$$ft_{i,j} = w_{i,j,1} + p_{i,j,1} + w_{i,j,2} + p_{i,j,2}$$

$$N = \sum_{j \in J} \sum_{i=1,2,\dots} 1$$

In computing flow time for a job i belonging to family j ($ft_{i,j}$) we distinguish between waiting times ($w_{i,j,1}, w_{i,j,2}$) and job processing times ($p_{i,j,1}, p_{i,j,2}$) for the first (batch) stage and the second stage respectively. Note how waiting time for the batch stage ($w_{i,j,1}$) includes set-up times ($s_{j_0,j}$).

*Family Based Dispatching in Manufacturing Networks**3.2.2 Framework*(a) Switching moment: When to select an other family of jobs for servicing.

Essentially, two types of events govern shop dynamics: job arrivals and job completions (compare Figure 1). As such the events correspond to elementary *switching moments*. At switching moments a planner is triggered to select the job family to be processed next (cf. b). Typically, family based dispatching rules consider a subset of switching moments. *Exhaustive* rules only allow family selection in case all jobs within the current family have been processed, including jobs arriving during processing. *Non-exhaustive* rules do not implement such a restriction. Here switching moments are related to static parameters, like time fences for processing a specific family (Russell and Philipoom 1991), or dynamic parameters building on local information, such as queue length (Mosier et al. 1984).

(b) Family type selection: Which of the families to process next

In order to select the family to process next, each family is assigned a priority. In principle, family priorities may be pre-defined. For example, family sequencing may follow a rotational scheme. Also thresholds may be implemented for family selection, such as, for example, a minimum batch size. Furthermore, in case of non-exhaustive rules, family selection may be combined with a decision on batch contents, in terms of, batch size or a pre-selection of available jobs. Again, such decisions may rely on dynamic parameters, i.e., local information, or static parameters, such as, for example, a fixed batch size. Most existing rules, however, tend not to put a-priori restrictions on the choice of family or batch contents. Two important examples will be discussed below.

A basic, benchmark rule for family priority setting is the so-called FCFAM rule (Flynn 1987). This rule prioritizes families by considering the *earliest entry moment* ($t_{i,j}$) of the jobs $i = 1, 2, \dots$, available in queue at the batch stage ($q_{j,1}$) for a family $j \in J$:

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$$j_{FCFAM}^* = \arg \min_{j \in J: q_{j,1} > 0} t_{i,j} \quad [2]$$

Most definitions for family priority setting aiming at mean flow time performance can be related to the well-known concept of the *weighted shortest processing time* rule (WSPT), see, for example, Pinedo (1995). A good illustration of such a rule for the single machine case is the Minimum Average Set-up and Processing time rule (MASP), see Russell and Philipoom (1991). According to this rule, system set-up is related to the choice of family j^* for which a minimum weighted work load is foreseen. Hereby work load is estimated by the sum of family set-up time ($s_{j_0,j}$) and cumulative processing time ($p_{f,n,1}$). Weights are related to queue length at the batch stage ($q_{j,1}$):

$$j_{MASP}^* = \arg \min_{j \in J: q_{j,1} > 0} \frac{s_{j_0,j} + \sum_{l=1}^{q_{j,1}} p_{i,j,l}}{q_{j,1}} \quad [3]$$

Alternative priority rules following the WSPT scheme are typically found by leaving out shop data from the above equation. For example, the so-called MAP, and MAS rules (Mosier et al. 1984, Nomden et al. 2008) can be found by omitting set-up times, and processing times respectively. Furthermore, Van der Zee (2010) proposes the MASP_AD, and MASP_HY rules. These rules extend the MASP rule by allowing for *alternative choices of batch size*, $k = 1..q_{j,1}$, within a family j . Note that alternative choices of batch size characterize MASP_AD and MASP_HY as being non-exhaustive. Also see Section 5 for further details.

(c) Job sequencing: Which job is to be selected from the chosen family.

Job sequencing is realized by employing *conventional dispatching rules*, such as, for example, the first come first serve rule (FCFS) and shortest processing time rule (SPT).

4 QUEUING THEORETICAL ANALYSIS

Before we develop and analyze the (extended) heuristics we explore which insights from queuing theory can be obtained. Queuing theory offers (approximated) analytical (closed form) expressions of the operation characteristics of a system. Here the system is the two-stage shop, discussed in Section 3.1 and shown in Figure 1. We are interested in the influence of the batch size on the flow time expression. Particularly, we study the behaviour of the optimal batch size, which minimizes the flow time, for several values of the number of families and the number of parallel machines in the second stage. Assuming fixed batch sizes, the applied family based dispatching rule belongs to the class of non-exhaustive rules. The priority setting is FCFS on the family level, which is similar to the FCFAM rule.

The details of the approach including analytical expressions of the operational characteristics are given in Van der Zee et al. (2011b). Equations in Van der Zee et al. (2011b) will be referenced as [Zx], with x being an integer identifying the respective equation. To calculate the (mean) flow times we will use numerical data similar to the data used in the simulation study (Sections 6, 7). See Table 1, and the Appendix for definitions of the parameters and variables.

[Insert Table 1 about here]

Note that for the chosen parameters values the utilization of the batch machine for $k = 1$ is $U_1 = 0.97$. This means that a batch size of one job is theoretically allowed.

The section is split into three parts: 4.1 focuses on characteristics of the first stage; 4.2 considers the total system (first and second stage), and finally in 4.3 conclusions are drawn.

*Family Based Dispatching in Manufacturing Networks***4.1 Characteristics of the first stage**

In this section we consider the process flow time (the flow time of the batch machine), as well as the (total) flow time of this stage for different numbers of families ($\bar{J} = 1, 4, 8$) as function of the batch size. Alternative definitions of flow time are meant to indicate the influence of the batch forming time, which is frequently ignored in literature. Using the flow time expressions [Z9] and [Z10] (see Van der Zee et al. (2011b)) results in Figure 2 and Table 1.

[Insert Figure 2 about here]

The (normalized) process flow time as function of the batch size (see Figure 2) shows a well-known behaviour: first decreasing and then increasing, with a unique minimum (Karmarkar 1987, Hopp and Spearman 2000). In contrast with Karmarkar (1987) and Hopp and Spearman (2000) the squared coefficients of variation of the inter-arrival time ($C_1^{a,B}$) and processing time (C_1^p) are functions of the batch size (see [Z5] and [Z6]). For (very) large batch sizes this implies that the process waiting time corresponds with the waiting time of a single job. In addition, from [Z9] it can be shown that the (normalized) process flow time for large batch size (k) will increase with $k/2$.

The minimum process flow time is $\bar{T}_1^{pr,\min} = 10.6$ at $k^{opt} = 4.2$ (in the Table 2 $\bar{T}_1^{pr,\min}$ is shown in the $\bar{T}_1^{n,\min}$ - column, $\bar{J} = 0$ - row). The process flow time is 10.6 times the processing time (\bar{p}_1) at the utilization $U_1 = 0.89$, which corresponds with the flow time of a queuing system with Poisson arrivals and service (M/M/1).

The (normalized) flow time of the first stage is the sum of the process flow time and the wait-to-batch time. As a result, the flow time increases, given a batch size k , for larger

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2
3 numbers of families (\bar{J}), see the curves for $\bar{J} = 1, 4, 8$ in Figure 2. For large batch sizes the
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5 flow time approaches the line $(k/2)((\bar{J}/U_1^0)+1)$ (see [Z11]). Table 2 shows the minimum
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7 flow times ($\bar{T}_1^{n,\min}$) and optimal batch sizes (k^{opt}) for alternative numbers of job families
8
9 (\bar{J}). In parentheses the % change is calculated with respect to $\bar{J} = 1$, as a benchmark. From
10
11 Figure 2 and Table 1 it can also be observed that the optimal batch size (k^{opt}) reduces for a
12
13 larger number of families (\bar{J}), while the minimum flow time increases. The optimal batch
14
15 size reaches its lowest value ($k = 1$) for $\bar{J} > 206$ - corresponding with a minimum flow time
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17 of $\bar{T}_1^{n,\min} = 33.6$. Another observation from Figure 2 is worth to mention. The sensitivity for
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19 (small) deviations of the batch size at the optimum value also depends on the number of
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21 families. Sensitivity increases for larger numbers of families.
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30 If the optimal batch determination is based on the myopic minimization of the process
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32 flow time, deviations from the minimum stage flow times happen. Table 2 shows the flow
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34 times for alternative settings for the number of families ($\bar{J} = 1, 4, 8$) at $k = 4.2$ (the optimal
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36 batch size). The % increase with respect to the minimum stage flow time shows the potential
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38 or urgency to optimize the total flow time of this stage.
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44 [Insert Table 2 about here]
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51 In sum, jobs arriving at a batch machine might be grouped into batches according to
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53 family characteristics, thereby causing wait-to-batch times. These wait-to-batch times have a
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55 relatively large impact on the stage flow time. Increasing the number of families increases the
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57 flow times for each given batch size. Moreover, the minimum flow time increases, while the
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59 corresponding optimal batch size decreases. Note how we focused on non-integer optimal
60
batch sizes. In practice the batch sizes can be realized by using a mix of integer batch sizes

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over a long period of time. However the differences with using “best” integer batch sizes are marginal and left out.

4.2 Characteristics of the system

The (normalized) flow time \bar{T}_2^n (see [Z18]) of the second stage depends on both the batch size (k) by means of the squared coefficient of variation of job inter-arrival times (C_2^a , see [Z15]) and the number of parallel machines (\bar{S}). Since C_2^a increases with k , the flow time will also increase as function of k . Moreover, the flow time is a linear increasing function of \bar{S} . These characteristics influence the (normalized) system flow time ($\bar{T}^n = \bar{T}_1^n + \bar{T}_2^n$). Figure 3 (with $\bar{J} = 1$ and $\bar{S} = 1$) demonstrates that \bar{T}^n has similar behaviour as \bar{T}_1^n : decreasing, increasing as function of k with a unique minimum. The figure also shows that around the optimal batch size the minimum first stage flow time and the second stage flow time are of the same magnitude.

[Insert Figure 3 about here]

For large batch sizes (k) the system flow time will approximately be equal to the line $\left(\frac{k}{2}\right)(1.6\bar{J} + 9.4\bar{S} + 1.2)$, which can be derived from adding [Z11] and [Z19]. This line indicates a stronger influence of the number of machines (\bar{S}) compared with the number of families (\bar{J}). In Figures 4 and 5 we consider several combinations of settings for \bar{J} and \bar{S} .

[Insert Figures 4, 5 about here]

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The number of parallel machines in stage 2 not only effects the system flow time, but also the optimal batch size. Table 3 gives the minimum system flow time and the optimal batch size for the selected settings of \bar{J} and \bar{S} . Results indicate an increase of the minimum flow time and a reduction of the optimal batch size for higher values of \bar{J} and \bar{S} . The number of parallel machines has a relatively strong influence upon that, but this influence diminishes for larger number of families. The % reduction of the optimal batch size calculated with respect to the optimal batch size of the first stage (see Table 2) confirms this. If the optimal batch size of the first stage is used instead of the optimal system batch size the system flow time (\bar{T}^n) increases relative to the minimum system flow time ($\bar{T}^{n,\min}$). For low number of families and number of parallel machines the differences are small. Significant improvements are possible for high values of \bar{J} and \bar{S} .

As can be observed in Figures 4 and 5 the sensitivity for deviations of the batch size around the optimum value depends on both the number of families and the number of parallel machines, i.e., higher values for \bar{J} and/or \bar{S} increase the sensitivity.

[Insert Table 3 about here]

All in all this subsection shows the influence of the second stage on the on optimal batch sizes of the batch machine in the first stage. The influence becomes important for large numbers of parallel machines in combination with large number of families.

4.3 Conclusions

Because of the impact of forming of batches of families in front of a batch machine the extra caused waiting (wait-to-batch) time should be accounted for in the (system) flow time. Characteristics of the second stage can also have influence on the system flow times, the

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3 optimal batch size and the minimum system flow time. If this stage consists of a number of
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5 parallel machines the influence might become strong.
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8 These findings hold for a specific non-exhaustive rule, and one might wonder whether the
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10 insights are valuable for exhaustive rules. Assume that the average batch size of an
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12 exhaustive rule can be compared with the fixed batch size policy of the queueing model.
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14 Then if the average batch size of the exhaustive rule is larger than the optimal batch size
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16 improvement options might exist. However, because the batch size is not adapted, the second
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18 stage might have a negative effect on the relative flow time performance. Note that
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20 differences in priority settings between the rules may influence this reasoning.
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24 The flow times expressions used here are two-moment parametric decomposition
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26 approximations. A simulation is used to verify the results in the Sections 4.1 and 4.2. The
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28 simulation outcomes show similar behaviour, though the influence of the number of parallel
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30 machines is less strong.
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34 **5 EXTENDING RULES FOR MANUFACTURING NETWORK CONTROL**

35
36 In this section we discuss extensions to existing family based dispatching rules in an attempt
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38 to (further) improve their performance in network environments. The extensions enable the
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40 respective rules to adapt their choice of family and batch size to the status of successor
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42 manufacturing stages.
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46 Motivated by their good performance in previous research (Nomden et al. 2008, Van der
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48 Zee 2010) we chose to extend rules MASP (Russell and Philipoom (1991), MAS (Nomden et
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50 al. 2008), MASP_AD (Van der Zee 2010), and MASP_HY (Van der Zee 2010) for network
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52 use. Note that there is no single rule showing overall best performance. However, our
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54 previous research (Van der Zee 2010) indicates that the aforementioned rules give a good
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56 coverage of a wide range of shop parameters.
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Essentially, the extensions proposed for existing rules address the setting of the *family priorities* (compare Section 3.2). Priority settings are adapted by accounting for the estimated waiting time at the second stage. Two alternative approaches are considered:

- (1) Rough-cut approach: Families associated with machines that are starved (zero delay) are preferred over other families.
- (2) Refined approach: Family priority settings are adjusted by including expected delay at the second stage.

Application of the first “intuitive” rule (1) results in the creation of two subsets of families – those referring to starved and non-starved machines respectively. Families within a subset compete on the basis of the original priority settings. For example, MAS is extended as follows, cf. [3]:

$$j_{MAS_S}^* = \arg \min_{j \in J: q_{j,1} > 0} \frac{s_{j_0,j}}{q_{j,1}} + WL_j$$

with

$$WL_j = \begin{cases} M & r_{2,m(j)} + \sum_{n \in J_{m(j)}} \sum_{i=1}^{q_{j,2}} p_{i,j,2} - (s_{j_0,j} + p_{1,j,1}) > 0 \\ 0 & \text{else} \end{cases} \quad [4]$$

$M = \text{a big number}$

Two subsets of job families (low priority, high priority) are created by distinguishing among two work load levels for the machine m in the second stage associated with a family j ($m(j)$). In case the machine has not starved before the first job in the batch arrives, work load (WL_j) is set to a big number (M). The machine status is checked by considering queue

contents ($\sum_{j \in J_{m(j)}} \sum_{i=1}^{q_{j,2}} p_{i,j,2}$), time to complete its current job ($r_{2,m(j)}$), and the times it takes

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before the first job in the batch arrives ($-(s_{j_0,j} + p_{1,j,1})$). On the other hand, $WL_j = 0$ if the machine is starved. Prioritizing families within subsets boils down to applying the original MAS logic, see Section 3.2. Aforementioned rules, i.e., MASP, MASP_AD, and MASP_HY can be extended in a similar – straightforward manner. Extended rules will be referred to as MAS_S, MASP_S, MASP_AD_S, and MASP_HY_S.

The second approach (2) is more refined. It aims to adjust the WSPT scheme (cf. [3]), by considering current work load for the second stage. Below we will discuss the extensions for MASP, MASP_AD, and MASP_HY. In principle, the construction of MAS hinders a similar type of extension due to its focus on a single specific job attribute in determining on family priority, i.e., set-up time. The extended rules will be referred to as MASP_N, MASP_AD_N, and MASP_HY_N.

MASP_N

The MASP rule relates its decision on family selection to weighted flow times for jobs in queue, cf. [3]. For MASP_N we extend this logic by including the estimated delay (WL_j) of the respective batch at the second stage:

$$j_{MASP_N}^* = \arg \min_{j \in J; q_{j,1} > 0} \frac{s_{j_0,j} + \sum_{i=1}^{q_{j,1}} p_{i,j,1}}{q_{j,1}} + WL_j \quad [6]$$

with

$$WL_j = r_{2,m(j)} + \sum_{n \in J_{m(j)}} \sum_{i=1}^{q_{j,2}} p_{i,j,2} - (s_{j_0,j} + p_{1,j,1})$$

The first and second term of WL_j represent the work load at the switching moment, i.e., the

sum of the processing times for items in queue at the second stage ($\sum_{n \in J_{m(j)}} \sum_{i=1}^{q_{j,2}} p_{i,j,2}$), and the

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time to complete the job currently being processed ($r_{2,m(j)}$). The third term corrects work load for the fact that the first job in the batch will arrive at the second stage not before completing set-up and processing at the batch stage ($s_{j_0,j} + p_{1,j,1}$).

MASP_AD_N

The non-exhaustive MASP_AD rule extends MASP by allowing for alternative choices of batch size. MASP_AD bounds batch size by considering the highest priority partial batch:

$$F_{MASP_AD} = \arg \min_{j \in J; k = k_j^{\min} \dots q_{j,1}; q_{j,1} > 0} \frac{s_{j_0,j} + \sum_{i=1}^k p_{i,j,1}}{k} \quad [7]$$

with

$$F_{MASP_AD} = (j^*, k^*)$$

$$k_j^{\min} = \text{round}(s_{j_0,j} / (1/\lambda_T - \bar{p}_1))$$

Formation of partial batches is realized by setting the batch size (k). The highest priority batch (F_{MASP_AD}) is characterized by the choice of family (j^*), and the choice of batch size (k^*). A lower bound is set for batch size (k_j^{\min}). It relates set-up time ($s_{j_0,j}$) to the mean job arrival interval ($1/\lambda_T$) and mean processing time per job at the batch machine over all families (\bar{p}_1). In case of a tie, i.e., all families do not meet their lower bound, $k_j^{\min} = 0$. For more details see Van der Zee (2010). Note how the size of the combinatorial problem associated with MASP_AD is typically larger than for FCFAM, MAS or MASP. This is due to its allowance for alternative batch sizes. We found, however, that the increase in problem size has a rather marginal effect on computational efficiency for MASP_AD. Also see Section 7.2 for more details.

Similar to MASP, MASP_AD is extended for network use by including work load estimates for the second stage in family priority setting:

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$$F_{MASP_AD_N} = \arg \min_{j \in J; k = k_j^{\min} \dots q_{j,1}; q_{j,1} > 0} \frac{s_{j_0,j} + \sum_{i=1}^k p_{i,j,1}}{k} + WL_j$$

with

$$F_{MASP_AD_N} = (j^*, k^*) \quad [8]$$

$$k_j^{\min} = \text{round}(s_{j_0,j} / (1 / \lambda_T - \bar{p}_1))$$

$$WL_j = r_{2,m(j)} + \sum_{n \in J_{m(j)}} \sum_{i=1}^{q_{j,2}} p_{i,j,2} - (s_{j_0,j} + p_{1,j,1})$$

MASP_HY_N

MASP_HY is characterized by a three stage approach. The initial stage is an application of MASP_AD. The second stage for MASP_HY addresses the possibility for increasing set-up efficiency by extending batch size for the chosen family (j^*):

1. Set $c = k^*$.
2. Determine the priority (P^H) for the next best family:

$$P^H = \min_{j \in J; j \neq j^*; k = 1 \dots q_{j,1}} \frac{s_{j_0,j} + \sum_{i=1}^k p_{i,j,1}}{k} \quad [9]$$

3. If $c < q_{j^*}$ then set $c = c + 1$ else go to 6.
4. Determine priority (P_c^I) for family j^* and batch size c :

$$P_c^I = \frac{s_{j_0,j^*} + \sum_{i=1}^c p_{i,j^*,1}}{c} \quad [10]$$

5. If $P_c^I < P^H$ then go to 3 else $c = c - 1$; go to 6.
6. Set $k^{*ex} = c$.

The above procedure checks whether a further increase of the batch in the same family (j^*) is possible (step 3), and priority found for the next-best family (P^H), cf. steps 2, 4, 5. This is reflected in the choice of batch size (k^{*ex}), cf. step 6.

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Finally, in the third stage, a decision is made on whether an exhaustive policy is followed or not. In case the (extended) batch size (k^{*ex}) is equal to queue length for the chosen family (j^*), an exhaustive policy is adopted. In all other cases the next switching moment is determined by the partial batch size, similar to MASP_AD.

MASP_HY is extended for network use similar to MASP and MASP_AD. This boils down to replacing equations [9], [10] by:

$$P^{II} = \min_{j \in J; j \neq j^*; k=1..q_{j,1}} \frac{s_{j_0,j} + \sum_{i=1}^k p_{i,j,1}}{k} + WL_j$$

with [11]

$$WL_j = r_{2,m(j)} + \sum_{n \in J_{m(j)}} \sum_{i=1}^{q_{j,2}} p_{i,j,2} - (s_{j_0,j} + p_{1,j,1})$$

and

$$P_c^I = \frac{s_{j_0,j^*} + \sum_{i=1}^c p_{i,j^*,1}}{c} + WL_{j^*}$$

with [12]

$$WL_{j^*} = r_{2,m(j^*)} + \sum_{n \in J_{m(j^*)}} \sum_{i=1}^{q_{j,2}} p_{i,j,2} - (s_{j_0,j^*} + p_{1,j^*,1})$$

respectively.

6 DESIGN OF THE SIMULATION STUDY

A simulation study was designed to consider the potential of existing and new family based dispatching rules. In this section we discuss research questions, the experimental design, and simulation details.

6.1 Research issues

In our simulation study we aim to gain an insight in the potential of new and existing rules for family based dispatching for manufacturing network control. More in particular, we study

Family Based Dispatching in Manufacturing Networks

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3 rules for settings where information on successor manufacturing stages is either available (1)
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5 or not (2).
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8 The first series of experiments (1) concerns the application of existing rules, i.e., FCFAM,
9 MAS, MASP, MASP_AD, and MASP_HY for shop control. The policies MAS, MASP,
10 MASP_AD, and MASP_HY are considered, because of their good overall performance in our
11 previous work (Nomden et al. 2008, Van der Zee 2010). For MASP this is confirmed in
12 earlier research by Russell and Philipoom (1991). MAS, MASP_AD, and MASP_HY are
13 new rules, introduced by Nomden et al. (2008) and Van der Zee (2010). Finally, FCFAM,
14 serves as a bench mark rule. It concerns an extension of the well-known FCFS rule, see
15 Section 3.2.
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26 Whereas FCFAM, MAS, MASP are exhaustive rules, MASP_AD and MASP_HY are
27 non-exhaustive rules. A key difference between both categories of rules (compare Sections 3,
28 5) is the batch size. Whereas aforementioned exhaustive rules set batch size equal to queue
29 contents, MASP_AD and MASP_HY consider the use of smaller batch sizes. In the initial
30 series of experiments (1) we will consider whether this characteristic makes a difference for
31 shop performance. After all, queueing approximations (Section 4) suggest that the flow time
32 of the successor stage increases with the batch size. Furthermore, Van der Zee (2010) reports
33 good performance of MASP_AD and MASP_HY for single stage environments. Both
34 findings underpin a hypothesis suggesting that non-exhaustive rules (MASP_AD,
35 MASP_HY) will outperform exhaustive rules (MAS, MASP) on shop performance.
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50 The second series of experiments (2) addresses potential of the new extended rules, i.e.,
51 MAS_S, MASP_N, MASP_AD_N, and MASP_HY_N, as proposed in this paper (Section 5).
52 By including local information on successor manufacturing stages the new rules aim to
53 improve decisions on family selection. Note how rules MASP_S, MASP_AD_S, and
54 MASP_HY_S (see Section 5), are not included in the study in the interest of space. We did
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3 test them in an initial series of experiments. However, the measured performance gains are
4 relatively small. Also these rules are consistently outperformed by the “more refined” rules,
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6 i.e., MASP_N, MASP_AD_N, and MASP_HY_N.
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6.2 Shop configurations

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12 As a starting point for a more detailed discussion of the experimental design, we use Table 4
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14 to specify fixed and experimental factors. Basically, our choice of fixed factors, experimental
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16 factors and their ranges are in line with literature on family based dispatching, see, for
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18 example, reviews by Frazier (1996), Shambu et al. (1996), and Nomden et al. (2006).
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25 [Insert Table 4 about here]
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30 All configurations studied concern a two-stage shop, see Figure 1. The first stage concerns a
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32 batch machine, whereas the second stage is made up of multiple identical machines in
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34 parallel, compare Section 3.1. The latter machines are dedicated to non-overlapping subsets
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36 of job families of equal size. Jobs are assumed to arrive according to a negative exponential
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38 distribution. Batch formation assumes jobs belonging to the same family to be ordered
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40 according to shortest processing time (SPT). Further, all job families have an equal share in
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42 the product mix. Job processing and set-up times for the batch machine are drawn from a
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44 negative exponential distribution, with mean of 1.
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51 Table 4 distinguishes among 6 experimental factors. The key factor is the family based
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53 dispatching rule. In line with the research issues (Section 6.1) each rule is tested for various
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55 shop configurations, as determined by alternative settings for the remainder 5 factors.
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58 Two alternative shop lay outs are considered – identified by the number of parallel
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60 machines in the second stage, i.e., 1 or 4. Alternative settings for the number of job families

Family Based Dispatching in Manufacturing Networks

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3 are chosen in accordance with literature. Many authors choose similar settings, see Frazier
4
5 (1996) for an overview.
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8 The set-up to run-time ratio equals mean set-up time divided by mean processing time.
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10 Set-up times are drawn every time a set-up is executed. For the set-up to run-time ratio two
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12 settings are considered: 0.125, and 0.5. Many other authors adopt similar settings; see, for
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14 example, Wemmerlov (1992), Frazier (1996), Russell and Philipoom (1991), Andrés et al.
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16 (2005). The relevance of this factor follows from its foreseen impact on set-up frequency.
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20 Alternative work load levels for the batch stage are chosen by adapting the mean inter-
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22 arrival time. The levels have been determined using FCFAM as a control rule. This
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24 benchmark configuration was used to determine two levels of work load for each setting of
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26 the number of job families and the set-up to runtime ratio. The levels correspond with 75%,
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28 and 90% machine utilization, respectively, which includes both processing times and set-ups.
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30 Previous research indicates that shop load has a major impact on (relative) performance of
31
32 family based dispatching rules (Wemmerlov and Vakharia 1991). Work load levels for the
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34 parallel machines in the second stage are realized by simply adjusting their mean processing
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36 times.
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6.3 Simulation modelling

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43 Plant SimulationTM 8.2 (Siemens PLM Software 2008) is used to carry out the simulation
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45 experiments. The principles of object oriented design underlying this language make it a
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47 flexible and efficient tool for model building. The performance for each rule is estimated
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49 using the replication deletion method (Hoover and Perry 1986, Law and Kelton 2000). A total
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51 of 60 runs is considered for each experiment. The length of the warm-up period is determined
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53 using the Welch procedure (Law and Kelton 2000). In accordance with the outcomes of the
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55 procedure the warm up period and run length are set at 10,000 and 110,000 time units,
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60 respectively.

7 ANALYSIS OF SIMULATION RESULTS

In this section we will analyse the outcomes of the simulation study, starting from the research issues identified in Section 6.

7.1 Family based dispatching – no local information on second stage available

The first research issue concerns the potential of existing family based dispatching rules for use in manufacturing networks, see Table 5. The table shows normalized stage waiting times and normalized overall flow time performance for each rule across all shop configurations. Results are normalized by considering rule performance relative to the FCFAM rule (FCFAM=100). Outcomes for best performing rules are printed in bold. Performance differences for the rules are tested for statistical validity using a paired t-approach, cf. Law and Kelton (2000). The tests point out that differences greater than 0.25% should be considered significant.

[Insert Table 5 about here]

Table 5 shows that the exhaustive rules (FCFAM, MAS, MASP) are outperformed by the non-exhaustive rules (MASP_AD, MASP_HY) by up to 20% (overall average flow time). Best overall flow time performance is found for MASP_AD. This is in line with our hypothesis (Section 6.1). Whereas the results for MASP_AD for the first stage confirm our previous research (Van der Zee 2010), results when including the second stage are in line with the queueing analysis (Section 4). Remark that a small batch size for MASP_AD relative to the exhaustive rules (Table 6) goes together with a good performance in the second stage.

[Insert Table 6 about here]

Family Based Dispatching in Manufacturing Networks

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Let us now consider effects of shop configuration on flow time performance. The number of parallel machines making up the second stage does influence normalized waiting times for the second stage (Table 5). Figures on waiting times indicate how the second stage performance of non-exhaustive rules relative to exhaustive rules is improved for a higher number of parallel machines. This is in line with findings from the queueing theoretical analysis (Section 4), suggesting an enlarged room for performance improvement at a higher number of parallel machines (compare Table 3). Remark, how increasing the number of parallel machines causes an increase of the second stage waiting times. Therefore, gains reported in terms of normalized overall flow time figures tend to be more like the – lower – gains reported for the second stage.

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Table 5 shows how an increase of the number of job families reduces relative gains of non-exhaustive rules over exhaustive rules. This may be explained by the fact that an increase of the number of job families tends to correspond with smaller batch sizes (compare Section 4.1; Figures 4, 5). Hence less room is left for flow time improvement by reducing the batch size.

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Other factors to consider are the set-up to run-time ratio, and work loads for both stages. Typically, best performance for non-exhaustive rules, especially MASP_AD, is found for low set-up to run-time ratio, high work loads for the batch machine, and low work loads for the second stage. This may be explained by the presence of longer queues at the batch stage (high work loads), which allow for forming small batches (containing jobs requiring short processing times) at low cost (short set-up times). Furthermore, alternative settings for set-up to run-time ratio, and/or work loads reduce relative gains of non-exhaustive rules over FCFAM, and exhaustive rules to about 0.5 – 2%.

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As far as *computational efficiency* is concerned, we found that computation times for heuristics are typically small. They range from about 0.11 milliseconds (FCFAM, MASP, MAS) to 0.12 milliseconds (MASP_AD and MASP_HY) for a shop configuration concerning 8 product families, 4 parallel machines for the second stage, and 90% work loads for both stages. Note how computational performance for the extended heuristics (see Sections 5 and 7.2) ranges from 0.12 milliseconds (FCFAM, MASP, MAS) to 0.13 milliseconds (MASP_AD and MASP_HY) for a similar type of shop configuration. Experiments are carried out on an Intel Dual Core 6300 – 1.86 GHz computer. Of course, for larger shops computation times may go up. However, the computation times indicated by the simulation experiments leave a lot of room for practical settings.

7.2 Family based dispatching – local information on the second stage available

The second series of experiments concerns the extended rules proposed in this article (Section 5). The outcomes of the experiments are shown in Table 7. Just like for the first series of experiments FCFAM is used as a benchmark for normalizing average stage waiting times per stage and average overall flow times.

[Insert Table 7 about here]

Results in Table 7 largely confirm findings for the initial series of experiments. A striking difference is found for configurations which start from 4 parallel machines in the second stage. For these configurations the use of extended rules pays off, allowing for improvements of overall flow time performance of up to 7%. Workings of the extended rules are illustrated by the worsening of waiting times for the batch stage, and a reduction of waiting times for the second stage. Furthermore, a slight increase of average batch size (Table 8) clarifies how

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gains essentially follow from a reduction of interbatch waiting times, i.e., waiting times caused by jobs already present at the second stage.

[Insert Table 8 about here]

Above we highlighted potential for extended rules, in case multiple machines are present for the second stage. No such potential seems to be apparent if the second stage is made up of a single machine. Basically, only a shift of waiting time from the second stage towards the batch stage is realized. Net effect of this move may be a slight worsening of average overall flow time.

8 CONCLUDING REMARKS

In this article we studied family based dispatching rules for use in manufacturing networks. Family based dispatching rules strive to reduce machine set-up frequencies by grouping similar type of jobs, i.e., families, for joint dispatching. Hence shop flow times may be improved. Starting points for this research are observations from a case study (Nomden and Slomp 2006, Bokhorst et al. 2008). The observations suggest how the use of family based dispatching rules for one stage may result in a bulky arrival pattern for successor stages. Consequently, overall shop flow time performance may be worsened. We observed how operators manage to avoid this effect to some extent, by adapting batch size to the local status of successor stages. Surprisingly, literature acknowledges the performance gains of family based dispatching for the batch stage, but neglects influence of successor stages.

The initial step in our research concerns improving understanding the effects of successor stages may have on the perceived benefits of family based dispatching. Therefore, we develop queueing theoretical approximations of shop flow times for a simple two-stage shop. Results indicate that a batch size which is optimal for the batch stage, should be adjusted, i.e.,

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3 reduced, to improve overall shop flow times. If the successor stage consists of a number of
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5 parallel machines the influence might become strong.
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8 Existing rules rely on local information on the batch stage only. The aforementioned case
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10 study, however, indicate potential of including local information on follow-up stages for
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12 family based dispatching. Starting from this notion, we propose several extensions to
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14 existing rules.
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17 The behaviour of existing and extended rules for network use is tested by an extensive
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19 simulation study. A first series of experiments concerns settings for which no local
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21 information on follow-up stages is available. Two categories of rules are considered, i.e.,
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23 exhaustive rules, assuming batches to be equal to queue contents for a job family, and non-
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25 exhaustive rules, allowing for smaller batch sizes. In line with aforementioned queueing
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27 approximations it is shown how the non-exhaustive rules may outperform the exhaustive
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29 rules by up to 20%. Highest gains are found for low set-up to run-time ratios, and high work
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31 loads for the batch stage.
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36 A second series of simulation experiments concerns the new extended rules. The
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38 outcomes indicate a further improvement of average overall flow times by up to 7%, resulting
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40 from the inclusion of local information of the second stage. As expected the gains are caused
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42 by a reduction of waiting times at the second stage.
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48 In this article we considered family based dispatching for its use in manufacturing networks.
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50 To foster understanding of effects and benefits of (new) rules for family based dispatching
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52 our study started from a simple two-stage network system. As such it offers basic insights,
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54 underpinning operators' success, as we found it for the aforementioned case study. An
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56 interesting avenue may be the study of alternative, more elaborate network configurations,
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58 starting from the decision framework, queueing theoretical analysis, and rules as proposed in
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3 this paper. As such relevance of findings for practical application may be increased. A
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5 relevant example concerns a job shop environment, which is much encountered in small
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7 batch discrete parts manufacturing. Such an environment would imply machines in successor
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9 phases being shared among product families, instead of being dedicated to a single or fixed
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11 subset of families (this paper). Consequently, gains of applying informed non-exhaustive
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13 rules may be less. However, for flow shops the opposite may be true.
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Family Based Dispatching in Manufacturing Networks

APPENDIX NOTATION

Indexes

- i job identifier = 1,2,... for jobs in the system, ordered by arrival time
 j, n family identifier = 1,2,...
 c, k batch size, i.e., number of jobs included in the batch
 m machine identifier = 1,2...

Parameters

- j_0 current family, i.e., the family for which the machine has been set-up
 j^* family for which a minimum weighted work load is foreseen
 k_j batch size for family j at first stage
 k_j^{\min} lower bound for batch size at first stage
 k^* batch size at first stage for which a minimum weighted work load is foreseen
 k^{opt} optimal batch size at first stage
 k^{*ex} maximum batch size at first stage for weighted work load is less than P^2
 $p_{i,j,1}$ processing time of job $i = 1, 2, \dots$ belonging to family j for first stage
 $p_{i,j,2}$ processing time of job $i = 1, 2, \dots$ belonging to family j for second stage
 $\bar{p}_{j,1}$ mean processing time for family j for first stage, $\bar{p}_{j,1} = \bar{p}_1$
 $q_{j,1}$ number of jobs in queue for family j at t_0 at first stage
 $q_{j,2}$ number of jobs in queue for family j at t_0 at second stage
 $s_{j_0,j}$ set-up time required for family j at first stage, given current family j_0
 $\bar{s}_{j,1}$ mean set-up time for family j at first stage, $\bar{s}_{j,1} = \bar{s}_1 = \bar{s}$
 t_0 switching moment, i.e., the moment the dispatcher is triggered to make a decision
 $t_{i,j}$ arrival moment at first stage of job $i = 1, 2, \dots$ belonging to family j
 $C_{j,1}^a$ SCV of job inter-arrival times of family j at first stage, $C_{j,1}^a = C_1^a$
 $C_1^{a,B}$ SCV of merged inter-arrival times at first stage
 $C_{j,1}^p$ SCV of job processing times of family j at first stage, $C_{j,1}^p = C_1^p$
 $C_{j,1}^s$ SCV of family j set-up time at first stage, $C_{j,1}^s = C^s$
 $C_{2,m}^a$ SCV of job inter-arrival times at machine m of second stage, $C_{2,l}^a = C_2^a$
 $C_{2,m}^p$ SCV of processing times at machine m of second stage, $C_{2,l}^p = C_2^p$
 J set of job families
 \bar{J} total number of job families ($|J|$)
 N total number of jobs processed over all families
 S set of machines at second stage
 \bar{S} total number of identical machines at second stage ($|S|$)
 λ_T total arrival rate to stage 1, $\lambda_T = \sum_{j=1}^J \lambda_{j,1} = \bar{J}\lambda$

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Variables

$ft_{i,j}$	flow time for job $i = 1, 2, \dots$ belonging to family j
$m(j)$	machine m in second stage assigned to family j
$r_{2,m}$	required time to complete job currently being processed at machine m at second stage
$w_{i,j,1}$	waiting time for job $i = 1, 2, \dots$ belonging to family j at first stage
$w_{i,j,2}$	waiting time for job $i = 1, 2, \dots$ belonging to family j at second stage
P^H	priority, i.e., minimum weighted work load, for the next best family $j \in J$ with $j \neq j^*$
P_c^I	priority, i.e., weighted work load, for the best family j^* given batch size c
\bar{T}	total system mean flow time
\bar{T}^n	total system normalized mean flow time
\bar{T}_1^n	normalized mean flow time at first stage, $\bar{T}_1^n = \bar{T}_1 / \bar{p}_1$
\bar{T}_2^n	normalized mean flow time at second stage, $\bar{T}_2^n = \bar{T}_2 / \bar{p}_2$
$\bar{T}_1^{n,\min}$	minimum normalized mean flow time at first stage
$\bar{T}_1^{pr,\min}$	minimum normalized mean process flow time at first stage (excluding $\bar{w}_{j,1}^{wtb}$)
$\bar{T}^{n,\min}$	minimum total system normalized mean flow time
U_1	utilization (including set-up times) of first stage
U_2	utilization of second stage
U_1^0	utilization (excluding set-up times) of first stage
$U_{2,m}$	utilization of machine m of second stage, $U_{2,m} = U_2$
WL_j	estimated work load at second stage for family j

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Family Based Dispatching in Manufacturing Networks

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Family Based Dispatching in Manufacturing Networks

Factors	Values
Number of job families (\bar{J})	1,4,8
Number of parallel machines for second stage (\bar{S})	1,2,4
Mean processing time for family j for first stage ($\bar{p}_{j,1}$)	1
Mean set-up time for family j at first stage ($\bar{s}_{j,1}$)	0.125
Total arrival rate to stage 1 (λ_T)	0.862
Utilization (excluding set-up times) of first stage (U_1^0)	0.862
Utilization of machine m of second stage ($U_{2,m}$)	0.9
SCV of job inter-arrival times of family j at first stage ($C_{j,1}^a$)	1
SCV of job processing times of family j at first stage ($C_{j,1}^p$)	1
SCV of family j set-up time at first stage ($C_{j,1}^s$)	1
SCV of processing times at machine m of second stage ($C_{2,m}^p$)	1

Table 1 Input data for queueing model

\bar{J}	$\bar{T}_1^{n,\min}$ (% incr.)	k^{opt} (% red.)	$\bar{T}_1^n, k = 4.2$ (% incr.)
0	10.6	4.2	
1	12.1	3.1	12.5 (3.1)
4	14.8 (22.3)	2.2 (28.3)	18.1 (22.0)
8	17.1 (41.3)	1.8 (40.3)	25.4 (88.8)

Table 2 First stage - minimum process and flow times with optimal batch sizes

\bar{J}	$\bar{S} = 1$			$\bar{S} = 2$			$\bar{S} = 4$		
	$\bar{T}^{n,\min}$	k^{opt} (% red.)	\bar{T}^n (% incr.)	$\bar{T}^{n,\min}$	k^{opt} (% red.)	\bar{T}^n (% incr.)	$\bar{T}^{n,\min}$	k^{opt} (% red.)	\bar{T}^n (% incr.)
1	22.4	2.9 (5.8)	22.5 (0.1)						
4	24.9	2.1 (2.6)	25.1 (0.1)	39.3	1.6 (26.2)	40.9 (4.0)	64.5	1.3 (38.9)	73.5 (13.0)
8	27.1	1.8 (1.8)	27.3 (0.8)	40.6	1.5 (16.7)	41.5 (2.3)	65.3	1.3 (28.1)	70.3 (7.7)

Table 3 Minimum system flow times, optimal batch sizes and system flow time using the first stage optimal batch size, dependent of \bar{J} and \bar{S} .

*Family Based Dispatching in Manufacturing Networks***Fixed factors**

Family mix	Equal share per family
Inter-arrival time distribution	Exp
Set-up time distribution for batch machine	Exp(Mean=1.00)
Processing time distribution batch machine	Exp(Mean=1.00)
Processing time distribution parallel machines	Exp ^a
Job selection in batch formation	SPT

Experimental factors

Number of job families	4;8
Number of machines for second stage	1;4
Set-up to runtime ratio ^b	0.125;0.50
Work load batch stage	75%;90%

Mean job inter-arrival times^c

Number of job families	Set-up to runtime ratio	Work load batch stage	Mean job inter-arrival times
4	0.125	75%	1.42
4	0.125	90%	1.16
4	0.5	75%	1.72
4	0.5	90%	1.34
8	0.125	75%	1.46
8	0.125	90%	1.19
8	0.5	75%	1.84
8	0.5	90%	1.44

Work load second stage	75%;90%
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Family based dispatching rules

(1) Existing Rules

FCFAM
MAS
MASP
MASP_AD
MASP_HY

(2) Extended Rules

FCFAM_S
MAS_S
MASP_N
MASP_AD_N
MASP_HY_N

^a Mean processing time depends on work load settings and number of machines for second stage

^b Mean set-up time divided by mean processing time

^c Mean job arrival intervals have been determined for alternative settings of the number of families, set-up to runtime ratio and work load for the batch stage, assuming FCFAM is chosen as the family based dispatching rule.

Table 4 Simulation study - Overview of fixed and experimental factors

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Shop configurations				Average waiting times stage I					Average waiting times stage II					Average flow times (stages I&II)					
#Machines 2 nd stage	# Job Families	S/R ratio	Work Load 1 st Stage (%)	Work Load 2 nd Stage (%)	FCFAM	MAS	MASP	MASP_AD	MASP_HY	FCFAM	MAS	MASP	MASP_AD	MASP_HY	FCFAM	MAS	MASP	MASP_AD	MASP_HY
1	4	0.125	75	75	100.00	95.17	85.40	69.57	80.27	100.00	100.89	98.52	95.73	99.27	100.00	98.74	94.53	88.12	93.11
1	4	0.125	75	90	100.00	95.17	85.40	69.57	80.27	100.00	100.43	99.48	98.35	99.65	100.00	99.51	97.25	93.96	96.64
1	4	0.125	90	75	100.00	93.62	86.14	64.17	72.49	100.00	101.48	96.48	87.05	99.72	100.00	96.49	90.92	75.55	83.49
1	4	0.125	90	90	100.00	93.62	86.13	64.17	72.49	100.00	100.79	97.05	92.09	98.29	100.00	98.06	93.39	82.67	88.94
1	4	0.5	75	75	100.00	86.93	85.96	83.41	83.82	100.00	101.64	99.60	97.07	100.16	100.00	96.71	95.55	93.69	95.14
1	4	0.5	75	90	100.00	86.93	85.96	83.41	83.82	100.00	100.73	100.00	98.98	100.15	100.00	98.73	98.04	96.98	97.93
1	4	0.5	90	75	100.00	81.85	84.69	80.83	77.59	100.00	101.94	96.85	91.64	99.18	100.00	91.20	91.22	87.76	88.23
1	4	0.5	90	90	100.00	81.85	84.68	80.82	77.59	100.00	101.13	98.49	94.92	99.25	100.00	95.49	94.71	91.48	93.15
1	8	0.125	75	75	100.00	89.25	73.81	64.68	69.70	100.00	101.74	97.49	96.56	98.33	100.00	97.02	90.07	86.58	89.00
1	8	0.125	75	90	100.00	89.25	73.81	64.68	69.70	100.00	100.77	99.06	98.64	99.32	100.00	98.75	95.00	93.28	94.59
1	8	0.125	90	75	100.00	83.58	73.43	56.84	60.34	100.00	102.24	92.67	90.49	96.12	100.00	90.59	82.25	71.74	75.14
1	8	0.125	90	90	100.00	83.58	73.43	56.84	60.34	100.00	101.26	94.51	93.67	96.18	100.00	94.60	87.30	80.76	83.32
1	8	0.5	75	75	100.00	74.89	73.62	71.56	71.63	100.00	103.56	100.25	99.29	100.82	100.00	93.35	91.56	90.48	91.15
1	8	0.5	75	90	100.00	74.89	73.62	71.56	71.63	100.00	101.37	100.14	99.73	100.41	100.00	97.33	96.24	95.65	96.14
1	8	0.5	90	75	100.00	63.40	67.59	61.03	59.59	100.00	105.02	95.85	95.55	99.07	100.00	81.52	81.34	77.70	77.86
1	8	0.5	90	90	100.00	63.40	67.59	61.03	59.59	100.00	102.40	97.87	97.42	99.29	100.00	90.29	88.96	86.70	87.37
4	4	0.125	75	75	100.00	95.17	85.40	69.57	80.27	100.00	100.74	98.97	93.22	96.17	100.00	99.86	97.57	92.02	95.19
4	4	0.125	75	90	100.00	95.17	85.40	69.57	80.27	100.00	100.34	99.68	97.62	98.62	100.00	100.07	99.05	96.59	97.92
4	4	0.125	90	75	100.00	93.62	86.14	64.17	72.49	100.00	102.59	100.79	73.17	81.87	100.00	99.80	96.76	75.62	82.65
4	4	0.125	90	90	100.00	93.62	86.13	64.17	72.49	100.00	102.24	101.57	88.11	91.84	100.00	100.97	99.52	86.30	90.23
4	4	0.5	75	75	100.00	86.93	85.96	83.41	83.82	100.00	99.94	99.38	96.13	98.38	100.00	98.59	98.10	95.76	97.25
4	4	0.5	75	90	100.00	86.93	85.96	83.41	83.82	100.00	100.04	99.77	98.67	99.43	100.00	99.50	99.24	98.20	98.86
4	4	0.5	90	75	100.00	81.85	84.69	80.83	77.59	100.00	98.65	99.00	85.55	92.31	100.00	95.41	96.20	87.56	90.82
4	4	0.5	90	90	100.00	81.85	84.68	80.82	77.59	100.00	99.78	99.87	94.40	97.10	100.00	98.19	98.50	93.74	95.64
4	8	0.125	75	75	100.00	89.25	73.81	64.68	69.70	100.00	100.30	98.44	96.36	97.40	100.00	98.80	95.74	93.28	94.58
4	8	0.125	75	90	100.00	89.25	73.81	64.68	69.70	100.00	100.10	99.43	98.70	99.06	100.00	99.56	98.25	97.19	97.74
4	8	0.125	90	75	100.00	83.58	73.43	56.84	60.34	100.00	100.08	97.15	85.00	88.26	100.00	95.26	90.87	79.79	82.45
4	8	0.125	90	90	100.00	83.58	73.43	56.84	60.34	100.00	100.32	99.09	93.96	95.22	100.00	98.12	95.86	89.76	91.19
4	8	0.5	75	75	100.00	74.89	73.62	71.56	71.63	100.00	99.82	99.22	98.03	98.86	100.00	97.03	96.50	95.47	96.04
4	8	0.5	75	90	100.00	74.89	73.62	71.56	71.63	100.00	99.92	99.70	99.31	99.58	100.00	98.86	98.62	98.21	98.43
4	8	0.5	90	75	100.00	63.40	67.59	61.03	59.59	100.00	97.69	97.05	91.79	94.09	100.00	90.12	90.76	86.30	87.26
4	8	0.5	90	90	100.00	63.40	67.59	61.03	59.59	100.00	99.27	99.04	97.00	97.86	100.00	95.79	96.02	93.75	94.32

Table 5 Normalized average job flow times – Series I : No local information on second stage

	FCFAM	MAS	MASP	MASP_AD	MASP_HY
Average batch size	1.90	1.79	1.74	1.33	1.60

Table 6 Batch sizes – averages over all configurations (Series I)

For Peer Review Only

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Shop configurations					Average waiting times stage I					Average waiting times stage II					Average flow times (stages I&II)				
#Machines 2 nd stage	# Job Families	S/R ratio	Work Load 1 st Stage (%)	Work Load 2 nd Stage (%)	FCFAM_S	MAS_S	MASP_N	MASP_AD_N	MASP_HY_N	FCFAM_S	MAS_S	MASP_N	MASP_AD_N	MASP_HY_N	FCFAM_S	MAS_S	MASP_N	MASP_AD_N	MASP_HY_N
1	4	0.125	75	75	100.00	98.29	90.28	80.21	87.20	100.00	101.46	95.59	86.85	93.75	100.00	100.01	94.99	88.13	93.22
1	4	0.125	75	90	100.00	96.90	93.86	89.75	92.88	100.00	101.13	97.83	93.74	96.87	100.00	100.31	97.50	93.96	96.64
1	4	0.125	90	75	100.00	96.63	90.52	71.02	79.38	100.00	102.58	92.44	69.65	86.31	100.00	98.56	92.54	75.57	84.46
1	4	0.125	90	90	100.00	95.37	94.14	82.96	88.05	100.00	102.09	94.36	78.95	89.49	100.00	99.39	94.94	82.83	90.17
1	4	0.5	75	75	100.00	92.02	95.26	95.56	91.12	100.00	102.02	94.48	89.20	95.59	100.00	98.43	96.20	94.03	95.41
1	4	0.5	75	90	100.00	89.54	101.89	104.70	95.81	100.00	101.39	97.37	95.11	98.03	100.00	99.58	98.36	97.08	97.98
1	4	0.5	90	75	100.00	89.34	97.74	90.14	85.08	100.00	102.71	87.53	78.59	91.87	100.00	95.28	95.30	88.86	90.01
1	4	0.5	90	90	100.00	86.31	110.03	102.36	90.91	100.00	103.10	91.63	85.92	94.45	100.00	97.94	97.88	92.32	94.10
1	8	0.125	75	75	100.00	96.04	83.58	77.44	80.57	100.00	103.41	90.57	85.77	89.29	100.00	100.00	90.66	86.66	89.12
1	8	0.125	75	90	100.00	92.93	91.32	89.46	90.24	100.00	102.21	95.41	92.86	94.73	100.00	100.36	95.36	93.28	94.65
1	8	0.125	90	75	100.00	91.35	83.82	65.89	69.80	100.00	105.82	80.83	69.20	76.66	100.00	96.10	85.82	72.35	76.41
1	8	0.125	90	90	100.00	88.00	93.66	82.61	83.95	100.00	105.49	86.23	76.57	82.23	100.00	98.42	90.57	81.47	84.90
1	8	0.5	75	75	100.00	82.99	89.29	85.27	82.98	100.00	104.00	90.29	89.50	92.91	100.00	96.16	92.48	90.84	91.53
1	8	0.5	75	90	100.00	79.22	101.60	95.94	91.05	100.00	102.33	95.07	95.00	96.58	100.00	98.67	96.69	95.80	96.29
1	8	0.5	90	75	100.00	75.10	90.59	71.74	69.46	100.00	107.26	75.06	78.42	85.40	100.00	88.46	88.26	78.93	79.56
1	8	0.5	90	90	100.00	70.06	121.49	86.87	79.61	100.00	106.39	79.60	85.44	90.32	100.00	94.61	94.76	87.62	88.19
4	4	0.125	75	75	100.00	98.16	98.28	93.58	97.16	100.00	96.09	93.37	84.97	91.89	100.00	97.34	95.61	89.69	94.54
4	4	0.125	75	90	100.00	96.93	100.85	97.51	100.57	100.00	98.09	96.89	94.81	96.74	100.00	98.24	97.43	95.51	97.29
4	4	0.125	90	75	100.00	97.35	97.98	86.78	93.50	100.00	93.45	87.70	52.53	78.42	100.00	95.68	92.65	70.14	86.29
4	4	0.125	90	90	100.00	96.28	102.35	91.69	99.33	100.00	94.81	90.37	78.78	88.56	100.00	95.49	92.78	82.42	91.00
4	4	0.5	75	75	100.00	93.85	100.04	103.37	94.86	100.00	96.81	94.81	89.88	95.06	100.00	97.30	96.65	93.82	96.29
4	4	0.5	75	90	100.00	90.70	102.75	105.34	96.82	100.00	98.70	97.85	96.60	98.08	100.00	98.52	98.27	97.31	98.23
4	4	0.5	90	75	100.00	92.25	101.02	100.83	88.33	100.00	92.24	88.04	70.69	87.40	100.00	93.88	93.26	83.17	90.20
4	4	0.5	90	90	100.00	88.37	107.65	102.46	91.08	100.00	95.82	92.72	88.69	93.99	100.00	95.57	94.81	91.08	94.34
4	8	0.125	75	75	100.00	94.71	96.03	94.39	94.87	100.00	94.28	90.57	86.93	89.61	100.00	95.78	93.61	91.15	92.91
4	8	0.125	75	90	100.00	92.07	100.20	99.47	99.64	100.00	97.71	96.39	95.53	96.25	100.00	97.71	96.98	96.22	96.82
4	8	0.125	90	75	100.00	91.48	95.27	86.64	86.88	100.00	84.84	75.01	58.99	68.68	100.00	89.64	85.67	74.84	79.96
4	8	0.125	90	90	100.00	88.38	103.86	96.52	96.19	100.00	92.65	86.58	82.79	85.72	100.00	92.84	90.16	86.30	88.51
4	8	0.5	75	75	100.00	84.94	99.36	96.40	91.07	100.00	96.06	92.47	91.10	93.37	100.00	95.77	95.09	93.87	94.74
4	8	0.5	75	90	100.00	79.92	104.84	99.78	94.17	100.00	98.73	97.23	97.01	97.70	100.00	98.06	97.86	97.47	97.79
4	8	0.5	90	75	100.00	79.03	102.57	85.50	77.60	100.00	87.90	77.59	74.86	82.20	100.00	88.41	88.25	82.72	84.91
4	8	0.5	90	90	100.00	71.78	118.44	90.37	82.16	100.00	95.50	89.38	90.70	92.94	100.00	93.63	93.35	91.63	92.60

Table 7 Normalized average job flow times – Series II : Local information on second stage.

	FCFAM_S	MAS_S	MASP_N	MASP_AD_N	MASP_HY_N
Average batch size	1.93	1.82	1.81	1.42	1.69

Table 8 Batch sizes – averages over all configurations (Series II)

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Family Based Dispatching in Manufacturing Networks

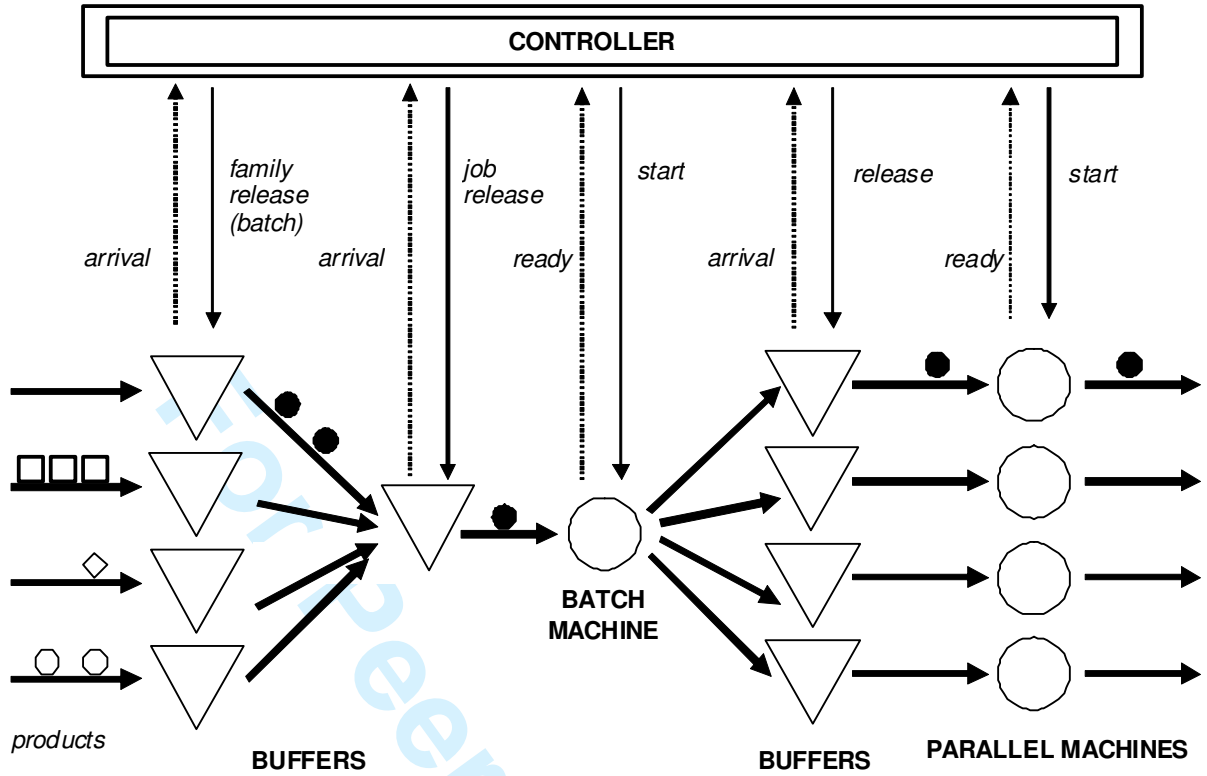


Figure 1 Shop lay-out

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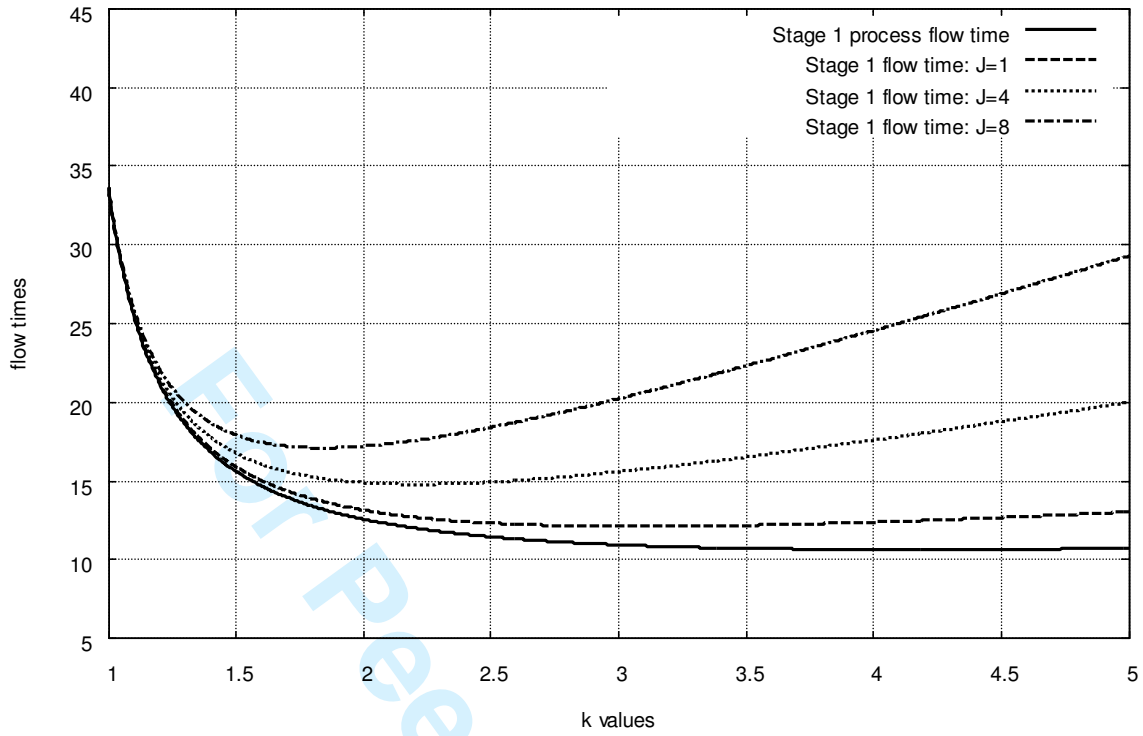


Figure 2 First stage flow times

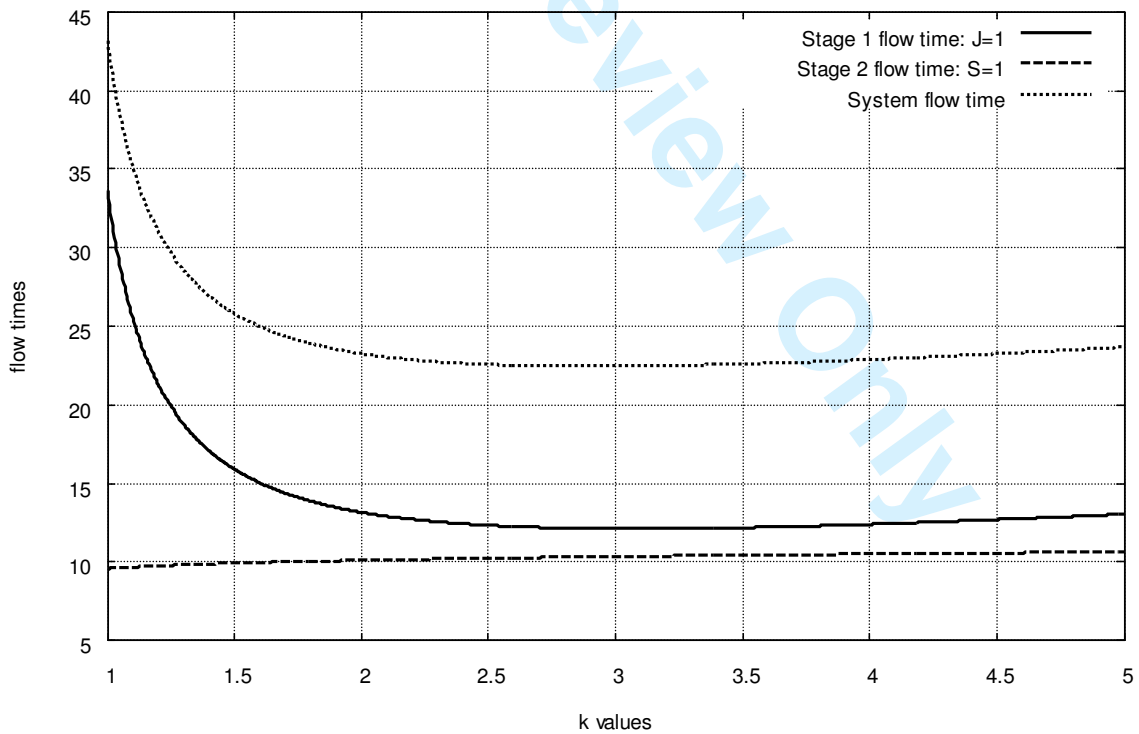


Figure 3 First stage, second stage and system flow times for $\bar{J} = 1, \bar{S} = 1$

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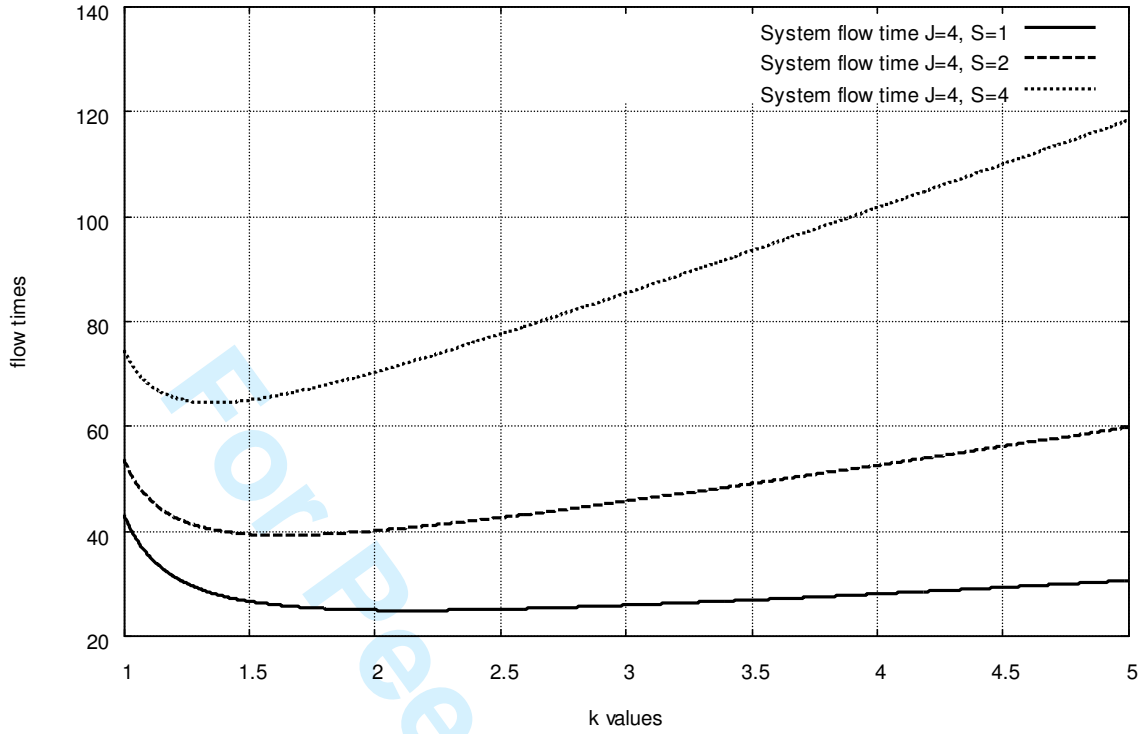


Figure 4 System flow times, $\bar{J} = 4$, $\bar{S} = 1, 2, 4$

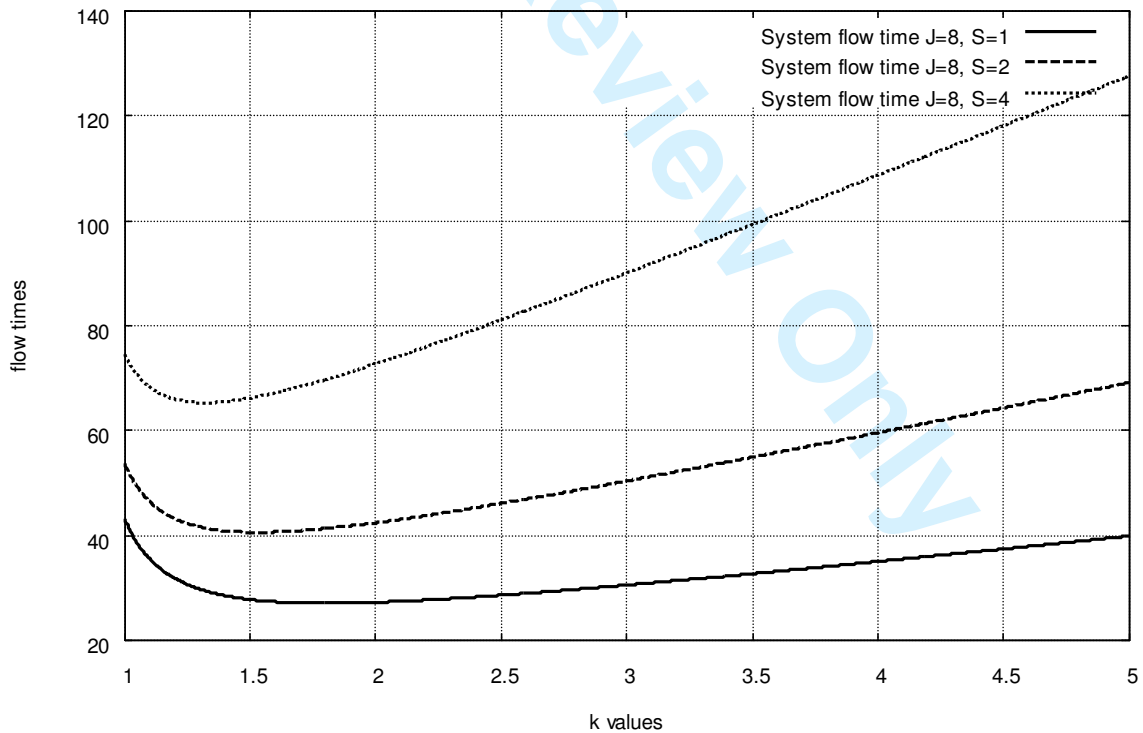


Figure 5 System flow times, $\bar{J} = 8$, $\bar{S} = 1, 2, 4$

Family Based Dispatching in Manufacturing Networks

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OVERVIEW OF DISPATCHING RULES

Supplementary online material

To be made available on-line: www.rug.nl/staff/d.j.van.der.zee

*Family Based Dispatching in Manufacturing Networks***OVERVIEW OF DISPATCHING RULES**

Name	Explanation	Type*	Exhaustive	Reference	Remarks
ECON	ECONomic trade-off between changing queues	FBD	no	Mosier et al. (1984), Ruben et al. (1993)	
EDD	Earliest Due Date	DP	-	Blackstone et al. (1982)	
FCFAM	First Come FAMily	FBD	yes	Flynn (1987)	Often used as benchmark
FCFS	First Come First Serve	DP	-	Blackstone et al. (1982)	
MAS	Minimum Average Set-up time	FBD	yes	Nomden et al. (2008)	Extension of MAS. Family priority settings consider work load for successor manufacturing stage.
MAS_S	Minimum Average Set-up time for Network use	FBD	yes	Van der Zee et al. (2011)	Extension of MAS. Family priority settings consider whether machines in successor manufacturing stage are starved or not.
MASP	Minimum Average Set-up plus Processing time	FBD	yes	Jensen et al. (1996)	
MASP_N	Minimum Average Set-up plus Processing time for Networks	FBD	yes	Van der Zee et al. (2011)	Extension of MASP. Family priority settings consider work load for successor manufacturing stage.
MASP_S	Minimum Average Set-up plus Processing time for Networks	FBD	yes	Van der Zee et al. (2011)	Extension of MASP. Family priority settings consider whether machines in successor manufacturing stage are starved or not.
MASP_AD	ADaptive Minimum Average Set-up plus Processing time	FBD	no	Van der Zee (2010)	Extension of MASP. It allows for alternative settings of batch size within job families
MASP_AD_N	ADaptive Minimum Average Set-up plus Processing time for Networks	FBD	no	Van der Zee et al. (2011)	Extension of MASP_AD. Family priority settings consider work load for successor manufacturing stage.
MASP_AD_S	ADaptive Minimum Average Set-up plus Processing time for Networks	FBD	no	Van der Zee et al. (2011)	Extension of MASP_AD. Family priority settings consider whether machines in successor manufacturing stage are starved or not.
MASP_HY	HYbrid Minimum Average Set-up plus Processing time	FBD	no	Van der Zee (2010)	Extends MASP_AD by considering possibilities to further improve set-up efficiencies. It allows for a temporary shift towards an exhaustive policy.
MASP_HY_N	HYbrid Minimum Average Set-up plus Processing time for Networks	FBD	no	Van der Zee et al. (2011)	Extension of MASP_HY. Family priority settings consider work load for successor manufacturing stage.
MASP_HY_S	HYbrid Minimum Average Set-up plus Processing time for Networks	FBD	no	Van der Zee et al. (2011)	Extension of MASP_HY. Family priority settings consider whether machines in successor manufacturing stage are starved or not.
SPT	Shortest Processing Time	DP	-	Blackstone et al. (1982)	
WSPT	Weighted Shortest Processing Time	DP	-	Pinedo (2005)	

* FBD = Family based dispatching rule, DP = Conventional dispatching rule

Table 1 Overview of dispatching rules

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Family Based Dispatching in Manufacturing Networks

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QUEUING THEORETICAL ANALYSIS

Supplementary online material

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QUEUING THEORETICAL ANALYSIS

We will use the two-moment parametric decomposition approximation for the waiting (flow) times in (open) queueing networks. See, for example, Kuehn (1979), Shanthikumar and Buzacott (1981), Whitt (1982, 1983), Albin (1984), and Buzacott and Shanthikumar (1993). In addition, many papers use the decomposition approximation in case of batch arrivals and batch processing in queueing networks. See, for example, Whitt (1983), Shanthikumar and Buzacott (1985), Segal and Whitt (1988), Bitran and Tirupati (1989) Hopp and Spearman (2000), Curry and Deuermeier (2002), Meng and Herague (2004).

The system consists of a two-stage (sequential) shop. Stage 1 concerns one (batch) machine and stage 2 is made up of a number of identical machines in parallel (\bar{S}), each with a buffer in front. The system serves a number of job families, with identical characteristics. Also see Van der Zee et al. (2011) for more details (especially, Section 3 and Figure 1). The notation for the parameters and variables is described in the Appendix.

1 Operational characteristics of the first (batch) stage.

Before individual jobs of a family arrive in the joint queue in front of the machine, batches of k_j jobs are formed. This causes a mean wait-to-batch delay of family j :

$$\bar{w}_{j,1}^{wtb} = \left(\frac{k_j - 1}{2\lambda_{j,1}} \right) = \left(\frac{k - 1}{2\lambda} \right) = \left(\frac{(k - 1)\bar{J}}{2\lambda_T} \right) = \bar{w}_1^{wtb} \quad [1]$$

The wait-to-batch delay is equal for all families because $\lambda_{j,1} = \lambda$ and increases with the batch size ($k_j = k$). Moreover, since we assume that the total arrival rate at the machine remains constant, regardless the number of families (i.e. $\lambda_T = \sum_{j=1}^J \lambda_{j,1} = \bar{J}\lambda$), \bar{w}_1^{wtb} also increases with \bar{J} .

The family batch arrival rate at stage 1 is:

Family Based Dispatching in Manufacturing Networks

$$\lambda_{j,1}^B = \left(\frac{\lambda_{j,1}}{k_j} \right) = \left(\frac{\lambda}{k} \right) = \left(\frac{\lambda_T}{k\bar{J}} \right) = \lambda_1^B \quad [2]$$

The squared coefficient of variation (SCV) of the inter-arrival times of batches of family j at stage 1 satisfies:

$$C_{j,1}^{a,B} = \left(\frac{C_{j,1}^a}{k_j} \right) = \left(\frac{C_1^a}{k} \right) \quad [3]$$

Next the \bar{J} families with batch sizes k enter the queue of the machine. The total batch arrival rate is:

$$\lambda_T^B = \sum_{j=1}^J \lambda_{j,1}^B = \left(\frac{1}{k} \right) \lambda_T \quad [4]$$

For an approximation of the merged SCV we use (see, for example, Bitran and Tirupati 1989):

$$C_1^{a,B} = \sum_{j=1}^J \left(\frac{\lambda_{j,1}}{\lambda_T} \right) C_{j,1}^{a,B} = \left(\frac{C_1^a}{k} \right) \quad [5]$$

The waiting batches in queue of the machine will be served using the First Come First Serve (FCFS) rule. In addition, it will be assumed that the chance of two (or more) family batches of the same type succeeding each other, can be neglected. This implies each batch will require a set-up. The mean processing time of a family j batch becomes $\bar{p}_{j,1}^B = \bar{s}_{j,1} + k\bar{p}_{j,1} = \bar{s} + k\bar{p}_1 = \bar{p}_1^B$, and is independent of the family type. The SCV of the processing time is:

$$C_1^{p,B} = \left(\frac{\text{var}(s) + k \text{var}(p_1)}{(\bar{s} + k\bar{p}_1)^2} \right) = \left(\frac{\bar{s}^2 C^s + k(\bar{p}_1)^2 C_1^p}{(\bar{s} + k\bar{p}_1)^2} \right) \quad [6]$$

For the batch waiting time of the first machine, a G/G/1 approximation (see, for example, Buzacott and Shanthikumar 1993) is used:

$$\bar{w}_1^B = \left(\frac{C_1^{a,B} + C_1^{p,B}}{2} \right) \cdot \left(\frac{U_1}{1-U_1} \right) \bar{p}_1^B, \quad [7]$$

Family Based Dispatching in Manufacturing Networks

with the utilization $U_1 = \lambda_T^B (\bar{s} + k\bar{p}_1) = U_1^{set} + U_1^0$, $U_1^0 = \lambda_T \bar{p}_1$

Immediately after processing, a batch is split into individual jobs that depart to the second stage. Consequently an extra mean waiting time is caused:

$$\bar{w}_1^{split} = \left(\frac{(k-1)\bar{p}_1}{2} \right) \quad [8]$$

The mean flow time of the batch machine (or process) in the first stage consists of three components, the waiting time of a batch in the queue, the processing time and the batch split time:

$$\bar{T}_1^{pr} = \bar{w}_1^B + (\bar{s} + k\bar{p}_1) + \bar{w}_1^{split} = \left(\frac{C_1^{a,B} + C_1^{p,B}}{2} \right) \left(\frac{U_1}{1-U_1} \right) (\bar{s} + k\bar{p}_1) + \bar{s} + \left(\frac{(k+1)\bar{p}_1}{2} \right) \quad [9]$$

Adding the wait-to-batch delay [7] gives the total flow time of the first stage:

$$\bar{T}_1 = \left(\frac{(k-1)\bar{J}}{2U_1^0} \right) \bar{p}_1 + \left(\frac{C_1^{a,B} + C_1^{p,B}}{2} \right) \left(\frac{U_1}{1-U_1} \right) (\bar{s} + k\bar{p}_1) + \bar{s} + \left(\frac{(k+1)\bar{p}_1}{2} \right) \quad [10]$$

For $k \rightarrow 0$ the batch waiting time becomes infinite. For $k \rightarrow \infty$ the waiting time approaches the waiting time of jobs in case of no set-ups. This type of behaviour is similar to Karmarkar (1987) using a simple M/M/1 queueing model. Also Hopp and Spearman (2000) consider a queueing model for one family with constant (not k dependent) SCV for the batch arrival and processing times. In addition, the authors leave out the wait-to-batch delay. The wait-to-batch delay and the batch split waiting increase linearly in k . Consequently, for large k the flow time approaches the line:

$$\left(\frac{k}{2} \right) \left(\left(\frac{\bar{J}}{U_1^0} \right) + 1 \right) \bar{p}_1 \quad [11]$$

In order to compare the operational characteristics in both stages, we will normalize all expressions with respect to the mean processing time \bar{p}_1 . Then the SCV of the processing

time becomes $C_1^{p,B} = \left(\frac{(\bar{s}^n)^2 C^s + k C_1^p}{(\bar{s}^n + k)^2} \right)$, with $\bar{s}^n = \bar{s} / \bar{p}_1$, and the flow time:

Family Based Dispatching in Manufacturing Networks

$$\bar{T}_1^n = \left(\frac{\bar{T}_1}{\bar{p}_1} \right) = \left(\frac{(k-1)\bar{J}}{2U_1^0} \right) + \left(\frac{C_1^{a,B} + C_1^{p,B}}{2} \right) \left(\frac{U_1}{1-U_1} \right) (\bar{s}^n + k) + \bar{s}^n + \left(\frac{(k+1)}{2} \right) \quad [12]$$

For the approximation of the SCV of the inter-departure times of the first stage we follow Curry and Deuermeyer (2002). Rewriting the SCV in a more attractive form gives:

$$C_1^d = k\{C_1^{a,B}(1-U^2) + U^2 C_1^{p,B}\} + (k-1)(1-U)^2 + (k-1)(U-U_1^0)(2-(U+U_1^0)) \quad [13]$$

The first component is the SCV of the inter-departure times of batches. For $k=1$ we get $C_1^d = \{C_1^a(1-U^2) + U^2 C_1^p\}$, a well known approximation (Whitt, 1984). In case of no set-up times $U = U^o$, giving $C_1^d = k\{C_1^{a,B}(1-U^2) + U^2 C_1^{p,B}\} + (k-1)(1-U)^2$ (also see Curry and Deuermeyer 2002). Thus the last component can be considered as extra term caused by set-up times (given batch processing). For very large k the first component becomes constant $\{C_1^a(1-(U_1^0)^2) + (U_1^0)^2 C_1^p\}$, the third component will be very small and the second component increases linearly with $k(1-U^o)^2$.

2 Operational characteristics of the second stage.

We assume that the k jobs of a family when served in stage 1 go to one of \bar{S} machines in the second stage. Each machine serves an equal number of families, given by the integer (\bar{J}/\bar{S}) . An arbitrary departing family has a chance $\kappa_m = (1/\bar{S})$, $\sum_{m=1}^{\bar{S}} \kappa_m = 1$ to visit a machine. It can be shown that using renewal assumptions the approximation of the SCV of the inter-arrival times of the first item of (successive) batches satisfies:

$$\kappa_m (C_1^d / k) + (1 - \kappa_m) \quad [14]$$

Since the inter-arrival times of the first jobs consists of k job (assumed independent) arrival times the SCV should be multiplied by k giving:

$$C_{2,m}^a = C_2^a = \kappa_m C_1^d + k(1 - \kappa_m) \quad [15]$$

The squared coefficient of variation C_2^a is a function $1/\bar{S}$ and an increasing function of k .

Family Based Dispatching in Manufacturing Networks

The arrival rate at a machine m in stage 2 is $\lambda_{2,m} = \kappa_m \lambda_T = \lambda_T / \bar{S}$. The utilization of a parallel machine is $U_{2,m} = U_2 = \lambda_{2,m} \bar{p}_{2,m} = \lambda_T \bar{p}_2 / \bar{S}$. Note that since we assume a constant total arrival rate λ_T and a constant utilization U_2 of all parallel machines, the processing time varies with the number of machines \bar{S} , ($\bar{p}_2 = \bar{S} \left(\frac{U_2}{\lambda_T} \right) = \bar{S} \left(\frac{U_2}{U_1^0} \right) \bar{p}_1$).

Since based on the assumptions the flow times of the parallel machines are equal, we need only to consider only one machine. The mean waiting time is approximated by the expression:

$$\bar{w}_2 = \left(\frac{C_2^a + C_2^p}{2} \right) \left(\frac{U_2}{1-U_2} \right) \bar{p}_2 \quad [16]$$

The flow time becomes:

$$\bar{T}_2 = \bar{w}_2 + \bar{p}_2, \quad [17]$$

and normalized flow time is:

$$\bar{T}_2^n = \left(\frac{\bar{T}_2}{\bar{p}_1} \right) = \bar{S} \left(\frac{U_2}{U_1^0} \right) \left(\left(\frac{C_2^a + C_2^p}{2} \right) \left(\frac{U_2}{1-U_2} \right) + 1 \right) \quad [18]$$

Since C_2^p is assumed to be constant, the flow time increases in k (because C_2^a does). In addition, \bar{T}_2^n is a linear function of \bar{S} . For very large k the flow time approaches to the line:

$$\left(\frac{k}{2} \right) \left((1-U_1^0)^2 + \bar{S} \right) \left(\frac{U_2}{U_1^0} \right) \left(\frac{U_2}{1-U_2} \right) \quad [19]$$

The total system normalized flow time is denoted by:

$$\bar{T}^n = \bar{T}_1^n + \bar{T}_2^n \quad [20]$$

Family Based Dispatching in Manufacturing Networks

APPENDIX NOTATION

Indexes

- j family identifier = 1,2,...
 k batch size, i.e., number of jobs included in the batch
 m machine identifier = 1,2...

Parameters

- $\bar{p}_{j,1}$ mean processing time for family j for first stage, $\bar{p}_{j,1} = \bar{p}_1$
 $\bar{p}_{j,1}^B$ mean batch processing time for family j for first stage, $\bar{p}_{j,1}^B = \bar{p}_1^B$
 $\bar{p}_{j,2}$ mean processing time for family j for second stage, $\bar{p}_{j,2} = \bar{p}_2$
 $\bar{p}_{j,2,m}$ mean processing time for family j visiting machine m of second stage, $\bar{p}_{j,2,l} = \bar{p}_2$
 $\bar{s}_{j,1}$ mean set-up time for family j at first stage, $\bar{s}_{j,1} = \bar{s}_1 = \bar{s}$
 $\bar{s}_{j,1}^n$ normalized mean set-up time for family j at first stage, $\bar{s}_{j,1}^n = \bar{s}_j^n = \bar{s}^n = \bar{s}_{j,1} / \bar{p}_1$
 $C_{j,1}^a$ SCV of job inter-arrival times of family j at first stage, $C_{j,1}^a = C_1^a$
 $C_{j,1}^{a,B}$ SCV of inter-arrival times batches of family j at first stage
 $C_1^{a,B}$ SCV of merged inter-arrival times at first stage
 $C_{j,1}^p$ SCV of job processing times of family j at first stage, $C_{j,1}^p = C_1^p$
 $C_{j,1}^s$ SCV of family j set-up time at first stage, $C_{j,1}^s = C^s$
 $C_1^{p,B}$ SCV of batch processing times at first stage, set-up time included
 C_1^d SCV job inter-departure times at first stage
 $C_{2,m}^a$ SCV of job inter-arrival times at machine m of second stage, $C_{2,l}^a = C_2^a$
 $C_{2,m}^p$ SCV of processing times at machine m of second stage, $C_{2,l}^p = C_2^p$
 J set of job families
 \bar{J} total number of job families ($|J|$)
 N total number of jobs processed over all families
 S set of machines at second stage
 \bar{S} total number of identical machines at second stage ($|S|$)
 $\lambda_{j,1}$ job arrival rate for family j at first stage, $\lambda_{j,1} = \lambda$
 λ_r total arrival rate to stage 1, $\lambda_r = \sum_{j=1}^J \lambda_{j,1} = \bar{J} \lambda$
 $\lambda_{j,1}^B$ batch arrival rate for family j at first stage
 $\lambda_{2,m}$ job arrival rate for machine m of second stage

Variables

- $\bar{w}_{j,1}$ mean waiting time for family j at first stage, $\bar{w}_{j,1} = \bar{w}_1$
 $\bar{w}_{j,1}^B$ mean waiting time for batch of family j at first stage, $\bar{w}_{j,1}^B = \bar{w}_{j,1}$
 $\bar{w}_{j,2}$ mean waiting time for family j at second stage, $\bar{w}_{j,2} = \bar{w}_2$
 $\bar{w}_{j,1}^{wtb}$ mean wait-to-batch delay for family j at first stage, $\bar{w}_{j,1}^{wtb} = \bar{w}_1^{wtb}$

Family Based Dispatching in Manufacturing Networks

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4	\bar{w}_1^{split}	mean delay due to splitting the batch into individual jobs after processing at first stage
5	\bar{T}	total system mean flow time
6	\bar{T}^n	total system normalized mean flow time
7		
8	\bar{T}_1	mean flow time at first stage
9		
10	\bar{T}_1^{pr}	mean process flow time at first stage
11	$\bar{T}_1^{pr,min}$	minimum mean process flow time at first stage
12		
13	\bar{T}_2	mean flow time at second stage
14	\bar{T}_1^n	normalized mean flow time at first stage, $\bar{T}_1^n = \bar{T}_1 / \bar{p}_1$
15		
16	\bar{T}_2^n	normalized mean flow time at second stage, $\bar{T}_2^n = \bar{T}_2 / \bar{p}_2$
17		
18	$\bar{T}_1^{n,min}$	minimum normalized mean flow time at first stage
19	$\bar{T}_1^{pr,min}$	minimum normalized mean process flow time at first stage (excluding $\bar{w}_{j,1}^{wtb}$)
20		
21	$\bar{T}^{n,min}$	minimum total system normalized mean flow time
22		
23	U_1	utilization (including set-up times) of first stage
24	U_2	utilization of second stage
25		
26	U_1^0	utilization (excluding set-up times) of first stage
27	U_1^{set}	utilization of first stage caused by set-up times at first stage
28		
29	$U_{2,m}$	utilization of machine m of second stage, $U_{2,m} = U_2$
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