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CHAPTER 6

Small manufacturing networks

In many practical instances, the choice whether to apply family-based dispatching or not can be decided per machine. This paper explores the impact of the location of family-based dispatching, load variations between machines, and routing of jobs on the flow time effect of family-based dispatching. These factors are explored in small manufacturing cells with and without labour constraints. An industrial case motivates the study. A simulation study is performed to assess the impact of these effects. The results show that shop floor characteristics such as routing and load variation impact the decision where to locate family-based dispatching in manufacturing cells without labour constraints. By contrast, the effect of family-based dispatching is much less vulnerable to shop floor characteristics in cells with labour constraints. Since workers are the bottleneck in these cells, it becomes less important at what machine the set-up time involving a worker is reduced. In general, there seems to be a trade-off between the positive effect of applying family-based dispatching at a (bottleneck) machine and the possible negative effect of the more irregular job arrivals at subsequent machines. The results further indicate that family based dispatching is more advantageous in cells with labour constraints than in cells without labour constraints, when both types of manufacturing cells have comparable machine utilisations.

6.1 Introduction

Due to increased globalization, Western manufacturers face an increasing competition. Producers of goods are under constant pressure to cut their costs, and improve delivery speed, quality, flexibility and dependability at the same time. Cellular Manufacturing (CM) has been proposed to meet these demands. CM is an

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application of Group Technology (GT), where machines and workers are grouped physically, and are dedicated to the manufacturing of a product family. Production scheduling based on the Group Technology concept is coined ‘group scheduling’ by the pioneers Hitomi and Ham (see e.g. Hitomi and Ham 1977, Ham, Hitomi and Yoshida 1985). Within manufacturing cells, Tooling Analysis (TA) can be applied to identify families of jobs which require the same tools at a machine. Subsequently, group scheduling heuristics or family-based dispatching (FBD) rules can be used to reduce setup times at the machine. FBD is promoted especially for bottleneck machines (Burbidge 1975, Karvonen and Holmström 1996). Virtual Cellular Manufacturing (VCM) has been proposed as an alternative to CM for those situations where a conversion to CM is not feasible because of technical or financial reasons (Choi 1996, Waterson, Clegg, Bolden, Pepper Warr and Wall 1999, Johnson and Wemmerlöv 2004). One implementation of VCM is that of applying FBD in a functional layout (Nomden, Slomp and Suresh 2006, Suresh and Meredith 1994, Kannan and Ghosh 1996a).

The focus of this paper is on the performance effects of applying FBD in (virtual) cells with and without labour constraints. A cell without labour constraints is still constrained by the machines. We will refer to this as a ‘machine limited’ (ML) system. A cell with labour constraints is constrained by machines as well as labour. We will refer to this as a ‘Dual Resource Constrained’ (DRC) system.

Thus far, the main body of literature on FBD has focused on ML systems. Ruben and Mahmoodi (1998) investigated several FBD rules in a machine limited situation where one of the machines was a bottleneck. Among their findings is that bottlenecks are preferable at the shop exit. They also found that increasing process batches at the bottleneck station did not necessarily improve overall shop performance. Mahmoodi and Mosier (1998) provide a comprehensive overview of family-based dispatching heuristics. They conclude that family-based dispatching almost always outperforms conventional single-stage dispatching heuristics.

Several empirical studies on (V)CM have been conducted in industry. Wemmerlöv and Hyer (1989) investigated companies that implemented (V)CM. Their study indicates the applicability of family-based dispatching. Further, 87% (27 out of 31) of the firms with manned cells in their survey claimed to have multifunctional operators, suggesting that there were more machines than workers. Wisner and Sifer (1995) state similar observations from practice. They also indicate the application of family-based dispatching rules in many shops and found that in most situations shop operation was not only constrained by machine capacity, but also by labour capacity. We conclude that FBD is widely used in (V)CM systems in practice and that these systems are mostly Dual Resource Constrained.

Wirth, Mahmoodi and Mosier (1993) were the first to investigate the impact of FBD in a DRC system. The performance rankings of family-based dispatching rules were different compared to those studied before within the ML system. In this study, set-up and transfer-to-run time ratio had the greatest impact on the rule rankings. Mosier and Mahmoodi (2002) investigate several group scheduling heuristics (i.e. FBD rules) in a DRC cell with varying degrees of automation. Their main conclusion was that rules for labour allocation had very little impact in automated manufacturing cells. Suresh and Slomp (2005) compare the functional layout (FL), cellular layout (CL) and virtual cellular manufacturing (VCM) systems in DRC settings. They experimented with labour flexibility, lot size, set-up reduction, and labour assignment rules, but did not include routing as an experimental factor. They also looked at mean and coefficient of variation of the flow ratio as a dependent variable, which is an aggregate measure that does not reveal individual machine performance. In the papers discussed above, FBD is applied at all machines in the shop model.

Conclusions regarding the effective use of FBD obtained from ML situations may not hold in DRC situations, as shown for instance for the performance ranking of FBD rules by Wirth et al. (1993). Furthermore, in the literature, FBD is mostly implemented shop-wide, while in many practical instances—such as in the case described in section 2—the choice whether to use FBD or not can be decided per machine. This last issue raises questions such as if it matters whether FBD is applied at a machine with a high load or at a machine with a low load, or if it matters at what location FBD is applied in the routing of jobs. If there are labour constraints (a DRC system), the relation between load variation, routing, and FBD may be different than in an ML system. We feel that the impact of the above shop characteristics on FBD and its effect on shop performance (ML or DRC) is not thoroughly investigated yet and this paper tries to fill in that gap.

The paper is structured as follows. In section 2 we discuss an industrial case that motivated the study. Next, in section 3, we describe the fixed and experimental factors of the simulation study. Section 4 analyzes the results of the experiments and section 5 is a concluding section.

6.2 Industrial motivation

In this section, we present a brief case-description of a pump manufacturer located in the north of the Netherlands, representing a typical situation encountered in many discrete manufacturing companies. The case illustrates the use of family-based dispatching in a system with labour constraints and shop floor interdependencies.

The company manufactures centrifugal pumps for the (petro)chemical industry, horticulture market, and shipbuilding industry. The pumps have a high level of customization. We focus on the mechanical processing department, which produces parts (casings, impellers, shafts, etc.) for the assembly stage. About 60% of the parts are make-to-stock, the other 40% are make-to-order as well as purchase-and-make-to-order. Delivery times are often tight and the department struggles to decrease throughput times while remaining efficient at the same time. FBD could help in this situation, since it tries to avoid set-ups, leading to a higher level of efficiency and lower average throughput times. With all kinds of shop floor interdependencies, which will be discussed next, the question is where to most effectively apply FBD.

Within the mechanical processing department, 14 distinct operations (e.g. turning, milling, drilling, grinding, etc.) are performed with about 40 machines and—on average—18 machine-operators. For most operations, more than one machine is available. Both conventional and CNC-machines are used for metal cutting operations. The load of the machines varies, some are heavily loaded, while other machines are hardly used. The shop layout is a hybrid one. In some instances, machines with equal functionality and controls—like the CNC lathes—are grouped together (functional layout), while other machines—used for the manufacturing of shafts—are grouped based on part routings (group layout).

The part mix can be divided into a number of natural families, with a common base part type and the same operations needed for each part family. For example, impellers are castings which require turning, milling, bench-work and balancing. However, within such a family, sub-families can be distinguished based on part size and material type. Due to the high level of customization, the number and sequence of operations is also not necessarily the same for all parts in a family.

Workers are multi-functional: they can operate multiple machines—5 on average—and most workers master different operation types—3 on average. Cross-training decisions are based on capacity requirements, worker preferences, and worker capabilities. Each operator has his ‘own’ machine where he usually works (note that in this specific case, all workers were male). At the beginning of a day, the operator checks whether there are orders to be processed on his main machine. If there are, then the operator chooses one or more orders to process and he collects the required documents, tools, and materials. Orders are selected based on due date.

Operators are allowed to cluster a half a day's work content to save set-up time between part families. This is how the firm has organized FBD at the work floor.

Changes in the geometry of parts and material type are main causes of set-up efforts. Grouping similar jobs (i.e. family-based dispatching) may then reduce the extent of a set-up. Consider the example of a turning operation. The diameter of the part determines which chucks have to be used, and changes of material require machine cleaning as well as different tool inserts. Hence, an operator groups several jobs requiring the same chucks first (since changing chucks is the most cumbersome activity) and within this group he sequences jobs by material type to avoid machine cleaning and changing tool inserts. The operators stressed that an initial job sequence also reduces set-ups at some other stations. Again, due to the high level of customization, this does not hold for all parts. An 'optimal' sequence at one operation may be different from that on the next one, because other job characteristics determine the required set-up activities. Finally, some machines hardly require set-ups, while other machines spend up to half of their time on set-ups.

To sum up, in this practical case, we can see that:

- FBD is used at the firm to increase the efficiency of the job shop. No investigation was done at the firm how to apply FBD best;
- There are labour constraints. The shop can be characterized as a Dual Resource Constrained manufacturing system in which machines and workers limit the maximal manufacturing capacity;
- There are (natural) families of parts each having a common base part type and requiring the same operations. However, sub-families can be distinguished with respect to material type, part size, and specific machine routings;
- Different issues may play a role at the various machines with respect to setup time reduction through FBD. At some machines, the extent of setup time reduction is determined by means of the similarity of cutting tools needed for various jobs. At other machines, the material type is essential for saving setup times.

From a managerial point of view, it is important to understand the effect of setup time reduction at a particular machine on the flow times of jobs through the manufacturing department. Applying FBD at any machine with a fair amount of set-up activities will probably reduce set-up time and result in a better overall shop performance, but will it be most beneficial if applied at the bottleneck machine? Even if there are labour constraints in the system? And do we have to take into account the routing of jobs when considering the application of FBD at a machine? In the next section, we explain the design of a simulation study to address these questions.

6.3 Simulation study

The simulated shop consists of three machines and two workers (DRC shop) or three workers (ML shop). We deliberately kept shop size small, to be able to disentangle and magnify the effects. If no effects are found in the small shop, it is probably not worthwhile to study larger shops. Workers in the shop are trained to operate all machines with equal efficiency. Jobs arrive at the system according to a negative exponential distribution with a mean arrival rate of lambda (λ). Each job belongs to one of three families and is routed through two of the machines. The exact routing per family is an experimental factor and will be discussed later. The processing times of jobs at the machines (mean 1.0, standard deviation 0.1) and the setup times (mean 0.2, standard deviation 0.1) are generated by a normal distribution.

As a dispatching rule, the Shortest Processing Time (STP) rule is used. This rule is in line with the studies objective to minimize the mean flow time. Further, in the DRC shop, the ‘when’, ‘where’, and ‘who’ labour assignment rules are specified. The Longest Queue where-rule is used, which sends a worker who is eligible for transfer to the machine which has most jobs in queue. As a when-rule, the centralised when-rule is used, which means that a worker is eligible for transfer after each job he/she has finished at a machine. As a who-rule (see Bokhorst, Slomp and Gaalman 2004), the ‘longest idle time’ rule is used. This rule assigns the worker who has been waiting the longest, in case more than one worker is available for assignment.

Factor	**Levels**	**0**	**1**	**2**	**3**
FBD	4	No	M1	M2	M3
LV	4	No	M1	M2	M3
RT	2		Flow	Mix	
Shop	2		ML	DRC	

Table 6.1: Experimental factors and levels

In a series of experiments, the possible impact of routing and load variations between machines on the effect of family-based dispatching is examined. Further, the effect of where FBD is applied (at which machine) is examined. These effects are examined for the DRC shop and the ML shop. For this, several experimental factors with different levels are used (see Table 6.1). We will discuss these factors successively, below.

6.3.1 Family based dispatching (FBD)

At each machine, two families can be distinguished. In our modelling, these setup/tooling families coincide with the routing families. A setup is required when switching between parts belonging to different families. Changing from one family to another family takes on average 0.2 time units with a standard deviation of 0.1. As an experimental variable, FBD is either not used (level 0) or applied at either machine 1, 2, or 3 (levels 1-3).

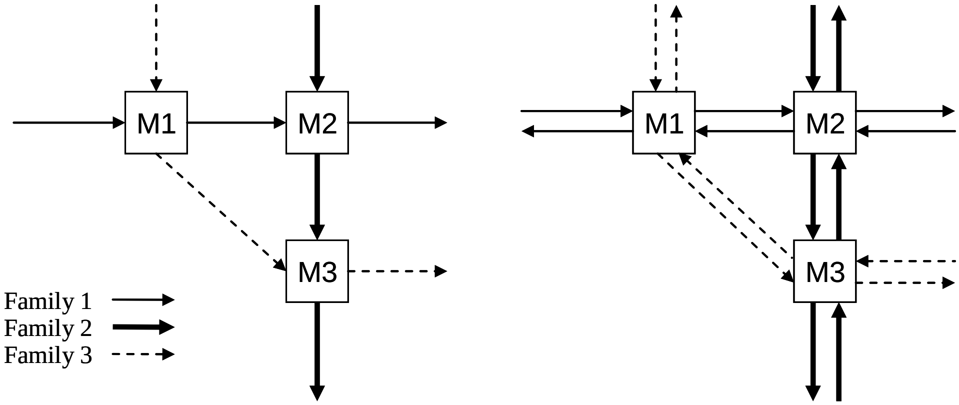
Without FBD, jobs in a machine queue are dispatched to the machine according to the Shortest Processing Time (SPT) rule without consideration of the family the job belongs to. In the situation modelled, with two families per machine, there is a 50 per cent chance that the next job to be processed belongs to the same family as the current job. This means that without FBD, half of the times a setup is required after finishing a job and the average processing time then becomes $1.1 = (1.0 + 1.2)/2$. With FBD, jobs are grouped based on family and processed according to the SPT rule within a family. A switch of family only occurs when no more jobs of the current family are in queue (exhaustive rule).

6.3.2 Modelling of Load Variation (LV)

In the case of load variation, one of the machines has a mean processing time of 1.2 instead of 1.0, with a standard deviation of 0.1, drawn from a Normal distribution. We modelled a situation without LV (level 0) and with a higher load on either machines 1, 2, or 3 (levels 1-3).

6.3.3 Routing of jobs (RT)

We modelled a flow routing (level 1) and a mix routing (level 2). In a flow routing, jobs of family 1 are routed through machines 1 and 2, jobs of family 2 are routed through machines 2 and 3, and jobs of family 3 are routed through machines 1 and 3 (see Figure 6.1a). As such, machine 1 only receives jobs from outside the system, machine 2 receives jobs from outside the system and from machine 1, and machine 3 receives jobs from machines 1 and 2. Jobs thus enter the system through machines 1 and 2 and exit the system through machines 2 and 3. In a mix routing, jobs are also routed in a reverse order, meaning that jobs of family 1, for instance, are routed through machines 1 and 2 either starting with machine 1 or with machine 2 (see Figure 6.1b). In this way, jobs enter and exit the system at all machines equally.



a. Flow routing b. Mix routing

Figure 6.1: Routing of families in a flow routing (a) and a mix routing (b)

6.3.4 Labour constraints (Shop)

Three workers are modelled in the ML shop—meaning that there are no labour constraints—and two workers in the DRC shop. In the ML shop, the arrival rate (λ) of the jobs arriving at the shop is set at 1.0227. Since each job is routed through two machines, the shop has to process all jobs twice (2·1.0227). In the shop, three machines (servers) are available to process these jobs with an average processing time of 1.1. This results in an average machine utilisation in the setting without load variation (LV) and without family-based dispatching (FBD) of 75%: $2 \cdot 1.0227 \ \cdot (1.1/3)$. Modelling load variation will increase the utilisation, while modelling family-based dispatching will decrease the utilisation. The maximum machine utilisation of a single machine in the ML shop is found at a bottleneck machine (with an average processing time of 1.2) without family-based dispatching (which increases the average processing time by 0.1, since half of the time a setup of 0.2 time units is needed). This machine is then utilized for 88,6% (2/3 of the jobs visit the machine which has an average processing time of 1.3: $(2/3 \cdot 1.0227) \cdot 1.3$.

In the DRC shop, the arrival rate (λ) is set at 0.7727. Again, the shop has to process all jobs twice (2·0.7727). In the shop, two workers (servers) are available to process these jobs with an average processing time of 1.1. This results in an average worker utilisation in the setting without load variation (LV) and without family-based dispatching (FBD) of 85%: $(2 \cdot 0.7727) \cdot (1.1/2)$. Note that in an ML shop, average worker utilisation equals average machine utilisation and in a DRC shop, average worker utilisation is higher than average machine utilisation since there are fewer workers (2) than machines (3). The maximum worker utilisation in the DRC shop is also based on a shop with load variation (where one of the machines has an average processing time of 1.2) and without family-based dispatching (which increases all average processing times by 0.1). The maximum worker utilisation is then 90,2%: $2 \cdot 0.7727 \cdot (1.3+1.1+1.1)/(3 \cdot 2)$.

The simulation models were written in the object-oriented simulation software package EM-Plant Version 7.5 (Stuttgart: Technomatix). The replication/deletion approach was used to estimate the steady-state means of the output parameters. Welch's method was applied to estimate on the warm-up period. Other graphical approaches, such as plotting the cumulative mean average of flow time against the number of replications as well as plotting the cumulative mean average of flow time against time, were used to gain insight in the number of replications and the run length required, respectively. Each experiment consisted of 35 replications with a length of 60000 time units and a warm-up period of 10000 time units. Different seeds were used for each replication to maximize sampling independence. The dependent variables are the overall mean flow time of jobs (OMFT) and the mean flow times of jobs at each machine (MFT M1, MFT M2, and MFT M3). It has to be noted that the OMFT is not simply the sum of all flow times of jobs at the machines. As indicated in Figure 6.1, routings always consist of only two operations. Therefore, OMFT equals 2/3·(MFT M1 + MFT M2 +MFT M3).

6.4 Results

Subsections 6.4.1 and 6.4.2 focus on the impact of routing and load variation on the effect of FBD within an ML shop and a DRC shop, respectively. Subsection 6.4.3 expands the analysis by comparing the effects of FBD within ML and DRC shops.

6.4.1 The machine limited shop

The main questions to be addressed here are whether the routing of jobs, load variations between machines, and the location of FBD have an impact on the mean flow time effect of FBD. We will first investigate the different effects of not applying FBD or applying it at machine 1, 2, or 3, in a flow routing and in a mix routing situation without load variation and then do the same for these situations with load variation. This is done to gradually increase the complexity of the situation and thus to be able to investigate some of the effects in isolation.

The mean flow time results—for jobs and for jobs at each machine—at different levels of FBD in an ML shop with a flow routing, without load variation, and a machine utilisation of 75% are displayed in Table 6.2.

	Location of FBD			
	no	M1	M2	M3
OMFT	5.04	5.04	4.90	4.87
MFT M1	2.70	2.40	2.69	2.70
MFT M2	2.50	2.62	2.22	2.52
MFT M3	2.36	2.54	2.44	2.09

Table 6.2. Flow time results for the ML shop with a flow routing, without LV, at different levels of FBD (no=no FBD applied, M1=FBD at machine 1, etc.)

Table 6.2 shows that the values of the overall mean flow time (OMFT) differ for different locations of FBD. In order to see where the significant difference(s) is/are, we did a Tukey test that performs a pairwise comparison of the means (see e.g. Toothaker, 1993). The Tukey results indicate that applying FBD at the first machine does not result in a better overall mean flow time (OMFT) compared to the situation without FBD (p=1.000). Even though the flow time at the first machine (MFT M1) decreases with about 11.1%, the flow times at the second (MFT M2) and third machine (MFT M3) actually increase (all differences are significant, $p < 0.001$). This effect can be explained by the impact of FBD on the arrival patterns at subsequent machines in the routing of jobs. That is, the departure pattern of jobs at the machine at which FBD is applied becomes more volatile. Instead of a mix of jobs of different families leaving the machine, FBD causes bursts of jobs of the same family to leave the machine. We suspect this causes the negative effect on the flow times at subsequent machines. In a flow routing, applying FBD at a machine will thus result in an increase of flow time at the downstream machines. The mean flow times at the machines are also depicted in Figure 6.2.

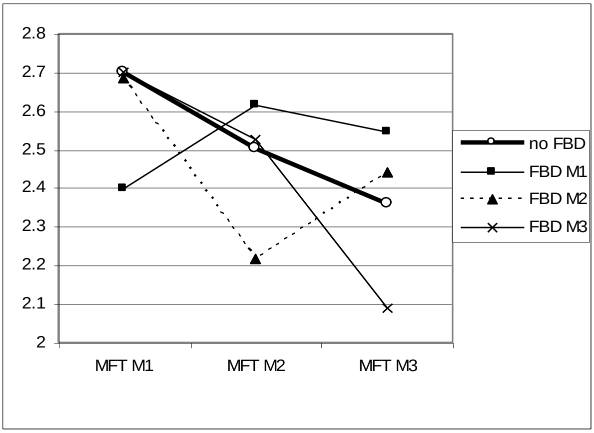


Figure 6.2: Flow time results at machines in the ML shop with a flow routing, without LV, at different levels of FBD

Applying FBD at the second machine decreases the OMFT somewhat (2.9%, $p < 0.001$). The flow time at the first machine does not change (p=0.686), which is logical, since only downstream machines may be influenced by applying FBD in a flow routing. The flow time at the second machine decreases (with 11.4%, $p < 0.001$), and that of the third increases ($p < 0.001$). Again, this can be explained by the more volatile departure pattern of the second machine, which negatively influences the flow time at the downstream machine (i.e. machine 3). Finally, applying FBD at the third machine decreases the OMFT (3.3%, $p < 0.001$), with the flow times at the first two machines remaining the same (p=0.999 and p=0.139) and a decreased flow time at the third machine (by 11.5%, $p < 0.001$).

In the flow routing, the benefits of FBD at the individual machine can thus clearly be seen, as well as negative effects at subsequent machines in the routing. The OMFT remains the same or improves when applying FBD at a machine, depending on where it is applied in the routing.

In a mix routing (see Table 6.3 and Figure 6.3), applying FBD at either machine 1, 2, or 3 is equally beneficial (about 3% decrease in OMFT) compared to not applying FBD (Tukey results indicate that all differences are significant, $p < 0.001$). The mean flow time decreases at the machine at which FBD is applied (with about 11.5%, significant effects) and remains the same or slightly increases at the other machines.

	Location of FBD			
	no	M1	M2	M3
OMFT	5.18	5.04	5.03	5.00
MFT M1	2.60	2.30	2.62	2.62
MFT M2	2.59	2.63	2.29	2.60
MFT M3	2.58	2.63	2.63	2.28

Table 6.3. Flow time results for the ML shop with a mix routing, without LV, at different levels of FBD

These effects indicate that with a mixed routing, the effect of FBD on the arrival patterns at subsequent machines in the routing of jobs is limited because of the variety of routings of job family members.

We conclude that the management of a firm needs to consider the routings of jobs when considering the application of FBD at a machine. In case of a clear flow of jobs, it is advantageous for the OMFT to apply FBD at a down-stream machine, preferably the last machine in the flow. If there is not a clear flow, then the effect of FBD on the OMFT is equal when applied at any of the machines. FBD, however, still has a negative effect on the flow times at machines that receive jobs from the machine at which FBD is applied.

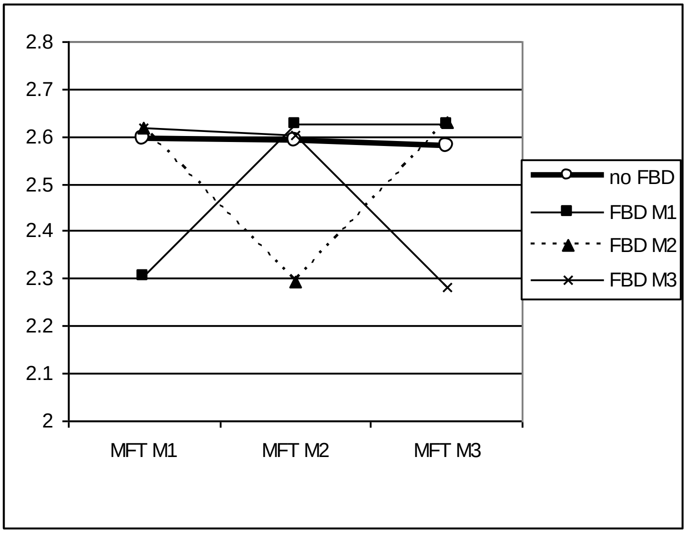


Figure 6.3: Flow time results at machines in the ML shop with a mix routing, without LV, at different levels of FBD

As we have observed in the case, in practice, machine loads will often not be equal. Table 6.4 shows the flow time results for the ML shop with a flow routing and a load variation at the first, second, and third machine, respectively. It appears that applying FBD at the machine with the highest load, results in the best OMFT performance, independent of the position of that machine. This supports the recommendation to apply FBD at the bottleneck machine (Burbidge 1975, Karvonen and Holmström 1996) and corresponds to the practice we have observed in several companies. The extent of performance improvement, however, is related to the effect that applying FBD at a particular machine has on the arrival patterns of jobs at down-stream machines. As indicated earlier, irregular arrivals may appear at subsequent machines in the routing, causing increased flow times at these machines. As shown in Table 6.4, the OMFT is 6.64 in case of a high load at the first machine in the routing and applying FBD at this machine, and 6.14 if the last machine in the routing is loaded highest and FBD is applied at this machine. Therefore, when organizing FBD at a particular machine, the position of that machine in the routings of jobs needs to be considered. It is interesting to note that when FBD is not applied, a high load at the first machine leads to better OMFT results than a high load at the last machine in the routing of jobs (7.21 compared to 7.33). This result can be explained by the fact that in case of a higher utilization of a machine, the departure pattern tends to take on the characteristics of the processing distribution. In our case, the processing distribution is less variable than the arrival distribution of jobs at the machine. Creating a bottleneck at the first machine in a flow routing thus results in better flow times at subsequent machines. This finding furthermore indicates the importance of routing analysis when considering FBD at a machine. When FBD is applied, depending on the position in the routings of jobs of the machine with the highest load, the OMFT improvement in our simulation varies between 7.9% ((7.21-6.64)/7.21) and 16.2% ((7.33-6.14)/7.33).

	Location of FBD				
LV		no	M1	M2	M3
M1	OMFT	7.21	6.64	7.07	7.01
	MFT M1	6.13	4.41	6.10	6.08
	MFT M2	2.40	2.71	2.15	2.40
	MFT M3	2.28	2.83	2.36	2.03
M2	OMFT	7.22	7.13	6.27	7.11
	MFT M1	2.70	2.39	2.70	2.69
	MFT M2	5.88	5.92	4.18	5.98
	MFT M3	2.25	2.39	2.54	2.00
M3	OMFT	7.33	7.32	7.17	6.14
	MFT M1	2.68	2.40	2.69	2.69
	MFT M2	2.50	2.62	2.22	2.50
	MFT M3	5.81	5.97	5.85	4.02

Table 6.4. Flow time results for the ML shop with a flow routing, with Load Variation (LV) at different levels of FBD

	Location of FBD				
LV		no	M1	M2	M3
M1	OMFT	7.39	6.42	7.27	7.17
	MFT M1	5.99	4.29	6.07	5.92
	MFT M2	2.54	2.67	2.27	2.58
	MFT M3	2.54	2.66	2.58	2.26
M2	OMFT	7.40	7.21	6.37	7.28
	MFT M1	2.53	2.27	2.66	2.58
	MFT M2	6.02	5.97	4.26	6.07
	MFT M3	2.54	2.58	2.64	2.26
M3	OMFT	7.41	7.22	7.22	6.41
	MFT M1	2.54	2.26	2.58	2.67
	MFT M2	2.54	2.57	2.26	2.66
	MFT M3	6.03	6.00	5.99	4.28

Table 6.5. Flow time results for the ML shop with a mix routing, with LV, at different levels of FBD

In a mix routing, applying FBD at the machine with the highest load is most beneficial (see Table 6.5). Applying FBD at the other machines also improves OMFT ($p < 0.05$), but much less.

To sum up, in an ML shop, applying FBD at a machine only results in a better mean flow time at that machine, and results in worse flow times at subsequent machines in the routing. Therefore, in case of equal machine loads, the best OMFT performance is realised if FBD is applied at the last machine in a flow routing and it does not matter at which machine FBD is applied in a mix routing. In our configurations modelling load variation, the benefit obtained by applying FBD at the machine with the highest load offsets the possible negative impact of the outgoing flow of that machine on the flow time at subsequent machines. Therefore, FBD should here be applied at the machine with the highest load, irrespective of the routing of jobs. In general, however, there seems to be a trade-off between the positive (local) effects of applying FBD at a (bottleneck) machine and the negative effect of the more irregular job departures on the performance of subsequent machines.

6.4.2 The dual resource constrained shop

In this subsection, we perform a similar analysis as in the previous section, but we now consider a DRC shop. The main questions to be addressed here are again whether the routing of jobs, load variations between machines, and the location of FBD have an impact on the mean flow time effect of FBD.

The mean flow time results—for jobs and for jobs at each machine—at different levels of FBD in a DRC shop with a flow routing, without load variation, and with a worker utilisation of 85% are displayed in Table 6.6 and Figure 6.4.

	Location of FBD			
	no	M1	M2	M3
OMFT	6.37	5.86	5.96	5.91
MFT M1	3.14	2.81	2.96	2.94
MFT M2	3.20	2.98	2.94	2.99
MFT M3	3.22	3.00	3.05	2.93

Table 6.6. Flow time results for the DRC shop with a flow routing, without LV, at different levels of FBD

Table 6.6 shows that applying FBD at either machine 1, 2, or 3 results in a better OMFT compared to not applying FBD (Tukey results show that the difference is significant, $p < 0.001$). When FBD is applied at a particular machine, the flow times at all machines decrease ($p < 0.001$). The largest decrease, however, is found at the machine at which FBD is applied. The decrease of flow times at other machines than the one at which FBD is applied can be explained by the fact that the workers are the main bottleneck in the system. Applying FBD at a particular machine saves some worker time, which means that the availability of the workers to serve all machines is increased and flow times at all machines thus decrease. Table 6.6 and Figure 6.4 show that the positive effect of applying FBD at a machine (due to less set-ups and increased worker availability) offsets the possible negative effect of more irregular arrivals at later machines in the routing. The latter effect is, to a certain extent, absorbed by the assignment flexibility of workers. That is, workers can easily switch between the various machines which reduces the importance of arrival patterns at the various machines.

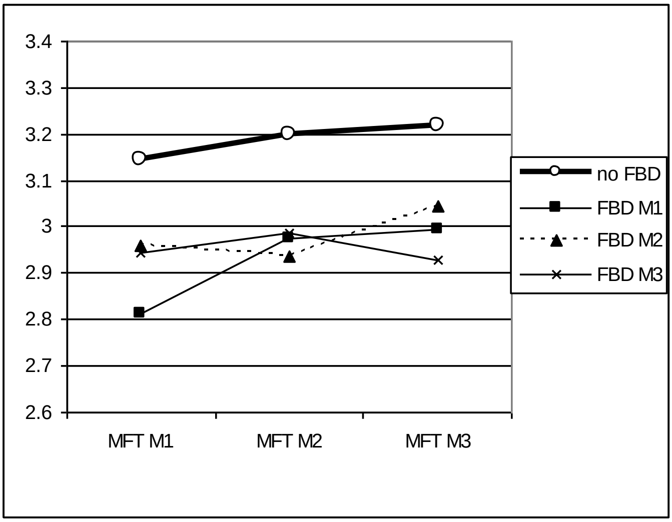


Figure 6.4: Flow time results at machines in the DRC shop with a flow routing, without LV, at different levels of FBD

Table 6.7 presents the flow time effects in case of a mix routing situation. Applying FBD at either machine 1, 2, or 3 results in a better OMFT compared to not applying FBD (Tukey results show that the difference is significant, $p < 0.001$). Moreover, it is indifferent for OMFT ($p > 0.05$) at what machine FBD is applied. When FBD is applied at a particular machine, the flow times at all machines decrease ($p < 0.001$). The largest decrease is then found at the machine at which FBD is applied. The decrease of flow times at the two other machines is equally large ($p > 0.05$), but less than the decrease of flow time at the machine at which FBD is applied.

	Location of FBD			
	no	M1	M2	M3
OMFT	6.45	6.04	6.01	6.00
MFT M1	3.22	2.96	3.04	3.03
MFT M2	3.23	3.05	2.94	3.03
MFT M3	3.23	3.05	3.03	2.94

Table 6.7: Flow time results for the DRC shop with a mix routing, without LV, at different levels of FBD

Table 6.8 shows the flow time results for the DRC shop with a flow routing and a load variation at the first, second, and third machine, respectively. In general, irrespective of the position of the machine with the highest load, it is indifferent for the OMFT at what machine FBD is applied. In other words, FBD does not necessarily have to be applied at the machine with the highest load, in order to get the best performance. With a high load at the first machine, however, applying FBD at that first machine turns out to be slightly better (OMFT 8.04) than applying FBD at either the second or third machine (OMFT about 8.35). Note that in this situation also, the OMFT improvement of applying FBD at any machine is substantial compared with not applying FBD at all (OMFT 9.67).

Again, no matter at what machine FBD is applied, the flow times at all machines decrease significantly ($p < 0.001$) compared to the flow time when no FBD is applied. Workers have less work at the machine where FBD is applied and they will use the saved time at the other machines.

	Location of FBD				
LV		no	M1	M2	M3
M1	OMFT	9.67	8.04	8.35	8.38
	MFT M1	5.16	4.23	4.54	4.56
	MFT M2	4.64	3.89	3.91	4.02
	MFT M3	4.71	3.95	4.08	4.00
M2	OMFT	9.43	8.16	8.18	8.32
	MFT M1	4.48	3.70	3.89	3.95
	MFT M2	5.10	4.62	4.40	4.58
	MFT M3	4.57	3.91	3.98	3.94
M3	OMFT	9.45	8.05	8.21	8.11
	MFT M1	4.47	3.65	3.86	3.86
	MFT M2	4.58	3.87	3.89	3.96
	MFT M3	5.11	4.55	4.57	4.34

Table 6.8: Flow time results for the DRC shop with a flow routing, with LV, at different levels of FBD

Table 6.9 presents the flow time results for a mix routing DRC situation. It appears that applying FBD is always beneficial for the OMFT and that the extent to which it is beneficial is indifferent from whether or not FBD is applied at the machine with the highest load. Similar to the flow routing DRC situation, the flow times at all machines decrease significantly ($p < 0.001$) when applying FBD at either machine 1, 2, or 3 compared to the flow time when no FBD is applied.

	Location of FBD				
LV	Data	no	M1	M2	M3
1	OMFT	9.58	8.33	8.36	8.35
	MFT M1	5.16	4.42	4.61	4.61
	MFT M2	4.61	4.04	3.91	4.01
	MFT M3	4.61	4.04	4.01	3.91
2	OMFT	9.59	8.42	8.24	8.29
	MFT M1	4.61	3.94	3.99	3.98
	MFT M2	5.16	4.64	4.38	4.57
	MFT M3	4.61	4.05	3.99	3.88
3	OMFT	9.71	8.44	8.33	8.27
	MFT M1	4.67	3.95	4.00	4.00
	MFT M2	4.67	4.05	3.90	4.00
	MFT M3	5.22	4.66	4.60	4.39

Table 6.9: Flow time results for the DRC shop with a mix routing, with LV, at different levels of FBD

To sum up, in a DRC shop, applying FBD at a machine results in better OMFT performance and better mean flow time performance at all machines. The flow time at the machine at which FBD is applied, however, decreases most. In our cases of equal machine loads and load variation, it does not matter for the OMFT at which machine FBD is applied or what routings jobs have. Apparently, in our cases, the positive effect of applying FBD at a machine, resulting in less setups and increased worker availability, offsets the possible negative effect of more irregular arrivals at later machines. The effect of these irregular arrivals at later machines is limited in DRC systems due to the assignment flexibility of workers.

6.4.3 Comparing the effects of FBD in an ML and DRC shop

It is known that the effects of FBD become larger when utilisation increases. The question is then how to deal with shop utilisation in order to fairly compare the ML and the DRC shop. One way of comparing the ML and DRC shop is to keep the arrival rate of jobs (lambda) fixed. FBD is a measure that groups jobs of the same family at the machine-level and in comparing systems fairly one may argue that the arrivals of jobs at machines—and thus the machine utilisation—must be equal. We therefore performed additional simulation experiments setting lambda at 0.6818, resulting in an average machine utilisation without LV and without FBD of 50% in both shop situations $(2\cdot 0.6818)(1.1/3)$ and a worker utilisation of 75% in the DRC shop $(2\cdot 0.6818)\cdot(1.1/2)$.

OMFT in a flow routing, without load variations

	no FBD	FBD M1		FBD M2		FBD M3	
DRC	4.444	4.31	*3.02%*	4.334	2.48%	4.305	*3.13%*
ML	3.148	3.155	*-0.22%*	3.137	0.35%	3.133	*0.48%*
	29.16%	*26.80%*		*27.62%*		*27.22%*	

OMFT in a mix routing, without load variations

	no FBD	FBD M1		FBD M2		FBD M3	
DRC	4.529	4.415	*2.52%*	4.402	*2.80%*	4.416	*2.50%*
ML	3.219	3.204	*0.47%*	3.202	*0.53%*	3.205	*0.43%*
	28.92%	*27.43%*		*27.26%*		*27.42%*	

Figure 6.5: Comparing the OMFT effects of labor constraints and location of family-based dispatching under 50% machine utilization, without LV in a flow and a mix routing. The numbers in italics vertically show the per cent differences between OMFT in a DRC shop and in an ML shop and horizontally show the per cent differences between not applying FBD and applying it at machine 1, 2, or 3, respectively.

The upper part of Figure 6.5 shows the OMFT results for a flow routing without load variation. Adding a worker in a DRC shop (which here results in an ML shop) without FBD decreases OMFT by 29,16%. Applying FBD at any machine in a DRC shop decreases OMFT by around 3%. In an ML shop, applying FBD at the first machine increases OMFT by 0.22%, while it marginally improves OMFT when applying it at the second or third machine. In a mix routing, the location of FBD does not impact the flow time effect in either the DRC and the ML shop. These results are in conformity with the results obtained in subsections 4.1 and 4.2. Additionally, the results show that applying FBD in a DRC shop results in larger OMFT improvements than applying FBD in an ML shop. An explanation for the larger effects of FBD in DRC systems is that the increased queue lengths enable more jobs of the same family to be processed successively, resulting in less set-ups.

6.5 Conclusions and future research

This paper has investigated whether the routing of jobs, load variation, and the location of family-based dispatching have an impact on the mean flow time effect of family-based dispatching in a Machine Limited shop and in a Dual Resource Constrained shop.

In an ML shop, applying FBD at a machine only results in a better mean flow time at that machine, and results in worse flow times at subsequent machines in the routing. The routing of jobs combined with the location of FBD has a significant impact in ML shops. In case of equal machine loads, it is best for the overall mean flow time to apply FBD at the last machine in a flow routing and it does not matter at which machine FBD is applied in a mix routing. Further, in an ML shop, when applying FBD, the flow time at a machine decreases most if that machine has the highest load. In general, there seems to be a trade-off in ML systems between the positive (local) effects of applying FBD at a (bottleneck) machine and the possible negative effect of the more irregular job departures on the performance of subsequent machines. Managers in ML situations have to be aware of the effect of applying FBD at a machine on the arrival patterns at subsequent machines.

By contrast, in a DRC shop, applying FBD at any machine results in a better mean flow time performance at all machines and consequently in a better overall mean flow time performance. For the overall mean flow time in DRC systems, load variation, the location of FBD and the routing of jobs do not have a relevant impact on the effect of FBD. In a DRC shop, the positive effects of applying FBD at a (bottleneck) machine are local (less set-ups required at that machine) and global (increased worker availability for all machines), while the possible negative effect of the more irregular job departures on the performance of subsequent machines seems to be limited due to the assignment flexibility of workers. The results further indicate that applying FBD in a DRC shop results in larger overall mean flow time savings than applying FBD in an ML shop, when both systems have comparable machine utilisations. These results have important managerial consequences. First, managers in DRC systems may feel stimulated by our findings to implement FBD at a machine. Secondly, when implementing FBD at a machine, the flow time advantages will be spread among all machines. These advantages need to be taken into account in the production control system of the department.

The results of this paper are based on a simulated setting with numerous fixed factors. For instance, we did not vary the setup-to-runtime ratio, the increase of the load in case of a load variation, the cross-training pattern of workers, nor the number of part families. Future research may address these factors and refine the outcomes of this study. Further, the exact impact of the more volatile departure pattern at the machine at which FBD is applied on the performance of subsequent machines in ML and DRC systems requires further research. Our study should be seen as a first attempt to indicate the global effects of local FBD improvements.