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Bokhorst, J.A.C.

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Chapter 4

Labor allocation

ON THE WHO-RULE IN DUAL RESOURCE CONSTRAINED (DRC) MANUFACTURING SYSTEMS[5]

Jos A.C. Bokhorst, Jannes Slomp, Gerard J.C. Gaalman

ABSTRACT

The who-rule is a labour allocation rule used in labour and machine limited Dual Resource Constrained (DRC) systems. A who-rule selects one worker out of several workers to be transferred to a work centre. By means of a practical instance, the paper shows that the who-rule plays a role in the daily practice of worker assignment. Previous simulation studies, however, either have not mentioned the who-rule or have treated it as a fixed factor. The present study will explore the need of including the who-rule in simulation studies. It will describe in detail at what decision moments the who-rule needs to be applied in simulation. Further, it will explore the flow time effects of applying different who-rules in several DRC systems where labour flexibility is limited and workers differ with respect to task proficiencies, the number of skills they possess, and the loads of work centres for which they are responsible. As with other labour allocation rules, the impact of the who-rule depends on the specific DRC shop modelled. The paper will show that the average labour utilisation, and the types and extent of worker differences, determine the impact of the who-rule on shop performance.

Key words: Dual Resource Constrained systems, labour allocation rules, who-rule, labour flexibility, disparity in work centre loads

1. Introduction

In Dual Resource Constrained (DRC) systems, two resources are considered to be constraining factors for the level of output. This paper considers labour and machines to be the two constraining resources of our concern. This type of DRC system is also called a labour and machine limited system, as opposed to a machine-limited system in which only machines are the constraining factor. In a labour and machine-limited system, jobs can only be processed if both a machine and a skilled worker are available. A key characteristic of labour and machine limited systems is that the number of workers is less than the number of machines, which implies that (some) workers need to be multifunctional and worker transfers between machines are necessary. For smooth operation of these systems, attention should thus be given to cross-training and labour allocation rules.

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From the early 1960s on, the issues of cross-training and labour allocation have received quite some attention in the literature. In a review paper of DRC system research, Treleven (1989) distinguishes design issues from operating issues. He considers labour flexibility, or cross-training, to be the single most important design factor. Operating issues concern decisions on dispatching rules as well as due date assignment methods, which also have to be made in machine limited systems, and decisions on labour allocation rules, which are specific for DRC systems. As for labour allocation rules, “when” and “where” rules are explicitly expressed in the literature. The when-rule determines when to consider transferring a worker from the work centre which he/she works in to another work centre. The where-rule determines to which work centre a worker needs to be transferred.

This paper focusses on the who-rule, which, besides the when-rule and the where-rule, can be regarded as another labour allocation rule. In the situation where a work centre requires a worker, and more than one skilled worker is available, only one worker can be assigned to that work centre. The who-rule then determines which worker should be transferred to the work centre and thus allocates that worker to it. In almost all DRC systems, choosing between workers is necessary at a certain point. A who-rule may affect flow time performance only in those systems where workers are not equal. Worker differences can be modelled in several ways, for example through differences in task proficiency, or differences in the number of skills of workers. This study will describe the role and explore the impact of the who-rule in DRC simulation systems with worker differences.

Section 2 describes the practical instance that motivates this study and will briefly review the literature with respect to worker differences in DRC systems and the application of the who-rule. Section 3 describes in detail at which decision moments the who-rule needs to be applied in simulation. Further, it will discuss what characteristics of DRC systems are likely to influence the decision processes at the decision moments, thereby possibly influencing the extent of the effect of the who-rule on system performance. Section 4 describes the modelling of the DRC systems studied and presents an experimental design for the simulation studies. We propose several alternative who-rules and include as experimental factors characteristics which are likely to influence the extent of the effect of the who-rule. Section 5 discusses the simulation modelling and performance measures. We present the results of the simulation experiments in section 6. Section 7 concludes the paper and identifies areas of future research.

2. Problem context and literature review

The problem addressed in this paper was motivated by the confrontation between labour assignment rules used in a practical instance and the rules studied in various theoretical papers. Besides highlighting the general elements of the problem, the practical instance described in subsection 2.1 serves as the empirical driver of the experimental factors chosen in our simulation experiments. Subsection 2.2 will briefly review the literature with respect to worker differences in DRC systems and the application of the who-rule.

2.1. Problem Context and Motivation

The practical instance concerns a firm that manufactures parts and small sub-assemblies used in the electro-mechanical industry. Over six weeks, worker flexibility issues in the machining and turning department of this firm were recorded (Slomp, 2000). The department operates in two shifts. Table 1 presents some basic data indicating the labour situation.

Table 1. Basic data indicating the labour situation in the machining and turning department

Number of workers per shift	14-17
Number of machines	24
Utilisation of machines	20%-80%
Variation in utilisation of each machine during the observation weeks	about 10%
Percentage of workers which have a main machine to work on	90%
Average percentage of time which a worker spends on his/her main machine	77%
Number of different machines to which workers are being assigned	1-7
Proficiency levels of workers	50%-100%

The machining and turning department is a typical DRC system. In the department, labour capacity and machine capacity are the major constraints and labour flexibility is a major design issue. The department operates in two shifts with 14-17 workers per shift and 24 machines. During a shift, (some) workers need to transfer to other machines. During the observation weeks, all machines differed in load varying by about 10%. The majority of the workers (90%) have a main machine on which they usually work (on average 77% of their time). The number of machines to which workers are assigned ranges from one to seven. Only few workers do not have a main machine and are assigned to machines according to job priorities. Task proficiencies of workers range from 50 to 100%, indicating their efficiency on the various machines. The foreman of the machining and turning department, who works in day-shift, is responsible for the assignment of workers to machines. Roughly, he applies the following rules. He will assign the workers to their main machines if there is sufficient work for these machines. Workers who do not have a main machine and the workers for whom there is not enough work on their main machines are assigned to machines and jobs in such a way that all jobs are performed in time, as efficiently as possible. Individual differences between workers play an important role in this assignment. These differences concern (i) the proficiency of workers to perform operations on the various machines, (ii) the level of multifunctionality of workers, and (iii) the load on the various machines which can be assigned to them. Basically, jobs and machines will be assigned to the most proficient worker. It may happen, however, that this worker is more urgently needed for other machines which he/she can handle. This urgency is a derivative of the particular qualifications of the worker and the amount of work that needs to be done on the other machines that can be handled by the worker. The choice which worker will perform a particular job on a machine can be seen as a result of the application of a who-rule. Of several available workers, the best worker is selected based on worker differences.

The foreman of the department is concerned with the who-issue in all his assignment decisions. These decisions are made during the working day, but particularly after the so-called “morning prayer” in which the foreman of the department, the planning manager and a process planner discuss the job priorities and problems of the department. Based on this information, the foreman makes basic assignment decisions. These decisions can be seen as a mix of who-, where- and when-rules. During the day decisions are adapted, depending on the situation.

The who-rule is different from the when- and where-rule mentioned in the literature (see e.g. Treleven 1989, Hottenstein and Bowman 1998). The latter rules do not include comparisons between workers with individual differences. These rules are focussed on individual workers and decide when a worker needs to be transferred to which machine. Based on worker differences, the who-rule determines which worker should be transferred to a work centre if more than one skilled worker is available. As indicated here, in practice a production manager, or foreman, will include the who-rule in the assignment decision.

This paper focusses on the role of the who-rule in simulation studies on labour flexibility. As will be indicated below, the who-rule is not systematically dealt with in simulation studies presented in the current literature. This forms the starting point for a descriptive study on the role of the who-rule in simulation studies in section 3. Based upon this descriptive study, simulations are performed to indicate the possible impact of who-rules in simulation studies. The final section relates the findings to the practice in manufacturing firms, as described in this section.

2.2. Literature review and discussion on worker differences

We expect that the who-rule may have an effect on performance only in DRC systems in which it is required to select one out of several *different* workers to be transferred to a work centre. Based upon the practical instance described in subsection 2.1, we will focus on worker differences with respect to (1) their task proficiencies, (2) the number of skills they possess, and (3) the loads of work centres in which they can operate. In the literature, attention has been given to the first two factors. Therefore, it is interesting to see what has been done there with respect to the who-rule. The third factor has not yet been dealt with in previous research and will be discussed in the third sub subsection.

<u>2.2.1. A difference in task proficiency</u>

Relatively few studies model heterogeneous labour with respect to task proficiencies, meaning that workers differ in their level of proficiency when performing their assigned tasks (e.g. Rochette and Sadowski 1976, Hogg *et al.* 1977, Bobrowski and Park 1993, Malhotra *et al.* 1993, Malhotra and Kher 1994, Fry *et al.* 1995). Although the who-rule can be of importance in this type of DRC system, most of the studies do not explicate how a choice is made between workers if more than one worker is available.

Bobrowski and Park (1993) and Malhotra and Kher (1994) study when and where labour allocation rules in a shop with task proficiency differences between workers, but do not mention a who-rule. The studies of Malhotra *et al.* (1993) and Fry *et al*. (1995) include, amongst other factors, worker learning and worker flexibility. Over time, workers will thus differ in their task proficiencies, and a who-rule may have an effect. However, these studies neither explicate a who-rule. Only the studies of Rochette and Sadowski (1976) and Hogg *et al.* (1977) provide a procedure for those situations which require a choice between workers and thus address the who-rule, without actually calling it a “who-rule”. Rochette and Sadowski (1976) use a rule that assigns that worker who has been idle for the longest period of time. Hogg *et al.* (1977) assign the most efficient worker if more than one worker is available. Both studies regard the who-rule as a fixed factor. The effect of applying different who-rules in systems where workers have different task proficiencies is thus unknown.

2.2.2. A difference in the number of skills

Felan and Fry (2001) distinguish single-level flexibility from multilevel flexibility. To obtain single-level flexibility, workers receive the same degree of cross-training, while with respect to multilevel flexibility, workers are trained to work in a different number of departments. Instead of connecting skills of workers to departments, skills can also be connected to work centres (see e.g. Nelson 1967, 1970, Hogg *et al.* 1977, Bobrowski and Park 1993). Single-level flexibility can then be regarded as the situation in which all workers have the same level of multifunctionality, where multifunctionality can be defined as the number of different work centres in which a worker can operate. In contrast, multilevel flexibility can be regarded as the situation in which workers are trained for different numbers of work centres.

In systems with multilevel flexibility, workers can differ from one another with respect to the number of work centres in which they are able to operate, and here the who-rule may have an effect. In contrast to prior DRC studies, Felan and Fry (2001), in their study on the subject, focus on multilevel flexibility and heterogeneous labour with respect to task proficiencies. However, they do not mention a who-rule, although the who-rule may be important in multilevel flexibility DRC systems with either homogeneous or heterogeneous labour with respect to task proficiencies. Research is needed to indicate the possible impact of the who-rule on flow time performance.

2.2.3. A difference in the loads of work centres in which workers can operate

A third factor causing differences between workers is the difference with respect to the loads of work centres in which they are able to operate. In practice, this difference is a reason to prefer one worker above another for assignment to a machine or job. To the best of our knowledge, this worker difference has not been dealt with before in DRC research. It may occur in shops with limited flexibility and a disparity in work centre loads. Or, in other words, in systems where not all workers are able to operate in all work centres and where a noticeable difference between the loads of work centres can be found. In these systems, some workers in a team may receive a larger workload than other workers, due to the fact that they are solely responsible for a number of heavily loaded work centres. Note that a workload difference between workers is thus also possible in systems where all workers have the same level of multifunctionality (i.e. single-level flexibility). Preventing heavily loaded workers from being allocated an equal share of the workload of all the work centres in which they can operate may be advantageous. In other words, it is probably more beneficial if the workload of work centres which are shared by heavily loaded and less loaded workers is allocated to a larger degree to the less loaded workers. Since the who-rule can –to a certain extent– influence the allocation of the load of shared work centres, the choice of a who-rule may have an effect on the flow time performance of the system.

To sum up, the literature thus far has only paid limited attention to the who-rule. Based upon industrial practice (see subsection 2.1), we believe that a study on the impact of the who-rule on flow time performance is needed and can be helpful in the identification of settings where a who-rule should be selected carefully.

3. The who-rule

This section explains at what decision moments labour allocation rules (i.e. the when-, where-, and who-rule) need to be applied in simulation studies. It further describes in detail the who-rule within these decision moments. In essence, the who-rule chooses one worker to be transferred to a work centre in case there are several workers available to choose from. As seen above, the who-rule is a labour allocation rule which has not received much attention in the literature. In contrast, the when and where labour allocation rules have received ample attention. The when-rule determines when to consider transferring a worker from the work centre which he/she has been working to another work centre. The most commonly used when-rules in literature are (1) the centralised when-rule, which means that a worker is eligible for transfer after each job which he/she has finished in a work centre, and (2) the decentralised when-rule, which means that after finishing a job, a worker is only eligible for transfer if the work centre should become idle. The where-rule determines to which work centre a worker needs to be transferred. Examples of where-rules often used in research are the First in System, First Served (FISFS) rule and the Longest Queue (LNQ) rule.

In general, labour allocation rules need to be applied during three specific decision moments: A) when a job arrives at an empty work centre, B) when a job is finished at a work centre, and C) when a worker becomes available for transfer. At decision moment A, when a job comes in at an empty work centre, the when- and where-rules do not apply (see table 2). Therefore, the only remaining question could be “who should be transferred to the work centre” in case more than one skilled worker is available. A who-rule will then decide which worker to transfer to the work centre. At decision moment B, when a job is finished at a work centre, the when-rule decides whether or not the worker who finished the job will become eligible for transfer. The where- and who-rule do not apply to this decision moment. Finally, at decision moment C, a worker working in a specific work centre becomes available for reassignment. This is actually one of the two possible outcomes of decision moment B, meaning that decision moment C is always preceded by decision moment B. Here, the where-rule and, possibly, the who-rule need to be applied.

Table 2. Three decision moments and the labour allocation rules which (may) have to be used at those moments

	Decision moment	when-rule	where-rule	who-rule
A	A job arrives at an empty work centre	no	no	possible
B	A job is finished at a work centre	yes	no	no
C	A worker becomes available for transfer	no	yes	possible

The who-rule may thus be part of the decision process at decision moments A and C. What decisions are actually made during these decision moments depends on the specific state of the system at that particular decision moment as well as on the characteristics of the DRC system. This will be described in detail below.

3.1. The who-rule applied in decision moment A

At decision moment A, a job comes in at an empty work centre. If more than one skilled idle worker is available, which is a specific state of the system at the decision moment, a who-rule will be applied in order to decide which of those workers will be sent to the work centre. Figure 1 shows a decision tree for decision moment A and clarifies where a who-rule needs to be applied within the decision tree.

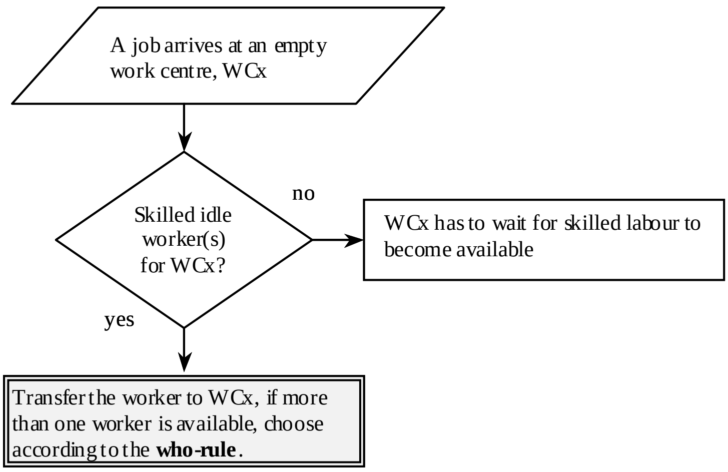

Figure 1. The who-rule (bold in shaded box) in a decision tree applied in decision moment A.

3.2. Decision moment C

In contrast to decision moment A, decision moment C is quite complex. This decision moment occurs if a worker working in a specific work centre becomes available for reassignment. In our further explanation, we will refer to this worker as “worker Y” and to this specific work centre as “Work Centre x” or “WCx”. Here, a who-rule should generally be applied in case there is still work in the queue in WCx, and if more than one skilled worker is available for assignment to WCx. Figure 2 shows the decision tree for decision moment C. With respect to this decision moment, we distinguish a team-based assignment approach from an individual-based assignment approach. This will first be described in sub subsection 3.2.1. The who-rule may be involved in the decision process at three different places (see box1, box2 and box3 in figure 2). This will be explained in sub subsection 3.2.2.

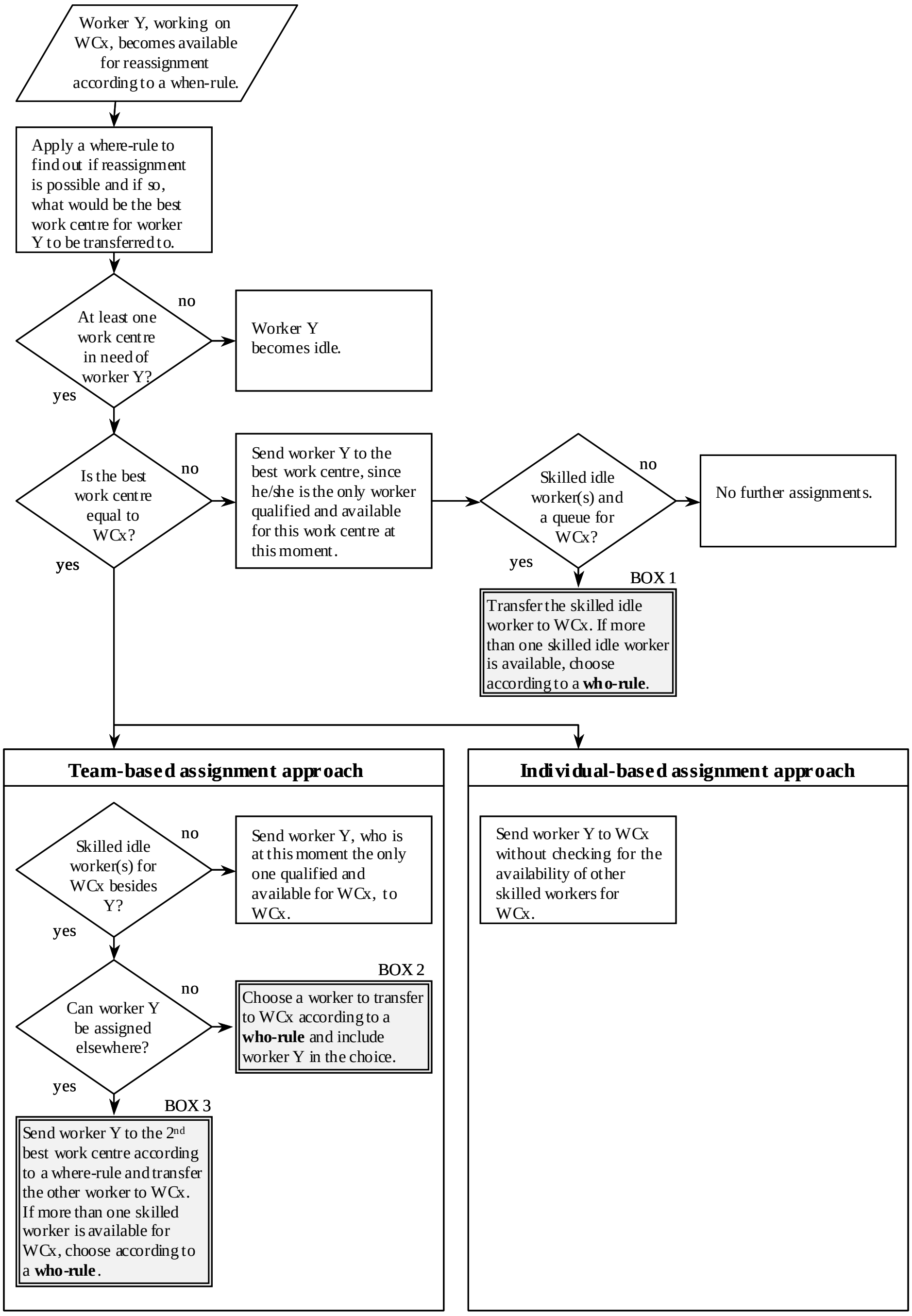

Figure 2. The who-rule (bold in three shaded boxes) in a decision tree applied in decision moment C.

3.2.1. The assignment approach in decision moment C

If the where-rule suggests that worker Y should be sent back to WCx, we can proceed in the following two ways: 1) send worker Y to WCx, or 2) check the availability of other skilled workers for WCx and then decide who to assign to WCx. We call the first option the individual-based assignment approach, since reallocation possibilities are only considered for worker Y. A choice between transferring either worker Y or another worker to WCx is not made: worker Y will be allocated to WCx. As far as we know, all prior DRC studies have followed the individual-based assignment approach.

Another option is to check the availability of other skilled workers for WCx. If other qualified workers are available for WCx, we should check if worker Y could be assigned to other work centres than WCx. Note that worker Y can only be sent to other work centres if the other workers have different qualifications. That is, worker Y must have at least one unique skill for another work centre which the other idle team members do not possess, otherwise one of the other idle team members might as well have been sent to this work centre. If worker Y could be assigned to another work centre than WCx, he/she should always be placed there. By doing so, worker Y is prevented from blocking WCx for other skilled idle workers, thereby making it possible to assign another worker to WCx at that same decision moment. In this way, unnecessary idle time of workers will be prevented. If worker Y cannot be assigned elsewhere, it may still be relevant to choose someone else who could be assigned to WCx, instead of just assigning worker Y. This team-based approach was also observed in the practical instance (see subsection 2.1). Therefore, we propose this team-based assignment approach which considers (re)allocation possibilities for all idle team members to prevent unnecessary idle time of workers and/or to be able to choose the right worker for assignment to WCx.

3.2.2. The who-rule applied in decision moment C

The first step in the decision tree (see figure 2) is to determine if reassignment is possible for worker Y, and if so, what would be the preferred order of work centres for reassignment. This information can be determined by applying a where-rule for worker Y without actually assigning the worker yet. So, in the preferred order of a where-rule, this step only provides the answer to the question what work centres are available for worker Y. For instance, the outcome of this step may be that worker Y can be assigned to work centres one and two (i.e. worker Y is skilled for work centres one and two, there is work in queue for these work centres, and at least one unoccupied machine is available in these work centres) and work centre one is preferred over work centre two. If there is no work centre available for worker Y at this moment, worker Y will become idle. On the other hand, if one or more work centres are available for worker Y, we will use this information (i.e. available work centres in the preferred order of the where-rule) in the next steps of the decision process. With this information, we will first check, according to a where-rule, whether or not the work centre which Y came from is actually the best work centre (i.e. WCx).

If, according to a where-rule, WCx is not the best work centre, we can instantly assign worker Y to another work centre. It will never be the case that other idle workers are also able to operate in this work centre, because otherwise they would already have been sent there. However, it is possible that there are idle workers, including skilled idle workers for WCx. In case there is still work in queue in WCx, another labour assignment could be established. If there are several skilled idle workers for WCx, a who-rule in box 1 (see figure 2) should be applied to choose who to assign to WCx. Note that this who-rule may be applied independently of what assignment approach will be conducted.

As we have discussed earlier, if, according to a where-rule, WCx is the best work centre, the distinction between an individual-based or a team-based assignment approach becomes relevant. An individual-based assignment approach coincides with a decision process resulting in a single labour assignment –that of worker Y– conform the where-rule used. A team-based approach goes together with a decision process which is more extensive and may involve the use of a who-rule in box 2 or box 3 (see figure 2). Specifically, in the case in which there are other skilled workers available for WCx and worker Y can also be reassigned to another work centre, worker Y will be transferred to the second best work centre according to a where-rule (please note that the best work centre was WCx). This will create the opportunity for a team-mate to be transferred to WCx. If more than one team-mate is available, a who-rule in box 3 will be applied to choose which worker should be transferred to WCx. If worker Y cannot be assigned to another work centre, a who-rule in box 2 is applied to decide which one of the available workers –including worker Y– should be transferred to WCx.

3.3. Influence of other DRC characteristics on the decision processes

We believe that system characteristics, such as labour utilisation, the use of the specific when-rule, and the number of identical machines in a work centre, influence the decision process at the three decision moments and may impact the extent of the effect of the who-rule. For decision moment A, characteristics of the DRC system, such as the use of the specific when-rule, or the number of identical machines in a work centre, do not have an impact on the decision process. In contrast, the decision process at decision moment C is quite susceptible to the specific characteristics of the DRC system. In DRC systems with full flexibility, who-rules in box 1 and box 3 will never be applied. This is because worker Y cannot be transferred to another work centre than WCx in case there are other workers idle, otherwise these workers would already have been transferred to that other work centre.

Further, in systems with a decentralised when-rule at decision moment B, workers will only become available if the queue is empty. This means that at decision moment C, WCx will have an empty queue and, according to a where-rule, the best work centre for worker Y can therefore not be WCx. The only question here is thus “where to assign worker Y” and none of the three boxes where the who-rules are applied will be relevant to the decision process.

The ratio of the number of workers who can operate in a work centre and the number of identical machines in a work centre also influences the effect of a who-rule. If this ratio is equal to or smaller than one, all skilled workers can be assigned to a work centre with a queue and there is no need to choose among them. Finally, labour utilisation influences the frequency of the occurrence of decision moments A, B and C, and it affects the chance that other workers are idle at decision moments A or C.

4. Modelling of the DRC shop and experimental design

Section 3 described the who-rule in detail for DRC simulation systems. Now, we will continue to present models of DRC systems in order to be able to study the effect of several alternative who-rules. We will first describe the general DRC shop and then explain the experimental design. Figure 3 shows the general DRC framework with workload parameters, design parameters, and control parameters. The distinction of these three elements has been derived from Nelson (1967).

Workload parameters

λ	The mean arrival rate of jobs into the system
r	The job routing pattern
μ	The mean service rate of the machines

Design parameters

K	The number of work centres in the shop (k = 1, 2, …, K)
c	The number of identical machines per work centre
M	The number of machines in the shop (M = K x c)
N	The number of workers in the shop (n = 1, 2, …, N)
p_{nk}	The proficiency of worker n on any machine m in work centre k

Control parameters

d	The dispatching rule used
wn	The “when” labour allocation rule used
wr	The “where” labour allocation rule used
who	The “who” labour allocation rule used

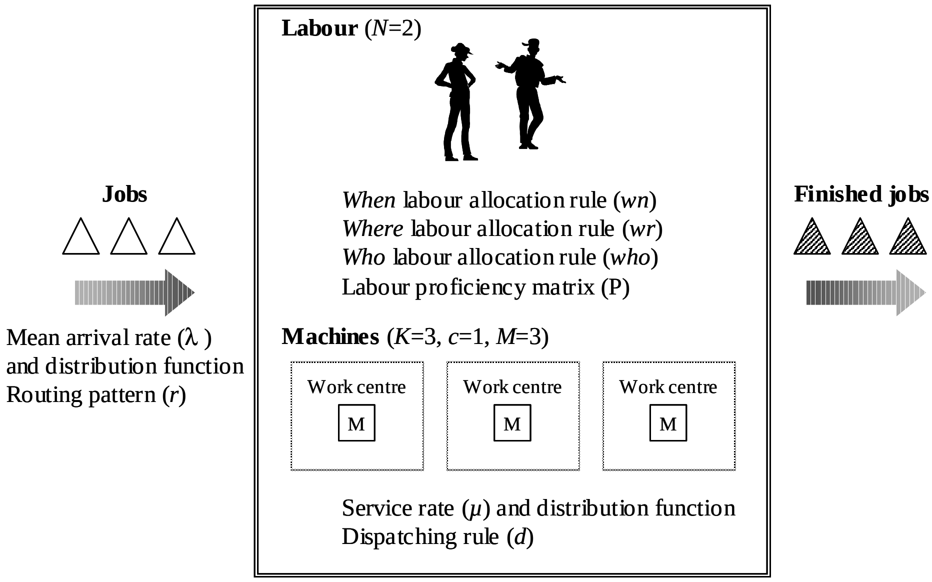

Figure 3. A general DRC framework with workload, design, and control parameters

Factors are the input parameters and structural assumptions which compose a model. The decision which parameters and structural assumptions are considered fixed aspects of a model and which are experimental factors depends on the goals of the study (Law and Kelton 2000: 622). The goal of our study is to investigate the importance of the who-rule in DRC systems. This means that not only the effect of the who-rule itself should be investigated, but also the interaction effects with factors likely to have an influence on the importance of the who-rule. In this paper, two experiments are conducted in order to study the effects of the who-rule.

In the first experiment, homogeneous labour with respect to task proficiencies is assumed. The experiment examines the effect of three different who-rules on the average flow time of the system. The other experimental factors of the first experiment are the disparity in work centre loads, the number of skills which workers possess (i.e. two of the factors discussed in sub subsections 2.2.2 and 2.2.3 causing differences between workers), and the level of labour utilisation. We expect the level of labour utilisation to have a large influence on the importance of the who-rule.

In addition to the first experiment, which assumes homogeneous labour with respect to task proficiencies, we conducted a second experiment to explore the effect of the who-rule in a system with task proficiency differences between workers (see sub subsection 2.2.1). For this experiment, the experimental factors are the who-rule and the disparity in work centre loads. The number of skills which workers possess and the level of labour utilisation are kept constant. Varying these factors in the second experiment will, in our opinion, not contribute to more insight in the impact of the who-rule than has already been gained from the first experiment. A detailed overview of the fixed factors and the experimental factors with their levels can be found below.

4.1. Fixed factors

4.1.1. Design of the shop

We modelled the smallest possible DRC shop to which the who-rule applies. We deliberately kept shop size small to investigate the basic effects of the who-rule. In this way, causal factors are easier to identify, and small systems provide a better insight in the role of operating variables. Fryer (1975) shows that the effects of dispatching and labour control decision rules on flow time measures are consistent with different size and labour flexibility combinations. Further, in practice, many large systems can be decomposed into smaller systems. In many companies, two or three workers are responsible for a small group of machines.

The shop consists of three work centres (K=3) with one machine (c=1) per work centre. This implies that there are three (M=3) machines in the shop. In contrast to shops with identical machines in work centres, here labour flexibility cannot be used to transfer more than one worker to a (temporary) heavily loaded work centre. Instead, labour flexibility in this shop means that a worker can replace another worker who is working elsewhere. Two workers (N=2) who are not fully cross-trained operate the shop. The system is thus one of limited flexibility.

4.1.2. Generation of job arrivals, routings, and processing times

Jobs come into the system according to a negative exponential distribution with a mean arrival rate of λ. Each job is assigned to only one work centre, meaning there is only one routing step per job. Therefore, a multiqueue, multichannel, single-phase system is modelled. The processing times of jobs at the machines are generated by a gamma distribution with $\alpha = 2$ and $\beta = 0.5$. This is equal to the 2-Erlang distribution, which is often used as a distribution function to represent operating times. The mean processing time ($1/\mu$) of this distribution is $\alpha*\beta$, and equal to one.

4.1.3. Control of the shop

The dispatching rule (d) used in the system is the First-Come-First-Served (FCFS) rule. As a counterpart to this dispatching rule, the First-In-System-First-Served where-rule (wr) is used. This where-rule sends workers who are eligible for transfer to the work centre with the job in queue that had the earliest entry into the system. 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 work centre. As explained in the previous section, who-rules during both decision moments A and C will occur if a centralised when-rule has been set, whereas with a decentralised when-rule, only the who-rule in decision moment A will occur. For looking at differences between who-rules, and particularly in combination with a team-based assignment approach, it thus seems more relevant to apply the centralised when-rule.

4.2. Experimental factors:

In the two experiments, four experimental factors with different levels are examined (see table 3): number of skills (NS), disparity in work centre loads (DISTR), the who-rule (WHO), and labour utilisation (UTIL).

Table 3. Experimental factors and levels in the two experiments

First experiment: homogeneous labour with respect to task proficiencies						
	Levels					
Factor	1	2	3	4	5	6
NS	4	5				
DISTR	0.4/0.5/0.1	0.1/0.4/0.5	0.5/0.1/0.4	0.3/0.5/0.2	0.2/0.3/0.5	0.5/0.2/0.3
WHO	LIT	RND	PRIO			
UTIL	60%	75%	90%			
Second experiment: heterogeneous labour with respect to task proficiencies						
	Levels					
Factor	1	2	3	4	5	6
DISTR	0.4/0.5/0.1	0.1/0.4/0.5	0.5/0.1/0.4	0.3/0.5/0.2	0.2/0.3/0.5	0.5/0.2/0.3
WHO	RND	MEF				

4.2.1. Number of skills (NS)

In the first experiment, the number of skills is an experimental factor. In this experiment, two matrices (see figure 4a and 4b) are examined. The first matrix (4a) represents single-level labour flexibility with a total number of four skills and no task proficiency differences, and the second matrix (4b) represents multilevel labour flexibility with a total number of five skills and no task proficiency differences. The homogeneity of the workforce with respect to task proficiencies reveals itself by the fact that p_{nk} is either one, denoting that worker n is fully efficient to operate in work centre k, or zero, denoting that worker n is not skilled to work in work centre k. Note that the second matrix encompasses the first one. Compared to the first matrix, worker 2 is trained for an additional work centre, i.e. work centre one, in the second matrix. The third matrix (4c) is used in the second experiment, where the number of skills is a fixed factor and labour is heterogeneous with respect to task proficiencies. In this matrix, the workers have different task proficiencies regarding the second work centre. Here, we multiply the expected processing time ($1/\mu$) by the proficiency factor p_{nk}. The processing time for work centre two is thus adjusted up or down by the proficiency factor p_{nk}, which is 1.25 for worker two and 0.75 for worker one.

(a)

Workers \ Work centres	1	2	3
1	1	1	0
2	0	1	1

(b)

Workers \ Work centres	1	2	3
1	1	1	0
2	1	1	1

(c)

Workers \ Work centres	1	2	3
1	1	0.75	0
2	0	1.25	1

Figure 4. Three labour proficiency matrices representing (a) a four-skills configuration with single level flexibility (b) a five-skills configurations with multilevel flexibility, and (c) a four-skills configuration with a difference in task proficiencies of workers.

4.2.2. Disparity in work centre loads (DISTR)

In both the first and the second experiment, six different divisions of the system arrival rate to the three individual work centres are investigated. For instance, at level one, 40% of the jobs which arrive in the system go to work centre one, 50% to work centre two, and 10% to work centre three. Level two and three use the same division of the system arrival rate as level one, but in another order. For levels 4-6, the division of the system arrival rate to the individual work centres is less extreme. Even though one work centre still gets 50% of the incoming jobs, the work centre loads of the other two work centres are more similar to each other than those of levels 1-3.

4.2.3. Who-rule (WHO)

In the first experiment, we will examine three who-rules. These who-rules are called (1) the “Longest Idle Time” who-rule (LIT), (2) the “Random” who-rule (RND), and (3) the “Priority” who-rule (PRIO). The RND who-rule will be simulated both in combination with an individual- and a team-based assignment approach. In that way, we can verify if the proposed team-based assignment approach actually performs better than the individual-based assignment approach. Note again that the distinction between a team-based and an individual-based assignment approach only applies to decision moment C (see figure 2). The other two who-rules are only applied in combination with a team-based assignment approach. The three who-rules will be explained below.

The LIT who-rule was already applied in research of Rochette and Sadowski (1976), but not within the team-based assignment approach. This who-rule performs well from a social viewpoint in that it seems fair to the team members to assign the worker who has been waiting –or at least not working on a work centre– for the longest period of time.

The RND who-rule chooses a worker randomly when a choice between workers has to be made. Combined with an individual assignment approach (RND-ind), only a who-rule in box 1 may be applied at decision moment C, after worker Y is reassigned to his/her best work centre. However, since we only modelled two workers, the RND-ind who-rule is actually only applied at decision moment A. The RND who-rule combined with a team-based assignment approach (RND-team) can be applied at decision moment A and in box 2 at decision moment C.

The PRIO who-rule is specifically designed for the shop modelled and it always gives priority to one of the two workers. Which worker is given priority to depends on the labour proficiency matrix used (NS), and in case of the four-skills configuration, also on the disparity in work centre loads (DISTR). In case of the four-skills configuration, each worker has a unique skill and thus a unique load for one work centre, and the other work centre is shared with the other worker. The PRIO who-rule compares the unique loads of the two workers and always assigns the worker with the lowest unique load to the shared work centre (please note that this is a static measure). We believe that this will result in a better balance between workers and expect this to result in better flow time performance. In case of the five-skills configuration, one worker is able to operate in all work centres and the other in only two work centres. Here, the PRIO who-rule always gives priority to the worker with two skills in case a choice between the workers has to be made.

The second experiment will compare the RND who-rule (as discussed above) with a who-rule based on task proficiency differences, which is derived from Hogg *et al.* (1977): the Most Efficient (MEF) who-rule. The MEF who-rule assigns the worker who is the most efficient at performing the task (i.e. the worker with the lowest proficiency factor).

4.2.4. Labour utilisation (UTIL)

Labour utilisation is an experimental factor in the first experiment, where we set λ at 1.2, 1.5, and 1.8, resulting in a labour utilisation of 60%, 75%, and 90%, respectively. In the second experiment, we keep λ fixed at 1.2, resulting in a labour utilisation of 60%.

5. Simulation modelling and performance measure

The simulation models were written in the object-oriented simulation software package EM-Plant Version 5.5 (Stuttgart: Technomatix). The simulation models used here are stochastic, steady-state, and non-terminating. The replication/deletion approach was used to estimate the steady-state means of the output parameters. Welch's method was applied to get clues on the warm-up period of the lowest level of labour utilisation. 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. It must be said that these approaches were only used to get an indication. The actual settings used for the experiments are based on these observations, but increased to be on the safe side. Each experiment consisted of 40 replications with a length of 30 000 time units and a warm-up period of 5000 time units. This means that data of at least 30 000 jobs have been used for statistical analysis. Different seeds were used for each replication to maximise sampling independence. To measure the effects of the who-rule, the average shop flow times are used.

6. Results

6.1. Results of the first experiment

The full-factorial design of the first experiment consists of six work centre load distributions, three who-rules, two configurations with different skills (i.e. a single-level flexibility configuration with four-skills and a multilevel flexibility configuration with five skills), and three levels of labour utilisation, which results in 108 unique experimental cells. The data have been analysed by using three separate 6 x 3 x 2 analyses of variance (ANOVA) between subjects designs –one for each level of labour utilisation– with disparity in work centre loads (DISTR), the who-rule (WHO), number of skills (NS) as independent variables and flow time as dependent variable. We have not included labour utilisation in our design, since this factor causes large differences in variances of flow time between each level, thereby violating the homogeneity of variance assumption that underlies ANOVA. Within the designs, cell sizes are equal. For each design, a Levene's test of equality of error variances has been performed which shows that the assumption of homogeneity of variance across populations was met. The ANOVA results are summarised in table 4.

Table 4. Separate ANOVA results of average flow time in three labour utilisation experiments

		Average Flow time	
UTIL	Source	F	p-value
60%	WHO	246.70	p<.001
	NS	319.15	p<.001
	DISTR	156.49	p<.001
	WHO x NS	28.85	p<.001
	WHO x DISTR	5.82	p<.001
	NS x DISTR	152.71	p<.001
	WHO x NS x DISTR	6.88	p<.001
75%	WHO	61.61	p<.001
	NS	245.29	p<.001
	DISTR	63.85	p<.001
	WHO x NS	10.46	p<.001
	WHO x DISTR	1.75	p=.065
	NS x DISTR	109.7	p<.001
	WHO x NS x DISTR	2.628	p=.004
90%	WHO	5.17	p=.006
	NS	144.48	p<.001
	DISTR	42.15	p<.001
	WHO x NS	1.94	p=.143
	WHO x DISTR	1.09	p=.368
	NS x DISTR	57.16	p<.001
	WHO x NS x DISTR	0.60	p=.816

It can be observed that in case the labour utilisation is 60%, each of the experimental factors as well as the two-way interactions and the three-way interaction are significant at the 0.01 level. With a labour utilisation of 75%, only the interaction effect of the who-rule

(WHO) with a disparity in work centre loads (DISTR) is not significant at the 0.01 level. Finally, with a labour utilisation of 90%, the two two-way interactions with the who-rule and the three-way interaction are not significant at the 0.01 level. In our further analysis, we have focussed on the significant main and interaction effects of all labour utilisation experiments and we have paid special attention to the main effect of the who-rule and the interaction effects accompanying the who-rule. If necessary, in the discussion of lower level effects, we will further specify the higher level effects. Table 5 shows the full factorial results of the experiments.

Table 5. Full factorial results of the three labour utilisation experiments. who-rules: 1 = LIT, 2 = RND-team, 3 = PRIO

		Disparity of work centre loads											
		0.4/0.5/0.1		0.1/0.4/0.5		0.5/0.1/0.4		0.3/0.5/0.2		0.2/0.3/0.5		0.5/0.2/0.3	
Utilisation	Number of skills	Who-rule	Mean Flow time	Who-rule	Mean Flow time	Who-rule	Mean Flow time	Who-rule	Mean Flow time	Who-rule	Mean Flow time	Who-rule	Mean Flow time
60%	4	1	2.11	1	2.09	1	2.01	1	2.08	1	2.02	1	1.99
		2	2.11	2	2.09	2	2.02	2	2.08	2	2.02	2	1.99
		3	2.06	3	2.03	3	2.01	3	2.07	3	1.99	3	1.98
	5	1	2.01	1	2.08	1	2.07	1	1.98	1	2.02	1	2.01
		2	2.02	2	2.08	2	2.07	2	1.98	2	2.03	2	2.00
		3	1.99	3	2.00	3	2.00	3	1.94	3	1.97	3	1.94
75%	4	1	3.22	1	3.17	1	3.01	1	3.24	1	3.05	1	3.02
		2	3.21	2	3.13	2	3.02	2	3.22	2	3.02	2	3.00
		3	3.16	3	3.08	3	3.04	3	3.21	3	3.02	3	2.96
	5	1	3.03	1	3.12	1	3.10	1	2.99	1	3.08	1	3.03
		2	3.00	2	3.11	2	3.08	2	3.00	2	3.08	2	2.99
		3	2.96	3	3.01	3	2.97	3	2.94	3	3.03	3	2.94
90%	4	1	8.07	1	7.32	1	7.04	1	8.25	1	7.26	1	7.23
		2	8.09	2	7.55	2	7.11	2	8.32	2	7.36	2	7.24
		3	7.83	3	7.42	3	7.24	3	8.38	3	7.20	3	7.04
	5	1	7.10	1	7.16	1	7.26	1	7.24	1	7.52	1	7.24
		2	7.17	2	7.20	2	7.22	2	7.17	2	7.46	2	7.20
		3	6.98	3	6.94	3	7.12	3	7.17	3	7.40	3	7.01

Although the main effect of the who-rule (WHO) in table 4 is significant, a post-hoc test is needed to compare the means of the three who-rules. Table 6, therefore, shows the Tukey results with respect to the who-rule.

Table 6. Tukey's results of the who-rule (α = 0.01)
who-rules: 1 = LIT, 2 = RND team, 3 = PRIO

60% utilisation		75% utilisation		90% utilisation	
Who-rule	Mean Flow time	Who-rule	Mean Flow time	Who-rule	Mean Flow time
3	2.00	3	3.03	3	7.31
1	2.04	2	3.07	1	7.39
2	2.04	1	3.09	2	7.42

Table 6 indicates that the means of the LIT who-rule and of the RND who-rule do not significantly differ. With a labour utilisation of 90%, the means of the PRIO who-rule and the LIT who-rule neither differ significantly. As can be seen, the PRIO who-rule always performs best, but only about 2% better than the other who-rules. This effect even appears to decrease at higher levels of labour utilisation. This can be explained by the fact that with higher levels of labour utilisation, the chance that the two workers are simultaneously idle decreases and thus the number of times that the who-rule has to be applied decreases. The effect of the who-rule seems small in this experiment, but since some interaction effects occurring in the lower labour utilisation experiments are significant, there may be circumstances in which the who-rule shows a larger effect. Furthermore, in practice, managers who are responsible for labour allocation may take into account future information when assigning workers to work centres (see section 2.1). This basically means that the number of times that the who-rule will be applied increases significantly, which, consequently, also holds for the effect of selecting the most appropriate who-rule.

The significant main effect of the number of skills (NS) in table 4 indicates that the means of single-level flexibility with four skills and those of multilevel flexibility with five skills differ significantly. In all three labour utilisation experiments, the multilevel flexibility configuration performs better than the single-level flexibility configuration (see table 7). The finding that more skills perform better with respect to flow time performance than fewer skills, corresponds with intuition. The more skills are available in the system, the higher the labour flexibility, and the better the flow time.

Table 7. Mean flow time and standard deviation of the number of skills at all levels of labour utilisation

Labour utilisation	Number of skills	Mean Flow time	Standard deviation
60%	4	2.04	0.055
	5	2.01	0.054
75%	4	3.10	0.127
	5	3.02	0.104
90%	4	7.55	0.748
	5	7.19	0.533

Finally, the main effect of disparity in work centre loads is significant in all labour utilisation experiments. However, looking at the effect of a disparity in work centre loads without looking at the number of skills does not make much sense. The number of skills highly influences the flow time effects of a specific work centre distribution, as can be seen by the large interaction effect of these two variables (see table 4, NS x DISTR), which is significant in all labour utilisation experiments. Therefore, we will present the simple main effects of disparity in work centre loads at each level of the number of skills. The simple main effects show us that in all labour utilisation experiments, the work centre load distribution influences flow time in both skill configurations. The significant simple main effects of the disparity in work centre loads have been further analysed by pair wise comparisons using the Sidak adjustment for multiple comparisons (see table 8). The differences between the flow times of the 6 work centre load distributions are smaller in the five-skills configuration than in the four-skills configuration.

Table 8. Simple main effect of disparity in work centre loads at each level of the number of skills and pair wise comparisons of the simple effects using the Sidak adjustment for multiple comparisons (α = 0.01)

	60% utilisation		75% utilisation		90% utilisation	
NS	DISTR	Flow time	DISTR	Flow time	DISTR	Flow time
4 skills	0.5/0.2/0.3	1.99	0.5/0.2/0.3	2.99	0.5/0.1/0.4	7.13
	0.2/0.3/0.5	2.01	0.5/0.1/0.4	3.02	0.5/0.2/0.3	7.17
	0.5/0.1/0.4	2.01	0.2/0.3/0.5	3.03	0.2/0.3/0.5	7.27
	0.1/0.4/0.5	2.07	0.1/0.4/0.5	3.13	0.1/0.4/0.5	7.43
	0.3/0.5/0.2	2.08	0.4/0.5/0.1	3.20	0.4/0.5/0.1	8.00
	0.4/0.5/0.1	2.10	0.3/0.5/0.2	3.22	0.3/0.5/0.2	8.32
5 skills	0.3/0.5/0.2	1.97	0.3/0.5/0.2	2.98	0.4/0.5/0.1	7.08
	0.5/0.2/0.3	1.98	0.5/0.2/0.3	2.99	0.1/0.4/0.5	7.10
	0.4/0.5/0.1	2.00	0.4/0.5/0.1	3.00	0.5/0.2/0.3	7.15
	0.2/0.3/0.5	2.01	0.5/0.1/0.4	3.05	0.3/0.5/0.2	7.19
	0.5/0.1/0.4	2.05	0.2/0.3/0.5	3.06	0.5/0.1/0.4	7.20
	0.1/0.4/0.5	2.05	0.1/0.4/0.5	3.08	0.2/0.3/0.5	7.46

Figure 5 also illustrates the interaction effect of number of skills (NS) and disparity in work centre loads (DISTR) with a labour utilisation of 60%. Analysing this interaction from the viewpoint of the number of skills, it is interesting to see that even though the main effect of the number of skills shows that a configuration of five skills performs better than a configuration of four skills, the interaction with disparity in work centre loads shows that this is not the case with all work centre load distributions. Therefore, we also analysed the interaction effect of number of skills (NS) and disparity in work centre loads (DISTR) using a simple main effects analysis to analyse the number of skills within each level of disparity in work centre loads. The number of skills influences flow time performance for most configurations, but no influence was observed on the 0.2/0.3/0.5 and the 0.5/0.2/0.3 distributions in the 60% labour utilisation experiment, and neither on the 0.5/0.1/0.4 and 0.5/0.2/0.3 distributions in the 75% and 90% labour utilisation experiments. Most work centre load distributions show a higher flow time in the four-skills configuration, but the 0.5/0.1/0.4 distribution in the 60% labour utilisation experiment actually shows a higher flow time in the five-skills configuration (M = 2.05, SE = 0.003) than in the four-skills configuration (M = 2.01, SE = 0.003). In the 75% and the 90% labour utilisation experiments, the flow time of the 0.2/0.3/0.5 distribution increases when adding an extra skill. It is often assumed that increasing the number of skills in a DRC system will automatically result in higher effective labour flexibility. Therefore, it is interesting to see that increasing the number of skills in systems with a disparity in work centre loads and homogeneous labour with respect to task proficiencies does not always improve the performance of the system. Since the five-skills configuration encompasses the four-skills configuration, it should be able to at least perform equally well. For instance, if the labour allocation rules are adapted in such a way that worker two will never visit work centre one, then the five-skills configuration is similar to the four-skills configuration. Apparently, with respect to some work centre load distributions, labour allocation rules may result in worker assignments which have a negative impact on flow time in case one skill is added. Later on in the paper, when examining the three-way interaction (WHOxNSxDISTR), this statement will be checked with the three different who-rules.

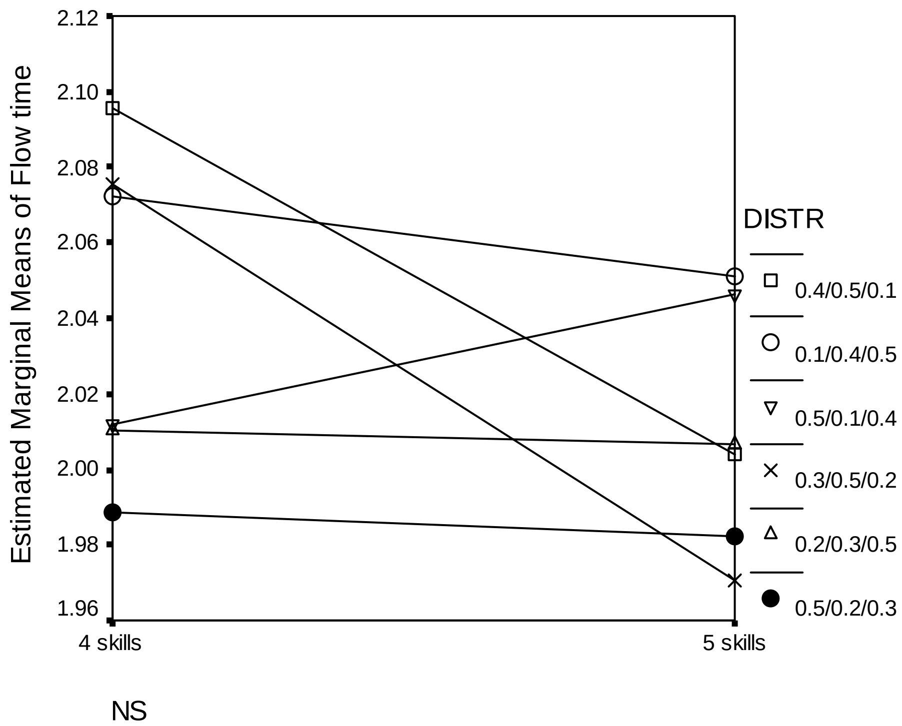

Figure 5. The interaction effect of number of skills (NS) and work centre load distribution (DISTR) in the 60% labour utilisation experiment.

The effect of number of skills (NS) on the who-rule (WHO) in the 60% labour utilisation experiment is illustrated in figure 6. The simple main effects that can be observed in the 60 and 75% labour utilisation experiments showed that the who-rule influences flow time within both skill configurations. These significant simple main effects of the who-rule have been further analysed by pair wise comparisons using the Sidak adjustment for multiple comparisons. In the 60% labour utilisation experiment, the PRIO who-rule performs significantly better ($M_{4\ skills}$ = 2.02, SE = 0.002; $M_{5\ skills}$ = 1.97, SE = 0.002) than the LIT and RND who-rules do ($M_{4\ skills}$ = 2.05, SE = 0.002; $M_{5\ skills}$ = 2.03, SE = 0.002), and the effect is larger on the configuration with five skills than on the configuration with four skills. The flow time effects of the LIT and RND-team who-rules are not significantly different from each other. In the 75% labour utilisation experiment, the PRIO who-rule performs significantly better ($M_{4\ skills}$ = 3.08, SE = 0.006; $M_{5\ skills}$ = 2.97, SE = 0.006) than the LIT who-rule ($M_{4\ skills}$ = 3.12, SE = 0.006; $M_{5\ skills}$ = 3.06, SE = 0.006) does. It also performs better than the RND who-rule ($M_{4\ skills}$ = 3.10, SE = 0.006; $M_{5\ skills}$ = 3.04, SE = 0.006) in the five-skills configuration. Therefore, in bringing down flow time, the PRIO who-rule appears to be more effective than the other who-rules, especially in the configuration with five skills. In the 90% labour utilisation experiment, the interaction effect is not significant (see table 4).

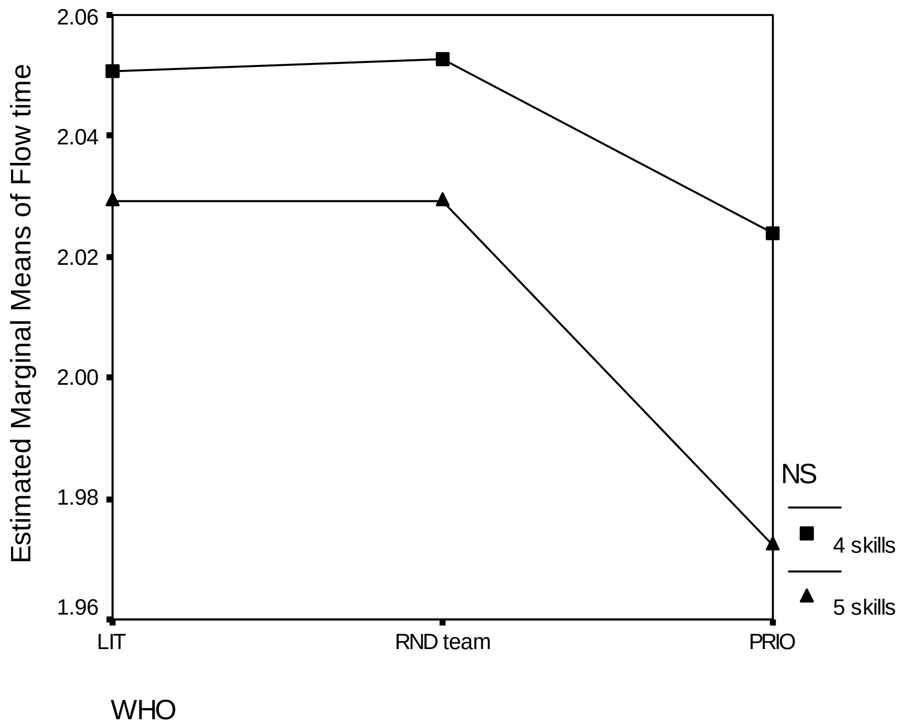

Figure 6. The interaction effect of who-rule (WHO) and number of skills (NS) in the 60% labour utilisation experiment.

The interaction effect of the who-rule (WHO) with the disparity in work centre loads (DISTR) indicates that with respect to some work centre load distributions, the differences between the flow times of the three who-rules are smaller than with other distributions. Or, in other words, the magnitude of the effect of applying another who-rule on flow time depends on the specific work centre load distribution. This effect is only significant in the 60% labour utilisation experiment. Here, the simple main effects of the who-rule shows that the who-rule influences flow time performance in all distributions. Further, the pair wise comparisons shows that the PRIO who-rule performs significantly better than the LIT and RND-team who-rules, and that in all distributions the difference between the LIT who-rule and the RND-team who-rule is not significant. With respect to some distributions, the flow time effect of the PRIO who-rule is larger compared to other distributions. If the labour utilisation is higher, the effect of the who-rule diminishes. Therefore, to each distribution applies that the differences between alternative who-rules also become smaller, and this explains the non-significant interaction effect of the who-rule with disparity in work centre loads in case of higher labour utilisation.

Finally, the significant three-way interaction effect of the who-rule (WHO), the number of skills (NS) and the work centre load distribution (DISTR) in the 60 and 75% labour utilisation experiments is interpreted by means of simple interaction effects and simple, simple main effects. The interaction between the number of skills (NS) and the disparity in work centre loads (DISTR) is significant in all levels of the who-rule (WHO). These simple interaction effects are to a large extent identical to the interaction effect shown in figure 5, except that the flow time within the five-skills configuration is never higher than the flow time within the four-skills configuration with the PRIO who-rule. This confirms our statement that for some work centre load distributions, the negative impact on flow time in case a skill is added may be undone by choosing another who-rule. This result shows that, despite the small effects, labour allocation rules, such as the who-rule, can prevent deterioration of flow time performance in case a skill is added.

In the 60% labour utilisation experiment, the interaction effect of who-rule (WHO) and number of skills (NS) is significant for the 0.5/0.1/0.4 distribution as well as the 0.5/0.2/0.3 distribution. In these distributions, there is no significant flow time difference between any of the who-rules in the four-skills configuration, but the PRIO who-rule performs significantly better ($M_{0.5/0.1/0.4}$ = 2.00, SE = 0.005; $M_{0.5/0.2/0.3}$ = 1.94, SE = 0.005) than the LIT and RND-team who-rules do ($M_{0.5/0.1/0.4}$ = 2.07, SE = 0.005; $M_{0.5/0.2/0.3} \approx$ 2.01, SE = 0.005) in the five-skills configuration. Further, with respect to the LIT and RND-team who-rules, the flow times of the five-skills configuration are higher than those of the four-skills configuration. In the 75% labour utilisation experiment, the interaction effect of who-rule (WHO) and number of skills (NS) is only significant for the 0.5/0.1/0.4 distribution.

In the 60% labour utilisation experiment, the interaction effect of the who-rule (WHO) and the disparity between work centre loads (DISTR) is not significant in the four-skills configuration ($p = 0.011$), but significant in the five-skills configuration ($p < 0.01$).

The mean flow time results of the who-rule regarding number of skills and work centre load distribution in the 60% and 75% labour utilisation experiments are shown in table 9. Pair wise comparisons of the simple, simple effects of the who-rule have been performed (α = 0.01) using the Sidak adjustment for multiple comparisons. With respect to the four-skills configuration, the largest effect of the who-rule can be found with the 0.1/0.4/0.5 work centre load distribution (2.9 % improvement). It seems that the effect of the who-rule is stronger if the difference of the load of the work centres which the workers have unique skills for (i.e. work centres one and three) is larger and the shared load (i.e. work centre two) is higher. With respect to the 0.5/0.1/0.4 distribution, in which the shared work centre load is low and the difference between the load of the work centres which the workers have unique skills for is small, flow time performance is not altered by any of the three who-rules used. By contrast, in the 0.4/0.5/0.1 distribution, the average flow time performance difference between the RND-team who-rule or the LIT who-rule, and the PRIO who-rule is 2.4% in the 60% labour utilisation experiment.

The effect of the who-rule is larger with the five-skills configuration than it is with the four-skills configuration. With a labour utilisation of 60%, the largest effect of the who-rule can be observed with the 0.1/0.4/0.5 work centre load distribution (3.8% improvement) and the smallest effect can be noticed with the 0.4/0.5/0.1 distribution (1.5 % improvement). The larger the unique load for worker two (i.e. the load of work centre three), the larger the effect of the who-rule.

Table 9. Results of who-rules regarding number of skills and work centre load distribution with labour utilisations of 60% and 75%. To analyse the significant 3-way interactions, pair wise comparisons of the simple, simple effects of the who-rule have been performed (α = 0.01) by using the Sidak adjustment for multiple comparisons. who-rules: 1 = LIT, 2 = RND-team, 3 = PRIO

		Distribution of work centre loads											
		0.4/0.5/0.1		0.1/0.4/0.5		0.5/0.1/0.4		0.3/0.5/0.2		0.2/0.3/0.5		0.5/0.2/0.3	
Utilisation	Number of skills	Who-rule	Mean Flow time	Who-rule	Mean Flow time	Who-rule	Mean Flow time	Who-rule	Mean Flow time	Who-rule	Mean Flow time	Who-rule	Mean Flow time
60%	4	3	2.06	3	2.03	3	2.01	3	2.07	3	1.99	3	1.98
		1	2.11	2	2.09	1	2.01	1	2.08	1	2.02	2	1.99
		2	2.11	1	2.09	2	2.02	2	2.08	2	2.02	1	1.99
	5	3	1.99	3	2.00	3	2.00	3	1.94	3	1.97	3	1.94
		1	2.01	2	2.08	1	2.07	2	1.98	1	2.02	2	2.00
		2	2.02	1	2.08	2	2.07	1	1.98	2	2.03	1	2.01
75%	4	3	3.16	3	3.08	1	3.01	3	3.21	3	3.02	3	2.96
		2	3.21	2	3.13	2	3.02	2	3.22	2	3.02	2	3.00
		1	3.22	1	3.17	3	3.04	1	3.24	1	3.05	1	3.02
	5	3	2.96	3	3.01	3	2.97	3	2.94	3	3.03	3	2.94
		2	3.00	2	3.11	2	3.08	1	2.99	1	3.08	2	2.99
		1	3.03	1	3.12	1	3.10	2	3.00	2	3.08	1	3.03

Comparisons of the team-based assignment approach and the individual-based assignment approach (i.e. comparing the outcomes of the RND-ind who-rule and the RND-team who-rule) show that the team-based assignment approach always results in flow times which are better than or equal to the individual-based assignment approach. Better flow times are especially realized in the four-skills configuration, even in the 90% labour utilisation experiment. In the four-skills configuration, the chance that a worker gets “trapped” in the shared work centre and forces the other worker to become idle is higher than in the five-skills configuration, especially if the load of the shared machine is high compared to the unique loads of the workers.

6.2. Results of the second experiment

The full-factorial design of the additional second experiment consists of six work centre load distributions and two who-rules, resulting in 12 unique experimental cells. The data have been analysed by using a 6 x 2 analysis of variance (ANOVA) between subjects design with a disparity in work centre loads (DISTR), the who-rule (WHO) as independent variables and flow time as dependent variable. The ANOVA results are summarised in table 10. We see that at the 0.01 level all effects are significant.

Table 10. ANOVA results of average flow time (2nd experiment)

	Average Flow time	
Source	F	p-value
WHO	1577.65	p<.001
DISTR	1136.96	p<.001
WHO x DISTR	160.08	p<.001

The main effect of the who-rule (WHO) shows that the MEF who-rule results in a better performance (M = 1.95, SE = 0.002) than the RND who-rule (M = 2.08, SE = 0.002). The improvement is about 6%. To check upon disparity in work centre loads (DISTR), a post-hoc test is performed to compare the means of the six distributions. The 0.1/0.4/0.5 work centre load distribution performs best (M = 1.87, SE = 0.004), and the 0.2/0.3/0.5 distribution second best (M = 1.91, SE = 0.004). The 0.5/0.1/0.4 & 0.5/0.2/0.3 & 0.3/0.5/0.2 distributions perform equally well (M $\cong$ 2.01, SE = 0.004). Finally, the 0.4/0.5/0.1 distribution performs the worst (M = 2.26, SE = 0.004). We see that a high unique load for the second worker (i.e. the load of work centre three) is beneficial for flow time performance. This worker performs less proficient in the shared work centre two, and a high unique load keeps him/her from working there. Further, if the unique load is high for the second worker, it is more beneficial to have a higher load in the shared work centre two than in work centre one, which forms the unique load for worker one. Worker one then has to work more time in centre two, where he/she is most proficient.

Figure 7 illustrates the interaction effect of who-rule (WHO) with disparity in work centre loads (DISTR). The interaction effect indicates that the magnitude of the effect of applying the MEF who-rule instead of the RND who-rule on flow time depends on the specific work centre load distribution. The simple main effects of the who-rule show that the who-rule influences flow time performance in all distributions, except in the 0.5/0.1/0.4 distribution (p = 0.087). In this distribution, the load of the shared work centre (i.e. the load of work centre two) is low and therefore the who-rule will not contribute much. With respect to the other distributions, the beneficial effect of applying a MEF who-rule instead of a RND who-rule on flow time is 11.2% in the 0.3/0.5/0.2 distribution, 10.1% in the 0.4/0.5/0.1 distribution, 8.2% in the 0.1/0.4/0.5 distribution, 5.1% in the 0.2/0.3/0.5 distribution and 1.0% in the 0.5/0.2/0.3 distribution. The higher the load of the shared work centre, the higher the effect of the who-rule in this experiment. This result shows that if workers share a large part of their workload with other workers and there are proficiency differences between the workers in these shared work centres, the who-rule should be considered in simulation as well as in industrial practice.

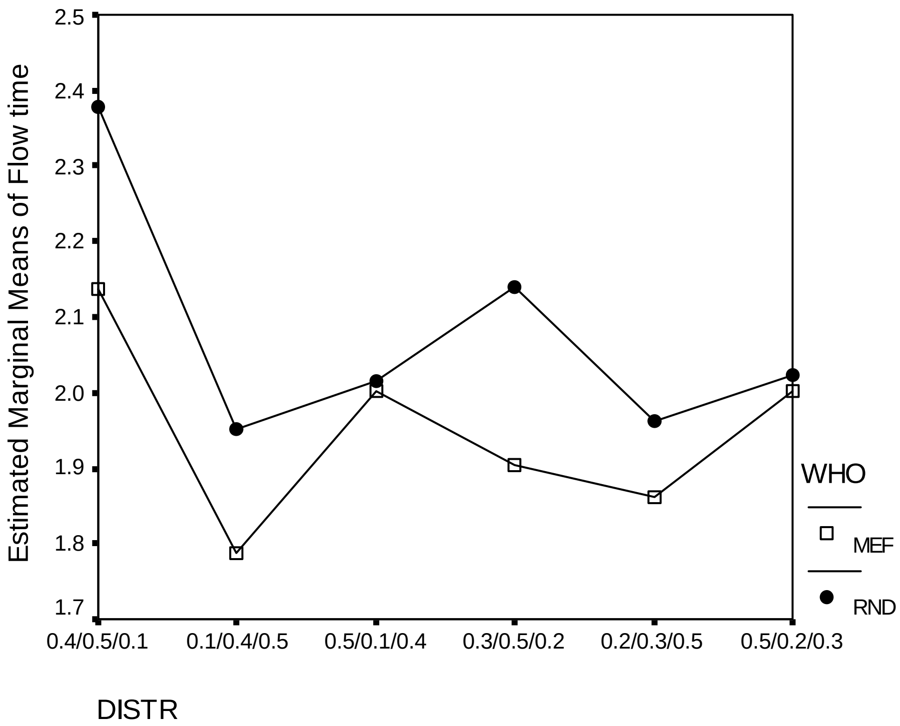

Figure 7. The interaction effect of who-rule (WHO) and work centre load distribution (DISTR)

7. Conclusions and future research

This paper has been devoted to the who-rule, which is a labour allocation rule that determines which worker should be transferred to a work centre if more than one skilled worker is available. It first indicated that the who-rule is used in industrial practice. In simulation studies, however, the who-rule is rarely referred to and not explicitly explored. This paper is intended to fill in this gap. It described in detail at what decision moments the who-rule needs to be applied in simulation. Further, it showed the flow time effects of the who-rule in several small DRC systems.

In contrast to the who-rule, the when-rule and the where-rule have been studied extensively in previous research. The impact of these assignment rules depends on the specific DRC shop modelled (e.g. worker transfer delays either modelled or not, homogeneous or heterogeneous labour with respect to task proficiencies, etc) and the performance measure considered (e.g. mean flow time, flow time variance, or delivery performance). The results of the present experiments show that DRC shop characteristics also influence the impact of the who-rule. In the present study, two experiments were conducted. The first experiment models DRC systems with homogeneous labour with respect to task proficiencies, single or multilevel flexibility, and a disparity in work centre loads under three levels of average labour utilisation. The second experiment models a DRC system with heterogeneous labour with respect to task proficiencies, single-level flexibility, and a disparity in work centre loads, with a 60% labour utilisation.

The first experiment shows that with a 60% labour utilisation, the effect of the who-rule is relatively larger with multilevel flexibility (i.e. workers possess different numbers of skills), and with distributions of work centre loads which create larger worker differences in terms of unique workloads of workers. With a 75% labour utilisation, only the number of skills of workers affects the flow time effect of the who-rule. On most work centre load distributions, the effect of the who-rule is larger in the multilevel flexibility configuration than in the single level flexibility configuration. Finally, with a 90% labour utilisation, there are no significant interaction effects of the who-rule and the disparity in work centre loads or number of skills, and the main effect of the who-rule is smaller than under lower levels of labour utilisation. The second experiment which models heterogeneous labour with respect to task proficiencies shows larger effects of the who-rule than the first experiment does. The higher the load of the shared work centre, the more the who-rule is applied and the more often the most efficient worker has to work in the shared work centre under the MEF who-rule. This results in better flow time performance.

It was also found that the team-based assignment approach introduced in this paper and observed in the practical instance outperforms the individual-based assignment approach used in prior studies. In a way, this is not surprising, since the team-based assignment approach prevents unnecessary idleness of workers. It is therefore suggested that in DRC systems with limited flexibility and a centralised when-rule, all idle team members should be involved in the assignment decisions. Or, in other words, in those systems the team-based assignment approach should be used instead of the individual-based assignment approach.

From a managerial viewpoint, it is important to note that the impact of the who-rule is probably higher in practical situations where future information can be used in assignment decisions, than has been indicated by the improvements reported in the results section. Our simulation experiments did not include the use of future information. As described in subsection 2.1, a who-rule is frequently used in practice, and future information on workloads of workers or work centres plays a role in labour allocation decisions. It is evident that the frequency by which the who-rule can be applied in practice is higher in case of practical situations where managers are able to anticipate on future events. That is, if future information is used, workers may, for instance, be kept idle during a short period to wait for a work centre to become available for which they are better suited than the worker who is operating the work centre at that moment. We believe that the factors that were included in the present study (i.e. the number of skills of workers, the disparity in work centre loads, and worker utilisation) play a role in practical situations where future information is used.

We believe that more work is needed to explore performance effects of the who-rule in different DRC systems with worker differences and to devise who-rules which result in good performance within those systems. Performance measures may be extended to include individual worker utilisation rates, due date related measures, number of worker transfers, etc. As we have already noted in subsection 3.3, several DRC characteristics influence the decision process at decision moments A and C, thereby influencing the use of the who-rule. Variations in shop size, staffing levels, job routings, transfer delays, when-rules, and where-rules are just a few examples which may be incorporated in future research. Further, the effects of learning and forgetting, and the use of future information in assignment decisions need to be examined.

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LABOUR ALLOCATION RULES IN DUAL RESOURCE CONSTRAINED (DRC) MANUFACTURING SYSTEMS WITH WORKER DIFFERENCES[6]

Jos A.C. Bokhorst, Jannes Slomp, Gerard J.C. Gaalman

ABSTRACT

This study evaluates labour allocation rules for DRC systems with worker differences. Skills of workers are considered to be an individual human factor within this research. Therefore, DRC systems are modelled with limited labour flexibility, task proficiency differences, and workers who differ in the number of skills they possess. Three simulation experiments are performed to examine the effect of the where-rule, the when-rule, and the who-rule on flow time performance within these systems. Prior research has often neglected the who-rule, which is a labour allocation rule that selects one worker out of several workers to be transferred to a work centre. However, in the presence of worker differences, evaluation of the who-rule is important. The results show that where-rules and who-rules based on task proficiency differences perform well. Further, a centralised when-rule is preferred in these systems. Within our experimental settings, most important on flow time is the effect of the where-rule, then the effect of the when-rule, and finally the effect of the who-rule.

Key words: Manufacturing, Simulation, Dual Resource Constrained systems, labour allocation

1. Introduction

In many manufacturing environments, human factors play an important role in the realisation of system performance. In (re)designing manufacturing systems, it may thus be advantageous to pay attention to these factors. Many studies, however, ignore human aspects, or assume that labour is always available and therefore do not model it. Research on Dual Resource Constrained (DRC) systems at least acknowledges that systems can be labour constrained as well, instead of only machine constrained. On the other hand, labour is often modelled in a quite simplistic manner in prior DRC research. That is, all workers are often able to operate all machines (i.e., full flexibility) with the same proficiency (i.e., homogeneous labour). In other words, labour is just considered as a homogeneous resource, without paying attention to differences between individual workers.

We argue that skills of workers should be regarded as an individual human factor. By this, we mean that the number of skills, as well as the task proficiency may differ by worker. As in prior research, a skill is defined as the ability of a worker to work on a machine. In practice, not all workers will be equally proficient on every machine. Further, it is not likely that they will be able to operate all machines or the same fixed number of machines as their colleagues do. In other words, workers will be different from one another with respect to skills. In this paper, we will study a DRC manufacturing system and include these individual differences with respect to worker skills.

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Within a DRC environment, labour allocation rules are needed to specify the timing of transferring workers and to specify where workers need to be transferred. Labour allocation rules considered in most DRC studies are the when-rule and the where-rule. The when-rule determines at what moment labour becomes eligible for transfer, while the where-rule determines to which work centre or machine a worker needs to be transferred. These labour allocation rules have received ample attention in literature (see e.g., the literature reviews of Treleven 1989, Gargeya and Deane 1996, Hottenstein and Bowman 1998). The impact of labour allocation rules on system performance seems to depend on the specific DRC shop modelled and the performance measure considered.

This study concentrates on labour allocation rules in DRC systems with worker differences. We treat the skills of workers as an individual human factor and evaluate when-rules, where-rules, and who-rules within these systems. A who-rule chooses who should be transferred to a machine if more than one skilled worker is available. If workers differ from each other, it is important to pay attention to the who-rule. For instance, a who-rule focusing on task proficiency differences may be able to redirect work from less proficient workers to more proficient workers, which will reduce mean flow time. Who-rules focussing on other worker differences, such as differences in the number of skills per worker, also impact the division of jobs to workers. An objective of a who-rule may be to try to equalise workloads of workers in case worker differences tend to create a disparity of workloads. This may also lead to better system performance. The focus of this paper is on the effect of the who-rule relative to the effects of the where-rule and the when-rule. Worker differences may impact the effect on system performance of these latter rules as well.

Section 2 reviews the literature on labour allocation rules in DRC systems with worker differences and discusses the focus of the current study. Then, in section 3, we explain how we model worker differences in task proficiency and in the number of skills per worker. This is followed by a description of the simulation model and the experimental design in section 4. Section 5 discusses the results of the simulation study and section 6 concludes the paper.

2. Literature review

In this section, we will review the literature on labour allocation rules in DRC systems with heterogeneous labour and workers with different numbers of skills. Further, we will discuss the focus of this study.

2.1 Labour allocation rules and worker differences

With respect to task proficiency, most prior studies model homogeneous labour. This means that all workers perform their assigned tasks with equal proficiency. Few studies incorporate heterogeneous labour, meaning that task proficiency differences exist within the shop (e.g., Nelson 1970, Rochette and Sadowski 1976, Hogg *et al.* 1977, Bobrowski and Park 1993, Malhotra *et al.* 1993, Kher and Malhotra 1994, Malhotra and Kher 1994, Fry *et al.* 1995, Felan and Fry 2001). Note that studies modelling learning and forgetting effects of workers, by definition, deal with heterogeneous labour.

Nelson (1970) models a system with two work centres consisting of two machines each, and two workers. Each worker is fully proficient at performing tasks on his/her own work centre, and the task proficiency on the other work centre is varied. As a where-rule, a worker is always assigned to the work centre where he/she is most proficient, unless there is no work there, and there is work at the other work centre. Further, three when-rules are evaluated. The decentralised when-rule only allows a labour transfer if the work centre is empty. The centralised when-rule allows a labour transfer after completion of each job. Finally, between these two extremes, a third when-rule is modelled which transfers a worker with a 50% chance after completing a job from a work centre that still has jobs in queue. Only the where-rule thus uses task proficiency information. Results show that if task proficiency is decreased, the choice of a when-rule is more important and a centralised when-rule is preferred.

Rochette and Sadowski (1976) model heterogeneous labour with limited flexibility. Workers are not fully efficient at centres other than their own within their department and are not allowed to transfer to other departments. They test different dispatching rules and vary the shop load and the number of machines per work centre. However, they do not consider different labour allocation rules. They use a centralised when-rule, and a where-rule that first tries to assign a worker to his/her own centre at which he/she is fully proficient, and if this is not possible, then to the centre with the highest priority job in queue. This where-rule thus uses information on task proficiency differences. Finally, they use a who-rule that assigns the worker who has been idle the longest in case more than one worker is available. Their results indicate that workforce flexibility and corresponding machine availability significantly improve mean flow time and mean tardiness performance of jobs for all six dispatching rules examined.

Hogg *et al.* (1977) model three different types of heterogeneous systems: Labour Differential Systems (LD), Machine Centre Differential Systems (MCD), and Labour and Machine Centre Differential Systems (L&MCD). All these systems are modelled as systems with full flexibility. In LD systems, the task proficiency differs between workers, but a single worker is equally proficient at all machine centres. In MCD systems, the task proficiency differs between work centres, but workers are equally proficient at a work centre. Finally, in L&MCD systems, task proficiency depends on both the machine centre and the worker who performs the job. For these three types of heterogeneous systems, they study two where-rules, one based on the time a job has been waiting (First Come First Served: FCFS), and another based on the proficiency of workers (Maximum Labourer Efficiency: MLE). The size of the system and labour utilisation are also varied. They supposedly use a centralised when-rule and they use a who-rule that selects the most efficient worker. The MLE where-rule and the who-rule they use thus take information on task proficiency differences into account. Their results show that the two where-rules do not perform differently in LD systems. This can easily be explained by the fact that a single worker is equally proficient at every work centre, and the MLE where-rule then reverts to the FCFS where-rule. For MCD systems, the FCFS where-rule is superior. The MLE where-rule results in good performance for the work centres at which workers are proficient, but at the expense of the performance of work centres at which workers are not proficient. An interesting result is that in L&MCD systems, the MLE where-rule is far superior to the FCFS where-rule, at least if no clear MCD pattern can be found within the L&MCD scheme.

Bobrowski and Park (1993) study labour allocation rules in a shop with full flexibility and differences in task proficiency. The heterogeneous system they model can be seen as an L&MCD system. They study five different when-rules and seven where-rules and include task proficiency information in two when-rules and six where-rules. They do not mention a who-rule. Their results show that the "efficiency" where-rule, which moves the worker to the work centre where he/she is most efficient, dominates all other where rules they included in their design. This is consistent with the observation of Hogg *et al.* (1977), that the MLE where-rule is superior in L&MCD systems. Further, they show that as long as the efficiency where-rule is selected, the selection of the when-rule is not important.

Malhotra *et al.* (1993) study the impact of worker learning, worker flexibility, and labour attrition on the performance of a DRC job-shop. Labour allocation rules are not included as experimental factors. They use a centralised when-rule and a “First in the system first served” where-rule, which do not use information on task proficiency differences. They also do not address a who-rule in their study. Their shop consists of six functional departments and labour flexibility is modelled as the number of different departments where a worker can work. Since all possible levels of worker flexibility are studied, both limited and full flexibility are modelled. Their conclusions are that incremental worker flexibility improves system performance even under conditions of high labour attrition and slow learning, for which labour efficiency losses are high.

Kher and Malhotra (1994) examine whether it is beneficial to cross-train workers in DRC job shops in the presence of worker transfer delays, worker learning effects, and worker attrition in order to improve shop performance. From a total of six departments, workers are trained to process jobs in two or in three departments, representing a system of limited flexibility. Even though they include the when-rule and the where-rule as experimental factors, these rules do not use information on task proficiency differences. The centralised and decentralised when-rules and the first-arrived-in-the-system-first-served (FISFS) and the least slack where-rules are evaluated. No mention is made of a who-rule. They conclude that in the presence of learning losses and transfer delays, a decentralised when-rule is superior and the FISFS where-rule is preferred because of ease of implementation and control.

Malhotra and Kher (1994) study two when-rules and five where-rules in a shop with full flexibility, heterogeneous resources (LD, MCD, and L&MCD systems), and worker transfer delays. Three of the where-rules use information on task proficiency differences. Their results show that the “Most Efficient” where rule, which is equal to the MLE where-rule of Hogg *et al.* (1977) and the efficiency where-rule of Bobrowski and Park (1993), is robust with respect to the when-rule chosen (i.e., centralised or decentralised) and with respect to the heterogeneous system modelled (i.e., LD, MCD, or L&MCD). The study does not explicate a who-rule.

Fry *et al.* (1995) study labour flexibility and attrition in a DRC shop with heterogeneous labour and worker training. Upon entering the system, workers are trained for their desired level of flexibility (i.e., a worker can perform operations in one, two, or three departments) and incur learning losses before becoming fully proficient. Since the shop consists of six departments and workers are able to work in three departments at most, a DRC shop with limited flexibility is modelled. They use a centralised when-rule and a FISFS where-rule, which do not include information on task proficiency differences. They do not evaluate other labour allocation rules and no mention is made of a who-rule. Their results show that each increase in attrition rate worsens system performance despite the level of worker flexibility. Increasing worker flexibility from one to two reduces the impact of changing attrition rates. Increasing worker flexibility results in improvements in inventory and due date performance, but at the cost of increased labour variance and more worker transfers.

Felan and Fry (2001) model heterogeneous labour by including labour attrition and learning rates. Further, this is the only paper we know of that models workers who are trained to work in a different number of departments (i.e., one, two, or four departments). Skills of workers are thus regarded as an individual human factor in this paper. The focus of their study is on labour flexibility. They evaluate 13 different flexibility configurations with nine different levels of average flexibility for systems with a learning rate of 85% and of 90%. One of these configurations represents full flexibility, the other configurations represent limited flexibility. In contrast to what we intend to do, labour allocation rules are not varied in this study. They use a decentralised when-rule and a "longest queue" where-rule, which do not use information on worker differences. Further, they do not explicate a who-rule. Their results show that an average flexibility level of 1.7 performs just as well as incremental flexibility (i.e., a flexibility level of 2.0). Also, their results suggest that it is better to mix the training between workers than to try to provide equal training. In this way, more workers are kept within one department and the efficiency of these workers can then be maximised. A few resulting workers with high levels of flexibility are able to respond to temporary overloads within departments.

2.2 Focus of this study

The focus of this study is on evaluating labour allocation rules in DRC systems with workers who differ in task proficiency and in number of skills they possess. As we have seen in the previous section, only the study of Felan and Fry (2001) model differences in the number of skills workers possess. However, they do not vary labour allocation rules and also do not use rules that take this worker difference into account. We intend to do this in this study.

Table 1. A taxonomy of DRC literature modelling heterogeneous labour based on evaluation of labour allocation rules and type of flexibility.[a] These studies vary levels of cross-training, where one level represents full flexibility and other levels represent limited flexibility.

	Full flexibility	Limited flexibility
Not evaluating labour allocation rules	I Malhotra *et al.* (1993)[a] Felan and Fry (2001)[a]	II Rochette and Sadowski (1976) Malhotra *et al.* (1993)[a] Fry *et al.* (1995) Felan and Fry (2001)[a]
Evaluating labour allocation rules	III Nelson (1970) Hogg *et al.* (1977) Bobrowski and Park (1993) Malhotra and Kher (1994)	IV Kher and Malhotra (1994) **Current study**

With respect to task proficiency differences between workers (i.e., heterogeneous labour), we made a taxonomy of the DRC studies that were reviewed in subsection 2.1 (see table 1). The horizontal dimension shows whether full flexibility or limited flexibility was modelled, and the vertical dimension distinguishes between studies that vary labour allocation rules or not. As can be seen in table 1, four studies (within quadrants I and II) did not vary labour allocation rules, while five studies (within quadrants III and IV) did. Of these five studies, only one study modelled a system with limited flexibility. This study by Kher and Malhotra (1994), however, does not include allocation rules that use information on task proficiency differences. We think limited flexibility is a quite realistic assumption that may impact the effect of labour allocation rules such as the where-rule and the who-rule. Therefore, the current study can be positioned in the fourth quadrant, since who-rules, when-rules, and where-rules are evaluated in systems with limited flexibility. While prior studies have not yet evaluated the who-rule in systems with heterogeneous labour, special attention will be given to this labour allocation rule.

3. Differences in task proficiency and number of skills

In this section, the modelling of worker differences in task proficiency and in the number of skills per worker is expounded. We consider static worker differences in task proficiency, meaning that it is assumed that no worker learning or forgetting takes place. While keeping the division of skills equal, three configurations of task proficiency differences are generated by increasing the task proficiency differences between workers. In this way, it can be studied whether the extent of worker differences affects the impact of allocation rules (including rules that make use of those worker differences) on flow time. With respect to differences in the number of skills per worker, we follow a similar approach by including two configurations with increasing differences between the number of skills per worker. In the last subsection, a configuration is presented that combines task proficiency differences and worker differences with respect to the number of skills.

3.1. Task proficiency

We consider systems that Hogg *et al.* (1977) call “Labour and Machine Centre Differential systems” or L&MCD systems. For these systems, task proficiency depends on the specific worker *and* machine performing the task. Nelson (1967, 1970) and Hogg *et al.* (1977) model task proficiency by introducing a factor e_{ji}, representing the relative efficiency of worker j (j = 1, 2, …, N) when using machine i (i = 1, 2, …, M). The expected processing time for a specific job will then be $1/e_{ji}\mu$. The expected processing rate (μ) is thus adjusted by multiplying it by factor e_{ji}, which is bound to a maximum of one in their research. In contrast, we multiply the expected processing time ($1/\mu$) by a proficiency factor p_{ji}. In accordance with work measurement studies, where basic and standard times are assessed, the processing time can be regarded as a distribution of the basic time, which is adjusted up or down by a proficiency factor p_{ji}, ranging from 0.8 to 1.2 within our experiments. For example, a proficiency factor of 0.9 indicates that the task is performed within 90% of the expected basic time. Proficiency factors lower than one thus result in processing times which are lower than the basic time, while proficiency factors higher than one result in above-average processing times.

Table 2. Three cross-training configurations representing three levels of task proficiency differences

Machine	I					II					III				
	Worker					Worker					Worker				
	W 1	W 2	W 3	W 4	W 5	W 1	W 2	W 3	W 4	W 5	W 1	W 2	W 3	W 4	W 5
M1	1	1	1			0.9	1	1.1			0.8	1	1.2		
M2		1	1	1			0.9	1	1.1			0.8	1	1.2	
M3			1	1	1			0.9	1	1.1			0.8	1	1.2
M4	1			1	1	1.1			0.9	1	1.2			0.8	1
M5	1	1			1	1	1.1			0.9	1	1.2			0.8
M6	1	1	1			0.9	1	1.1			0.8	1	1.2		
M7		1	1	1			0.9	1	1.1			0.8	1	1.2	
M8			1	1	1			0.9	1	1.1			0.8	1	1.2
M9	1			1	1	1.1			0.9	1	1.2			0.8	1
M10	1	1			1	1	1.1			0.9	1	1.2			0.8

Table 2 shows three cross-training configurations (I, II and III) for systems with ten machines and five workers. The three configurations show the same division of skills. Further, each worker is able to operate six machines (i.e., each worker has a multifunctionality of six) and each machine can be operated by three workers (i.e., each machine has a redundancy of three). Since not all workers are able to operate all machines, these configurations represent limited labour flexibility. The basic configuration, which is configuration I, models homogeneous labour: the task proficiency for each skill is the same. Configuration II and III model heterogeneous labour, with task proficiency deviations from the basic time of 10% in the second configuration and of 20% in the third configuration. To make the three configurations comparable, the following holds true for each configuration:
$\frac{1}{MF}\sum_i p_{ji} = 1 \; \forall j$, and $\frac{1}{RE}\sum_j p_{ji} = 1 \; \forall i$,

where MF denotes the multifunctionality of workers j and RE denotes the redundancy of machines i. The average task proficiency of each machine and the average task proficiency of each worker thus equal one. Further, $p_{ji} \geq 0$, and at least one $p_{ji} = 1 \; \forall i$. This means that workers cannot be negatively skilled and of the three workers who are able to operate a machine, at least one worker performs conform the basic times (average times). In case of task proficiency differences, one of the other workers performs below average and another performs above average, since the average is set at one. We expect that allocation rules that incorporate task proficiency information lead to lower average flow times than rules that do not incorporate that information. For labour allocation rules that incorporate task proficiency information, configurations with larger differences in task proficiency may provide more opportunities to improve flow time performance than configurations with lower differences in task proficiency. In contrast, for labour allocation rules that do not incorporate proficiency information, flow time performance may decrease for configurations with larger differences in task proficiency, because of the higher variation of processing times of machines and workers.

3.2. Number of skills

Two cross-training configurations (IV and V in table 3) are used in this study to model systems where each worker possesses a different number of skills. Note that even though the multifunctionality of each worker is different, we kept the redundancy of all machines at three. In configuration IV, the first worker possesses four skills, the second worker five, and so on. The number of skills per worker thus ranges from four to eight. The differences in number of skills per worker are somewhat higher in the fifth configuration, where the number of skills ranges from two to ten. The fifth worker is fully cross-trained in this configuration. We expect that configuration four performs better than configuration five. In other words, we expect that a configuration with a more equal division of skills per worker will result in better flow times than a configuration with large differences between the number of skills per worker. Workers who possess more skills will be assigned more often than workers who possess fewer skills and therefore, a more unequal division of the number of skills per worker will result in larger differences between the utilisation of workers.

Table 3. Two cross-training configurations with differences in the number of skills per worker (IV and V) and a configuration representing large task proficiency differences and large differences in the number of skills workers possess (VI).

Machine	IV					V					VI				
	Worker					Worker					Worker				
	W 1	W 2	W 3	W 4	W 5	W 1	W 2	W 3	W 4	W 5	W 1	W 2	W 3	W 4	W 5
M1	1		1	1		1		1		1	0.8		1.2		1
M2	1		1	1		1		1		1	1.2		1		0.8
M3	1		1		1		1		1	1		0.8		1	1.2
M4	1		1		1		1		1	1		1.2		0.8	1
M5		1	1		1		1		1	1		1		1.2	0.8
M6		1		1	1		1		1	1		1		0.8	1.2
M7		1		1	1			1	1	1			0.8	1.2	1
M8		1		1	1			1	1	1			0.8	1	1.2
M9		1		1	1			1	1	1			1.2	0.8	1
M10			1	1	1			1	1	1			1	1.2	0.8

3.3. Combination of task proficiency and number of skills

Configuration VI (see table 3) is used to model a combination of task proficiency differences and differences in the number of skills of workers. Actually, it is an adaptation of configuration V to include task proficiency differences of 20%. In this configuration, task proficiency differences as well as differences in the number of skills of workers are large. For this configuration, it will be interesting to see whether the who-rule should incorporate information on task proficiency differences or information on the difference in number of skills per worker. Further, the extent of the effect of where-rules and who-rules that incorporate information on worker differences in a system with large worker differences can be evaluated.

4. Simulation model and experimental design

4.1. DRC model

We used the object oriented simulation software package EM-Plant Version 5.5 (Stuttgart: Technomatix) for building the DRC simulation models. The DRC shop consists of ten machines and five workers. Job arrivals follow a negative exponential distribution with a mean interarrival time of 1.294 time units. This is selected to create an average labour utilisation of 85% using task proficiency factors of one (i.e., basic times). Jobs need to visit between 1 and 10 machines in a random order. This means that a job needs to visit an average number of 5.5 machines. Additionally, a job may visit a specific machine only once. Machine processing times are drawn from a gamma [2, 0.5] distribution, which is equal to a 2-Erlang distribution. This distribution is often used to represent operating times. The First-In-System-First-Served (FISFS) dispatching rule is used in the system.

4.2. Experimental design

Three experiments are conducted to study the effects of when, where and who-rules in systems with differences in tasks proficiency (Experiment I), differences in the number of skills of workers (Experiment II), and a combination of differences in task proficiency and the number of skills (Experiment III). Table 4 shows these three experiments and the experimental factors within each experiment.

Table 4. Three experiments with their experimental factors and levels

Experiment	Experimental factor	Level 1	Level 2	Level 3
1	TP: task proficiency differences	0%	10%	20%
	WR: where-rule	FISFS	PL	
	WHO: who-rule	RND	PL	
2	NS: differences in number of skills	6-6	4-8	2-10
	WHO: who-rule	RND	FNS	
3	WN: when-rule	CEN	DECEN	
	WR: where-rule	FISFS	PL	
	WHO: who-rule	RND	FNS	PL

Legend
FISFS: First In System First Served; FNS: Fewest Number of Skills
PL: Proficiency Level; CEN: Central
RND: Random; DECEN: Decentral

The first experiment focuses on the where-rule and the who-rule in systems with increasing differences in task proficiency of workers. Cross-training configurations I, II and III (see table 2) are used in this experiment to represent three levels of task proficiency differences. The First-In-System-First-Served (FISFS) where-rule is compared with the Proficiency Level (PL) where-rule. The PL where-rule assigns workers to the machine where they are most proficient. As we have seen in section 2.1, this rule has been shown to give good results in L&MCD systems with full flexibility. The random (RND) who-rule is compared with the Proficiency Level (PL) who-rule. The PL who-rule assigns the worker who is most proficient to the machine that requires labour. Within this experiment, the centralised when-rule is used.

The second experiment focuses on the who-rule in systems with increasing differences in the number of skills that workers possess. Configurations I, IV and V (see tables 2 and 3) are used here to represent three levels of differences in the number of skills per worker. The random (RND) who-rule is compared with the “fewest number of skills” (FNS) who-rule, which assigns the worker who possesses the fewest number of skills to the machine that requires labour. The FISFS where-rule and the centralised when-rule are used.

Finally, the third experiment focuses on the when-rule, the where-rule and the who-rule in a system with a large difference in task proficiency and a large difference in the number of skills workers possess. Configuration VI in table 3 is used for this. The centralised when-rule is compared to the decentralised when-rule. Further, the FISFS where-rule is compared to the PL where-rule, and the RND, FNS and PL who-rules are evaluated. To measure system performance, the average flow time of jobs is used.

5. Results and discussion

For each combination within the three full-factorial experiments, 40 observations were collected using the replication/deletion approach (see e.g., Law and Kelton 2000: 525). Each observation has a warm-up period of 6000 time units, and subsequently, data is collected over a period of 30 000 time units. Different seeds were used for each replication to maximise sampling independence. The results of the three experiments are discussed separately below.

5.1. Experiment I: Differences in task proficiency

Table 5. Full factorial results for experiment I

TP	WR	WHO	Average flow time	Std. Deviation
0%	FISFS	RND	12.13	0.320
		PL	12.20	0.378
	PL	RND	12.52	0.417
		PL	12.60	0.404
10%	FISFS	RND	12.48	0.376
		PL	11.84	0.417
	PL	RND	10.98	0.219
		PL	10.50	0.217
20%	FISFS	RND	12.79	0.315
		PL	11.84	0.407
	PL	RND	10.22	0.146
		PL	9.33	0.129

The full factorial results for the first experiment are shown in table 5. The data were analysed using a 3 x 2 x 2 analysis of variance (ANOVA) between subjects design with task proficiency differences (TP), the where-rule (WR), and the who-rule (WHO) as independent variables and flow time as dependent variable. A Levene’s test of equality of error variances showed that the assumption of homogeneity of variance across populations was violated. However, since we conduct a between subjects ANOVA with equal cell sizes, the risk of drawing false conclusions is small. As long as the group sizes are approximately equal, the F statistic is robust against heterogeneous variances (Stevens 1996: 249). Therefore, the analysis is continued. The largest variance in this experiment is about ten times the smallest variance. As can be seen in table 5, this difference in variance (or standard deviation in table 5) is mainly caused by the decreasing variance in cells with 10% or 20% task proficiency differences combined with a PL where-rule.

The ANOVA results in table 6 show that all main effects and two two-way interactions are significant ($p < 0.05$). In our further analysis, we will discuss the significant main and interaction effects and, if necessary, we will revise the higher level effects when studying the lower level effects.

Table 6. ANOVA results for average flow time within Experiment I

	Average Flow time	
Source	F	p-value
TP	673.00	p < 0.001
WR	1572.80	p < 0.001
WHO	246.88	p < 0.001
TP x WR	813.20	p < 0.001
TP x WHO	94.43	p < 0.001
WR x WHO	1.60	p = 0.207
TP x WR x WHO	0.57	p = 0.563

To find out whether all three levels of TP are significantly different from each other, we performed a post-hoc, paired-comparison test with a Sidak adjustment to correct the alpha level of 0.05. The Sidak adjustment is slightly less conservative than the Bonferroni correction. It uses an adjusted critical alpha, which is calculated as follows: $\alpha_{critical} = 1 - (1-\alpha)^{1/N}$, where N is the number of tests to be performed. It turns out that all levels are significantly ($p < 0.001$) different from each other (TP 0%: Mean = 12.36, Standard Error = 0.026; TP 10%: M = 11.45, SE = 0.026; TP 20%: M = 11.04, SE = 0.026). The main effect of TP thus shows that larger differences in task proficiency result in better flow times. This indicates the advantages of taking worker differences into account in the where-rule and who-rule. This will be made more clear in the discussion of the interaction effects between the proficiency level and the where-rule, and the proficiency level and the who-rule.

The main effect of the where-rule (WR) indicates that the PL where-rule results in better flow times (M = 11.02, SE = 0.021) than the FISFS where-rule (M = 12.21, SE = 0.021). This result is in conformity with that of Hogg *et al.* (1977), Bobrowski and Park (1993), and Malhotra and Kher (1994), who also included a rule based on efficiency, and found that such a rule is superior compared with other where-rules in L&MCD systems. Limited flexibility apparently does not alter this conclusion.

The main effect of the who-rule (WHO) indicates that the PL who-rule results in better flow times (M = 11.38, SE = 0.021) than the RND who-rule (M = 11.85, SE = 0.021). For the who-rule as well as for the where-rule, it thus seems advantageous to make choices based on individual task proficiency differences.

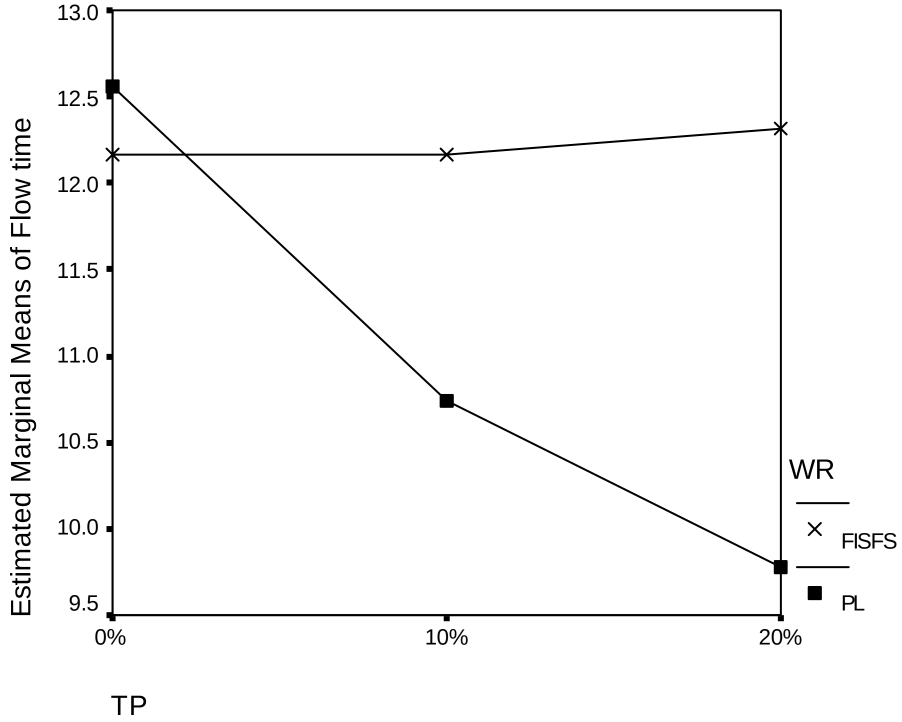

Figure 1. The interaction effect of task proficiency differences (TP) and the where-rule (WR).

The effect of task proficiency differences (TP) on the where-rule (WR) is illustrated in figure 1. The simple main effects showed us that the FISFS where-rule and the PL where-rule are significantly different ($p < 0.001$) within each level of TP. Without task proficiency differences (i.e., TP = 0%), the PL where-rule performs worse (M = 12.55, SE = 0.037) than the FISFS where-rule (M = 12.16, SE = 0.037). This can be explained by the fact that the PL where-rule chooses a machine randomly if the choice cannot be based on task proficiency differences. In contrast, if task proficiency differences are present, the PL where-rule results in much better flow times (TP 10%: M = 10.74, SE= 0.037; TP 20%: M = 9.77, SE = 0.037) than the FISFS where-rule (TP 10%: M = 12.16, SE= 0.037; TP 20%: M = 12.32, SE = 0.037). While the main effect of TP showed a decrease in flow time with larger task proficiency differences, the interaction with the where-rule shows that flow time only decreases if a PL where-rule is used. The PL where-rule, which incorporates task proficiency information, can thus benefit from proficiency differences to reduce system utilisation, thereby decreasing average flow time. A further analysis of the significant simple main effects of TP ($p < 0.001$ within the PL where-rule, $p = 0.003$ within the FISFS where-rule) using the Sidak adjustment for multiple comparisons shows that for the PL where-rule, all levels of TP differ significantly, while for the FISFS where-rule, the TP levels of 0% and 10% do not differ significantly. At the TP level of 20%, the average flow time actually increases significantly for the FISFS where-rule, compared with the lower levels of TP. This confirms our earlier expectation that if task proficiency differences increase, the average flow time of jobs also increases in case labour allocation rules do not incorporate task proficiency information. To conclude, in this experiment, the largest effect of the where-rule is found at a TP level of 20%, resulting in a 20.6% reduction of flow time.

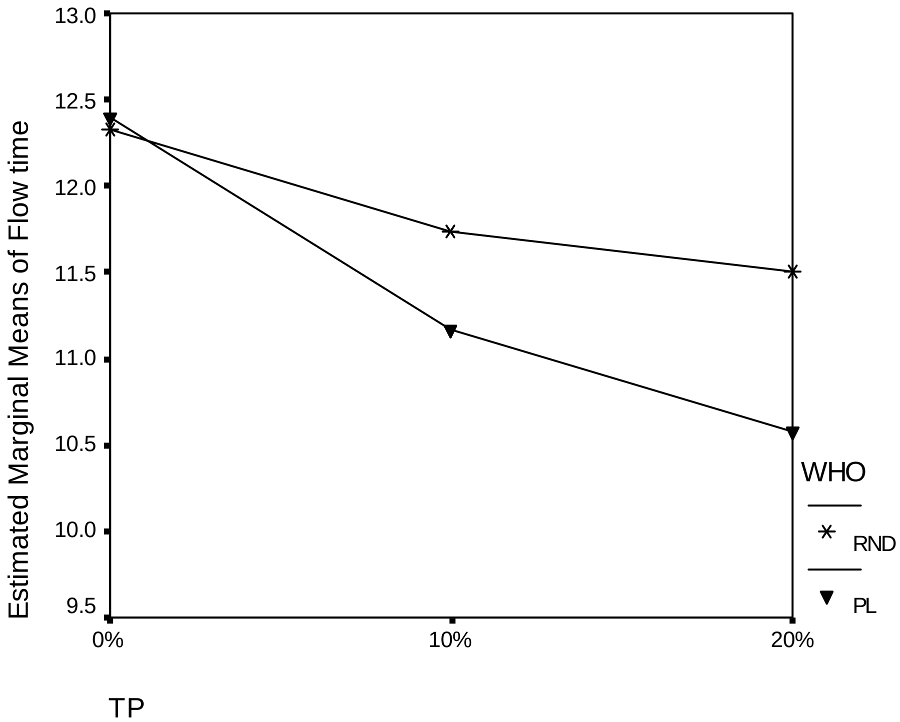

Figure 2. The interaction effect of task proficiency differences (TP) and the who-rule (WHO).

The effect of task proficiency differences (TP) on the who-rule (WHO) is illustrated in figure 2. The simple main effects of the who-rule show that the RND who-rule and the PL who-rule differ significantly at the TP levels of 10% and 20% ($p < 0.001$). As expected, the who-rule is not significant at the TP level of 0% ($p = 0.158$), since the PL who-rule reverts to the RND who-rule if no task proficiency differences between workers exist. At a TP level of 20%, the effect of the who-rule is stronger (PL: M = 10.58, SE = 0.037; RND: M = 11.51, SE = 0.037) than at a TP level of 10% (PL: M = 11.17, SE = 0.037; RND: M = 11.73, SE = 0.037). Here, the largest effect of the who-rule results in an 8.0% reduction of flow time. The PL who-rule, which incorporates task proficiency information, can thus also benefit from task proficiency differences.

5.2. Experiment II: Differences in the number of skills

Table 7. Full factorial results for experiment II

NS	WHO	Average flow time	Std. Deviation
6-6	RND	12.20	0.323
	FNS	12.12	0.484
4-8	RND	12.49	0.371
	FNS	12.45	0.451
2-10	RND	15.19	0.873
	FNS	14.54	0.665

The full factorial results for the second experiment are shown in table 7. The data were analysed using a 3 x 2 analysis of variance (ANOVA) between subjects design with differences in number of skills (NS), and the who-rule (WHO) as independent variables and flow time as dependent variable. Again, the assumption of homogeneity of variances was violated, but as argued before, the risk of drawing false conclusions is small. Here, the largest variance is about seven times the smallest variance. Table 7 shows that larger differences in number of skills (NS) increase the standard deviation of the average flow time within the cells, especially in combination with a RND who-rule. The ANOVA results in table 8 show that all main effects and the two-way interaction are significant.

Table 8. ANOVA results for average flow time within Experiment II

	Average Flow time	
Source	F	p-value
NS	557.09	$p < 0.001$
WHO	12.69	$p < 0.001$
NS x WHO	7.49	$p = 0.001$

The significant main effect of differences in number of skills (NS) is further analysed using a post-hoc, paired-comparison test with a Sidak adjustment to correct the alpha level of 0.05. All levels of NS are significantly different from each other ($p \leq 0.002$), while larger differences in the number of skills per worker result in higher flow times (NS 6-6: M = 12.16, SE = 0.063; NS 4-8: M = 12.47, SE = 0.063; NS 2-10: M = 14.86, SE = 0.063). This result is in conformity with our earlier expectations, but it contrasts with that of Felan and Fry (2001), who state that it is better to mix the training between workers than to try to provide equal training. This contradiction can be explained by the fact that Felan and Fry (2001) also model labour learning. In their experiment, workers with few skills are able to maximize the task proficiency of those skills, while the few workers with many skills are able to respond to temporary overloads.

The significant main effect of the who-rule shows that the FNS who-rule results in better flow times (M = 13.04, SE = 0.051) than the RND who-rule (M = 13.29, SE = 0.051). Individual differences with respect to the number of skills can thus be used to base a who-rule on in order to improve flow time performance.

The significant interaction effect of differences in number of skills (NS) on the who-rule (WHO) is analysed by looking at the simple main effects of the who-rule. It turns out that the who-rule is only significant ($p < 0.001$) at NS 2-10, representing large differences in number of skills per worker. Here, the FNS who-rule reduces flow time with 4.3% (M = 14.54, SE = 0.089) compared to the RND who-rule (M = 15.19, SE = 0.089). In other words, differences in number of skills per worker must be large in order for the FNS who-rule to have a relatively small (4.3%), but statistically significant effect on flow time.

5.3. Experiment III: Differences in task proficiency and number of skills

Table 9. Full factorial results for experiment III

WN	WR	WHO	Average flow time	Std. Deviation
CEN	FISFS	RND	16.14	0.891
		PL	15.00	0.763
		FNS	15.71	0.817
	PL	RND	10.87	0.162
		PL	10.15	0.158
		FNS	10.73	0.212
DECEN	FISFS	RND	20.47	1.413
		PL	19.74	1.320
		FNS	19.77	1.176
	PL	RND	14.06	0.364
		PL	13.57	0.363
		FNS	13.89	0.420

The full factorial results for the third experiment are shown in table 9. The data were analysed using a 2 x 2 x 3 analysis of variance (ANOVA) between subjects design with the when-rule (WN), the where-rule (WR), and the who-rule (WHO) as independent variables and flow time as dependent variable. The assumption of equality of error variances was violated here as well. As can be seen in table 9, the standard deviations of the average flow time of cells using a decentralised when-rule are higher than those using a centralised when-rule. Further, cells using a PL where-rule show substantial lower standard deviations than cells using a FISFS where-rule. The ANOVA results in table 10 show that all main effects and two two-way interactions are significant ($p < 0.05$).

Table 10. ANOVA results for average flow time within Experiment III

	Average Flow time	
Source	F	p-value
WN	2725.10	$p < 0.001$
WR	5852.28	$p < 0.001$
WHO	37.10	$p < 0.001$
WN x WR	59.03	$p < 0.001$
WN x WHO	3.57	$p = 0.029$
WR x WHO	2.84	$p = 0.060$
WN x WR x WHO	0.71	$p = 0.494$

The significant main effect of the when-rule (WN) shows that the centralised when-rule performs considerably better (M = 13.10, SE = 0.052) than the decentralised when-rule (M = 16.92, SE = 0.052), which is an improvement of 22.6%. The significant main effect of the where-rule (WR) shows that the PL where-rule performs substantially better (M = 12.21, SE = 0.052) than the FISFS where-rule (M = 17.81, SE = 0.052), which is an improvement of 31.4%. The significant main effect of the who-rule (WHO) is further analysed using a post-hoc, paired-comparison test with a Sidak adjustment to correct the alpha level of 0.05. All three who-rules differ significantly from each other ($p < 0.001$), where the PL who-rule performs best (M = 14.62, SE = 0.063), followed by the FNS who rule (M = 15.02, SE = 0.063), and finally the RND who-rule (M = 15.39, SE = 0.063). Here, the who-rule can thus result in a flow time improvement of 5%.

The significant interaction effect of the when-rule (WN) on the where-rule (WR) is analysed using the simple main effects of the where-rule. Even though the where-rule is significant ($p < 0.001$) within both levels of the when-rule, for a centralised when-rule the relative flow time difference between a FISFS where-rule and a PL where-rule is slightly larger (FISFS: M = 15.62, SE 0.073; PL: M = 10.58, SE 0.073; flow time difference: 32.2%) than for a decentralised when-rule (FISFS: M = 20.00, SE = 0.073; PL: M = 13.84, SE = 0.073; flow time difference: 30.8%). This result is in conformity with Nelson (1970), who indicates that a centralised when-rule is preferred if task proficiency differs. Also, the simple main effects of the when-rule (WN) show that the when-rule is significant ($p < 0.001$) within both levels of the where rule. The flow time difference between the centralised and the decentralised when-rule is 21.9% within a FISFS where-rule, while it is 23.5% within a PL where-rule. This means that the selection of the when-rule is important. This outcome contrasts with that of Bobrowski and Park (1993) and Malhotra and Kher (1994), who claim that as long as the efficiency based where-rule (i.e., “efficiency” or “Most Efficient”, respectively) is selected, the choice of a when-rule does not matter much. The fact that we model limited flexibility may contribute to this contrasting outcome. With limited flexibility, workers have less choice in moving to a work centre than with full flexibility. This will reduce the chance that they are allocated to a work centre at which they are very proficient. Moreover, with a decentralised when-rule, they can be trapped in work centres at which they are not very proficient until the queue is empty.

The simple main effects of the who-rule are analysed to explain the significant interaction effect ($p = 0.029$) of the when-rule (WN) on the who-rule (WHO). Since the who-rule is significant for both levels of the when rule ($p < 0.001$), pairwise comparisons were made using the Sidak adjustment for multiple comparisons. The results are shown in table 11.

Table 11. Simple main effect of the who-rule within each level of the when-rule and pairwise comparisons of the simple effects using the Sidak adjustment for multiple comparisons ($\alpha = 0.05$)

WN	WHO	Average flow time
CEN	PL	12.58
	FNS	13.22
	RND	13.50
DECEN	PL	16.66
	FNS	16.83
	RND	17.27

Using a centralised when-rule, the difference between a RND who-rule and a FNS who-rule is not significant ($p = 0.073$), all other differences are significant ($p < 0.001$). This implies that incorporating information on differences in the number of skills of workers in the who-rule does not help in reducing flow time. Within a decentralised when-rule, only the difference between a PL who-rule and a FNS who-rule is not significant ($p = 0.426$). The effect of the who-rule on flow time is larger in case of a centralised when-rule (a flow time difference of 6.9%) than in case of a decentralised when-rule (a flow time difference of 3.5%). The explanation may be that the choice between workers has to be made more often, resulting in a better fit of machines and workers who are most proficient for those machines. Within this configuration, we have seen that the where-rule has the largest flow time effect, then the when-rule, and finally the who-rule.

6. Conclusions

This study focuses on labour allocation rules in DRC systems with limited flexibility in which skills of workers are regarded as an individual human factor. That is, workers differ in task proficiency and in number of skills they possess. When-rules, where-rules and who-rules are evaluated within these systems. Since prior studies have not evaluated the who-rule in systems with heterogeneous labour yet, special attention is given to this labour allocation rule.

In DRC systems with limited labour flexibility and differences in task proficiency, it is advantageous to base the where-rule and the who-rule on these task proficiency differences. In other words, the where-rule should send a worker to the machine at which he/she is most proficient, which is in conformity with prior research of DRC systems with full flexibility (Hogg *et al.*1977, Bobrowski and Park 1993). Additionally, the who-rule should transfer the worker who is most proficient in case a choice between workers has to be made. Larger differences in task proficiency result in a larger effect of these rules. Further, the flow time effect of the where-rule is larger than the flow time effect of the who-rule.

DRC systems with differences in the number of skills per worker perform worse than systems where skills are divided equally. If differences in the number of skills per worker are present and task proficiencies do not differ, a who-rule based on large differences in the number of skills can slightly improve (4.3%) flow time performance by assigning the worker with the fewest number of skills.

In systems with task proficiency differences and differences in the number of skills per worker, a where-rule based on task proficiency differences performs well. In these systems, it seems more advantageous to base the who-rule on task proficiency differences than on differences in the number of skills per worker. Further, the centralised when-rule is preferred over the decentralised when-rule, even if the where-rule is based on proficiency differences. This result is different from that of prior research (Bobrowski and Park 1993, Malhotra and Kher 1994) in a system with full flexibility.

This study suggests that in DRC systems with limited labour flexibility and worker differences, it is advantageous to select where-rules and who-rules that make use of these worker differences. To reduce flow time, the where-rule should be considered first, then the when-rule, and finally the who-rule. However, DRC systems can be found in a large variety of settings and can display quite different characteristics. We specifically modelled a DRC system with limited labour flexibility and worker differences, but even this more restricted set of DRC systems can be modelled in many ways. The outcomes of this study may be different if other factors are included. For instance, variations in staffing levels, shop size, job routings, processing times, or variability of processing times, may influence the impact of labour allocation rules such as the who-rule on system performance, turning it into interesting issues for further research. Also, transfer delays and learning and forgetting effects are not yet incorporated in our study.

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