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ABSTRACT

Cross-training is becoming increasingly important to firms in order to cope with the more stringent performance requirements they are faced with in today's market. However, many firms put considerable effort into cross-training their workers only to find out that their workers favour the familiar tasks and hardly use and maintain the newly acquired skills. In this paper we explore the hypothesis that reducing the amount of work in process in a CONstant Work In Process (CONWIP) controlled job shop with worker preferences forces workers to make a more balanced use of the skills they possess. We test this hypothesis by means of a simulation study with the level of cross-training as moderating variable. Based on this study, it can be concluded that the control and limitation of the amount of work in process breaks the pattern of workers remaining at their preferred machines and constrains the workers to use and maintain their other skills more.

Key words: CONWIP, cross-training, worker preferences

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1. Introduction

Both in practice and in the literature, the design and operation of a cross-trained workforce is recognized to play an important role in supporting an organization's strategy. Taking into consideration the strategic focus of an organization and the characteristics of the production environment, decisions should be made with respect to the training of workers and with respect to the assignment of workers to tasks (see Hopp and Van Oyen, 2004). That is, for each process involving labour, decisions such as how many workers to assign to the process (i.e. staffing level), who to train for which tasks (i.e. cross-training configuration), when to assign which workers to what tasks (i.e. labour assignment rules), etc. should be made in line with the organisation's objectives and its particular production environment.

Many organizations nowadays feel the competitive pressure to extend the flexibility of their labour force by means of cross-training. Workers thus increasingly need to be able to perform several tasks and take over tasks or help other workers with their tasks. However, in practice, investing in more training does not always guarantee that workers are actually going to use their newly acquired skills. Individual attitudes and personality characteristics can influence a person's motivation to transfer training (i.e. use the skills acquired in a training program), see e.g. Seyler et al. (1998) and the references therein. Oftentimes, workers prefer working on a small set of machines. Reasons for this include that machine-related tasks differ in (perceived) attractiveness, or in task significance. Another reason may simply be that some workers resist changes and are most happy when performing the same task continuously (see e.g. Phillips et al., 1991). Particularly in production systems where workers can—to a certain extent—work independently of each other and have some autonomy in deciding when to work on which tasks, they are able to fulfill their preferences. This means that they will work for a considerable part of their time on their preferred machines, which they sometimes even refer to as 'their own machines'. A typical example of such a system, commonly found in practice, is a dual resource constrained job shop with ample work in process. Labour assignment rules are often found to be implicit in these systems or based on simple rules that do not stimulate the transfer of workers. Worker preferences then lead to a situation in which workers do not use their potential flexibility to the fullest, resulting in an unequal deployment of their set of skills. This may even result in workers not being able to perform their under-utilised skills in the long term, due to forgetting effects, which erodes the flexibility of the production system. Furthermore, worker preferences may exacerbate the development of work-related musculoskeletal disorders, which we will not study in this paper.

Previous studies on labour flexibility mostly do not take into account that workers may have preferences to work on one or some of the machines they are trained for. The balanced designs in these studies will result in a balanced use of the skills of workers. Furthermore, studies that do model worker differences that may lead to a different use of skills (e.g. heterogeneous workers, where workers possess a different number of skills and/or have different skill proficiencies) often report flow time or due date related performance measures and do not give insights into the exact use (utilisation) of individual skills per worker.

In this paper, we model a CONstant Work In Process (CONWIP) job shop where jobs require machine capacity as well as worker capacity and where workers prefer working at their own machines. CONWIP has been successfully implemented in many manufacturing environments (see e.g. Framinam et al., 2003). We give insight into the effect of worker preferences on the use of skills and explore the hypothesis that reducing the fixed amount of work in process (WIP) forces workers to make a more balanced use of the skills they possess. Our assumption is that a balanced use of skills will result in equal worker proficiencies for these skills. It will help workers to maintain their skills, which ensures a steady actual level of worker flexibility. From a managerial viewpoint, it is important to know how to effectively cope with worker preferences. This means that the measures taken to balance the use of worker skills should not jeopardise the output of the production system and/or lead to (much) additional coordination effort and worker transfers.

The paper is structured as follows. Section 2 reviews three studies that focus on worker related issues when constraining the work in process and further positions the current paper. Section 3 elaborates on Dual Resource Constrained (DRC) systems and worker preferences. It presents a brief overview of key characteristics of DRC systems taken into account in previous studies. Furthermore, it illustrates the existence of worker preferences in practice. Section 4 presents the research model, indicating factors that may influence the use of cross-training. Section 5 presents a simulation study and section 6 discusses the results and the managerial impact. Section 7 is a concluding section.

2. Worker related issues when constraining the work in process

Several studies report on the impact of low-inventory operations (obtained by reducing the amount of WIP) on worker related issues. We will discuss these studies and position the current paper.

Philipoom and Fry (1999) model worker preferences by including what they call ‘cherry picking’ behaviour of workers. Cherry picking occurs when a job is selected for processing based on the difference in standard allowable processing time and actual processing time and not based on its formal priority. They show that cherry picking can significantly worsen shop due date performance. Furthermore, they show that a controlled release of jobs in the system by means of a path-based order review/release methodology will reduce some of the negative impacts of dysfunctional worker behaviors, such as those on due date performance and differences in labour efficiencies. Philipoom and Fry (1999) limit the release of jobs into the shop as a means to enforce management preferences by allowing workers to select only those jobs which management wishes to be processed. Their system is single resource constrained: each machine is staffed by one worker. Limiting the release of jobs impacts the worker's alternatives for dispatching. Our study concerns a dual resource constrained system where worker preferences are related to machines. However, we explore a similar principle, namely that of limiting the release of jobs to impact the worker's alternatives for choosing a machine to work on (the where-rule, see section 3.1). Our purpose is not to investigate the impact on flow time or due date performance, but on the (balanced) use of skills the workers possess.

Schultz et al. (2003) identify some of the negative side effects of worker flexibility. They address two issues that may cause productivity loss in low-inventory operations with flexible work assignments. The first issue is that workers may operate more slowly when there is less incentive-building feedback. Usually, in low-inventory operations, the changes in buffer inventory provide clear feedback to workers. Worker flexibility obscures this mechanism, but the authors have shown that providing an explicit work-pace signal in serial systems with worker flexibility can improve processing times compared to not providing this explicit performance feedback. Even though we acknowledge the importance of such behavioural effects when limiting the amount of WIP, we do not study them in this paper.

The second issue Schultz et al. (2003) investigate is that more frequent work interruptions may cause workers to be less productive. They state that in environments with worker flexibility, workers usually do not remain on the same machine for a long period of time and a work interruption occurs whenever a worker changes machines. The authors have empirically shown that moving between machines can cause a processing rate penalty beyond the time lost while moving. They demonstrate a performance loss after small work interruptions and thus suggest small breaks in the worker's rhythm as another cause of productivity losses next to the more traditional explanation of forgetting effects. In our study, we keep track of the number of worker transfers, which can indirectly be related to transfer delay times. Prior studies (e.g. Gunther 1979, 1981) have shown that transfer delays (i.e. work interruptions) have a predictable impact on the performance. Increasing transfer delay time increases mean flow time, the percent of the time the worker spends in transferring, and flow-time variance. As worker transfer delay times increase, the performance of any system configuration that increases the number of worker transfers will deteriorate and the configuration that minimizes transfers would logically lead to superior system performance. Since (average) transfer delay times can be very different in different practical settings, reporting the number of transfers will be sufficient to relatively compare the different scenarios.

Gel et al. (2007) characterise the optimal worksharing policy for single resource constrained serial CONWIP lines with hierarchical cross-training patterns. They focus on the effect of worksharing policies on throughput and therefore do not provide insights into the exact use (utilisation) of individual skills of the flexible worker in their experiments. They show that partial cross-training (in a hierarchical way) can lead to a significant performance improvement over static allocation of workers to stations (i.e. lines without labour flexibility). Their major finding is that in systems with partial cross-training in hierarchical patterns, the 'fixed-before-shared' principle is beneficial in very different environments. This means that a flexible worker should do the tasks that only he/she can perform (i.e. fixed tasks) before helping other workers with shared tasks. Reducing the amount of WIP increases the importance of minimizing the idling of the specialist worker, which requires that the fraction of time the flexible worker spends on his/her own tasks should be maximized. In this paper we will model a CONWIP controlled dual resource constrained job shop with partial cross-training, but not in a hierarchical way. Furthermore, our study does not focus on operating policies (worksharing policies), but on the effect of the amount of WIP on the use of cross-training.

3. Dual Resource Constrained systems and worker preferences

3.1. Key characteristics of DRC systems

DRC literature indicates that the extent and division of cross-training impacts the performance of DRC processes, as well as do the assignment rules chosen to assign skilled workers to machines or tasks (see e.g. the reviews of Treleven 1989, Gargeya and Deane 1996, and Hottenstein and Bowman 1998).

The extent and division of cross-training in a DRC system can be represented by a 'cross-training configuration'. A cross-training configuration indicates which workers are trained for which machines. It can for instance be represented by a worker-machine matrix or by a bipartite graph with workers and machines as vertices and skills as edges. Note that even though a 'cross-training' may be regarded as the result of training someone for a skill already mastered by someone else—an overlapping skill—a cross-training configuration represents all trainings or qualifications of workers, including cross-trainings. It is well known that training all workers for all machines (i.e. full flexibility) is often not necessary since about the same performance can be obtained with less flexibility (e.g. Malhotra *et al*. 1993, Fry *et al*. 1995, Campbell 1999). The concept of chaining has received much attention as a worthy alternative to full flexibility, but predominantly in Single Resource Constrained systems (e.g. Jordan and Graves 1995, Sheikhzadeh *et al*. 1998; Gurumurthi and Benjaafar 2004) and more specifically applied to cross-training in SRC environments (e.g. Daniels *et al*. 2004, Hopp *et al*. 2004, Inman *et al*. 2004, Jordan *et al*. 2004, Iravani *et al*. 2005, Iravani *et al*. 2007). Within DRC environments, Bokhorst *et al*. (2004b), Slomp *et al*. (2005) and Yue *et al*. (2008) incorporate the concept of chaining in cross-training configurations linking workers to machines. The skills in a chained cross-training configuration are arranged in such a way that all workers and machines are either directly or indirectly connected. This results in the ability to shift work from a worker with a heavy workload to a worker with a lighter workload, leading—directly or indirectly—to a more balanced workload. The underlying assumption in the existing literature is that workers do indeed make use of this ability to transfer to the machines that need them most by strictly following the labour assignment rules set instead of giving preference to favourite machines.

Labour assignment 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. Common when-rules are the 'central' when-rule and the 'decentral' when-rule. With a central when-rule, a worker is eligible for transfer after each job he/she has finished at a machine and with a decentral when-rule, a worker is eligible for transfer after finishing all jobs at a machine. The where-rule determines to which work centre or machine a worker needs to be transferred once he/she is eligible for transfer. Common where-rules are for instance the First In System First Served (FISFS) where-rule and the 'longest queue' where-rule, which send workers to the available machine with the 'oldest' job in queue or with the longest queue, respectively. Bokhorst *et al*. (2004a) studied the effect of a third assignment decision which they termed the who-rule. 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. The impact of labour assignment rules on system performance seems to depend on the specific DRC shop modelled and the performance measure considered (Kher and Fry 2001, Bokhorst and Slomp 2007).

To the best of our knowledge, the impact of worker preferences on the use of cross-training has not been studied before. There are studies in which workers are modelled in such a way that they are skilled for and most efficient in their 'own' or 'home' department and are also skilled for a second or even third department in which they are less efficient (see e.g. Nelson 1970, Hogg *et al.* 1977, Bobrowski and Park 1993, Malhotra and Kher 1994, Yang 2007, Davis *et al.* 2009). When this is combined with a where-rule that assigns workers to their most efficient department, this resembles the modelling of worker preferences. However, these studies report on other performance measures than the use of cross-training.

3.2. Worker preferences in industry

Philipoom and Fry (1999) state that managers implicitly encourage their workers to choose favourable jobs by emphasizing direct labor efficiency due to the use of a traditional standard cost accounting system. Nembhard and Osothsilp (2005) state that in managerial practise, worker–task selections are often based on criteria that may not directly relate to productivity. They include worker preferences as an example, as well as workers' seniority, and previous skill of workers on other jobs.

The author of this paper has encountered several practical examples of DRC production systems with worker preferences (see e.g. the practical instance described in Bokhorst *et al.* 2004a). These systems can be characterised as follows. The number of machines is larger than the number of workers and workers cannot operate all machines. Most workers have a 'main machine' or 'preferred machine' they work on regularly. The average time spent on the preferred machine is much higher than the time spent on the remaining machines (the average time spent on the preferred machine was 77% in the case described in Bokhorst *et al.* 2004a). Workers will start working at their preferred machine (often they are most proficient at these machines and will thus be initially assigned to these machine by their supervisors) and continue working till there is no work left. This thus represents a decentral when-rule for the preferred machine. Since a lot of work is pushed into the system, workers remain at their preferred machine for a long period of time. In some cases, workers even release new work for ‘their’ machine into the system instead of transferring to other machines in need of labour. This even creates more work in process. If workers work at other machines, they often do not finish all work for those machines and instead tend to return to their preferred machine as quickly as possible. In other words, the central when-rule rather than the decentral when-rule is applied at the non-preferred machines and the actual ‘where-rule decision’ is based on worker preferences instead of on productivity related criteria.

In sum, worker preferences do exist in practice and they influence the ‘when’ and ‘where’ decisions made by the workers. This results in an unbalanced use of the skills of workers. The next section presents the research model, indicating factors that may influence the use of cross-training in production systems with worker preferences.

4. Research model on the use of cross-training

The focus of this paper is on the impact of WIP on the use of cross-training. We explore the hypothesis that reducing the amount of WIP in a CONWIP controlled job shop with worker preferences forces workers to make a more balanced use of all their skills without having to change the existing (implicit) assignment rules. Changing the amount of WIP in a system may be an easier instrument to balance the use of skills than attempting to change the attitudes with respect to preference-based labour assignment. Our assumption is that a balanced use of skills will result in equal worker proficiencies for these skills. It will help workers to maintain their skills, which ensures a steady actual level of worker flexibility.

Thus far, research on CONWIP has mainly focused on its effect on flow time reduction. As a side-effect of implementing a CONWIP based system in a high-variety/low-volume environment (described in Slomp et al. 2009), we noted that the decrease in WIP pursued in this production system with worker preferences required workers to transfer more often to a larger set of machines. Workers were thus stimulated (forced by the system) to move from their preferred machines to other machines they were skilled for. In this study, we explore this observation further by explicitly focusing on the impact of the amount of WIP in a CONWIP controlled job shop on the use of skills.

Of course, the amount of WIP in the system also impacts, among other things, the average flow time, the inventory costs, and possibly the number of transfers or even the throughput rate. Since we do not want to balance the use of worker skills at the expense of the throughput rate or without having an insight in the possible change in number of transfers, we will monitor both the throughput rate and the number of transfers when reducing the amount of WIP. We assume equal and constant worker proficiencies to not unnecessarily complicate the interpretation of these additional measures.

A lower amount of WIP will increase the chance that one or more machines in the job shop are temporarily idle (i.e. have no jobs). Workers who are eligible for transfer and cannot be transferred to their preferred machine(s) due to machine idleness will then be assigned to another machine. This will probably help to balance worker skills. In practice, many cross-training configurations are used. We expect the type of cross-training configuration to be a moderating variable for the relation between the amount of WIP and the balanced use of skills, the number of transfers, and the throughput rate. The cross-training configuration may influence the chance of workers becoming idle, especially when the amount of WIP is low. For cross-training configurations where workers have few skills, lowering WIP too much may increase the risk that there is no work at all for a worker at times. Therefore we include this moderating variable in our study.

Figure 1 shows the research model with all relations. In order to be able to clearly assess the impact of worker preferences, we also consider all relations in a CONWIP controlled job shop without worker preferences as a reference.

Figure 1 to be inserted about here

5. Simulation study

We use discrete event simulation to gain insights in the impact of the amount of Work in Process on the use of cross-training. All simulation models are written in the object-oriented simulation software package Tecnomatix Plant Simulation 8.2 (Siemens Product Lifecycle Management Software II (DE) GmbH). The replication/deletion approach is used to estimate the steady-state means of the output parameters (see e.g., Law and Kelton 2000: 525). We performed 40 replications per experiment, with a warm-up period of 5 days and a total length of 300 days (24h/day). Different seeds are used for each replication to maximize sampling independence.

5.1. Model description

We modelled a job shop consisting of eight machines and four workers controlled by a CONWIP production control system. The number of jobs in the shop is fixed and is equal to the amount of WIP set. If a job finishes and leaves the shop, a new job will enter. We assume that there are always jobs available to enter the shop when required. Other assumptions are that there are no machine-failures, no absenteeism, workers remain at the machine when it is processing (i.e. 100% machine tending), and workers are equally proficient at all machines. There are half as many workers as machines in our systems (i.e. a staffing level of 50%). If the amount of WIP is equal to or larger than a minimal amount of WIP, workers are fully utilised and the machine utilisation equals 50%.

The routing length of jobs, or the number of machines to visit, is uniformly distributed between one and eight machines. The average routing length is thus 4.5. The machines a job visits are randomly chosen and we assume that once a job visits a machine, it cannot visit the same machine again. The processing times of jobs at the machines (in seconds) are generated by a gamma distribution with an α of 2 and a β of 600. 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/μ) of this distribution is α*β, and equals 20 minutes.

The dispatching rule used in the system is the First-In-System-First-Served rule. This dispatching rule chooses the oldest job (i.e. the first job that entered the shop) from the machine queue if a machine and worker request it. As a when-rule, the central when-rule is used. As a who-rule the 'longest idle time' rule is used (see e.g. Rochette and Sadowski 1976). This rule assigns the worker who has been waiting the longest, in the case more than one worker is available for assignment, or chooses randomly if waiting times for eligible workers are equal or zero. Worker preferences are modelled in a labour assignment procedure, which is described in the next section.

5.2. Experimental factors and levels

The experimental factors are the worker preferences (Prefs), the amount of Work in Process (WIP), and the cross-training configuration (CT). Worker preferences are either modelled or not modelled. In the case of worker preferences, each worker (n) prefers two of the eight machines (m). Worker n prefers machine m=2*n-1 and machine m=2*n. When a worker becomes eligible for transfer after finishing a job, or a job arrives at a machine, the assignment procedure first tries to assign idle workers to their preferred machines, starting with the worker who is idle for the longest period of time. If a worker can be assigned to both his/her preferred machines, meaning that there are jobs to be processed and no other workers are assigned, the worker will choose the preferred machine with the 'oldest' job in queue (FISFS where-rule for preferred machines). Only if workers cannot be assigned to their preferred machines, the where rule will consider the remaining machines for possible assignment in FISFS order. If more than one worker is able to work on a non-preferred machine considered, the who-rule decides which worker is transferred. In the case no worker preferences are modelled, the FISFS order of machines is applied directly for determining possible assignment of workers, followed by a who-rule if more than one worker is able to work on the machine considered.

Note that in the case a job shop with worker preferences is modelled, the central when-rule means that a worker who finishes a job at one of his/her preferred machines will first check whether jobs are available at his/her preferred machines and if so, the worker will be assigned to the available preferred machine with the oldest job. Only if the worker cannot be assigned to his/her preferred machine, other assignment possibilities are investigated. When a worker finishes a job at a non-preferred machine, he/she will be assigned to one of his/her preferred machines if possible. The central when rule with worker preferences thus resembles the situation of having a decentral when-rule for the combined set of preferred machines and a central when-rule for the non-preferred machines. This situation was also encountered in practise (see section 2.2).

We use 21 amounts of WIP: 4-15, 20, 25, 30, 35, 40, 45, 50, 55, and 60, where the number represents the amount of jobs in the shop. Figure 2 shows the two cross-training configurations examined.

Figure 2 to be inserted about here

The two cross-training configurations represent two levels of cross-training. In the full flexibility configuration, all workers can operate all machines. This configuration represents the highest possible total number of skills (32), where workers can operate eight machines (the multifunctionality of workers is eight) and each machine can be operated by four workers (the redundancy of machines equals four). The 4-skill chaining configuration represents a limited flexibility configuration based on chaining principles. A path can be created that links every worker directly or indirectly to every other worker. The total number of skills in the 4-skill chaining configuration is 16. In the 4-skill chaining configuration, the multifunctionality of workers is four and the redundancy of machines is two.

5.3. Performance measures

The performance measures give insight into (1) the use of skills, (2) worker transfers, and (3) the throughput rate. For the use of skills, the worker utilisation (ρ) is divided into the utilisation of workers from their preferred machines (ρP) and their utilisation from the remaining machines (ρR). The total worker utilisation is simply the sum of ρP and ρR. We do not need to distinguish these measures for each worker separately, since all workers are equal (i.e. each worker faces the same circumstances) within each cross-training configuration.

A worker transfer takes place if a worker transfers from one machine to another machine. Note that if a worker returns to a machine he/she worked on before he/she became idle, it is not considered to be a worker transfer. This is in line with previous research (e.g. Gunther 1979, Kher and Malhotra 1994). We deliberately chose to keep track of the number of transfers (Transf) instead of modeling transfer delay times, as motivated in section 2. We furthermore distinguish the number of transfers per worker per hour between preferred machines (Transfers Preferred ↔ Preferred: TPP), between preferred machines and remaining (i.e. non-preferred) machines (PR) or visa versa (RP) (Transfers Preferred ↔

Remaining: TPR) and between remaining machines (Transfers Remaining ↔ Remaining: TRR). Note that Transf = TPP + TPR + TRR. Figure 3 shows these different types of transfers in a from-to table for worker 1, who prefers machines 1 and 2.

Figure 3 to be inserted about here

The throughput rate is denoted by the throughput per worker per hour (TWH). TWH is measured as the division of the total number of orders that departed the shop (expressed in normalised jobs) by the man-hours that were available during production. Under the assumption that workers can always work, the maximum TWH can be calculated and equals 0.667 jobs/worker/hour. However, if the amount of WIP is too low and/or the workers are too specialised, workers cannot constantly work in the job shop with variable routings and processing times and TWH is affected.

By measuring not only how skills are used, but also how many transfers are required and how much throughput is generated, we can check whether decreasing the amount of WIP leads to a more balanced use of skills at the expense of a reduced throughput and/or more worker transfers, or not.

6. Results

Under worker preferences, the data have been analyzed by using analyses of variance (ANOVA) between subjects designs with the amount of Work in Process (WIP) and the cross-training configuration (CT) as independent variables and the performance measures as dependent variables. For all performance measures considered, each of the experimental factors as well as the two-way interaction are significant at the 0.01 level. In the subsections below, we further analyse the simple effect of WIP by means of pair-wise comparisons using the Sidak adjustment for multiple comparisons. Section 6.1 first describes the impact of WIP on TWH for both configurations. In practise it may be an important constraint that TWH is not affected when lowering the amount of WIP to balance the use of skills. By looking at the impact on TWH first, the minimal amount of WIP can be set. Section 6.2 focuses on the impact of WIP on the use of skills and section 6.3 elaborates on the impact on worker transfers.

6.1. Results on throughput per worker per hour (TWH)

Figures 4 and 5 to be inserted about here

Figures 4 and 5 show the throughput per worker per hour (TWH) results with and without worker preferences for the 4-skill chaining configuration and the full flexibility configuration, respectively. Both configurations show that a minimal amount of WIP ($\text{WIP}_{\min}^{TWH}$) is required before the maximum TWH is reached. This minimal amount is lower for the full flexibility configuration than for the 4-skill chaining configuration. Pairwise comparisons of the simple effect of WIP under worker preferences show that for the four-skill chaining configuration, the TWH results of the WIP amounts between 4-40 all differ significantly from each other ($p < 0.001$). The WIP amounts beyond 40 do not show significant differences with respect to TWH. For the full flexibility configuration there are significant differences till a WIP amount of 14 and above that there are no significant differences in TWH. Taking a TWH of 0.662 with a worker utilisation of 99.3% as threshold value, $\text{WIP}_{\min}^{TWH}$ will be around 10 for the full flexibility configuration and around 25 for the 4-skill chaining configuration. From $\text{WIP}_{\min}^{TWH}$ onwards, all workers are fully utilised and TWH reaches the maximum, which could also be calculated beforehand. Furthermore, the figures show that modelling worker preferences or not does not have a significant impact on TWH.

6.2. Results on the use of skills

Figures 6 and 7 to be inserted about here

Figures 6 and 7 show the utilisation of workers from their preferred machines (ρP) and non-preferred or remaining machines (ρR) with and without worker preferences for the 4-skill chaining configuration and the full flexibility configuration, respectively.

If workers do not have preferences, they use all their skills equally. Figure 6 shows that in the 4-skill chaining configuration, the utilisation from the two 'preferred' machines equals the utilisation from the two 'non-preferred' machines. Similarly, figure 7 shows that in the full flexibility configuration, ρP is one fourth and ρR is three fourths of the total worker utilisation. The amount of WIP does not have an influence on the balanced use of skills. Below $\mathrm{WIP}_{\min}^{TWH}$, the worker utilisation drops and all skills are used less.

With worker preferences, workers do not use their skills equally: ρP is much larger than ρR. Decreasing the amount of WIP results in a more equal use of skills. Pairwise comparisons of the simple effect of WIP show that for both cross-training configurations, all amounts of WIP differ significantly ($p < 0.001$) with respect to ρP as well as with respect to ρR. At lower WIP amounts, the chance increases that a worker who is eligible for transfer cannot be assigned to either one of his/her preferred machines. In figure 6, for the 4-skill chaining configuration at a WIP amount of 60, ρP equals 97.6% and ρR only 2.3%. By contrast, at a WIP amount of 25, ρP equals 93.0% and ρR equals 6.3%. Further reducing the amount of WIP balances worker skills more, but at the expense of some TWH. For instance, at a WIP amount of 15, TWH equals 0.652, ρP equals 86.3% and ρR equals 11.5%. For the full flexibility configuration, figure 7 shows that at a WIP amount of 60, ρP equals 98% and ρR only 2.0%. By contrast, at a WIP amount of 10, ρP equals 71.0% and ρR equals 28.2% A further reduction of the amount of WIP balances worker skills more, but at the expense of TWH.

6.3. Results on worker transfers

Figure 8 to be inserted about here

Figure 8 shows for the 4-skill chaining configuration that the number of transfers per worker per hour (Transf) is not influenced by the amount of WIP after a minimum amount of WIP (WIP_{min}^{transf}) of about 10 without worker preferences. Under worker preferences, pairwise comparisons of the simple effect of WIP show that after a WIP amount of 25, all amounts of WIP do not differ significantly with respect to Transf. Furthermore, there are fewer transfers with preferences than without worker preferences. This can be explained by the fact that workers with preferences remain at their preferred machines longer to process more jobs sequentially. In other words, it is the effect of creating a decentral when-rule for the preferred machines.

Figure 9 to be inserted about here

In figure 9, the transfers between preferred machines (TPP), the transfers between preferred machines and remaining machines or visa versa (TPR) and the transfers between remaining machines (TRR) are distinguished for the 4-skill configuration. Without preferences, there is no influence of the amount of WIP on TPP, TRR and TPR. That there are more TPR transfers than TPP and TRR transfers (which are equal) can be explained by looking at the from-to matrix in figure 3. With preferences, there are virtually no transfers between remaining machines (TRR). In the WIP range of 25-60, most transfers are between the preferred machines (TPP) and fewer transfers are between preferred and non-preferred machines (TPR). When lowering the amount of WIP from 60 to 25, TPP decreases from 1.52 to 1.34 transfers per worker per hour and TPR increases from 0.09 to 0.25 transfers per worker per hour. Pairwise comparisons of the simple effect of WIP show that all differences shown in figure 9 with respect to TPP and with respect to TPR are significant. For TRR, above a WIP amount of 20 there are no significant differences.

Figure 10 to be inserted about here

Figure 10 shows the number of transfers per hour (Transf) for the full flexibility configuration. There are fewer transfers with preferences than without worker preferences. After a minimum amount of WIP (WIP_{min}^{transf}), the number of transfers per worker per hour (Transf) remains constant. Without preferences WIP_{min}^{transf} is about 8, with preferences WIP_{min}^{transf} is about 20. Under worker preferences, pairwise comparisons of the simple effect of WIP show that after a WIP amount of 20, the differences in the number of transfers are not significant. Contrary to the effect in the 4-skill chaining configuration with worker preferences, the number of transfers first increases till a WIP amount of around 7 and thereafter drops until a steady level is reached at a WIP amount of around 20 (WIP_{min}^{transf}). Pairwise comparisons show that all these differences in the number of transfers till a WIP amount of 20 are significant. Note that this relatively high number of transfers below WIP_{min}^{transf} will result in a loss of throughput in the case there are transfer delay times. Beyond WIP_{min}^{transf}, the number of transfers in the full flexibility configuration equals the number of transfers in the 4-skill configuration. These effects will be discussed below. Obviously, without worker preferences, the more skills a worker has the larger the number of worker transfers.

Figure 11 to be inserted about here

Figure 11 shows that without preferences, there is no influence of the amount of WIP on TPP, TRR and TPR. The differences can be explained by the from-to matrix in figure 3, where TPP represents 2/56 of the total transfers, TRR 30/56 and TPR 24/56. With preferences, there are only few transfers between remaining machines (TRR) when the amount of WIP is above $\mathrm{WIP}_{\min}^{transf}$. In the WIP range of 20-60, most transfers are between the preferred machines (TPP) and fewer transfers are between preferred and non-preferred machines (TPR). Beyond $\mathrm{WIP}_{\min}^{transf}$, this pattern is the same as for the 4-skill configuration, since for both configurations workers have the same preferred machines to which they tend to transfer to if possible. This thus explains the fact that beyond $\mathrm{WIP}_{\min}^{transf}$, the number of transfers in the full flexibility configuration equals the number of transfers in the 4-skill configuration. When lowering the amount of WIP from 60 to 20, TPP decreases from 1.53 to 1.24 transfers per worker per hour, TPR increases from 0.08 to 0.32 transfers per worker per hour, and TRR increases from 0.01 to 0.06 transfers per worker per hour. Pairwise comparisons of the simple effect of WIP show that all differences with respect to TPP and with respect to TPR are significant. For TRR, above a WIP amount of 45 there are no significant differences.

Since $\mathrm{WIP}_{\min}^{TWH}(10) < \mathrm{WIP}_{\min}^{transf}(20)$ for the full flexibility configuration, it is interesting to see what happens between the WIP amounts of 10 and 20, where the number of transfers is larger than after a WIP amount of 20 and the TWH remains at the maximum level. Decreasing the amount of WIP below 20 results in an increase in worker transfers mainly caused by an increase in the transfers between remaining machines (TRR, see figure 11). It seems that the relatively large number of non-preferred machines that a worker is able to operate in the full flexibility configuration prevents him/her from starving under low amounts of WIP, at the expense of extra transfers.

6.4. Managerial impact

The results of this study may aid managers who are confronted with worker preferences at the shop floor in their decisions towards a more balanced use of worker skills. As shown, the effect of worker preferences on the use of skills can be quite detrimental in the sense that workers hardly use their non-preferred skills anymore. Since workers remain at their preferred machines, there is a higher risk of workers forgetting how to efficiently operate their other machines. The only advantage compared to having no worker preferences is that the number of worker transfers may be lower (especially for cross-training configurations where workers have many skills).

To overcome these detrimental effects of worker preferences, managers may opt to have workers strictly adhere to the where-rule set. The worker preferences are then overruled. This, however, may lead to resistance and feelings of lost autonomy on the part of the workers. Another option shown in this paper is to leave worker preferences intact and decrease the amount of WIP to $\text{WIP}_{\min}^{TWH}$ (or $\text{WIP}_{\min}^{transf}$). This leads to a more balanced use of skills. Even though the improvements are modest and a fully balanced situation cannot be reached, the decreased workload of workers on their preferred machines and the increased workload on their remaining machines may be enough to prevent the loss of valuable skills. If $\text{WIP}_{\min}^{TWH} < \text{WIP}_{\min}^{transf}$, the manager should decide whether the advantage of having a lower amount of WIP in the system when decreasing the amount of WIP from $\text{WIP}_{\min}^{transf}$ to $\text{WIP}_{\min}^{TWH}$ outweighs the extra worker transfers incurred. Decreasing the amount of WIP below $\text{WIP}_{\min}^{TWH}$ strongly benefits an equal use of skills, but should be decided upon with caution since it entails a loss of throughput.

7. Conclusions and future research

Cross-training is recognized to play an important role in supporting an organization's strategy. Prior research has suggested successful training and assignment policies to improve a firm's performance. However, these studies did not consider worker preferences. Workers who prefer to work within their preferred skill set and are unwilling to acquire or maintain new skills, a situation which we observed in several job shops, may nullify the assumed positive effects of investments in cross-trainings. In this paper, we modeled worker preferences in a CONstant Work In Process (CONWIP) controlled job shop and give insights into the effect of reducing the fixed amount of WIP on the exact use (utilisation) of skills of individual workers. We hypothesized that reducing the amount of WIP would force workers to make a more balanced use of the skills they possess. This is of importance to reduce forgetting effects and thus help workers to maintain their skills, which ensures a steady actual level of worker flexibility.

The results of our simulation study show that the effect of worker preferences on the use of worker skills is quite detrimental under large amounts of WIP. For both cross-training configurations modelled, decreasing the amount of WIP to the minimal amount of WIP required for a steady throughput of the system ($\mathrm{WIP}_{\min}^{TWH}$) results in a more balanced use of skills. The control and limitation of the amount of work in process breaks the pattern of workers remaining at their preferred machines and enforces the workers to use and maintain their other skills more. This may be enough to overcome the loss of valuable skills due to forgetting effects. Future research may be directed towards refining the relation between worker preferences and learning and forgetting effects. We assumed equal and constant worker proficiencies and relaxing this assumption in future research may shed more light on the relation between the use of cross-training (balanced or not), the resulting (long-term) worker proficiency differences, and their impact on system throughput. Also, empirical research may reveal other structures of worker preferences that need further exploration.

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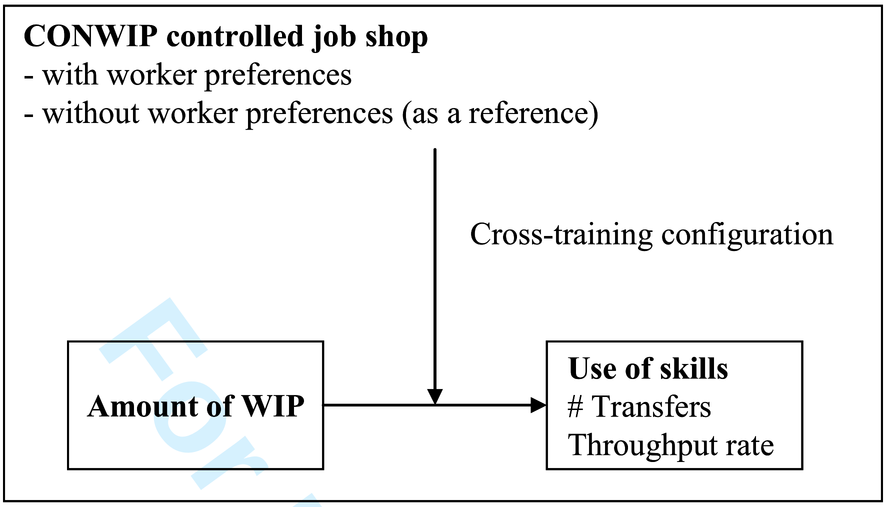
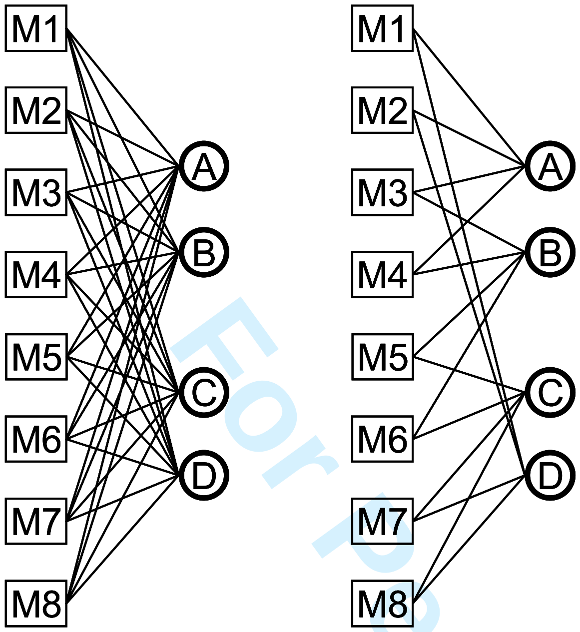


Figure 1 Research model



a. Full flexibility b. 4-skill chaining

Figure 2 Cross-training configurations

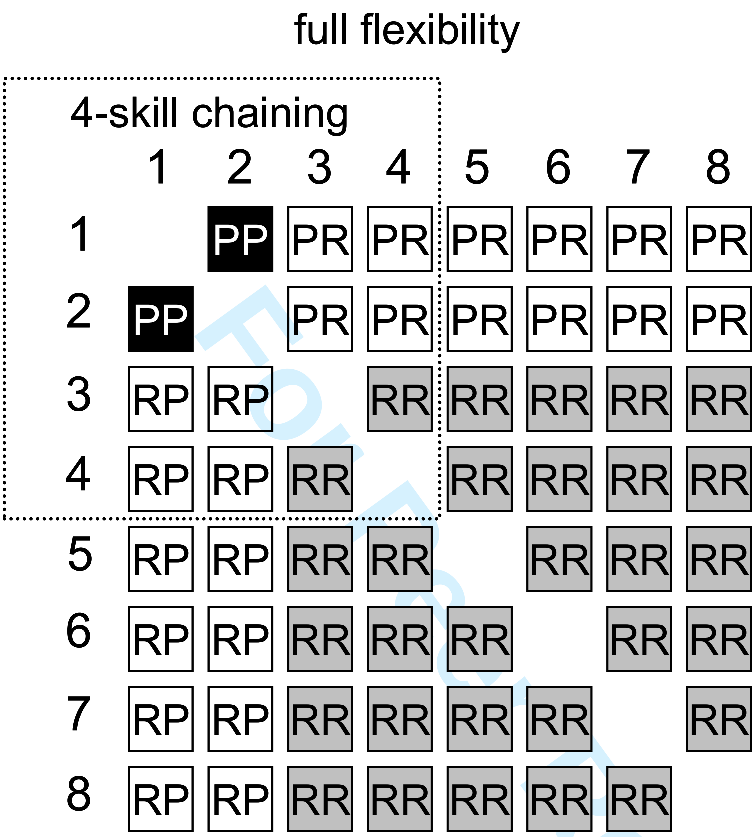


Figure 3 A from-to table for worker 1 with the different types of transfers distinguished

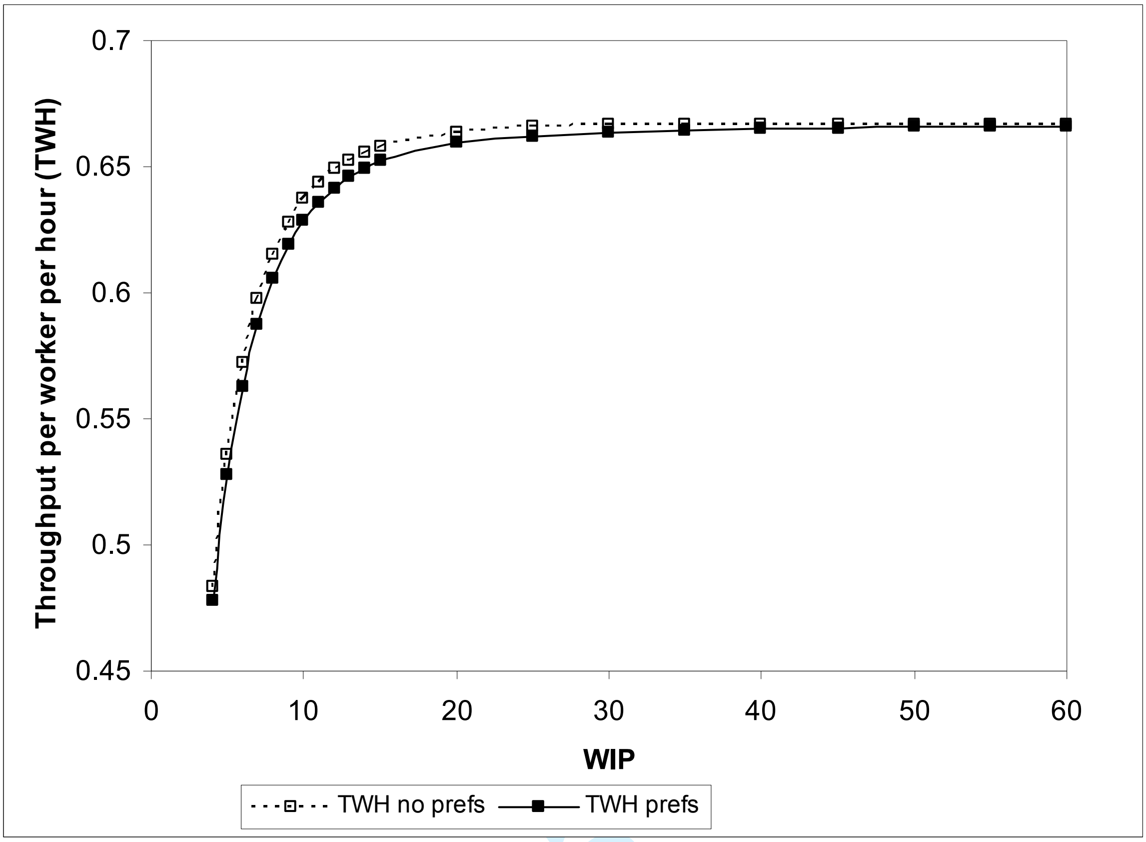


Figure 4 TWH results with and without worker preferences for the 4-skill chaining configuration.

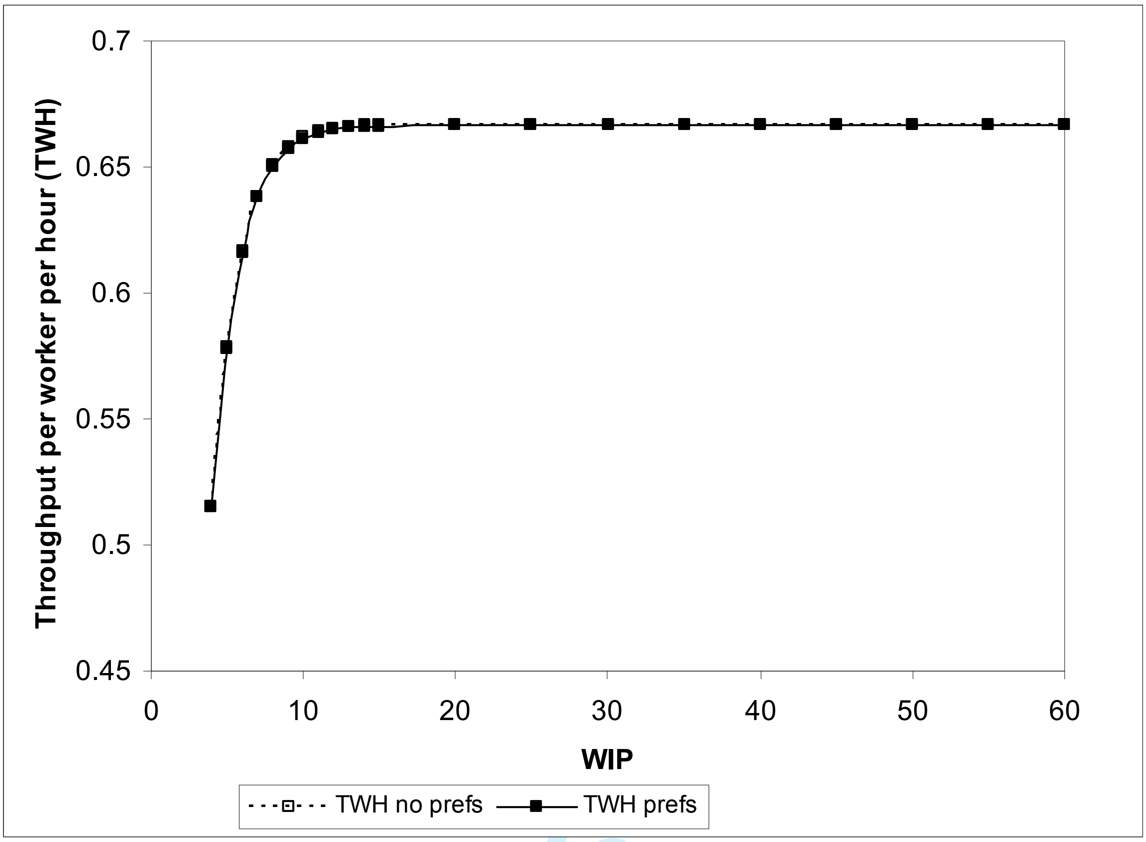


Figure 5 TWH results with and without worker preferences for the full flexibility configuration.

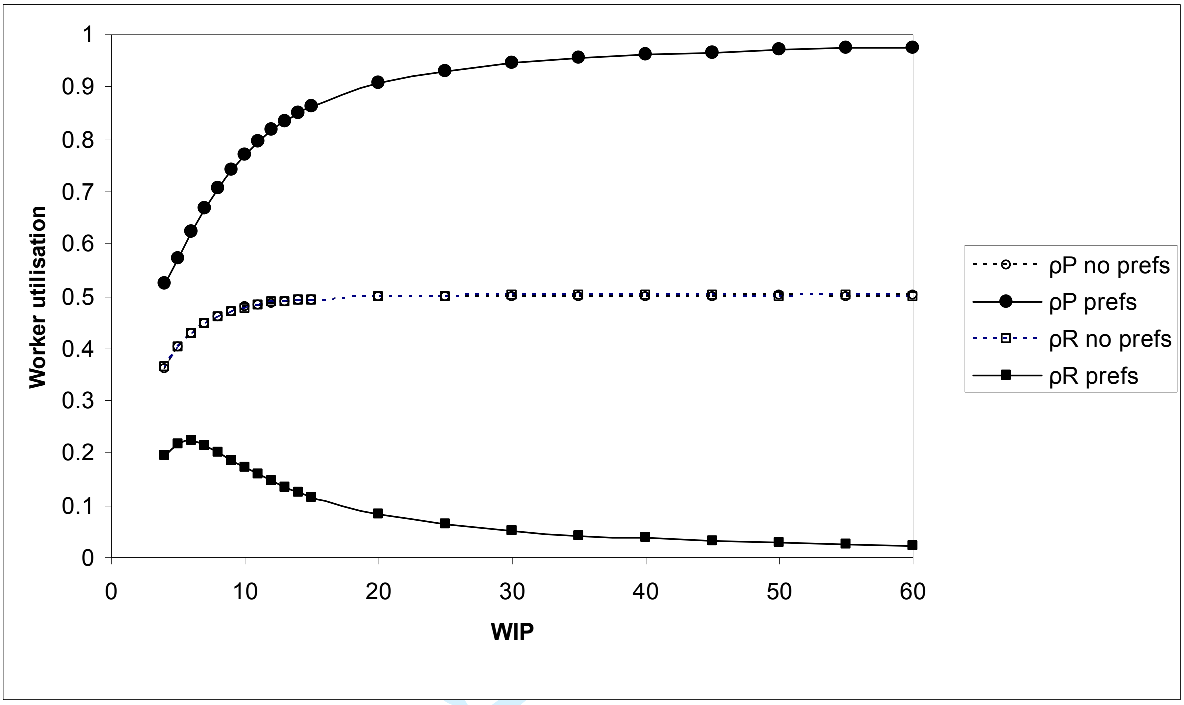


Figure 6 Utilisation of workers from their preferred machines (ρP) and remaining machines (ρR) with and without worker preferences for the 4-skill chaining configuration.

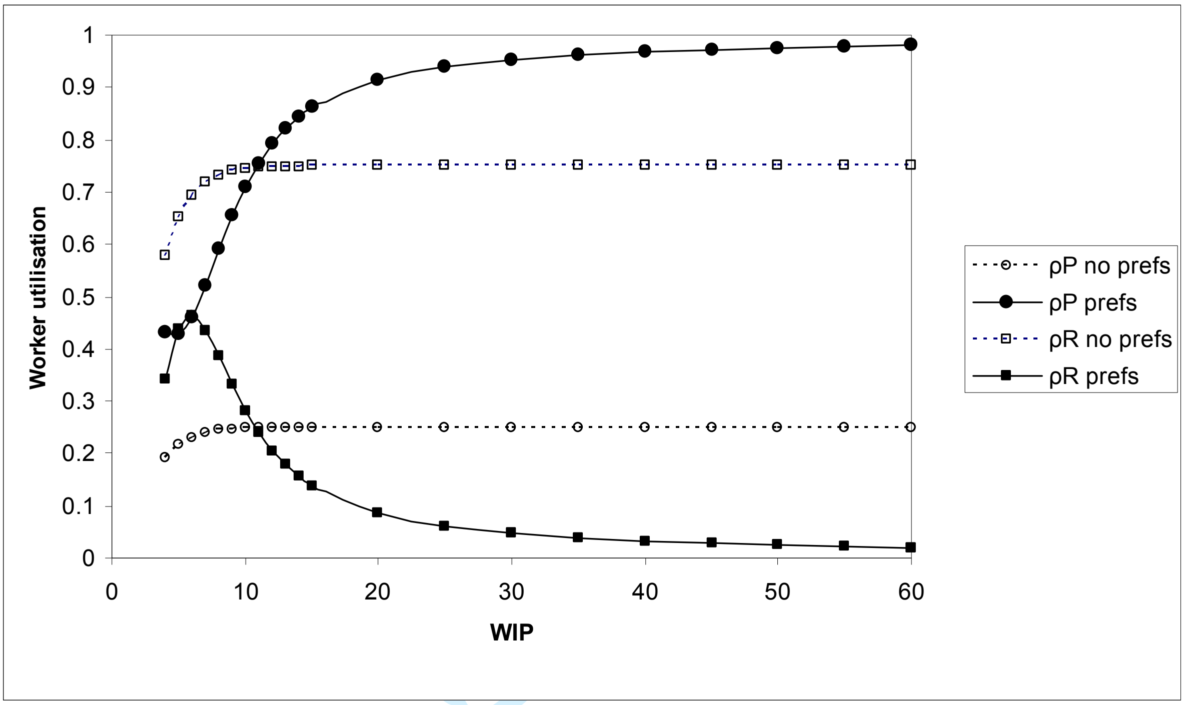


Figure 7 Utilisation of workers from their preferred machines (ρP) and remaining machines (ρR) with and without worker preferences for the full flexibility configuration.

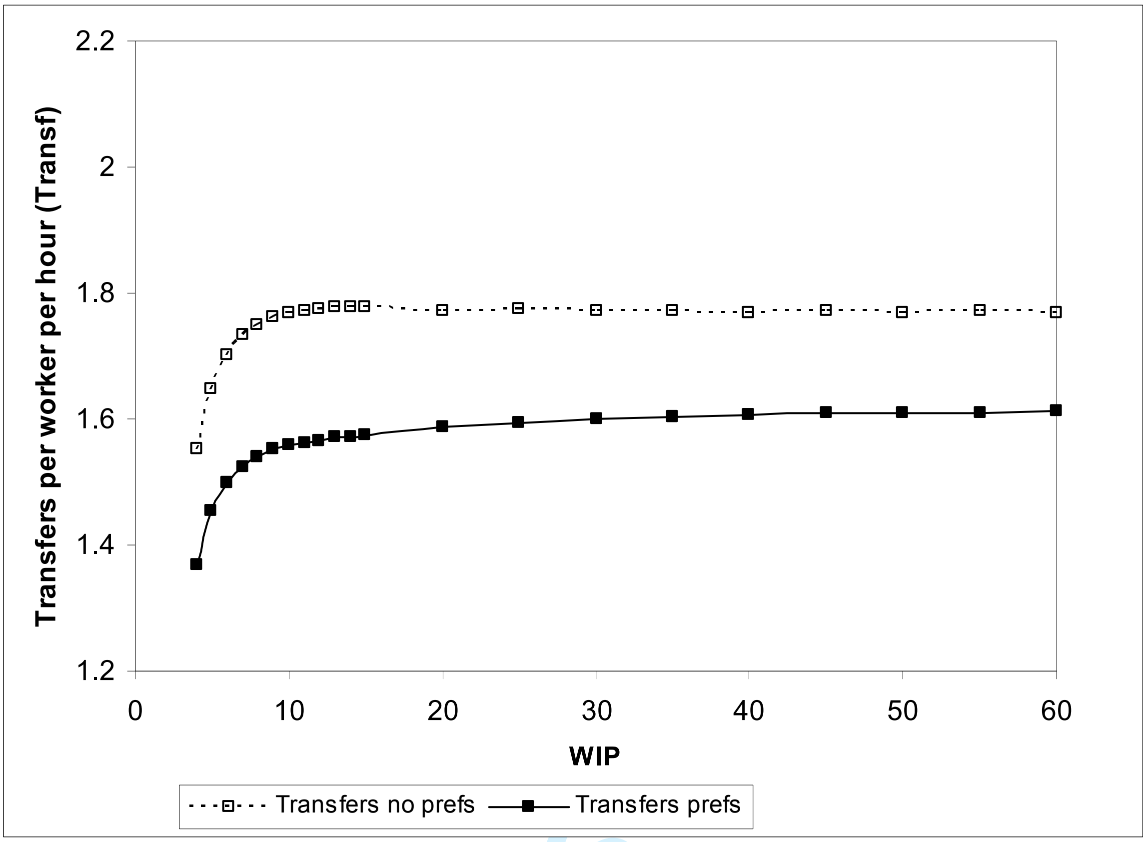


Figure 8 Transfers per worker per hour with and without worker preferences for the 4-skill chaining configuration.

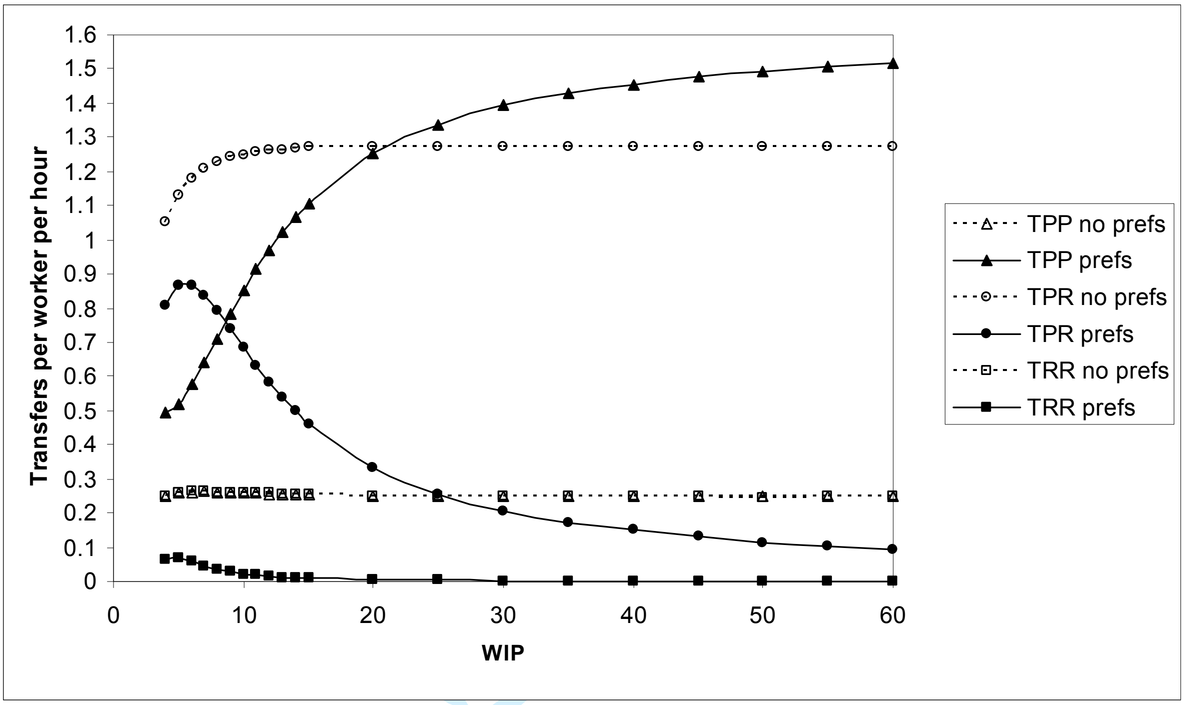


Figure 9 Transfers per worker per hour between preferred machines (TPP), between preferred machines and non-preferred machines (TPR) and between non-preferred machines (TRR) with and without worker preferences for the 4-skill chaining configuration.

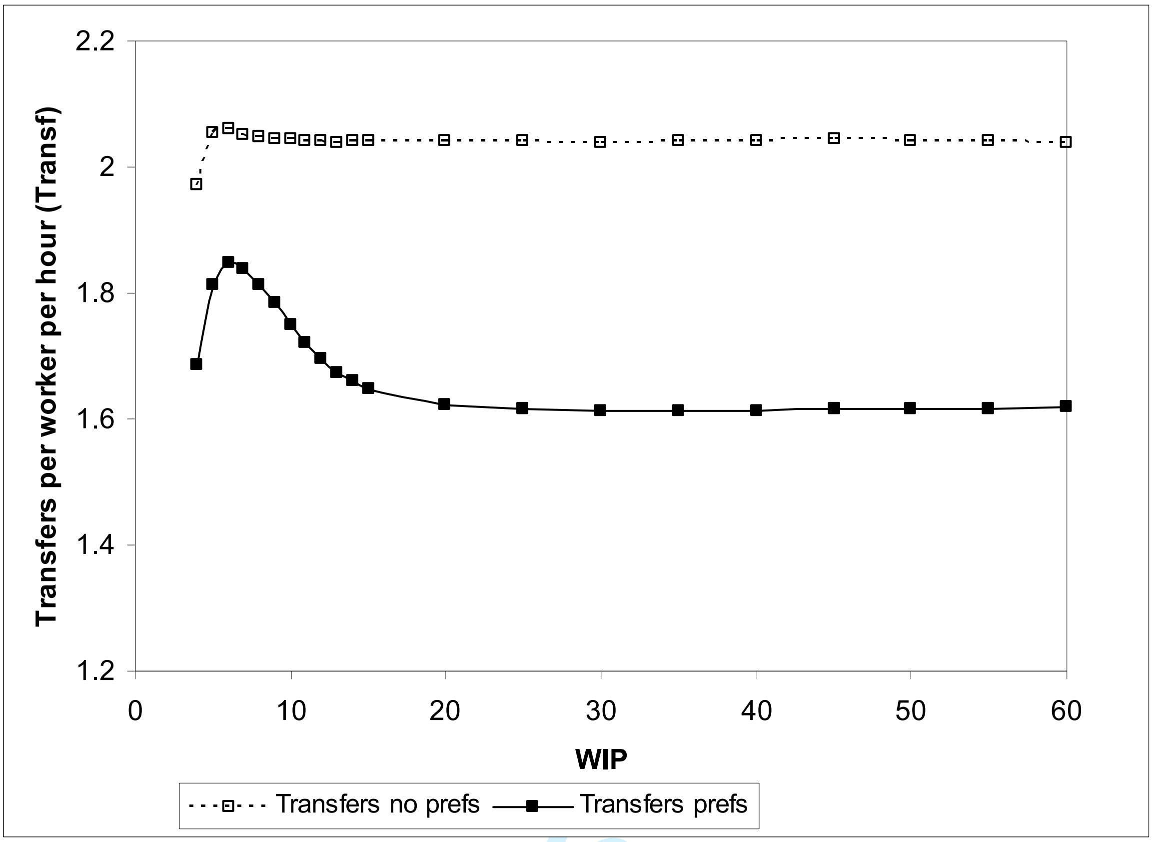


Figure 10 Transfers per worker per hour with and without worker preferences for the full flexibility configuration.

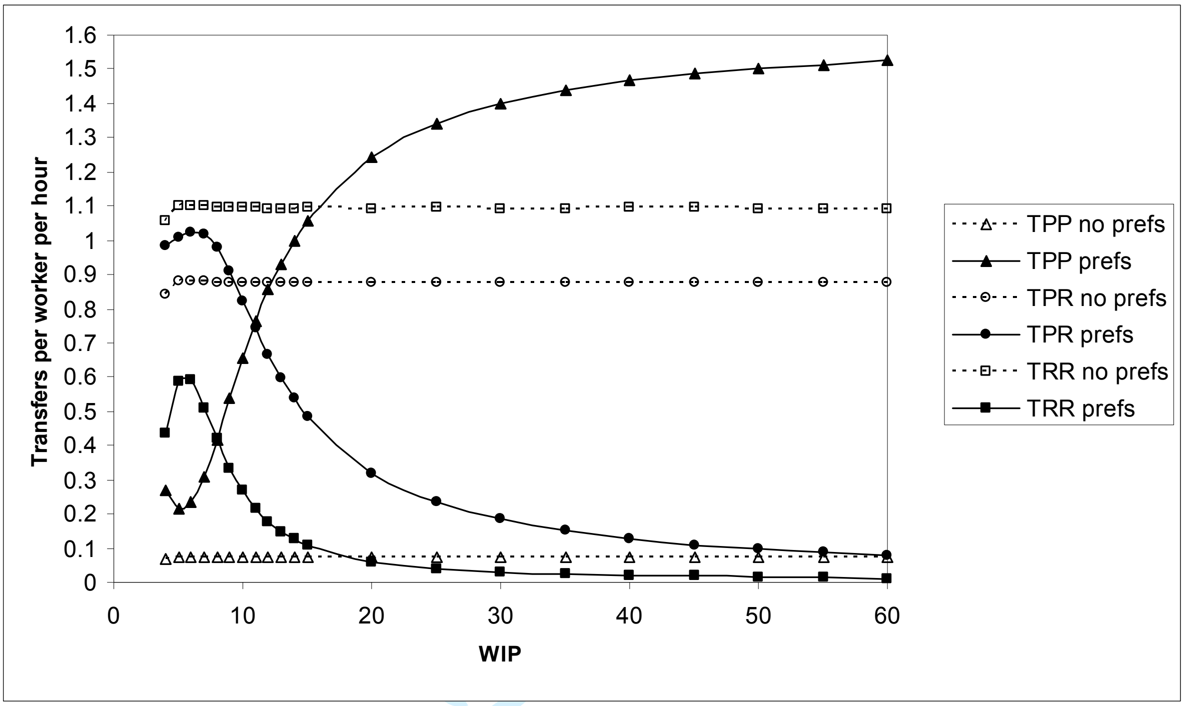


Figure 11 Transfers per worker per hour between preferred machines (TPP), between preferred machines and non-preferred machines (TPR) and between non-preferred machines (TRR) with and without worker preferences for the full flexibility configuration.