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Worker flexibility in dual resource constrained (DRC) shops

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CHAPTER 4

WORKER FLEXIBILITY IN A DRC ASSEMBLY LINE

4.1 Introduction

A DRC assembly line has more stations than workers. An important advantage of such a system is that its production capacity can be readily adjusted by changing the number of workers. This kind of assembly line has become increasingly popular, and has been adopted by a growing number of firms to cope with demand fluctuations. In such a system, workers may become idle for three reasons: starving, product blocking, and worker blocking. Starving occurs when a worker is idle because there is no work in the input buffer to process. Product blocking occurs when a worker is idle because there is no room to place output. When workers are cross-trained and share stations, it happens that a worker may become idle because another worker is processing a product in a shared station. This is termed worker blocking. As workers are the constrained resource that limits the system output, reducing worker idle rates is the key to increased productivity.

This chapter is concerned with worker flexibility in a DRC assembly line with limited buffer sizes, and in particular, addresses four issues, namely the level of cross training, chaining, worker deployment policies, and station-to-worker ratios. These issues are inspired by a real life case in a Dutch manufacturing firm (Kalk 2005, and van. den. Brink 2005).

A Dutch manufacturer of mailing systems has recently built up an assembly line, in which there are more stations than workers, and a relatively small buffer size is used between stations. The tasks in the line are complicated in terms of the number of processing steps involved, and a resulting long task time for each station. 50 percent of the workers are hired on a short-term basis due to the fluctuations in production demand. Due to the complexity of the tasks and the dynamics of the workforce, the line managers consider that it is more realistic to train workers for only a limited number of skills.

Many questions remain to be answered for the management of the firm. Firstly, to what extent should workers be cross-trained? Is it sufficient to train workers for a number of skills that is enough to cover all the stations? How will an increase in cross training improve system performance? Secondly, given a certain level of cross training, how should these workers be allocated to stations? Is it better to form one long chain (i.e., a big group), in which worker skills overlap, and all the workers and stations are linked together? Or is it better to form a number of short chains (i.e., several small groups), where each chain is exclusively responsible for a restricted number of stations? Next, when a worker has finished his task at a station, how should he select the next station? To which direction, upstream or downstream, should the worker start searching? A worker may first start searching upstream, and if no station is available in this direction, he may check the downstream stations. He may also do it in the opposite way. Finally, as the demand fluctuates, the number of workers varies as well. How will this change affect system performance? Will worker flexibility policies, such as the optimal level of cross training, the degree of chaining, and the directions for searching the next station, be affected by the change of station-to-worker ratio?

Current literature fails in providing direct answers to these questions, which are of significant managerial importance as they are frequently encountered by managers in similar contexts. Worker flexibility issues have been studied extensively in the previous research. A number of authors (e.g. Allen 1963, Nelson 1967, and Malhotra and Ritzman 1990) have indicated that the increase of worker flexibility, i.e., an incremental increase in addition to basic skill requirements, seems to improve system performance. It has been noted that chaining, creating links between tasks and skills, helps to shift work from a heavily loaded worker to a less loaded worker (Jordan and Graves 1995, Brusco and Johns 1998, Slomp and Molleman 2002, Bokhorst and Slomp 2000). Hopp et al. (2004) and Inman et al. (2004) have demonstrated that the chaining concept is useful in an assembly line environment, and that chaining can be used to compensate production uncertainties, i.e., task time variations and worker absenteeism.

Most of these studies have focused on DRC contexts, in which there are more stations than workers, and machines or assembly stations are duplicated and buffer sizes are relatively large. For example, most of the DRC studies assumed two identical machines for a department in a job shop (Treleven 1979). Hopp et al. (2004) and Inman et al. (2004) assumed a fully staffed duplicated tooling assembly line, in which two assembly tables are set for one station, and two workers can work at this station at the same time. In fact, a worker has his own home station, and can move to help other workers whenever it is needed. The competition for the available stations is not very intensive. Furthermore, they assumed a big buffer size between stations, which absorbs most of product uncertainties attributable to task time variations. As such, tasks in such an assembly line are less interdependent. In other words, the timing of one task has a small impact on the timing of other tasks. Within such a context, the increase of cross training and worker skill overlapping is always helpful to alleviate bottlenecks, and in turn contributes to increased system output.

Our study addresses a context different from the ones assumed in previous research. We focus on a DRC assembly line, in which there are more stations than workers, but assembly tables are not duplicated, and there are small buffers between stations. There is only one assembly table at a station, and workers have to compete for using the sharing stations. Due to the small buffer size, tasks are highly interdependent. For example, it happens that a task is waiting for processing at a station, while the stations downstream may suffer from starving because no jobs are available.

In such a DRC assembly line, cross training and chaining may help to assign workers to available stations, and consequently reduce worker idle time, which in turn improves system performance. However, cross training and chaining may entail some unexpected consequences, such as starving, product blocking, and worker blocking. Given these possible negative consequences, whether cross training and chaining will lead to the improvement of system performance in a highly task interdependent line is still a question.

There seems to be a trade-off between the benefits of cross training and the inferences attributable to station sharing. For example, workers may be trained for a minimal level of skills, and each worker has a clearly divided territory. In other words, there are no skill overlaps or shared stations. In this particular circumstance, workers become idle due to two reasons, starving and product blocking. The interference among workers has been reduced to a limited extent, but the benefits of worker flexibility may have also been compromised. In contrast, workers may be trained for a high level of skills. In this case, they have obtained more assignment opportunities, and have less chances of becoming idle. Since workers share stations, the interferences among workers will increase. For example, a worker may be blocked by another worker at a shared station.

When several workers process tasks in a row, the finished products may not be able to move smoothly down the line, which in turn causes product blocking. In other words, the chances of worker blocking and product blocking both have been driven up by the increased level of cross training. The degree of chaining may affect worker idle rates as well. In general, chaining involves more workers in the competition for the shared stations, and therefore, increases the chances of worker blocking. Understanding these effects is important to manufacturers who are constantly trying to balance the benefits of cross training against the costs of increased idle time.

There are other issues closely related to worker flexibility, i.e., worker deployment rules, and station-to-worker ratios. A worker may start searching for the next job downstream or upstream. Differences in the search directions may have impact on WIP levels, which in turn affect starving, product blocking, and worker blocking rates. Station-to-worker ratios determine the competition intensity for the stations in a line, which may have influence on the performance of worker flexibility policies.

This chapter investigates the impact of the level of cross training, chaining, worker deployment policies, and station-to-worker ratios on the system output rate in a DRC assembly line. Given the complexities involved in this study, a simulation model is used as a research vehicle to explore these questions. The parameters and structure of the model are based on a Dutch firm, but have been generalized. As such, the conclusions are more broadly applicable. The results of findings will provide important insights into worker flexibility issues in DRC assembly lines.

The remainder of the chapter is structured as follows. Section 4.2 describes the problem context and the motivation for this chapter, driven by the case situation. Section 4.3 provides a literature review on worker flexibility issues related to the level of cross training, chaining, worker deployment policies, and station-to-worker ratio, and specifies our research questions. The model and experimental design are discussed in Section 4.4. This is followed by the experimental results and discussion of these results in section 4.5. The final section 4.6 provides conclusions and the directions for future research.

4.2 Problem context and motivation

The case described in this section presents a real life context for the research issues addressed in this chapter, and indicates the relevance of our study. Furthermore, it highlights the general elements of the research context, and it serves as an empirical base for our study.

The products made by this firm are mailroom equipment, including outgoing mail systems, which fill envelopes with letters and forms, and incoming mail systems, which take letters and forms out of envelopes. The firm manufactures parts, and subsequently, assembles these parts into final products. About 150 employees are directly involved in the production process. The production department consists of two sections, a parts production department and an assembly department. The main manufacturing processes include stainless steel processing, turning, and spray-painting. Parts are produced at lot sizes that are sufficient to supply the assembly lines for at least six weeks. The assembly department is operated as a pull system, or in other words, production activities are organized according to customer orders. The assembly department consists of thirteen different lines. Each of them is dedicated to a product or a family of highly similar products.

Since March 2004, the firm has set up a new line for one of its major products. In the past, the old line was fully staffed with 9 stations and 9 workers. The task time per station was approximately 25 minutes, accompanied with high variations. As a result, the line was not well balanced. To overcome this problem, a relatively large buffer size of 4 units between each of two stations was used to cover the efficiency losses caused by processing time variations.

The new line was designed with 17 stations and 16 buffers with size one. The maximal output of this line is expected to be 40 products per day. The task time per station is approximately 10 minutes. The number of workers on the line, however, is varied according to the changes in production demand. When the demand is 40 products per day, the line will be almost fully staffed, and there will be around 15 to 17 workers on the line. When the demand is less than 40 products, the number of workers will be reduced accordingly. In this case, some workers will be responsible for more than one station.

The firm has a policy of hiring temporary workers to respond to the fluctuations in demand. Actually 50% of the workers are hired on a short-term contract basis. Temporary workers generally have a lower skill level upon entry. It usually takes a considerable amount of time for them to build up their experience and to increase their efficiency level due to task complexity. A hierarchy of skills exists in the line, which is mainly based on task complexity and the range of knowledge with respect to production processes (i.e. the number of stations that a worker can operate). A new employee starts at a subassembly station where tasks are the easiest (subassembly is however not included in our study). After a certain period, the worker is given the opportunity to work on the line. The tasks in the line, in general, are more complex. When he/she becomes more skilled, in terms of being able to work at a normal pace without making mistakes, the worker starts to learn to work at other stations. After a considerably long period, the worker may gain enough knowledge about the production process and become highly skilled. Then he/she may become a tuner or tester. These three categories of jobs, subassembly, assembly, and tuner and tester, have their own wage levels, and tuners and testers get the highest wages.

This assembly line is made of modular workstations. A workstation is a table, with a size large enough to hold one product. The product is placed on a board. When the board is not fixed with a pneumatic system, it can be freely rotated on roller balls. The standard parts like screws and bolts are placed in small bins within worker's grasp distance. Common tools like pneumatic screwdrivers are kept in holders on the table. The cabinets behind the workers display the larger parts and the subassembly parts. The worktables in the line are connected through a roller track. The roller tracks are long enough to keep one unfinished product in store.

Managers have the following concerns regarding worker flexibility. The task time per station of 10 minutes falls into the range of a long task time in terms of assembly line design. It implies that many assembly steps are involved in a single station. Therefore, it is difficult for a worker to remember all the procedures, to build up routines, and to follow them efficiently and precisely. Even for the permanent workers, it might be better to set a limit on their level of cross training. It usually takes time to get oriented at several stations, and therefore, their efficiency level may be affected. Especially for the temporary workers, it is better to train them just for a limited number of stations due to the limitations on their learning capacity and related learning costs.

The number of workers working in the line is dependent on the production demands. When the demand level is low, for instance, 18 products per day, 9 workers are assigned to the line. In particular, 8 workers are each responsible for two stations, and the last station is assigned to one worker. When the demand increases to 24 products per day, more workers are assigned to the line. Then the line is divided into three teams. Each team is responsible for the workstations within its own section. However, this arrangement seems not to function properly, and problems arise frequently, for example, daily demand cannot be met, quality is not guaranteed, severe blocking and starving occurs, and workers are stressed.

The management of the firm believes that the answers to these problems may lie in the improvement of workforce management. They are wondering how to assign the cross-trained workers to the line. In particular, given that workers are trained for a number of skills, how should they be allocated on the line? How many teams should be formed? How large should the team size be? How should workers be assigned to tasks? When a worker is ready for transfer, how to choose the next station? How will the number of workers in the line affect the system output?

This study incorporates the key concerns of our industrial contacts while maintaining ties to the relevant body of academic literature. Based on iterative input from the industry contacts, as well as reliance upon previous literature, we developed a model to study the important issues posed above. In particular, we examine the impact of the level of cross training, chaining, worker deployment rules, and station-to-worker ratios on the assembly line performance.

4.3 Literature review and research questions

This section provides a review of the literature relevant to the level of cross training, chaining, worker deployment policies, and station-to-worker ratios, respectively. The relevant literature for this study is broad, covering traditional operations management topics, and extending into areas of human resource management. At the end of this section, we specify the basic elements of our research context, and elaborate the research issues in this particular context.

4.3.1 Level of cross training

The benefits of worker flexibility have been well acknowledged by industrial practitioners and academic researchers. Cross training creates a buffer of capacity, which helps to deal more efficiently with shifts in demand (e.g. Allen 1963, Nelson 1967, and Malhotra and Ritzman 1990). It also helps to handle fluctuations in the supply of human resources caused by, for example, attrition, turnover, absenteeism or illness (Malhotra et al, 1993, and Van den Beukel and

Molleman 1998). It has been well established that a limited level of flexibility, i.e., workers trained for two or three skills, most often achieves the majority of benefits associated with full flexibility (Allen 1963, Nelson 1967, Fryer 1973,1974, and 1976). However, the benefits of cross training have not been examined in a highly task interdependent assembly line.

4.3.2 Chaining

How workers should be assigned to stations when they are cross-trained is another important decision in the management of a flexible work force. Chaining is an important concept with respect to the allocation of cross-trained workers to stations, and it has been investigated in the fields of operations management and human resource management.

In the operations management literature, chaining has been used as an important principle in worker allocation. Chaining is aimed at creating links between tasks and worker skills. In this way, work may be shifted from a heavy loaded worker to a less loaded worker, and consequently, system performance may be improved. A long chain, in which two kinds of resources (i.e. worker skills and stations) are linked to the greatest extent, is believed to offer a better performance than several short chains (Jordan and Graves 1995). The advantages of chaining have been confirmed in a variety of contexts, i.e. Brusco and Johns (1998) and Slomp and Molleman (2002) in the service operations, and Bokhorst and Slomp (2000) in manufacturing cells.

Only Hopp et al. (2004) and Inman et al. (2004) focused on assembly lines. Hopp et al. (2004) showed that chaining of skills provides robust and efficient performance in responding to variations in service times. Inman et al. (2004) demonstrated that chaining is useful for compensating the impact of absenteeism. However, these two studies focused on the fully staffed duplicate tooling assembly line. Additionally, they assumed a relatively large buffer size between stations, which absorbs most of the impact of task time variations, and therefore, decreases the interdependency among stations. Due to these assumptions, extrapolating their findings to our study can be risky.

In the human resource management literature, task interdependence has been regarded as an important factor in the decisions of worker allocation (Thompson 1967, Steiner 1972, Mintzberg 1979, Huber & Brown 1991, and Wilke and Meertens 1994). In our study, it refers to the extent to which the timing of one task affects the timing of other tasks. Three types of interdependence may be distinguished, namely pooled interdependence, sequential interdependence, and reciprocal interdependence.

Task interdependence to a certain extent is determined by shop layout. In a functional or traditional job shop layout, workers have more or less similar skills in a unit. Workers can do their job rather independently and most likely only have to share resources such as tools or space. The timing of one task will not affect the timing of other tasks that much. This type of interdependence is referred to as *'pooled'*, which is considered to be a weak form of interdependence (Thompson 1967). The performance of the shop is the result of each individual worker's effort, which directly adds together (Steiner, 1972).

An assembly line consists of many sequential processing steps, which are distributed among workers. As a result, workers usually have different skills. They are dependent on each other, as the output of an upstream worker will be the input of his downstream neighbour. The timing of one task will affect the timing of other tasks to some extent. This type of interdependence is termed *'sequential'*, which is regarded as a rather strong form of interdependence (Mintzberg 1979, and Huber & Brown 1991). The performance of the line will predominantly determined by its weakest link. In general, an assembly line has a relatively high level of task interdependence.

In our DRC assembly line, task interdependence is increased by the limitations on buffer sizes. When workers share stations resulting from the higher level of cross training, task interdependence is further increased. In such cases, a worker may be blocked by another worker processing in a shared station, or by the finished products left by other workers. The outputs of each worker become inputs for the others. The timing of one task directly affects the timing of other tasks, and vice verse. Therefore, the task interdependence in our DRC assembly line can be considered as 'reciprocal', which is regarded as the strongest form of interdependence (Thompson 1967).

In the order as introduced above, the three types of interdependence are increasingly difficult to coordinate because they contain increasing degrees of contingency. With pooled interdependence, action in each station can proceed without regard to actions in other stations so long as the overall shop remains viable. With sequential interdependence, however, each station in the shop must be readjusted if any one of them acts improperly or fails to meet expectations. There is always an element of potential contingency with sequential interdependence. With reciprocal interdependence, contingency is not merely potential, for the actions of each station in the shop must be adjusted to the actions of one or more others in the shop.

Because the three types of interdependence are, in the order indicated, more difficult to coordinate, it is believed that they are more costly to coordinate. It has been noted that the measurement of such costs is far from perfect (Thompson 1967).

Task interdependence has a great impact on the optimal team size, as indicated by Wilke and Meertens (1994). When task interdependence is weak, i.e. 'pooled', a larger team will provide a better performance, as the teamwork requires little coordination effort, and more workers increases the ability to absorb demand variations. In the case of sequential interdependence, a small team is preferred. A larger team has a longer chain of interdependencies, more chance of a weak link, and as a result, the performance might easily suffer.

There are other arguments supporting the choice of small teams. First of all, team size is believed to relate to coordination cost. If a team member has to adjust his/her efforts and decisions with each teammate, the team size will be exponentially related to the total coordination costs. Moreover, in a large team it is more difficult to create mutual trust, which is especially important if workers are mutually interdependent and have to cooperate and communicate intensively. Besides, in a large team the individual contribution to the overall performance will be less noticeable, which is likely to inhibit motivation and to increase "free-rider" behaviour (Wilke & Meertens, 1994). This will cause feelings of inequity among the hard workers, who will also intend to lessen their efforts. These arguments indicate that in case of high interdependence, "small is beautiful".

Task interdependence has not yet been associated with worker flexibility issues in the operations management literature. So far, chaining has been examined in the contexts where task interdependence is relatively low, i.e., DRC job shops, or the duplicated tooling assembly lines. Task interdependence has been reduced to a great extent in the fully staffed assembly lines, by duplicate tooling and by a relatively big buffer size. Two assembly tables for one station make the competition for tools or other shared resources much less intensive. A small increase in buffer size was found to recover most of the capacity losses due to task time variations (Zavadlav et al. 1996, and Bischak 1996). The concept of chaining has not been explored in a highly task interdependent environment like the DRC line in our study.

We argue that task interdependence may have impact on the worker flexibility policies such as the degree of chaining. A long chain or a big team may be preferable in a low task interdependence environment such as a DRC job shop, or a fully staffed duplicated tooling assembly line. Short chains or small teams may be more valuable in a high task interdependence environment such as a DRC assembly line with a limited buffer size and without duplicated tooling. Furthermore, in our DRC assembly line, the level of cross training may affect the degree of task interdependence as well. At a low level of cross training, when there is no skill overlaps, we expect that task are sequentially interdependent. At a high level of cross training, there are multiple skill-overlaps, and tasks may become reciprocally interdependent. The effectiveness of chaining may vary according to the level of cross training.

Many questions remain to be answered. For example, how does chaining improve system performance? Given a certain level of cross training, how should workers be allocated to stations? Does a long chain configuration always perform better than a short chain configuration? Is the effectiveness of chaining contingent upon the level of cross training and the resulting overlaps of skills?

4.3.3 Worker deployment rules

Since there are more stations than workers, when a worker finishes his task at one station, a deployment rule is needed to guide him in the search of another station.

Worker deployment rules have been explored to a certain extent by previous studies. For example, in a bucket brigade system, buffers between stations have been used as control buffers to guide the workers in their use of shared stations (Ostolaza et al. 1990 an McClain 2000). Control rules targeted at maintaining buffers near half full were found to increase the system output rate. In particular, when a worker has finished a task at a station, if the buffer in this station is above half full, he moves downstream; and if it is below half full, he moves upstream. Half-full provides a safety margin to reduce starving, while half-empty similarly reduces blocking. Actively maintaining inventory at or near the target thereby reduces idle time.

None of the existing studies have investigated worker deployment rules in a DRC assembly line with buffer size one. When a worker has finished a task at a station, if the buffer is full, the worker may stay in the station and continue to work; but if the buffer is empty, the worker has to leave. We cannot use buffer contents in directing workers in this respect. Instead, we have the choices between sending a worker upstream or downstream. Sending a worker downstream helps to get products out of the line, and therefore, it helps to lower the WIP level and to reduce the chance of blocking. On the other hand, sending a worker upstream helps to bring in more products into the line, and as a result, it increases the WIP level, but reduces the chance of starving. Which direction gives a better performance is still not clear. We would like to explore these two possibilities in our study.

4.3.4 Station-to-worker ratios

One of the advantages of a DRC assembly line is its volume flexibility, i.e., the output can be adjusted by changing the number of workers in the line.

Zavadlav et al. (1996) and McClain et al. (2000) found that station-to-worker ratios affect the system output rate. Increasing station-to-worker ratio gives workers more opportunities to be busy with their tasks, with less interference with each other, and therefore, improves the system output rate per worker. Zavadlav et al. (1996) showed that a low station-to-worker ratio can cause idle time even with inventory in the system. This is because task sharing is less effective in offsetting process uncertainty caused by task time variations, when there is substantial competition for stations.

We are interested in how station-to-worker ratios affect the line performance, and whether worker flexibility policies should vary with station-to-worker ratio. In other words, some policies may perform better at a high level of station-to-worker ratio, while others may work better at a low level of station-to-worker ratio.

Furthermore, we do not know whether worker deployment rules will perform in the same manner when station-to-worker ratio changes. When a station-to-worker ratio is low, the number of available stations becomes less, and consequently, the difference in searching next station upstream or downstream may become trivial. For example, if upstream has the priority, a worker will first look for an empty station upstream. If none is available, he/she has to go downstream anyway. We would like to investigate the impact of worker deployment rules at various levels of station-to-worker ratio.

4.3.5 Research questions

The current study examines the impact of the level of cross training, the degree of chaining, worker deployment rules, and station-to-worker ratio on system performance. The general model is depicted in Figure 4.1.

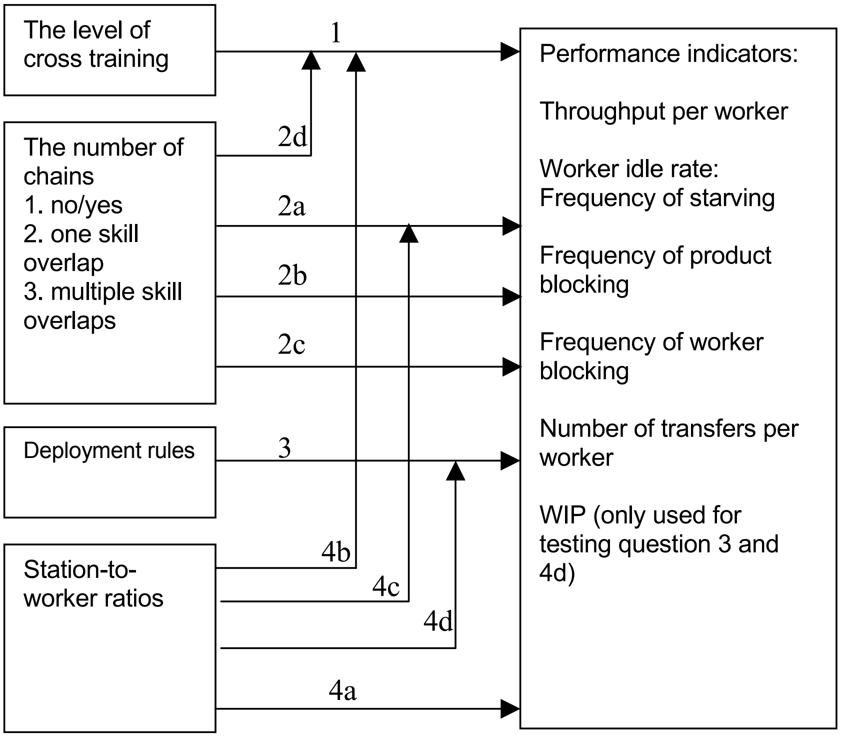


Figure 4.1
Conceptual framework: worker flexibility issues in a DRC assembly line

Our research specifically addresses the following questions and sub-questions:

1. To what extent should workers be cross-trained? Is it sufficient to train workers for a number of skills that is just sufficient to cover all the stations? How will the incremental increase of cross training improve system performance?

2. 2a. In comparison with a no-chaining situation, will chaining improve system performance?
   2b. Given one skill overlap, will a long chain outperform two short chains?
   2c. In the case of multiple skill overlaps, will the performance of long chain differ from two short chains?
   2d. Is the effectiveness of chaining related to the level of cross training?

3. How should workers be deployed? When a worker finishes his task at a station, how should he select the next station? To which direction, upstream or downstream, should the worker start searching?

4. 4a. What is the impact of station-to-worker ratios on system performance?
   4b. Does the impact of cross training on system performance vary with station-to-worker ratios?
   4c. Does the effectiveness of chaining differ under various station-to-worker ratios?
   4d. Do worker deployment rules perform in the same way under a variety of station-to-worker ratios?

4.4 Methodology

4.4.1 Simulation model

Our simulation model was based on the case of the Dutch firm. However, we have made some assumptions and modifications in order to produce more general results. In the model, the assembly line consists of 12 stations and 8 workers. There are more stations than workers, but stations cannot operate unattended.

These stations are laid out in a U-shaped configuration. The physical layout of the U-shaped assembly area is such that workers are able to move easily from station to station without significant loss of time related to movement. Therefore, we could assume that a worker transfer from one station to another station takes no time. U-shaped lines are very popular in Japan and represent a crucial building block of their Just-in-Time (JIT) production systems. A U-shaped line allows easy communication, thereby enhancing the team concept.

In our model, there are storage buffers between stations, with capacity one. A product consists of multiple tasks, and each task is processed by a worker at a station. When a task is finished at a station, if the next buffer is empty, then the product is passed to the next buffer; if not, it stays at the current station, and waits for the next buffer becoming empty and then moves downstream. Upon completion of all the tasks of a product, this product is considered to be fully assembled and leaves the assembly line.

Because this research focuses on labour issues, material shortages are assumed not to occur. Therefore, when the final assembly schedule is initiated, it is assumed that sufficient materials and components are at each station ready to be assembled. The first station will never be starved. We also assumed that the finished product moves smoothly out of the line, thereby the last station will never be blocked by a finished product. Consequently, stations upstream may sometimes being blocked by finished products, and stations downstream may sometimes being starved because of the accumulation of task time variations.

Worker deployment policies are needed for assigning idle workers to the available stations. A station is unavailable at one of the three states: (a) starving, the buffer of the station is empty; (b) product blocking, i.e., the assembly table is occupied by a finished product, which cannot be passed to the next station because its buffer is full; and (c) worker blocking, i.e., another worker is processing a product at that station. A station becomes available when the buffer is full, and the assembly table is not occupied by a finished product. Two policies will be examined in our study. One is to start searching upstream, and if no station is available, then look downstream. It is referred to as Up-Down rule. The other follows the opposite sequence, and is termed Down-Up rule.

The instructions for the Down-up rule are: When finished at a station, if the item just finished has been passed to the next buffer, and if the buffer at the current station is full, then start an item at that station. Otherwise check other stations, in the sequence of first downstream and then upstream. If there is a station where the assembly table is not occupied by a finished item, and its buffer is full, start an item on that station; otherwise, fall idle. The instructions for the Up-Down rule are similar to the Down-Up rule. The only difference is the searching sequence, which starts from upstream to downstream.

We assumed an average task processing time of 10 minutes, which is close to the case of the Dutch firm. Boothroyd (1992) indicated that times of discrete assembly processes range form 30 s to 2 hrs, with ten minutes per task being a reasonable value. Each product has a total of 12 tasks in the assembly area. Therefore, each product has a standard unit processing time of 120 minutes, which is the total amount of time that a unit of product is worked on in the assembly area, assuming all the workers who assemble the product are fully proficient in performing their tasks.

Furthermore, there are variations around each product's average task time. In our study, task time variations are represented by a uniform distribution [8, 12], with the coefficients of variation (CV) 0.12. This setting is consistent with previous literature and industrial practice. The studies of Muth (1973) and Hendricks and McClain (1993) showed that holding constant the coefficient of variation, the shape of the processing time distribution makes little difference in serial lines. The coefficients of variation (CV) can be chosen between 0 and 0.577. Other studies confirmed their findings. For example, Bartholdi and Eisenstein (1996) reported CV – 0.1 for one worker. Muth (1973) suggested 0.1 or lower for an organized service. Knott and Sury (1987) reported values ranging from 0.22 to 0.57 for light assembly tasks. McClain et al. (2000) chose a uniform processing time distribution, with coefficient of variation 0.0 to 0.5. Based on interviews, McCreery and Krajewski (1999) selected task time variations of +/- 10 to +/- 20% of the standard processing times. Our setting of task time variations falls within this range.

4.4.2 Experimental design

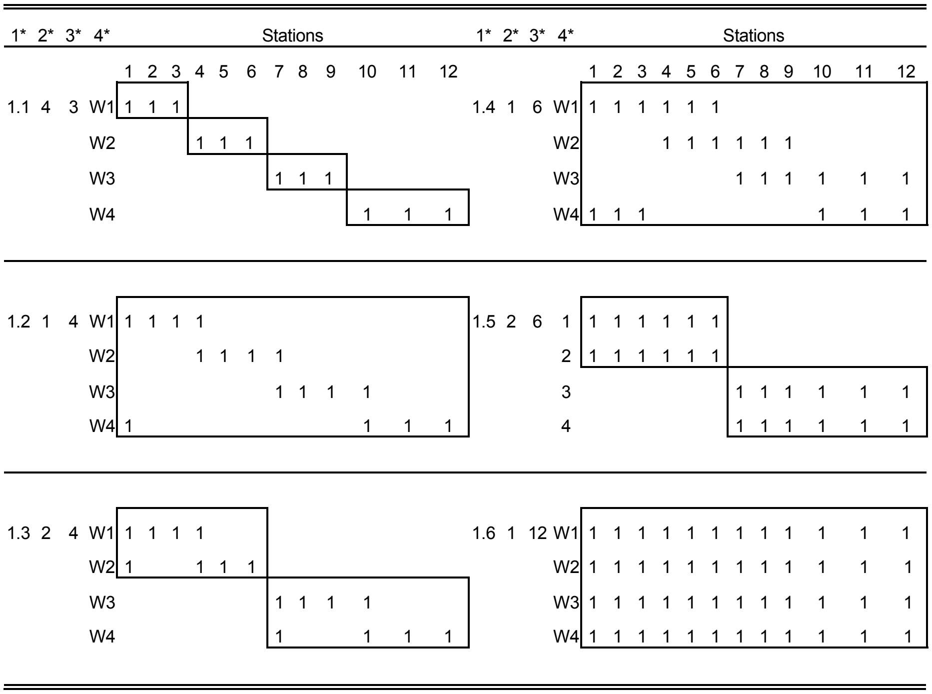
As discussed earlier, this research will investigate the impact of the level of cross training, the degree of chaining, and worker deployment rules on system output at various levels of station-to-worker ratio.

We selected three levels of station-to-worker ratio: 3, 2, and 1.5, which means that 4, 6 and 8 workers are assigned to a 12-station line, respectively (see Figures 4.2(a), (b) and (c)). In this way, we can see whether the impact of cross training and chaining follow the same pattern under a variety of station-to-worker ratios. We could also compare the impact of worker deployment rules in relation to the levels of station-to-worker ratio.

4.4.2.1 Worker allocation configurations

We considered some plausible worker allocation configurations, as shown in Figure 4.2. Workers are trained for various levels of skills, and for the same level of cross training, they are allocated in different ways. These configurations are based upon previous literature (Malhotra et al, 1993, Jordan and Graves 1995, Zavadlav et al. 1996, McClain et al. 2000, Hopp et al. 2004, and Inman et al. 2004), industrial practice (the Dutch firm), and common sense. For example, in our study we assumed that workloads (stations) are evenly distributed among workers for the sense of fairness and equity. We assumed that in all configurations, workers are trained for the same number of skills. We also assumed a limited level of cross training for most situations, because in reality managers are concerned with task complexity and training costs. However, we still kept full flexibility as a comparison base.

We first look at the station-to-worker ratio 3, the situation in which 4 workers are assigned to 12 stations (Figure 4.2(a)). Configuration (1.1) has each worker exclusively responsible for three stations, which represents the lowest possible level of cross training and the maximum number of chains. There is no overlap among worker skills, so the chaining concept is actually not applied here. We are interested in what performance a minimal level of skill coverage will provide.



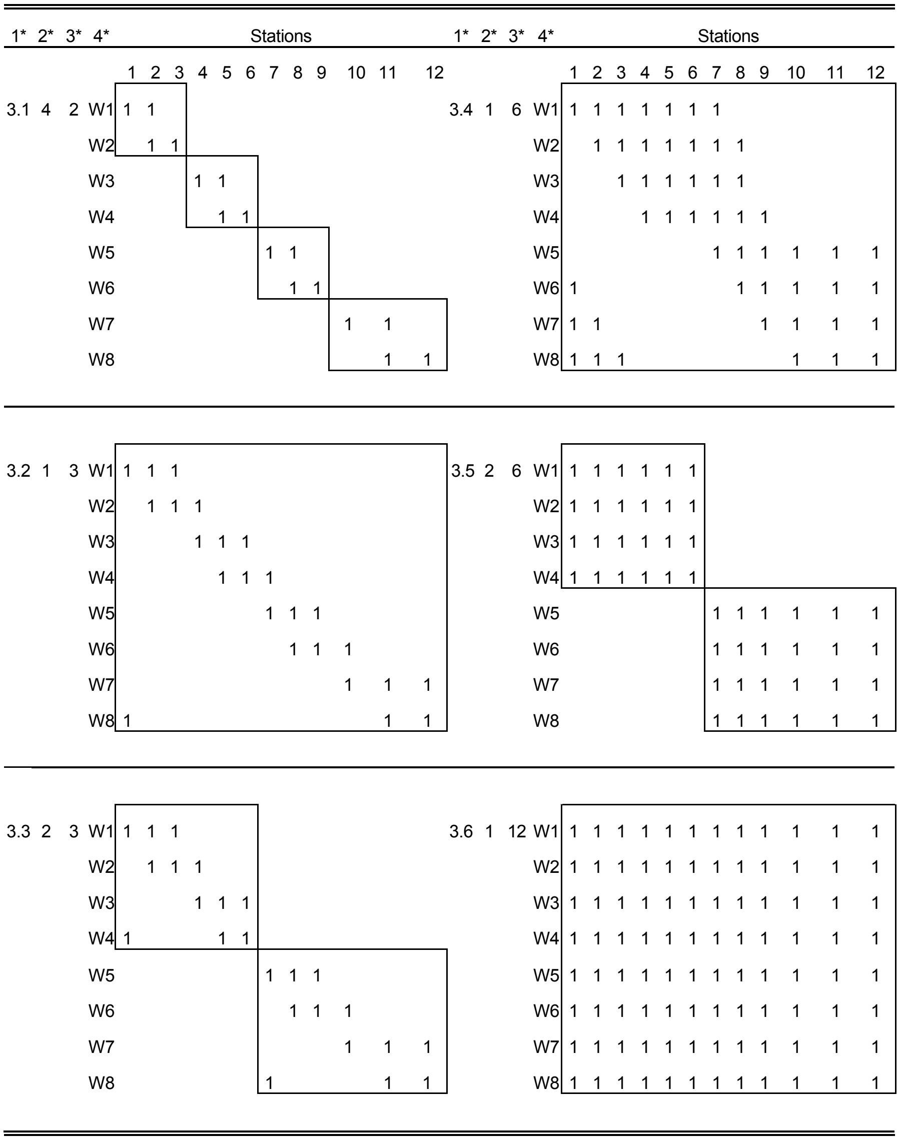
1*	2*	3*	4*	1	2	3	4	5	6	7	8	9	10	11	12
1.1	4	3	W1	1	1	1									
			W2				1	1	1						
			W3							1	1	1			
			W4										1	1	1
1.2	1	4	W1	1	1	1	1								
			W2				1	1	1	1					
			W3							1	1	1	1		
			W4	1									1	1	1
1.3	2	4	W1	1	1	1	1								
			W2	1			1	1	1						
			W3							1	1	1	1		
			W4							1			1	1	1
1.4	1	6	W1	1	1	1	1	1	1						
			W2				1	1	1	1	1	1			
			W3							1	1	1	1	1	1
			W4	1	1	1							1	1	1
1.5	2	6	1	1	1	1	1	1	1						
			2	1	1	1	1	1	1						
			3							1	1	1	1	1	1
			4							1	1	1	1	1	1
1.6	1	12	W1	1	1	1	1	1	1	1	1	1	1	1	1
			W2	1	1	1	1	1	1	1	1	1	1	1	1
			W3	1	1	1	1	1	1	1	1	1	1	1	1
			W4	1	1	1	1	1	1	1	1	1	1	1	1

(a). Station-to-worker ratio 3

1*	2*	3*	4*	Stations											
				1	2	3	4	5	6	7	8	9	10	11	12
2.1	6	2	W1	1	1										
			W2			1	1								
			W3					1	1						
			W4							1	1				
			W5									1	1		
			W6											1	1
2.2	1	3	W1	1	1	1									
			W2			1	1	1							
			W3					1	1	1					
			W4							1	1	1			
			W5									1	1	1	
			W6	1										1	1
2.3	2	3	W1	1	1	1									
			W2			1	1	1							
			W3	1				1	1						
			W4							1	1	1			
			W5									1	1	1	
			W6							1				1	1

1*	2*	3*	4*	Stations											
				1	2	3	4	5	6	7	8	9	10	11	12
2.4	1	6	W1	1	1	1	1	1	1						
			W2			1	1	1	1	1	1				
			W3					1	1	1	1	1	1		
			W4							1	1	1	1	1	1
			W5	1	1							1	1	1	1
			W6	1	1	1	1							1	1
2.5	2	6	W1	1	1	1	1	1	1						
			W2	1	1	1	1	1	1						
			W3	1	1	1	1	1	1						
			W4							1	1	1	1	1	1
			W5							1	1	1	1	1	1
			W6							1	1	1	1	1	1
2.6	1	12	W1	1	1	1	1	1	1	1	1	1	1	1	1
			W2	1	1	1	1	1	1	1	1	1	1	1	1
			W3	1	1	1	1	1	1	1	1	1	1	1	1
			W4	1	1	1	1	1	1	1	1	1	1	1	1
			W5	1	1	1	1	1	1	1	1	1	1	1	1
			W6	1	1	1	1	1	1	1	1	1	1	1	1

(b). Station-to-worker ratio 2



1*	2*	3*	4*	1	2	3	4	5	6	7	8	9	10	11	12
3.1	4	2	W1	1	1										
			W2		1	1									
			W3				1	1							
			W4					1	1						
			W5							1	1				
			W6								1	1			
			W7										1	1	
			W8											1	1

1*	2*	3*	4*	1	2	3	4	5	6	7	8	9	10	11	12
3.4	1	6	W1	1	1	1	1	1	1	1					
			W2		1	1	1	1	1	1	1				
			W3			1	1	1	1	1	1				
			W4				1	1	1	1	1	1			
			W5							1	1	1	1	1	1
			W6	1							1	1	1	1	1
			W7	1	1							1	1	1	1
			W8	1	1	1							1	1	1

1*	2*	3*	4*	1	2	3	4	5	6	7	8	9	10	11	12
3.2	1	3	W1	1	1	1									
			W2		1	1	1								
			W3				1	1	1						
			W4					1	1	1					
			W5							1	1	1			
			W6								1	1	1		
			W7										1	1	1
			W8	1										1	1

1*	2*	3*	4*	1	2	3	4	5	6	7	8	9	10	11	12
3.5	2	6	W1	1	1	1	1	1	1						
			W2	1	1	1	1	1	1						
			W3	1	1	1	1	1	1						
			W4	1	1	1	1	1	1						
			W5							1	1	1	1	1	1
			W6							1	1	1	1	1	1
			W7							1	1	1	1	1	1
			W8							1	1	1	1	1	1

1*	2*	3*	4*	1	2	3	4	5	6	7	8	9	10	11	12
3.3	2	3	W1	1	1	1									
			W2		1	1	1								
			W3				1	1	1						
			W4	1				1	1						
			W5							1	1	1			
			W6								1	1	1		
			W7										1	1	1
			W8							1				1	1

1*	2*	3*	4*	1	2	3	4	5	6	7	8	9	10	11	12
3.6	1	12	W1	1	1	1	1	1	1	1	1	1	1	1	1
			W2	1	1	1	1	1	1	1	1	1	1	1	1
			W3	1	1	1	1	1	1	1	1	1	1	1	1
			W4	1	1	1	1	1	1	1	1	1	1	1	1
			W5	1	1	1	1	1	1	1	1	1	1	1	1
			W6	1	1	1	1	1	1	1	1	1	1	1	1
			W7	1	1	1	1	1	1	1	1	1	1	1	1
			W8	1	1	1	1	1	1	1	1	1	1	1	1

(c). Station-to-worker ratio 1.5

Figure 4.2

Worker allocation configurations at various station-to-worker ratios

1*, configurations; 2*, the number of chains; 3*, the levels of cross training, and 4*, workers

Configuration (1.2) has each worker assigned to four stations. It represents a marginal increase of cross training in addition to the minimal level in configuration (1.1). Workers 1, 2 and 3 have one skill overlap with the neighbouring worker downstream, whereas worker 4 shares the first station with worker 1. This is a practical consideration in practice, as managers would like to have workers help their neighbours sometimes. By comparing the performance of configurations (1.1) and (1.2), we will know, to what extent a marginal increase of cross training together with chaining, will improve system performance (i.e., research question 2a).

Configuration (1.3) has the same level of cross training as configuration (1.2), but workers are grouped in a different way. Workers 1 and 2 form one short chain, responsible for the first six stations. Among these stations, they share stations 1 and 4. Workers 3 and 4 form another chain, covering the last six stations, and they share stations 7 and 10. There is no overlap between these two chains. In other words, there are two separate short chains in the line.

Configurations (1.2) and (1.3) both have a marginal increase in the level of cross training as compared to configuration (1.1). We would expect to see an improvement in system performance due to the increase in flexibility as indicated by previous literature. Furthermore, since configurations (1.2) and (1.3) have the same level of cross training, we could isolate the effects of chaining. In this way, we can investigate whether one long chain performs better than two short chains in a DRC assembly line, when workers have a marginal increase in the level of cross training and form one overlap of skill with neighbouring workers (i.e., research question 2b).

Configurations (1.4) and (1.5) have each worker assigned to six stations, which represents an average level of cross training between the lowest level of cross training and full flexibility for a 12 station line. We expect to see further improvement in system performance due to the higher level of cross training. Workers form one chain in configuration (1.4) and two separate chains in configuration (1.5). Because the line length is constant, there are multiple skill overlaps between neighbouring workers. As such, we examine when workers have a high level of cross training and multiple overlap of skill with neighbouring workers, whether one long chain performs better than two short chains in a DRC assembly line (i.e., research question 2c).

Configurations (1.2) and (1.3) differ from configurations (1.4) and (1.5) in terms of the level of cross training. Whereas in configurations (1.2) and (1.4), workers form a long chain, in configurations (1.3) and (1.5), workers form two short chains. By observing the performances of chaining at a low level of cross training, i.e., configurations (1.2) and (1.3), and at a high level of cross training, i.e., configurations (1.4) and (1.5), we will be able to understand whether the effectiveness of chaining is related to the level of cross training (i.e., research question 2d).

Configuration (1.6) presents the extreme case of full flexibility, which may not be realistic in a real life situation due to the limitations in task complexity and training costs. However, theoretically it should be most efficient in the use of the available worker time. It is similar to a single, shared waiting line in a parallel queuing system: we never face the situation in which there is work available while one or more workers remain idle. If a station is not starved, blocked by a product, and blocked by another worker, any worker may use it. Since it provides the best efficiency performance that we could probably have, we include it in our study for comparison reason.

The worker allocation configurations in Figures 4.2(b) and 4.2(c) were formed in a way similar to the configurations mentioned in Figure 4.2(a). In Figure 4.2(b), configuration (2.1) presents the lowest possible level of cross training, in which each worker is responsible for two stations. Configurations (2.2) and (2.3) have a marginal increase in the level of cross training. Workers are trained for three stations, but grouped in different ways. One chain is formed in configuration (2.2), two chains in configuration (2.3). Workers are assigned to six stations in configurations (2.4) and (2.5), but form one chain and two chains, respectively. Configuration (2.6) provides a full flexibility scenario.

However, when the station-to-worker ratio is 1.5, the number of stations cannot be evenly distributed among individuals. The smallest chain is that two workers are responsible for three stations. For the smallest chain, we include cross training level two as in configuration (3.1), in which a worker has his own station and shares the station in the middle with the other worker in the chain. We also consider cross training level three as in configurations (3.2) and (3.3), and cross training level six in configurations (3.4) and (3.5), whereas workers are grouped into one chain and two chains, respectively. Again, configuration (3.6) represents full flexibility.

Figures 4.2(a), 4.2(b) and 4.2(c) offer us with the opportunities to explore the worker flexibility issues at a variety of station-to-worker ratios. In a real life situation, managers may also wonder whether or not workers should be cross-trained, allocated, and deployed in a different way, when the number of workers in the line varies. The operational performance of various configurations in Figures 4.2(a), 4.2(b) and 4.2(c) will provide insights into the nature of the relationship between station-to-worker ratios and worker flexibility policies.

We selected two worker deployment policies, which have already been described in subsection 4.1.

4.4.2.2 Performance indicators

Four types of performance criteria will be collected, namely throughput per worker; worker idle rate, which is the sum of starving rate, product blocking rate, and worker blocking rate; the number of transfers per worker, and WIP.

The first type, throughput per worker, which is the standard work content of the products built in the assembly operation within 1 day (24 hours) by a worker. It directly measures the line productivity (McClain et al. 2000, and McCreery et al. 2004).

The second type, worker idle rate, is measured by the frequency that workers become idle within a day (24 hours). It represents how well workers are utilized. As workers are the constrained resource that limits the system output rate, it is expected that worker idle rates should be negatively related to throughput. According to the causes of worker idleness, worker idle rates can be further divided into three sub-indicators: starving rates, product blocking rates, and worker blocking rates.

The sub-indicators may further have an impact on workers' behaviour, which in turn may affect worker efficiency. As far as we are aware, none of the previous papers has explicitly addressed this issue. Only Kenneth et al. (1998), in a laboratory study, demonstrated that workers' processing speeds are not independent as most studies assumed, and workers may vary their speed according to the size of the buffer, the processing speed of co-workers, or the amount of inventory in the system. Similarly, we argue that when a worker is forced to take breaks, he may experience frustration and stress, which in turn may affect his efficiency level. We are not going to direct measure how starving, product blocking, and worker blocking are related to the level of frustration or the decrease of worker efficiency level. Yet these sub-indicators can still be used to reflect how frequently workers are disturbed, and to predict the possible deterioration in their motivation and performance.

Previous literature indicated that worker idle times may be theoretically very trivial in a DRC assembly line. Zavadlav et al. (1996) demonstrated that a bucket brigade system has the property of balancing itself, by shifting the workloads continuously and automatically in response to changes in the state of the system. Theoretically, a perfectly balanced line will have machine idle time, but no worker idle time. A DRC assembly line is similar to a bucket brigade system in terms of more stations than workers. As a result, in a well-balanced DRC assembly line, worker idle time will be rather short. The frequency of a worker becoming idle and its consequences on worker behaviour may have a bigger impact on system performance. Therefore, we choose using worker idle rates instead of worker idle times as our performance indicator.

Worker idle rates are computed as follows. A worker is responsible for a number of stations. A station becomes unavailable when it is starved, or blocked by a product, or blocked by a worker. When all the stations in his section are not available simultaneously, the worker becomes idle. For example, a worker has to take care of three stations. When the first station is starved, the second is blocked by a product, and the third is blocked by another worker at the same time, the worker becomes idle.

At the moment the worker becomes idle, each event at each station is recorded in a worker's production file. For example, we record that station 1 starving once, station 2 product blocking once, and station 3 worker blocking once. Each time a worker becomes idle, the situations he encounters at each station are recorded.

At the end of the day, we sum up how many times the worker encounters starving over all the stations in his section. In the same way, we sum up the total times of product blocking, and worker blocking. These sums are then divided by the number of stations in his section, which results in the frequency of starving, product blocking, and worker blocking within a day. The sum of these frequencies gives the total frequency that he becomes idle within a day. Finally, according to the number of workers in the line, we sum up the total frequency of workers becoming idle within a day. Table 4.1 provides an example, which explains how the calculation has been carried out.

The third performance criterion is the number of transfers. It indicates the number of movements between stations in an assembly line that a worker makes within a day. The number of transfers has been adopted as a performance indicator by many previous DRC studies (Treleven 1989), and it has been used to represent the degree of worker flexibility for a system. Later, Gunther (1979, and 1981) acknowledged the existence of transfers delay and information delay in a DRC system. He showed that it takes time for a worker to obtain the updated information necessary to make the appropriate transfer decision, to move from one station to another station, and to get oriented at the new station. In other words, the benefits of worker flexibility are not acquired without paying any prices.

To avoid unnecessary complexity, we assumed zero transfer time in our study. However, we select the number of transfers to estimate the possible negative consequences related to worker flexibility policies. This choice is in accordance with managerial practice, in which too many transfers are not appreciated in an assembly line, especially when tasks are complicated in terms of multiple processing procedures and long task time per station. When transferred, workers need time to get oriented at a new station.

Table 4.1 Computation of worker idle rates per 24 hours

		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	Mean	Sub Total	Total
W1	Starving	0	0.04	0	0									0.01		
	Product blocking	4.54	7.67	7.7	7.68									6.9		
	Worker blocking	3.17	0	0	0.03									0.8		
															7.7	
W2	Starving				0.44	0.65	0.36	0.36						0.45		
	Product blocking				3.66	6.49	6.78	6.76						5.93		
	Worker blocking				3.04	0	0	0.02						0.76		
															7.14	
W3	Starving							1.16	1.4	1.09	1			1.16		
	Product blocking							3.44	7.82	8.13	8.15			6.88		
	Worker blocking							4.61	0	0	0.07			1.17		
															9.22	
W4	Starving	0									0.85	0.88	0.88	0.65		
	Product blocking	0.82									0	0	0	0.21		
	Worker blocking	0.06									0.03	0	0	0.02		
															0.88	
																24.9

The fourth performance criterion measures WIP, which indicates how many unfinished products are in the line. A high WIP level in a DRC assembly line is believed to contribute to decreased worker idle time and increased throughput (Zavadlav et al. 1996). Though a high WIP level may be linked to a long throughput time, it is useful in case of a high number of product failures. This indicator is mainly used for comparing the effectiveness of worker deployment rules.

4.4.3 Simulation experiments

Two experimental factors: worker allocation configurations, and worker deployment rules, are considered at three levels of station-to-worker ratio. The level of cross training and chaining are interrelated, together forming 6 worker allocation configurations for each level of station-to-worker ratio. The impact of the level of cross training and chaining are investigated by comparing some of these worker allocation configurations. The results are then examined at different levels of station-to-worker ratio as well. 6 worker allocation configurations together with 2 worker deployment rules result in 12 conditions for each level. For three levels of station-to-worker ratio, 36 conditions have been considered in total.

An object-oriented programming language, EM-Plant 5.5, was used to build the simulation model. The replication/deletion approach (Law and Kelton 2000) was adopted to collect 30 independent samples for each experiment. Welch analysis of outputs (Law and Kelton 2000) indicated that steady state was reached after approximately 100 hours. Thus, data from a warm-up period of 20 days was discarded for each sample. Observations were collected for 100 days.

4.5 Results

As indicated earlier, we selected four performance criteria, throughput per worker, worker idle rates, the number of transfers per worker, and WIP. Throughput per worker directly measures the line productivity, and can be regarded as a main performance indicator. As workers are the constraint resource that limits the line output rate, worker idle rates directly affect throughput levels. In other words, worker idle rates and throughput per worker are highly correlated. To avoid repetition, the ANOVA results for worker idle rates will not be presented. Nevertheless, the results of worker idle rates will be used for the interpretations of the difference in throughput per worker.

Table 4.2 presents the resulting F-values and p-values from a one-way Analysis of Variance (ANOVA) for three levels of station-to-worker ratio. It can be seen that for each level of station-to-worker ratio, the main and interaction effects of the experimental factors, worker allocation policies and worker deployment rules, are significant at the 0.001 level for the performance measures, throughput per worker, the number of transfers per worker, and WIP. Thus, these three performance measures were affected by worker allocation policies and worker deployment rules, and there were interactions between worker allocation policies and worker deployment rules. A Tukeys multiple comparison test has been carried out for each level of station-to-worker ratio. Results showed that the differences between each combination of worker allocation policy and worker deployment rule are all significant. In the remaining of this section, we discuss each research question in turn.

4.5.1 Level of cross training

Research question 1:
To what extent should workers be cross-trained? Is it sufficient to train workers for a number of skills that is just sufficient to cover all the stations? How will the incremental increase of cross training improve system performance?

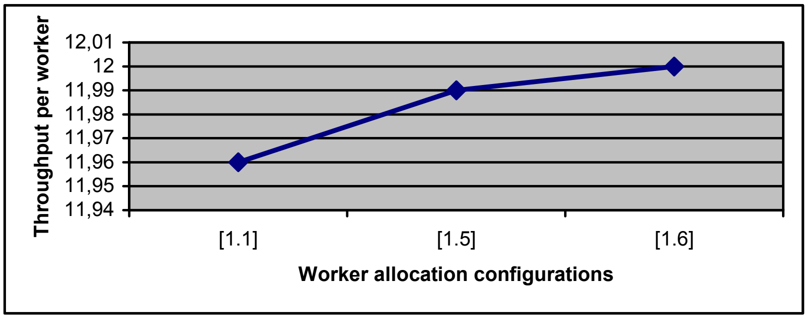
In order to address this first set of research questions regarding the level of cross training, we compare the performance results of configurations (1.1), (1.5) and (1.6), which are shown in Figure 4.2 (a). Configuration (1.1) has each worker trained for three stations. Under station-to-worker ratio 3, this level of cross training is just sufficient to cover all the stations, and it is therefore referred to as the minimal level of cross training in our study. In configuration (1.6), each worker is trained for 12 stations, which is the highest level of cross training and represents full flexibility. In configuration (1.5), each worker is trained for six stations, which represents an average level of cross training between the bottom as in configuration (1.1) and the ceiling as in configuration (1.6). By comparing the performance of these three configurations, we will understand how the levels of cross training affect system performance (see Figure 4.3).

Configuration (1.4) has the same level of cross training as configuration (1.5), but workers are grouped in a different way (see Figure 4.2 (a)), and it performs worse than configuration (1.5) in terms of throughput per worker (see Figure 4.6 (a)). In this subsection, we concentrate on the differences in performance attributable to the levels of cross training. Therefore, for the same level of cross training, we choose the one which gives a comparably better performance. To be more specific, configuration (1.5) is selected to represent a high level of cross training. Configuration (1.4) is not discussed in this subsection, but will be discussed later in the subsequent subsection, in which the allocation of worker skills will be our focus.

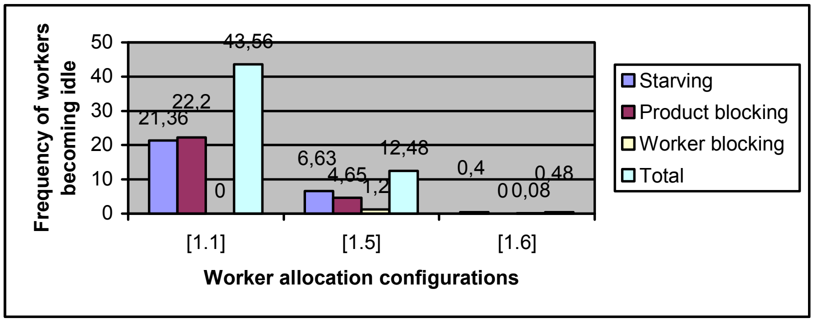
Table 4.2

ANOVA results with dependent variables: throughput per worker, number of transfers per worker, and WIP, and independent variables: worker allocation configurations (Conf), and deployment rules (Deploy), at various levels of station-to-worker ratio.

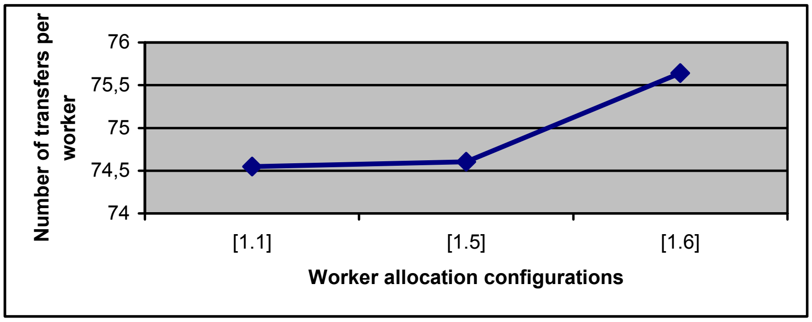
Station -to- worker ratio	Configurations		Throughput per worker		Number of transfers per worker		WIP	
			F	P<	F	P<	F	P<
3	(1.1), (1.2), (1.3), (1.4), (1.5), and (1.6)	Conf	3340.12	0.001	8715.77	0.001	376.80	0.001
		Deploy	5912.55	0.001	599.25	0.001	87889.24	0.001
		Conf*Deploy	2052.76	0.001	11607.66	0.001	3317.55	0.001
2	(2.1), (2.2), (2.3), (2.4), (2.5), and (2.6)	Conf	23727.31	0.001	16880.11	0.001	3200.38	0.001
		Deploy	1739.18	0.001	14306.77	0.001	165168.51	0.001
		Conf*Deploy	425.83	0.001	14401.85	0.001	17696.45	0.001
1.5	(3.1), (3.2), (3.3), (3.4), (3.5) and (3.6)	Conf	5745.25	0.001	602.89	0.001	1476.56	0.001
		Deploy	154.16	0.001	3729.70	0.001	20817.65	0.001
		Conf*Deploy	17.96	0.001	1495.33	0.001	3210.71	0.001



(a) Throughput per worker



(b) Worker idle rates



(c) Number of transfers per worker

Figure 4.3

The impact of the level of cross training on performance under deployment rule 2
Configuration [1.1], cross training level 3;
Configuration [1.5], cross training level 6;
Configuration [1.6], cross training level 12.

Table 4.3 Worker idle rates in times per 24 hours

(a) Configuration (1.1) under deployment rule 2

	Frequency				Percentage		
	Starving	Product Blocking	Worker Blocking	Idle Frequency	Starving	Product Blocking	Worker Blocking
W1	0	9.81	0	9.81	0%	100%	0%
W2	3.94	7.5	0	11.44	34%	66%	0%
W3	6.02	4.89	0	10.91	55%	45%	0%
W4	11.4	0	0	11.4	100%	0%	0%
Total	21.36	22.2	0	43.56			

(b) Configuration (1.2) under deployment rule1

	Frequency				Percentage		
	Starving	Product Blocking	Worker Blocking	Idle Frequency	Starving	Product Blocking	Worker Blocking
W1	5.94	0.63	2.69	9.26	64%	7%	29%
W2	57.6	2.88	14.1	74.58	77%	4%	19%
W3	75.7	3.08	16	94.78	80%	3%	17%
W4	40.9	13.2	11.8	65.9	62%	20%	18%
Total	180.14	19.79	44.59	244.52			

(c) Configuration (1.2) under deployment rule 2

	Frequency				Percentage		
	Starving	Product Blocking	Worker Blocking	Idle Frequency	Starving	Product Blocking	Worker Blocking
W1	0.01	6.9	0.8	7.71	0%	89%	10%
W2	0.45	5.93	0.76	7.14	6%	83%	11%
W3	1.16	6.88	1.17	9.21	13%	75%	13%
W4	0.65	0.21	0.02	0.88	74%	24%	2%
Total	2.27	19.92	2.75	24.94			

(d) Configuration (1.3) under deployment rule 2

	Frequency				Percentage		
	Starving	Product Blocking	Worker Blocking	Idle Frequency	Starving	Product Blocking	Worker Blocking
W1	0	11.6	0.36	11.96	0%	97%	3%
W2	0.21	3.27	0.66	4.14	5%	79%	16%
W3	5.72	10.9	1.25	17.87	32%	61%	7%
W4	2.44	0.13	0.11	2.68	91%	5%	4%
Total	8.37	25.9	2.38	36.65			

(e) Configuration (1.4) under deployment rule 2

	Frequency				Percentage		
	Starving	Product Blocking	Worker Blocking	Idle Frequency	Starving	Product Blocking	Worker Blocking
W1	0.08	44	3.31	47.39	0%	93%	7%
W2	0.37	32.1	2.09	34.56	1%	93%	6%
W3	0.95	0	0	0.95	100%	0%	0%
W4	0.2	0.36	0.12	0.68	29%	53%	18%
Total	1.6	76.46	5.52	83.58			

(f) Configuration (1.5) under deployment rule 2

	Frequency				Percentage		
	Starving	Product Blocking	Worker Blocking	Idle Frequency	Starving	Product Blocking	Worker Blocking
W1	0	2.29	0.26	2.55	0%	90%	10%
W2	0.06	2.25	0.26	2.57	2%	88%	10%
W3	3.22	0.05	0.33	3.6	89%	1%	9%
W4	3.35	0.06	0.35	3.76	89%	2%	9%
Total	6.63	4.65	1.2	12.48			

(g) Configuration (1.6) under deployment rule 2

	Frequency				Percentage		
	Starving	Product Blocking	Worker Blocking	Idle Frequency	Starving	Product Blocking	Worker Blocking
W1	0	0	0	0	0%	0%	0%
W2	0.11	0	0.02	0.13	85%	0%	15%
W3	0.14	0	0.03	0.17	82%	0%	18%
W4	0.15	0	0.03	0.18	83%	0%	17%
Total	0.4	0	0.08	0.48			

(h) Configuration (2.1) under deployment rule 2

	Frequency				Frequency		
	Starving	Product Blocking	Worker Blocking	Idle Frequency	Starving	Product Blocking	Worker Blocking
W1	0	38.8	0	38.8	0%	100%	0%
W2	9.13	33.5	0	42.63	21%	79%	0%
W3	13	29.3	0	42.3	31%	69%	0%
W4	17.4	26.1	0	43.5	40%	60%	0%
W5	22	18.6	0	40.6	54%	46%	0%
W6	37.8	0	0	37.8	100%	0%	0%
Total	99.33	146.3	0	245.63			

(i) Configuration (2.2) under deployment rule 2

	Frequency				Frequency		
	Starving	Product Blocking	Worker Blocking	Idle Frequency	Starving	Product Blocking	Worker Blocking
W1	4.84	43.45	16.45	64.73	7%	67%	25%
W2	11.09	34.36	17.68	63.13	18%	54%	28%
W3	12.83	38.97	18.39	70.19	18%	56%	26%
W4	14.62	45.16	21.08	80.87	18%	56%	26%
W5	16.9	60.61	22.67	100.19	17%	60%	23%
W6	13.69	5.67	14.23	33.59	41%	17%	42%
Total	73.98	228.23	110.5	412.7			

(j) Configuration (3.1) under deployment rule 2

	Frequency				Frequency		
	Starving	Product Blocking	Worker Blocking	Idle Frequency	Starving	Product Blocking	Worker Blocking
W1	0	11.6	6.05	17.65	0%	66%	34%
W2	100	176	93.5	369.5	27%	48%	25%
W3	33.8	12.6	33	79.4	43%	16%	42%
W4	107	119	86.9	312.9	34%	38%	28%
W5	54.9	13.6	46.6	115.1	48%	12%	40%
W6	112	80.5	83.8	276.3	41%	29%	30%
W7	87.1	14.4	66.3	167.8	52%	9%	40%
W8	127	6.42	81.6	215.02	59%	3%	38%
Total	621.8	434.12	497.75	1553.67			

Two worker deployment rules are applied in our study. It will be later indicated that there are interaction effects between worker allocation configurations and worker deployment rules. In general, deployment rule 2, first searching upstream and then downstream, performs better than deployment rule 1. For simplification, for most of the questions, only the results from deployment rule 2 (Up-Down) are presented. Only when we compare the performance of the two deployment rules (see section 4.3), the results from the two deployment rules are presented.

As can be seen in Figure 4.3 (a), the throughput performance improves as the level of cross training increases. In Figure 4.3 (b), worker idle rates decreases with the increase of the level of cross training. When workers are trained for higher level of skills, they have obtained more assignment opportunities, and therefore, the possibilities of becoming idle are reduced. The details regarding starving, product blocking, and worker blocking are provided in Table 4.3 (a), (f), and (g). Figure 4.3 (c) shows that as the level of cross training increases, the number of transfers per worker is increased. This can be explained by the fact that, workers are trained for more skills, they have more places to be assigned to, and more transfers can be realized.

Though the differences in performance are statistically significant, the magnitude of these differences is not very substantial. Indeed, configuration (1.1) has achieved 99.6% of the throughput level of configuration (1.6). In other words, the minimal level of cross training can realize most of the benefits associated with full flexibility. However, it is accompanied by the highest worker idle rates as well. Configuration (1.6) has the highest throughput level and the least worker idle rates, but the highest number of worker transfers as well, whereas configuration (1.5) has all the results in between. It seems that each configuration has its advantages and disadvantages.

The optimal level of cross training may depend upon management considerations. When transfer is the main concern due to the resulted time consumption and the decreased worker efficiency, managers may prefer a lower level of cross training. When managers value worker utilization more, they may choose a higher level of cross training.

4.5.2 Degree of chaining

Research question 2
2a. In comparison with a no-chaining situation, will chaining improve system performance?
2b. Given one skill overlap, will a long chain outperform two short chains?
2c. In the case of multiple skill overlaps, will the performance of long chain differ from two short chains?
2d. Is the effectiveness of chaining related to the level of cross training?

To answer the second set of questions regarding the functioning of chaining, we compare the performance of configurations (1.1), (1.2), (1.3), (1.4), and (1.5) in Figure 4.2 (a).

We first investigate how chaining affects performance by comparing a chained configuration (1.2) with a non-chained configuration (1.1). After that, for the one-skill overlap situation, we compare the long chain configuration (1.2) with the two short chain configuration (1.3). Next, for the multiple-skill overlap situation, we compare the long chain configuration (1.4) and the two short chain configuration (1.5). Finally, by comparing the performance of the one skill overlap configurations ((1.2), (1.3)) and the multiple skill overlap configurations ((1.4), (1.5)), we examine whether the effectiveness of chaining depends on the skill overlaps, which results from the increased level of cross training.

4.5.2.1 Question 2a

2a. In comparison with a no-chaining situation, will chaining improve system performance?

To examine in comparison with a non chained configuration how chaining affects performance, we compare configurations (1.2) and (1.1) of Figure 4.2 (a). In configuration (1.1), a worker is trained for three skills, and there is no skill overlap between workers. In configuration (1.2), a worker is trained for four skills, and one skill overlap is formed between neighbouring workers.

Chaining and the level of cross training are two worker flexibility issues, which are closely related to each other. From no chaining to chaining, one more skill has to be first developed, and then, this increased skill should be allocated properly. Theoretically, it is better to separate chaining and cross training as much as possible to isolate their effects, but in reality, their effects are intermingled to some extent, and it is difficult to segment them completely. For example, in a real life situation, the line managers may keep each worker in his own section or may allow workers to help each other at neighbouring stations. To understand how such changes may affect system performance is important for making proper decisions.

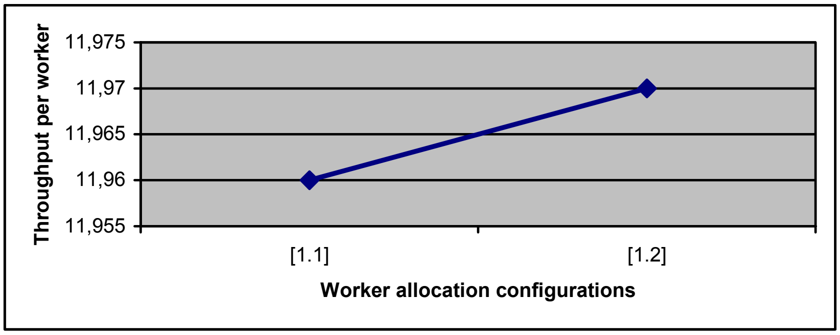
Figure 4.4 shows that configuration (1.2) outperforms configuration (1.1) on all the performance indicators, a higher throughput rate, a lower worker idle rate, and a lower number of worker transfers. In other words, in comparison to no chaining, chaining (i.e., a long chain with one skill overlap) leads to performance improvement in all the respects.

The improvement of configuration (1.2) may be due in part to the increased level of cross training. In configuration (1.2), worker 1 is trained for one more station, which means one more assignment opportunity, and the chances of being starved or blocked by products are therefore reduced to a certain extent. For example, when stations 1, 2, and 3 are all blocked as all the buffers and stations are occupied by the finished jobs, worker 1 may still be able to be assigned to station 4. In contrast, if the same situation occurs in configuration (1.1), he will become idle.

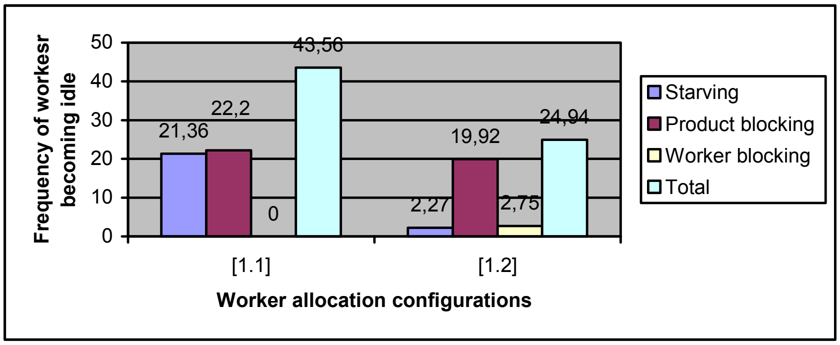
The skill overlap with a neighbour downstream may also play an important role. For example, worker 1 has an overlap with his neighbour downstream. Being able to work on station 4, worker 1 helps to move products down the line. The overlaps between workers 2 and 3, and workers 3 and 4, have the same function. As can be seen in Table 4.3 (a) and (c), upstream workers suffer slightly less from product blocking, and because products are moving smoothly downstream, downstream workers have significantly less chances of being starved. On the whole, the chances of becoming idle because of starving and product blocking are reduced.

One negative aspect of skill overlap is that a worker may be blocked by other workers, who are busy at the sharing stations. For example, it may happen that worker 4 is working on station 1, worker 2 occupies station 4, and stations 2 and 3 are blocked by products or starved, then worker 1 will become idle.

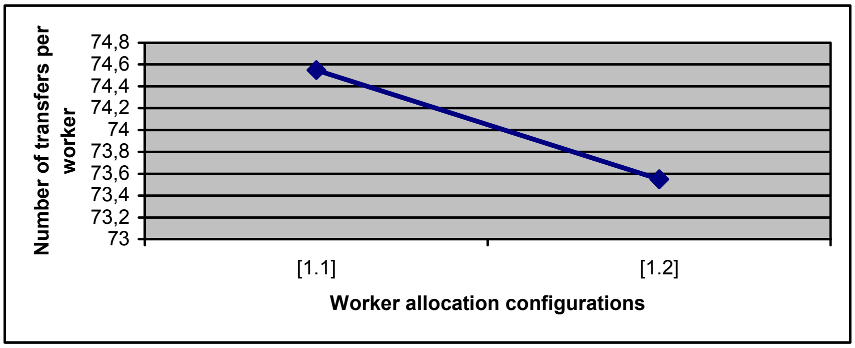
Overall, in configuration (1.2), the reduction in product blocking and starving seem to outweigh the increase in worker blocking, and consequently, the total frequency of a worker becoming idle is lower than in configuration (1.1), which in turn contributes to a higher output rate.



(a). Throughput per worker



(b). Worker idle rates



(c). Number of transfers per worker

Figure 4.4 The performance of chaining versus no chaining under deployment rule 2
Configuration [1.1], no chaining
Configuration [1.2], a long chain with one skill overlap

Configuration (1.2) yields a lower number of worker transfers than configuration (1.1) (see Figure 4.3(c)). This is due to skill overlaps between neighbouring workers. In particular, skill overlaps increase the chance that a worker can continue working on a station because of the increased chances that other workers will fill the input buffer of the stations or empty the input buffer of the next station.

The results suggest that configuration (1.2) is rather beneficial. Though the magnitude of the improvement in throughput is not substantial, the decrease in worker idle rates is more important, given their positive impacts on worker behaviours and worker efficiency. Additionally, the number of worker transfers is also decreased to a limited extent.

4.5.2.2 Question 2b

2b. Given one skill overlap, will a long chain outperform two short chains?

To explore the effectiveness of chaining in the one skill overlap situation, we compare the performance of configurations (1.2) and (1.3), a long chain versus two short chains.

Figure 4.5 shows that configuration (1.2) performs better than configuration (1.3) on throughput and worker idle rates, but not on the number of worker transfers. In other words, a long chain yields higher productivity and worker utilization, but at a price of a higher number of worker transfers.

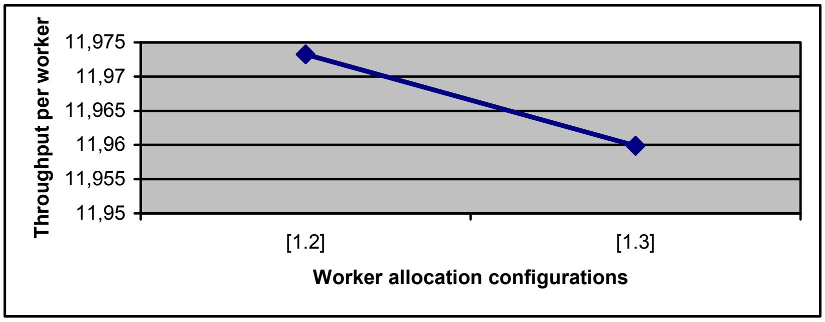
We first look at the differences in worker idle rates. The related information is presented in Table 4.3 (c) and (d). As mentioned earlier, in configuration (1.2), each worker has one skill overlap with his downstream neighbour. This helps to bring products downstream, and consequently, reduces product blocking upstream. As products move smoothly downstream, starving downstream is also alleviated.

Nevertheless, a long chain involves more workers in the competition for the shared stations. For example, at the first six stations, three workers compete for stations 1 and 4, which result in slightly higher chances of worker blocking. As can be seen in Figure 4.5 (b), configuration (1.2) has a worker blocking rate 2.75, which is higher than 2.38 of configuration (1.3).

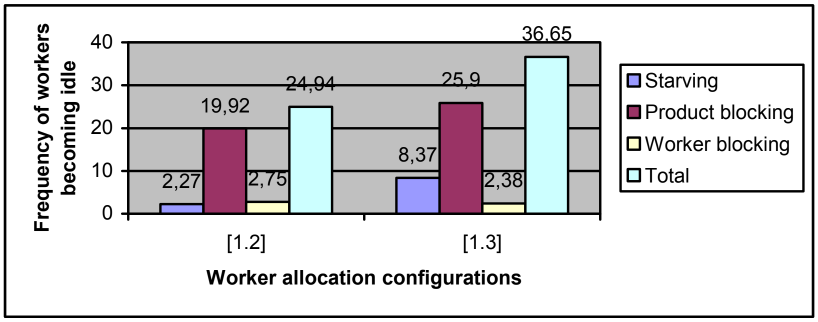
On the whole, the reduction in starving and product blocking compensates the increase in worker blocking, and consequently, configuration (1.2) has a lower total worker idle rate, which leads to a higher throughput rate.

In contrast, in configuration (1.3), one skill overlap is missing in the middle of the line. In particular, worker 2 does not have a skill overlap with his downstream neighbour. Instead of working at station 4 to help move products down stream, worker 2 is now sometimes busy at station 1, bringing more products into the line. Consequently, products may block stations upstream, and as products cannot move downstream smoothly, stations downstream may suffer more frequently from starving. In other words, the frequencies of starving and product blocking have both been driven up by the missing of skill overlap in the middle of the line. Yet a short chain has one advantage over a long chain in a sense that fewer workers are involved in the competition for the shared stations. For example, at the first six stations, two workers compete for stations 1 and 4, there are less chances of worker blocking. Overall, the increase in starving and product blocking outweighs the decrease in worker blocking, and configuration (1.3) ends up with a higher total worker idle rate, which corresponds to a lower throughput rate.

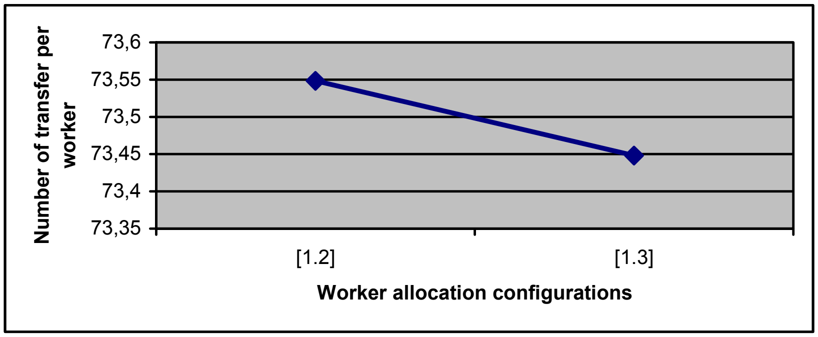
The differences in the number of transfers between a long chain and two short chains can be explained as follows. In a long chain there are more options for workers to move around. For example, in configuration (1.2), worker 2 shares station 4 with worker 1, and station 7 with worker 3. Worker 1 has three stations, i.e., stations 1, 2, and 3, to work on, which keeps him away from the shared station 4. So does worker 3. As a result, worker 2 has more chances of realizing his transfer in his own section. In contrast, in configuration (1.3), worker 2 shares stations 1 and 4 with worker 1. Worker 1 has only two stations in which he can move away from the shared stations with worker 2. Consequently, worker 2 may have high chances of running into worker 1 at the shared stations, and less chances of realizing his transfer.



(a) Throughput per worker



(b) Worker idle rates



(c) Number of transfer per worker

Figure 4.5 The impact of chaining, a long chain versus short chains, with one skill overlap and under deployment rule 2
Configuration [1.2], a long chain
Configuration [1.3], two short chains

The results suggest that when there is one skill overlap, a long chain is beneficial in terms of a higher throughput and lower worker idle rates. Lower worker idle rates help to reduce worker frustration and stress. However, a long chain also yields a higher number of worker transfers, which may have negative impacts on the system performance due to resulted transfer times and decreased worker efficiency. As such, the long chain configuration should be used cautiously.

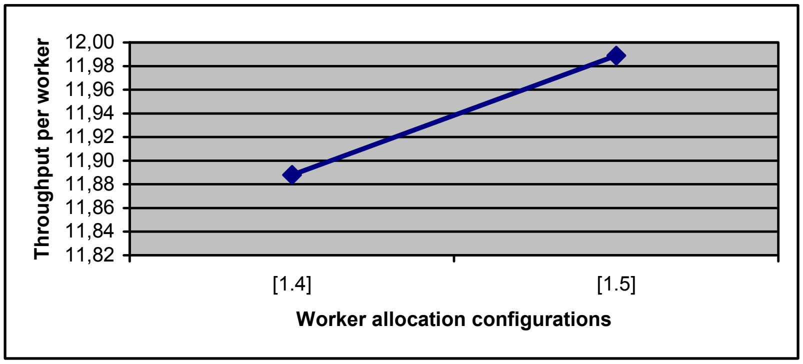
4.5.2.3 Question 2c

2c. In the case of multiple skill overlaps, will the performance of long chain differ from two short chains?

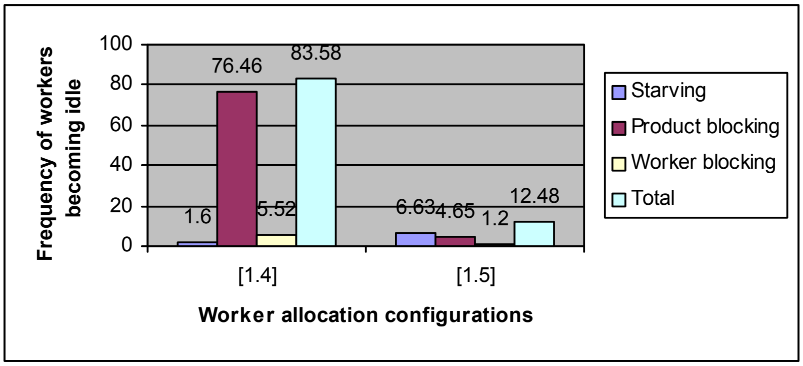
To understand how chaining affects performance in the multiple skill overlap situation, we compare the performance of configurations (1.4) and (1.5), a long chain versus two short chains.

Figure 4.6 demonstrates that the configuration (1.5) results are significantly better for all the performance criteria, a higher throughput, a lower worker idle rate, and a lower number of worker transfers. In other words, when there are multiple skill overlaps, two short chains outperform a long chain in all the respects.

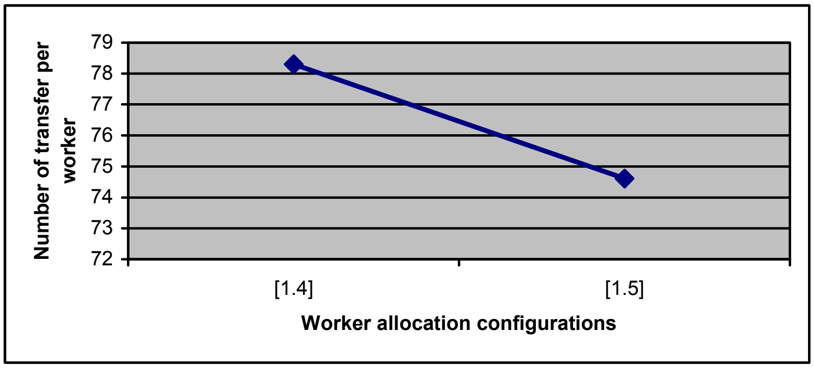
We first analyse the differences in worker idle rates. The related information can be found in Table 4.3 (e) and (f). Configuration (1.4) has a significantly higher frequency of product blocking. It can be explained as follows. In configuration (1.4), worker 1 is assigned to the first six stations, but he shares the first three with worker 4, and the last three with worker 2. In other words, three workers share the first six stations. These three workers may happen to work on the stations subsequently next to each other. By the time they complete their tasks, the finished products may not be able to pass down the line, and block these stations. As posted earlier, upstream stations suffer more from product blocking, and workers 1 and 2 spend most of their times upstream. Therefore, the possibilities that workers 1 and 2 are blocked by the finished products are largely increased, as shown in Table 4.3 (e). In addition, configuration (1.4) has a slightly higher worker blocking frequency because three workers compete for the shared stations. One the whole, configuration (1.4) has a significantly higher worker idle rate, which explains its lower throughput.



(a) Throughput per worker



(b) Worker idle rates



(c) Number of transfer per worker

Figure 4.6 The impact of chaining, a long chain versus short chains, with multiple skill overlaps and under deployment rule 2
Configuration [1.4], a long chain
Configuration [1.5], two short chains

In contrast, in configuration (1.5), since two workers share six stations, the chances that three workers work on the stations subsequently next to each other are lower, which in turn leads to less chances of product blocking. Yet the chances of starving are slightly higher due to the missing of skill overlap in the middle of the line. Additionally, two workers compete for the shared stations, which results in a lower worker blocking frequency. Overall, configuration (1.5) has a significantly lower worker idle rate, which results in a relatively better performance.

Configuration (1.4), the long chain, has a higher number of worker transfers. The explanation is similar to a long chain with one skill overlap. Basically, a long chain offers workers more options to move around.

The results suggest that when there are multiple skill overlaps, it is better to form several short chains instead of one long chain, in such a way to avoid unnecessary worker interference and transfers.

4.5.2.4 Question 2d

2d. Is the effectiveness of chaining related to the level of cross training?

The results of research question 2b indicate that when there is one skill overlap, a long chain performs better than two short chains in terms of higher productivity and worker utilization, but at a price of a higher number of worker transfers. The results of research question 2c show that when there are multiple skill overlaps, two short chains outperform a long chain in all the respects. It suggests that the effectiveness of chaining is related to the level of cross training. A long chain performs better when there is one skill overlap, but short chains provide a better performance when there are multiple skill overlaps.

4.5.2.5 Summary

In this sub-section, we first examined how chaining improves performance by comparing a chained configuration (1.2) with a non-chained configuration (1.1). After that, we explored the effectiveness of chaining, in a one-skill overlap situation by comparing a long chain, configuration (1.2), and two short chains, configuration (1.3); and in a multiple-skill overlap situation by comparing a long chain, configuration (1.4), and two short chains, configuration (1.5). The impacts on performance have evaluated from three perspectives, throughput, worker idle rates, and the number of worker transfers.

The results indicate that, when there is no chaining at all, a small degree of chaining might be beneficial in terms of a higher throughput, a lower worker idle rate, and a lower number of worker transfers. In other words, the introduction of a small amount of skill overlaps among neighbouring workers may help to improve performance in all the aspects.

It is most likely that the effectiveness of chaining is contingent upon the level of skill overlaps. A long chain performs better when there is one skill overlap, but worse when there are multiple skill overlaps, in terms of throughput and worker idle rates. However, a long chain is always associated with a higher number of worker transfers, regardless of the level of skill overlaps.

Our finding differs from the results from previous research (Jordan and Graves 1995, Brusco and Johns 1998, Slomp and Molleman 2002, Bokhorst and Slomp 2000, Hopp et al. 2004, and Inman et al. 2004), which indicated that chaining always leads to a better performance, and a long chain performs better than short chains. As indicated earlier, these previous research were conducted in a low task interdependent environment, whereas our study assumed a high task interdependent context.

Our finding is somehow consistent with team theory, which indicates that the optimal team size depends on the characteristics of team tasks, and if workers are highly interdependent, a small team is preferred (Wilke and Meerten 1994). Here in our study, the overlap of skills can be considered as an indicator for task interdependence, and a small team corresponds to a short chain.

In general, the differences in throughput between the five worker allocation configurations studied in this subsection are not really substantial, though they are statistically significant. Therefore, the impacts of the human related indicators should be carefully considered when making decisions.

4.5.3 Worker deployment rules

Research question 3:
How should workers be deployed? When a worker finishes his task at a station, how should he select the next station? To which direction, upstream or downstream, should the worker start searching?

We proposed two deployment rules. In rule 1 (Down-Up), when a worker is finished at a station, he/she first searches for the available station in the direction of downstream, and if no station is available, he/she starts searching upstream. Rule 2 (Up-Down) follows the opposite order. Rule 1 is similar to pulling, which is prioritised in getting jobs out of the system, and yields a low WIP level. Rule 2 is like pushing, which aims to bring more jobs into the system, and results in a high WIP level. In a DRC assembly line, a high level of WIP may cause product blocking, but a low level of WIP may let workers suffer from starving. How the two deployment rules affect the line performance is still not clear.

To reflect the impact of worker deployment rules on the line performance in general, we averaged the performance indicators over the six worker allocation configurations for each given station-to-worker ratio (see Figure 4.2). To be more specific, we took the average of the throughput per worker, worker idle rates, WIP, and the number of transfers per worker. Doing so will help us understand how worker deployment rules affect the overall performance of worker allocation configurations under various station-to-worker ratios.

Figure 4.7 (a) indicates that deployment rule 2 outperforms deployment rule 1 in terms of higher throughput rates at various levels of station-to-worker ratio. Deployment rule 2 also corresponds to a higher WIP level, as shown in Figure 4.7 (b). It implies that a DRC assembly line performs better at a higher WIP level.

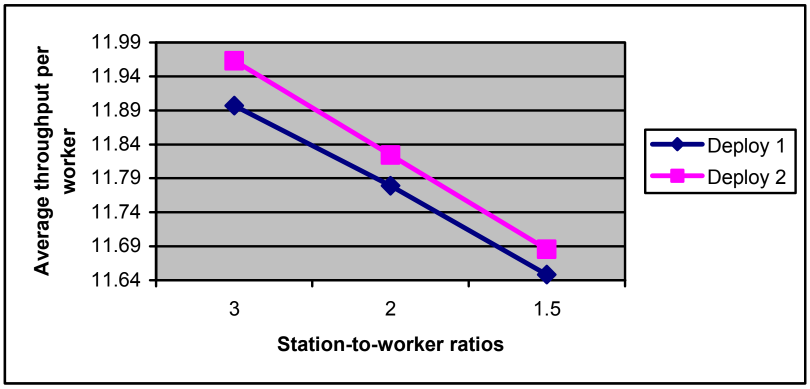
Deployment rule 2 has lower worker idle rates for the three station-to-worker ratios, as shown in Figure 4.7 (c). The explanation can be found in Figure 4.7 (d). Deployment rule 1 is associated with a higher starving rate and a higher worker blocking rate, but a lower product blocking rate. Under deployment rule 1, there is less WIP in the line, and workers have higher chances of becoming starved. When a product appears on the shared stations, the starved workers will compete for the only job opportunity, and as a result, one worker gets the job, while the others become blocked. In other words, worker blocking rates have been driven up by starving. Of course, when there is less WIP in the line, the chances of product blocking is reduced. Overall, the decrease in product blocking cannot compensate the increase in starving and worker blocking, which results in a higher worker idle rate for deployment rule 1.

Figure 4.7 (e) shows that deployment rule 2 has a higher level of worker transfers, especially for the lower station-to-worker ratios (i.e., station-to-worker ratios 2 and 1.5). When there is less starving under deployment rule 2, workers have more places to be assigned to, and more transfers can be realized. At the low station-to-worker ratios, since fewer stations are available for workers, the availability of jobs becomes more important. Deployment rule 2 becomes more useful, as it brings more jobs into the line. This explains the increased differences in number of transfers between the two deployment rules for the lower station-to-worker ratios.

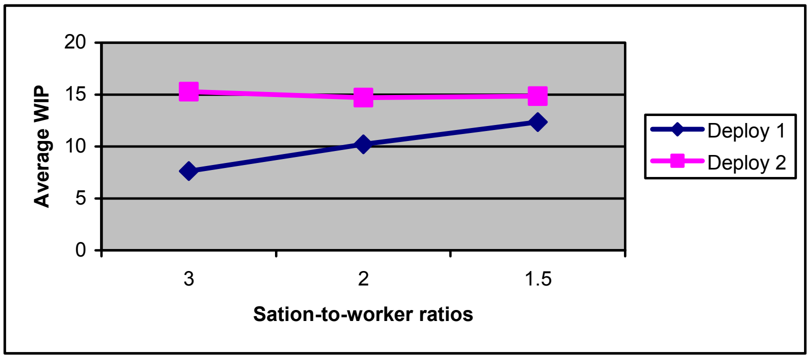
Foregoing indicates that deployment rule 2 performs significantly better than deployment rule 1. However, there is one exception. There are some worker allocation configurations, which provide the same performances under the two deployment rules. These configurations are the ones with the minimal level of cross training, namely, configuration (1.1) in Figure 4.2 (a), configuration (2.1) in Figure 4.2 (b), configuration (3.1) in Figure 4.2 (c).

Figure 4.8 indicates that these configurations perform equally in terms of throughput level as well as the number of worker transfers under the two deployment rules. In other words, the two deployment rules do not make any differences in the performance of these configurations. When a worker is trained for the minimal number of skills, he can be assigned to a limited number of stations. For example, in our study, we assumed station-to-worker ratios 3, 2 and 1.5. In such cases, a worker does not have many choices to make when searching for the available stations. In other words, searching direction does not play an important role.

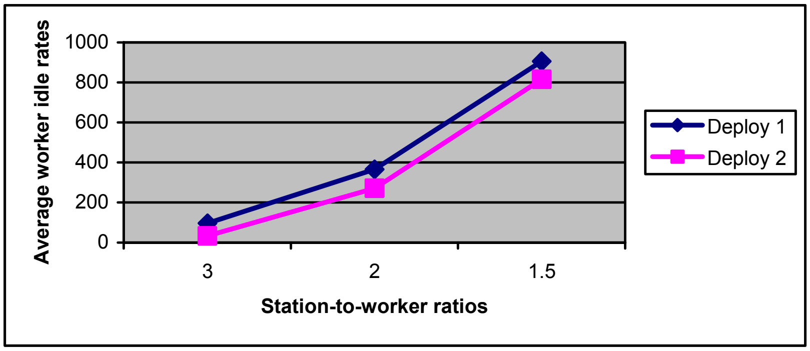
To sum up, in a DRC assembly line, sending worker upstream brings more jobs into the line and raises WIP level, which in general leads to improvement in performance in all the respects. There is one exception. When workers are trained for the minimal level of cross training, and there are no overlaps of skills, which direction to start searching for the next job does not make any differences in performance.



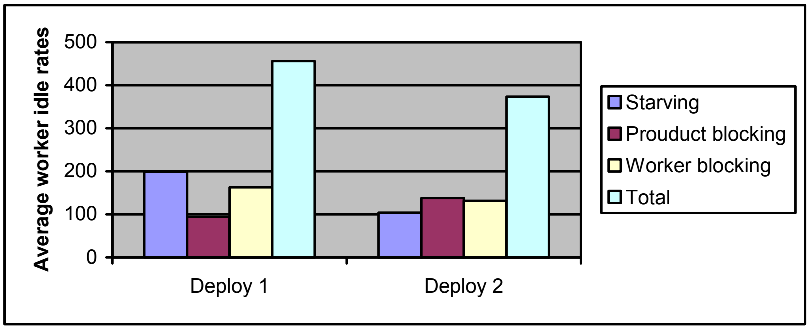
(a) Average throughput per worker at various station-to-worker ratios



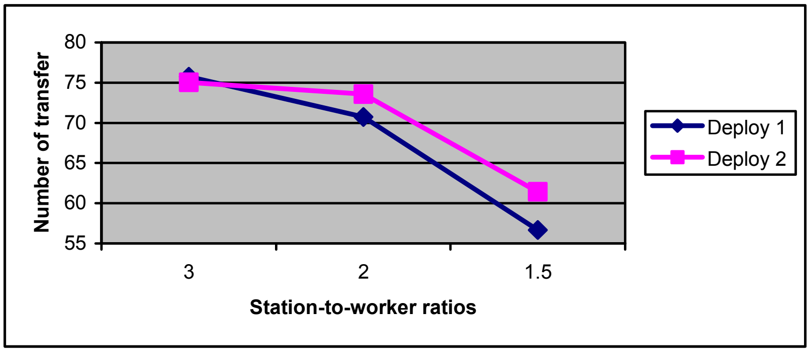
(b) Average WIP at various station-to-worker ratios



(c) Average worker idle rates at various station-to-worker ratio

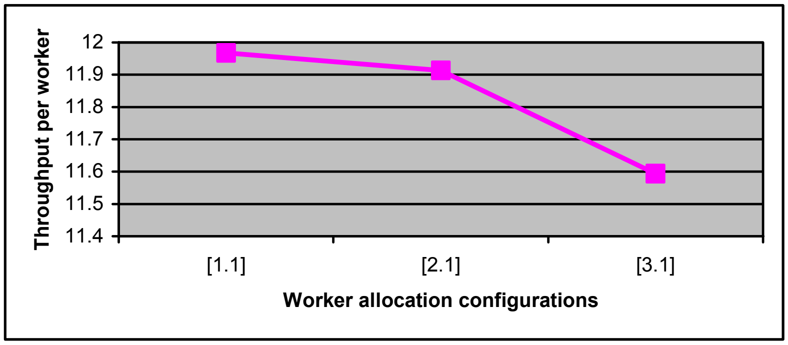


(d) Average starving, product blocking, and worker blocking rates under two deployment rules

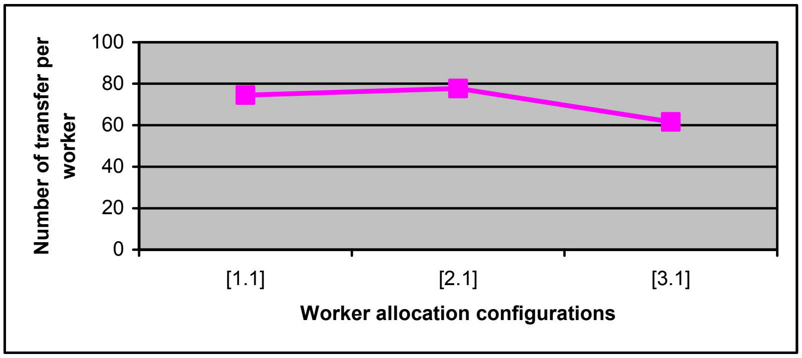


(e) Average number of transfer per worker at various station-to- worker ratios

Figure 4.7. The impact of worker deployment rules on throughput per worker, worker idle rates, the number of transfer per worker, and WIP



(a) Throughput per worker under two deployment rules 1 and 2



(b) Number of transfer per worker under two deployment rules 1 and 2

Figure 4.8. The impact of worker deployment rules for the worker allocation configurations with minimal level of cross training

4.5.4 Station-to-worker ratios

Research question 4:
4a. What is the impact of station-to-worker ratios on system performance?
4b. Does the impact of cross training on system performance vary with station-to-worker ratios?
4c. Does the effectiveness of chaining differ under various station-to-worker ratios?
4d. Do worker deployment rules perform in the same way under a variety of station-to-worker ratios?

The station-to-worker ratio is a primary parameter, which determines the competition intensity for stations in a DRC assembly line. It is expected to have impacts on many aspects of the line, such as the overall system performance, the effectiveness cross training and chaining, as well as the relevance of specific worker deployment rules. Below examines how each of these aspects is affected by station-to-worker ratios.

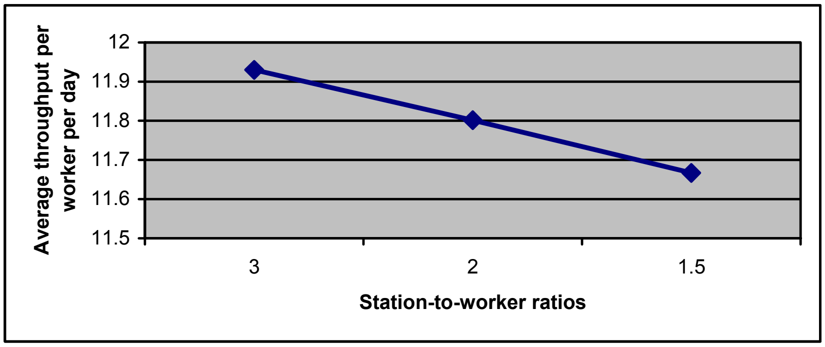
4a. What is the impact of station-to-worker ratios on system performance?
To evaluate the overall impact of station-to-worker ratios on system performance, we take the average over the six configurations of each station-to-worker ratio under two deployment rules.

The average throughput per worker decreases with the reduction of station-to-worker ratios, as shown in Figure 4.9 (a). It suggests that a DRC assembly line provides a better throughput performance at a lower staffing level.

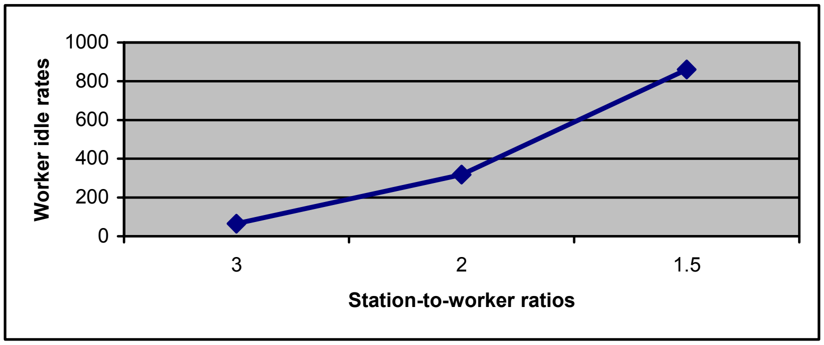
The average worker idle rates increase with the reduction of station-to-worker ratios, as indicated in Figure 4.9 (b). It implies that when the line gets more crowded, workers more often interfere with each other. Figure 4.9 (c) makes clear that all the sub-indicators, starving, product blocking, and worker blocking, increase substantially with the decrease of station-to-worker ratios.

The average number of worker transfers decreases with the decrease of station-to-worker ratios, as demonstrated in Figure 4.9 (e). It suggests that as the station-to-worker ratio decreases, the line becomes more crowded, and workers have fewer opportunities to move freely.

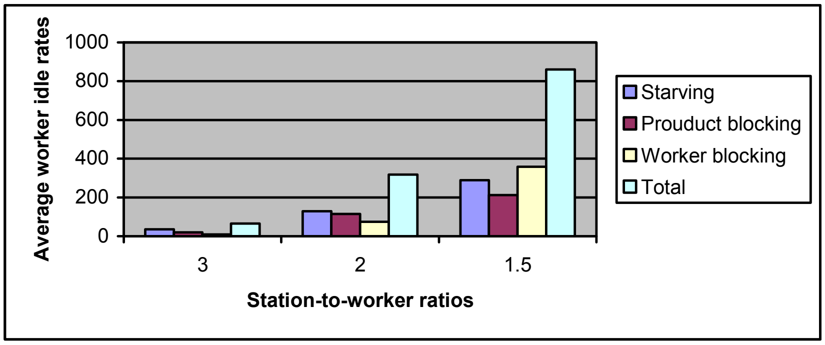
In general, a high station-to-worker ratio is beneficial in terms of higher throughput, lower worker idle rates, and a higher number of worker transfers.



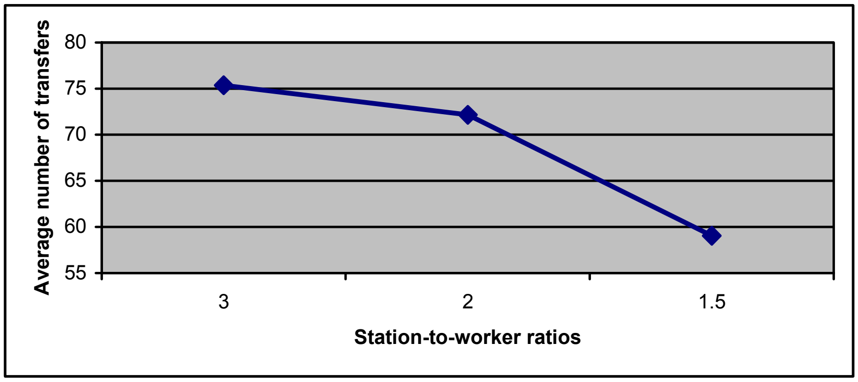
(a) Average throughput per worker over the six worker allocation configurations at various station-to-worker ratios



(b) Average worker idle rates over the six worker allocation configurations at various station-to-worker ratios



(d) Average starving, product blocking, and worker blocking rates over the six worker allocation configurations at various station-to-worker ratios



(e) Average number of transfers over the six worker allocation configurations at various station-to-worker ratios

Figure 4.9 The impact of station-to-worker ratios on the overall performance

4b. Does the impact of cross training on system performance vary with station-to-worker ratios?

As indicated earlier, deployment rule 2 gives better performance, and therefore, we assume that it will be adopted by the assembly line. When evaluating the impact of station-to-worker ratios on the performance of the level of cross training, for simplification, we only present the results of deployment rule 2.

As can be seen in Figure 4.10, in general, the minimal level of cross training has achieved a reasonable throughput level under various levels of station-to-worker ratio (see configurations (1.1), (2.1) and (3.1)). The reason can be explained as follows. In a DRC assembly line, there are more stations than worker. When workers are trained for a minimal level of skills, each of them has several stations to work on, and they are kept busy most of the time. The results suggest that in a DRC assembly line with small buffers between stations, though the number of workers may vary with changes in demand, in most of the cases, to train workers with the minimal level of skills and to let them have their own territory seem to be a good option.

The marginal increase of cross training (i.e. configuration (1.2)), when forming a long chain, may slightly improve throughput level, as compared with the minimal level of cross training (i.e., configuration (1.1)). However, this may only hold for a high station-to-worker ratio, i.e., three stations per one worker, and with deployment rule 2. In contrast, at a low level of station-to-worker ratio, the marginal increase of cross training (i.e., configurations (2.2) and (3.2)), may actually deteriorate throughput level due to the increased competition for stations.

The difference in the performance of the marginal increase of cross training between the high and low station-to-worker ratios can be explained as follows. At a high station-to-worker ratio, sharing one station with a neighbour downstream helps to pass products down the line, and consequently, reduces the chance of starving at downstream stations (see Figure 4.4). Because a worker has several stations to work on, the competition for the shared station is less intensive than in the case of lower station-to-worker ratio, and therefore, worker blocking rates remain at a limited level. Overall, the decrease at the starving rate outweighs the increase in worker blocking, and consequently, worker idle rates are reduced, which in turn leads to a higher throughput level.

At a lower station-to-worker ratio, sharing one station with a neighbour downstream still reduces starving rates (see Figure 4.11). As a worker has fewer stations to work on, the competition for the shared station is more intensive than in the case of a higher station-to-worker ratio, and therefore, worker blocking rates have been largely increased. Furthermore, workers have more chances of working next to each other, and the finished products may not be able to move smoothly down the line, which causes more product blocking. On the whole, the increase in worker blocking and product blocking prevails over the reduction in starving, and as a result, worker idle rates have been substantially increased, which in turn leads to a decrease in throughput level.

A relatively high level of cross training (i.e., configurations (1.5), (2.5), and (3.5)) yields a higher throughput level at various levels of station-to-worker ratio. At a relative high level of cross training, workers get more assignment opportunities, and are better utilized. In addition, a worker shares several stations with others, and the competition for the shared stations is less intensive than in the case of only one shared station.

To sum up, it seems that the effectiveness of cross training is partially sensitive to station-to-worker ratios. In particular, the minimal level of cross training and the high level of cross training perform well at various levels of station-to-worker ratios. In other words, they are not sensitive to station-to-worker ratios. In contrast, the marginal level of cross training is sensitive to station-to-worker ratios. To be more specific, it performs well at a high level of station-to-worker ratio, but badly at a low level of station-to-worker ratio.

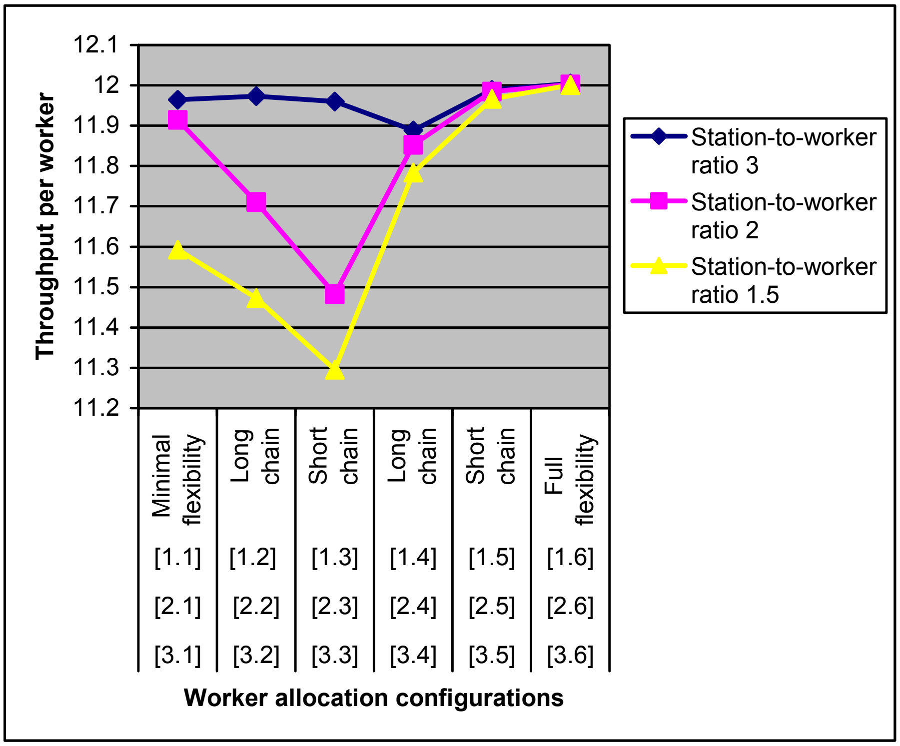
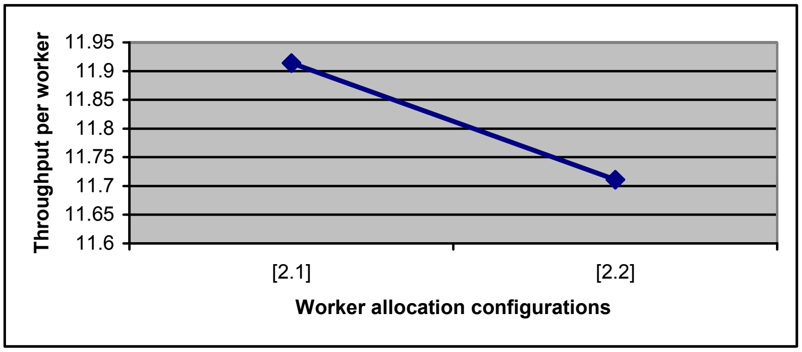
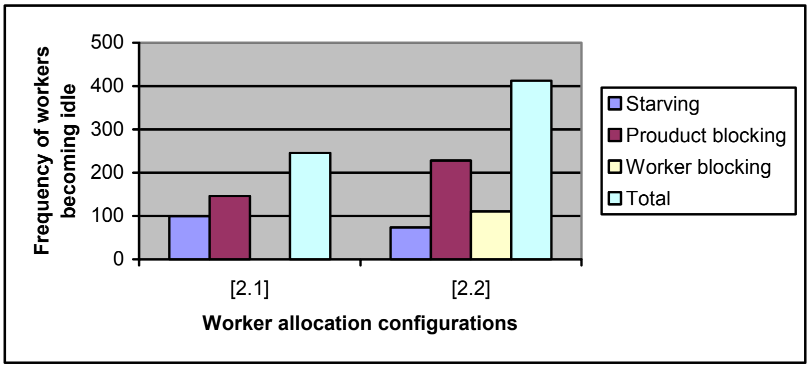


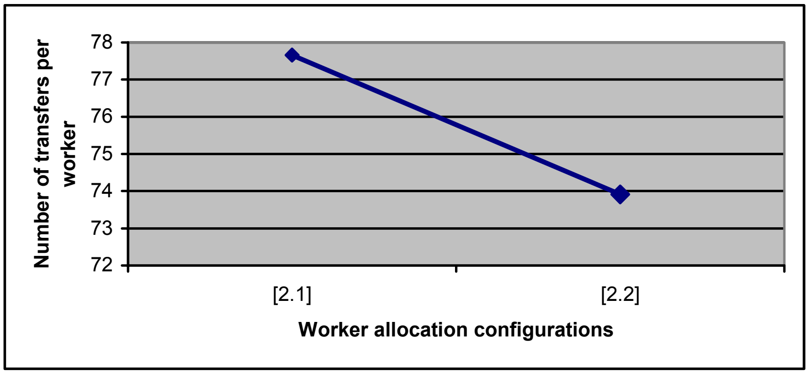
Figure 4.10 Throughput rates of worker allocation configurations at various station-to-worker ratios under deployment rule 2



(a) Throughput per worker



(b) Worker idle rates



(c) Number of transfers per workers

Figure 4.11 Station-to-worker ratio 2.
Configuration [2.1], no chaining,
and [2.2], a long chain with one skill overlap,
under deployment rule 2.

4c. Does the effectiveness of chaining differ under various station-to-worker ratios?

The degree of chaining is not sensitive to station-to-worker ratios in terms of throughput per worker, as indicated in Figure 4.10. In other words, regardless of station-to-worker ratios, with one skill overlap, one long chain always performs better than two short chains (i.e., configurations (1.2) versus (1.3); (2.2) versus (2.3); and (3.2) versus (3.3)), whereas with multiple skill overlaps, two short chains always outperform one long chain (i.e., configurations (1.5) versus (1.4); (2.5) versus (2.4); and (3.5) versus (3.4)).

The degree of chaining is also not sensitive to the station-to-worker ratio in terms of the number of worker transfers, as shown in Figure 4.12. In other words, it holds for various station-to-worker ratios, that one long chain involves more worker transfers, whereas short chains entail fewer worker transfers (i.e., configurations (1.2) versus (1.3); (2.2) versus (2.3); and (3.2) versus (3.3); (1.4) versus (1.5); (2.4) versus (2.5); and (3.4) versus (3.5)).

4d. Do worker deployment rules perform in the same way under a variety of station-to-worker ratios?

When the station-to-worker ratio decreases, there are less available stations for a worker to choose, and we expect that worker deployment rules will become less active. Figure 4.7 (a) indicates that the difference in throughput per worker between the two deployment rules decreases slightly with the decrease in the station-to-worker ratio. Figure 4.7 (b) demonstrates that the difference in WIP between the two deployment rules reduces more obviously as the station-to-worker ratio decreases. The results suggest that if there are a few workers in the line, it is important to send a worker to the right direction by the time he finishes his job. However, when the line is crowded with workers, searching direction does not matter that much any more.

Conversely, the differences in the number of transfers per worker increase with the decrease of the station-to-worker ratio, as shown in Figure 4.7 (e). For example, when station-to-worker ratio is 3, deployment rules 1 and 2 have almost the same number of transfers. At station-to-worker ratio 1.5, the number of worker transfers is higher for deployment rule 2. It seems that when the line is crowded with workers (i.e., station-to-worker ratio 1.5), the number of transfers is more dependent upon the level of WIP. When there is more WIP (i.e., deployment rule 2) in the line, more transfers can be realized.

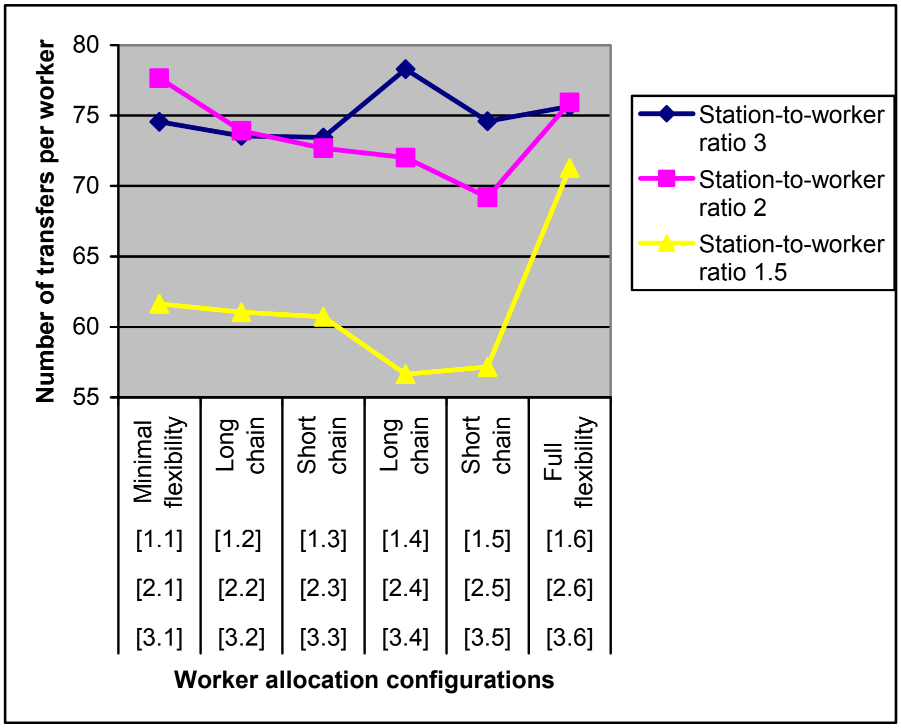


Figure 4.12 Number of transfer per worker for worker allocation configurations at various station-to-worker ratios under deployment rule 2

4.6 Discussion and conclusions

This study addressed worker flexibility issues in a particular DRC assembly line. The line has a relatively high task interdependency due to the lack of resource duplication and small buffer sizes. A survey of literature made clear that in case of low task interdependency, increasing cross training and creating skill overlaps across stations would improve shop performance.

Our results indicate that in a highly task interdependent context, cross training and chaining may entail some negative consequences, such as starving, product blocking, and worker blocking, which in turn counteract their benefits.

Our results show that in a DRC assembly line, a minimal level of cross training may provide most of the benefits of full flexibility. Furthermore, the impact of chaining on throughput performance seems to be contingent upon the level of skill overlaps, which results from the increase of cross training. For one skill overlap, a long chain may be valuable, but for multiple skill overlaps, short chains may be preferable. In contrast, the impact of chaining on the number of worker transfers seems not to be dependent upon the level of skill overlaps. A long chain always has a higher number of worker transfers, whereas short chains have a lower number of worker transfers, regardless of the level of skill overlaps. Moreover, a DRC assembly line seems to perform better at a relative high WIP level, which is determined by the worker deployment rule that puts its priority upstream. Finally, system performance and the impact of worker deployment rules diminish with the decrease of station-to-worker ratio.

Our results have important managerial implications. In a highly task interdependent DRC assembly line, how to avoid unnecessary worker interference should be an important concern. Small teams with a minimal level of cross training may be a good choice. If it is possible, to maintain a high station-to-worker ratio by assigning fewer workers to a line helps to increase the system output rate per worker. The concept of chaining is not always beneficial, and it should be used judiciously.

Our findings contribute to the team theory by elaborating task interdependence in a DRC assembly line. It is established in the previous literature that task interdependence is affected by shop layout. Our results suggest that worker flexibility policies may have impact on the degree of task interdependence as well. To be more specific, our results indicate that the level of cross training and the degree of chaining are both positively related to task interdependence.

When workers are trained for a minimal level of skills and there is no skill overlap and there are no shared stations, a worker has his own territory and will not conflict directly with others. The output of an upstream worker will be the input of his downstream neighbour, and in this case, the task interdependence is ‘sequential’.

When workers are trained for a high level of skills and there are multiple skill overlaps, workers directly compete with each other for the shared stations. The outputs of each worker become inputs for the others, the task interdependence becomes ‘reciprocal’.

Chaining involves more workers in the competition for the shared stations, causing more blocking by workers, and as such, leads to increased task interdependence. Our results demonstrate that a long chain is always associated with a higher worker blocking rate. Here, a worker blocking rate directly indicates how often workers encounter each other at the shared stations.

Team theory suggests that 'reciprocal' interdependence is stronger than 'sequential', and as task interdependence increases, it becomes more difficult to coordinate and more costly to coordinate. Our results show that the minimal level of cross training has a lower worker idle rate and a higher throughput level than the higher level of cross training. This implies that with the introduction of additional task interdependency and the absence of appropriate coordination rules, the performance of the system may deteriorate despite of the increased level of cross training. Managers who are interested in the benefits of cross training should also be aware of the possible negative impacts on task interdependency. The utilization of proper coordination rules may reduce worker interference and improve performance, and requires further investigation.

In our study, workers may become idle because of three reasons: starving, product blocking, and worker blocking. We believe that these three causes may have different impact on worker stress and frustration. Future research may pay more attention to how workers react to each of these situations.