Analyzing Kanban and CONWIP controlled assembly systems

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Submitted to the Graduate School of Systems and Information Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science in Policy and Planning Sciences

at the University of Tsukuba

January 2006
ABSTRACT

There exists controversy on the superiority of logistics control systems. CONWIP and Kanban systems are focused on and analyzed in this thesis. CONWIP is a well-known production control system, and some papers have shown it has better performance than a Kanban system. Our research shows that the Kanban system is more flexible for the assembly system under concern with respect to a given objective than CONWIP system. We examine single-product assembly systems with unlimited demand at the end of the assembly line. In some cases, if the number of kanbans at each manufacturing/assembling station is optimally set, the Kanban system outperforms CONWIP system with a lower average WIP and the same level of throughput. That is, the distribution of kanbans can be an important design parameter of the system.
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CHAPTER 1
INTRODUCTION

1.1 Introduction

This thesis makes some comparison between Kanban and CONWIP system, both of which are used for production control. Production control is the function of management which plans, directs and controls the material supply and processing activities through the entire manufacturing cycle. It plays a key role in the success or failure of any corporation. Effective control policies are necessary in any manufacturing firm desiring to maintain high quality service with minimum inventory at a minimum cost. Production control systems that control material flow and inventory are therefore necessary for balancing such objectives. Systems used for production control can be further categorized as push, pull, or hybrid depending on the type of planning strategy they utilize.

Push systems schedule periodic releases of raw materials into the production line, while pull systems authorize parts to be processed in response to the actual demand arrival. A “push system” releases jobs to the first stage of production and, in turn, each stage pushes the work-in-process (WIP) to the following stage and so forth until the production reaches the final stage. On the other hand, a “pull system” does not schedule the start of the job, but authorizes productions.

In a “pull” controlled system, the start of a job is triggered by the completion of an earlier job. Control of WIP becomes much easier and hence can be significantly reduced in a pull system (Monden, 1983). Push systems batch and control release rate (and hence
throughput) and observe WIP from time to time, while pull systems control WIP and observe throughput. See Spearman et al. (1990), Spearman and Zazanis (1992), Hopp and Spearman (2001) for advantages of the pull systems over the push systems.

A pull mechanism can be implemented in many ways. The best known is a Kanban policy (Monden 1983). In the Kanban control system, production authorization cards, called Kanban, are used to control and limit the releases of parts into each production stage. The advantage of this mechanism is that the number of parts in every stage is limited by the number of kanbans of that stage. Its disadvantage is that the system, especially in the upstream stages, may not respond quickly enough to changes in the demand. In a Kanban system, instead of directly controlling the throughput, kanbans (cards) are used to authorize production or transportation of materials such that the parts are pulled and WIP is visualized and controlled. The constant number of cards used in a Kanban system, and the limited lot sizes of the attached containers create an upper limit on the WIP level and the finished good inventory (Akturk and Erhun, 1999).

Another pull control system originated from inventory control technique is Base Stock system (Kimball 1988). The Base Stock system was initially proposed for production/inventory systems with infinite production capacity and uses the idea of a safety stock for finished good inventory as well as safety buffers between stages for coordination. In the Base Stock control system, every stage has a target inventory of finished parts, called basestock. When a demand for an end item arrives, it is immediately transmitted to every stage to authorize the release of a new part. An advantage of this mechanism over JIT is that it avoids demand information blockage by transferring the demand information immediately to all production stages. The downside is that it provides no limit on the number of parts in the system.
CONWIP (CONstant Work In Process) control system proposed by Spearman et al. (1990) uses a single card type to control the total amount of WIP permitted in the entire line. It is a generalization of a Kanban system and can be viewed as a single stage Kanban system. A CONWIP system behaves as follows: when a job order arrives to a CONWIP line, a card is attached to the job, provided cards are available at the beginning of the line. Otherwise, the job must wait in a backlog. When a job is processed at the final station, the card is removed and sent back to the beginning of the line, where it might be attached to the next job waiting in the backlog. No order can enter the line without its corresponding card. The primary difference between CONWIP and Kanban systems is that CONWIP pulls a job into the beginning of the line and the job goes with a kanban between workstations, while Kanban pulls jobs between all stations (Hopp and Spearman, 2001).

1.2 Literature review

There are many studies on control policies for manufacturing systems. However, we will consider only policies that compare Kanban and CONWIP systems. In a survey paper, Framinan et al. (2003) discussed operations and applications of different CONWIP production control systems. Detailed comparisons for some of the systems were also made in the paper. Spearman et al. (1990) proposed that the CONWIP concept could be applied to an assembly system fed by two fabrication lines. Hopp and Roof (1998) studied such fabrication assembly systems using statistical throughput control (STC) method.

Zhang and Chen (2001) developed an integer nonlinear mathematical programming model to determine an optimal production sequence and lot sizes in a CONWIP
single production line. Cao and Chen (2005) developed a nonlinear mixed integer programming model for a CONWIP based production system where an assembly station is fed by two parallel fabrication lines. Optimal part assignment, production sequence and lot sizes are simultaneously determined by solving the model.

Hopp and Spearman (1991), Duenyas and Hopp (1992, 1993), Duenyas (1994) and Hazra and Seidmann (1996) addressed the application of CONWIP control to assembly operations. The analyses used in each of these references rely on queueing network approximations in computing the throughput. Hopp and Spearman (1991) approximated the throughput of a flow-shop (sequence of tandem queues) under CONWIP control. They assumed that processing times are deterministic but service can be interrupted by machine failures that are exponentially distributed in duration. Duenyas and Hopp (1992, 1993) approximated the throughput of an assembly system, consisting of multiple station tandem production lines, feeding an assembly operation under the CONWIP control. Duenyas (1994) generalized this approximation to a cyclic assembly system with general processing time distributions. His approach is similar to that of Duenyas and Hopp (1992). Hazra and Seidmann (1996) considered closed tree structured assembly systems with exponential machine processing times and developed an aggregation/disaggregation algorithm to approximate the system throughput and mean queue lengths at the workstations. A summary of applications of CONWIP is given in Table 1.1.

There are also some studies about comparing of Kanban and CONWIP systems. Several authors have shown through both simulation and analytical models that CONWIP outperforms Kanban when processing times are variable. In a flow line that produces a single part type, Spearman and Zazanis (1992) showed that CONWIP produces a higher mean throughput than Kanban. In the same scenario, Muckstadt and
Table 1.1: A summary of applications of CONWIP

<table>
<thead>
<tr>
<th>Reference</th>
<th>System characteristics</th>
<th>Determined parameters</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hopp and Roof (1998)</td>
<td>An assembly station fed by two fabrication lines</td>
<td>Determining the number of cards.</td>
<td>Stochastic Throughput Control (STC)</td>
</tr>
<tr>
<td>Cao and Chen (2005)</td>
<td>An assembly station fed by two fabrication lines</td>
<td>Determining optimal part assignment, production sequence,</td>
<td>Non-linear programming</td>
</tr>
<tr>
<td></td>
<td></td>
<td>lot sizes</td>
<td></td>
</tr>
<tr>
<td>Zhang and Chen (2001)</td>
<td>Single production lines</td>
<td>Determining optimal production sequence, lot sizes</td>
<td>Non-linear programming</td>
</tr>
<tr>
<td>Hopp and Spearman (1991)</td>
<td>Conwip flow-shop subject to failures</td>
<td>Determining system throughput</td>
<td>Queuing network</td>
</tr>
<tr>
<td>Duenyas and Hopp (1992, 1993)</td>
<td>An assembly operation fed by multiple stations</td>
<td>Determining system throughput</td>
<td>Queuing network</td>
</tr>
<tr>
<td>Duenyas (1994)</td>
<td>Cyclic assembly system with general processing time distributions</td>
<td>Determining system throughput</td>
<td>Queuing network</td>
</tr>
<tr>
<td>Hazra and Seidmann (1996)</td>
<td>Closed tree structured assembly system</td>
<td>Determining system throughput and mean queue length at the stations</td>
<td>Queuing network (aggregation/dis-aggregation algorithm)</td>
</tr>
</tbody>
</table>

Tayur (1995a, b) showed that CONWIP produces a less variable throughput and a lower maximal inventory than Kanban. Takahashi et al. (2005) applied Kanban, CONWIP and synchronized CONWIP to supply chains to determine the superior system. Their considered supply chains contain assembly stages with different lead times. A summary of comparison between Kanban and CONWIP system is given in Table 1.2.
Table 1.2: A summary of comparison between Kanban and CONWIP

<table>
<thead>
<tr>
<th>Reference</th>
<th>CONWIP (Single line)</th>
<th>CONWIP (SCM)</th>
<th>Synchronized CONWIP (SCM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takahashi et al. (2005)</td>
<td>⬤</td>
<td>⬤</td>
<td></td>
</tr>
<tr>
<td>Spearman and Zazanis (1992)</td>
<td>⬤</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gstettner and Kuhn (1996)</td>
<td>⬤</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muckstadt and Tayur (1995a, b)</td>
<td>⬤</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Most researches have pointed out that CONWIP would result in lower WIP levels than Kanban system with the same throughput in most cases (Spearman et al., 1990; Spearman and Zazanis, 1992; (see Framinan et al. 2003)). However, Gstettner and Kuhn (1996) arrived at the opposite conclusion. According to their results, Kanban achieves a given throughput level with less WIP than CONWIP. They showed that by choosing appropriate number of cards at each station, Kanban can outperform CONWIP system. They considered a linear production line with exponential service time distributions and unlimited demand at the final buffer.

1.3 Objective

In this thesis, we consider a single-product assembly system in which the assembly of parts proceeds in three stages. The third stage is an assembly line with
several work stations, such that the first one is fed by sub-assembly lines in stage 2. The first station of sub-assembly lines are fed by fabrication lines in the first stage. Each work station is a production (or assembly)/inventory system made up of a manufacturing (or assembly) process and an output buffer. The manufacturing process may consist of a single machine or a sub-network of several machines. Figure 1.1 shows the schematic model. The manufacturing/assembling processes at each stage are drawn as circles, the

![Diagram of an assembly system having three stages](image)

Figure 1.1: An assembly system having three stages
intermediate and output buffers as triangles, and raw material buffers are drawn as shaded triangles. Solid lines represent material flows.

We assume the following assumptions to focus on essential aspects of comparison and to limit the scope of the study:

- The system makes a single part type.
- There is no setup time at each machine.
- Material is transported in units of one with ignorable transfer time.
- Information flows instantaneously.
- Parts authorized for loading follow a first come first serve (FIFO) dispatching policy at all stations.
- The first stations of all fabrication lines are fed by raw parts which are assumed to be infinite (never starved).
- There is an unlimited demand at the end of the assembly line in the final stage.

The objective is to compare performance of two Kanban and CONWIP systems with respect to average WIP to verify whether Kanban outperforms CONWIP system or vice versa. We also introduce two different policies to release the cards in the CONWIP system followed by the result of their comparison, in order to find out the superior policy which provides the system with a less average WIP level given the same rate of throughput.

As a scheduling production control system, CONWIP has been shown in several studies to outperform other control strategies such as Kanban in terms of throughput and work in process. However, as it was mentioned in the previous section, Gstettner and
Kuhn (1996) arrived at the opposite conclusion so that, according to their results, Kanban achieves a given throughput level with less WIP than CONWIP. They showed that by choosing appropriate number of cards at each station, Kanban can outperform CONWIP system. They considered a linear production line with exponential service time distributions and unlimited demand at the final buffer. From this point of view, in this research, we verify the role of Kanban distribution in assembly systems whether Kanban outperforms CONWIP by choosing a suitable distribution of cards within the Kanban system.

1.4 Structure of the thesis

The remainder of this thesis is organized as follows. Chapter 2 details concepts of Kanban and CONWIP in assembly systems. Two proposed CONWIP control policies for the mentioned model are also presented in this chapter.

Simulation results for comparison between two proposed CONWIP control policies, SCB and DCB, are given in Chapter 3.

Chapter 4 presents the simulation results of 1) comparing the performance of two Kanban and CONWIP systems with respect to average WIP as well as comparing them given the same total number of circulating cards within the system, and 2) verifying the effect of card distribution in Kanban system.

Chapter 5 discusses the conclusions drawn from the experiments and also outlines the suggestions for future research in this field.
CHAPTER 2
KANBAN AND CONWIP CONCEPTS IN ASSEMBLY SYSTEMS

In this chapter, we will describe the operation and control characteristics of Kanban and CONWIP control in assembly systems. For the both systems, we firstly give a brief description as the general concept. In addition, for CONWIP system, we will propose two different policies to release the cards in CONWIP-controlled assembly systems. For the sake of simplicity, the Activity Interaction Diagrams (AID) of each control policy are shown in an assembly system having two sub-assembly lines each of which is fed by two fabrication lines. Multi-line system can be modeled based on these simple models.

2.1 Kanban-controlled assembly system

2.1.1 General concept

Kanban control system is probably the most famous pull-type mechanism for multi-stage production system during the last few decades. This control discipline limits the amount of inventory to a fixed maximum for each cell consisting of a process and its output buffer, where the maximum is equal to the number of kanban circulating within the cell.

In a Kanban system, when a station requires material from the output buffer of the preceding station, two basic alternatives can be identified (Gstettner and Kuhn, 1996). In the first alternative (called “immediate material transfer” (IMT)) material is taken from the preceding buffer immediately after information about a demand arrives at a
station. In the second alternative (called “late material transfer” (LMT)), the material is not taken until the station is ready to start production. The main difference between the two systems is the possible WIP between two stations, i.e. the number of containers (Mitra and Mitani, 1990 and 1991). The difference is illustrated in Figure 2.1.

The situation shown in the figure occurs when a workpiece has occupied a station $n$ for a long time (e.g. due to a breakdown). During this time, demand has arrived at station $n$ from station $n+1$. Using the IMT policy the demand orders (kanbans) are immediately matched with containers in the output buffer of station $n-1$. Since containers are removed from the buffer, demand is indicated at the station $n-1$ and the station begins production. In the LMT policy, kanbans wait in the bulletin board until processing at station $n$ is finished. Thus, maximum inventory levels between the stations are ($K_{n-1} + K_n - 1$) containers and $K_{n-1}$ containers, respectively.

Figure 2.1: Different control policies in a Kanban system (Gstettner and Kuhn, 1996, p.3257)
Gstettner and Kuhn (1996) showed that both Kanban policies have similar performance data if the card distribution is adapted to the respected system. In the remainder of this thesis, we focus on the LMT Kanban system.

**Assembly Kanban systems:**

In assembly systems, different part flows join at some points along the flow path. These joining points are assembling stations where two or more components are combined to form a whole product. Let us consider a single-product assembly system having two sub-assembly lines and four fabrication lines. Activity interaction diagram of the model is constructed in Figure 2.2. The manufacturing/assembling processes at each stage are drawn as circles, the intermediate and output buffers as triangles, and raw material buffers are drawn as shaded triangles. Queue $K_i$ contains station $i$’s kanbans/signals. Queue $B_i$ is the output buffers of station $i$ containing both finished parts and station $i$ kanbans. Queue $K_i$ contains station $i$ kanbans. Solid lines represent material flows and the kanban movement is shown by the dotted lines.

The Kanban control operates as follows. When a customer demand arrives at the system (which it is infinite here), it joins queue $D$ requesting the release of a finished product from $B_2$ to the customer. At that time there are two possibilities:

- If a part is available in $B_2$, it is released to the customer after removing the kanban that was attached to it. This kanban is transferred upstream to $K_2$ carrying with it a demand signal for the production of a new station 2 finished part.
- If no part is available in $B_2$, the demand is backordered and waits in $D$ until a new part completes from station 2 arrives in $B_2$. The newly finished part will be released to the customer instantly and the attached kanban will transfer to $K_2$ queue instantly too.

As soon as a kanban signal arrives in $K_2$, it authorizes the production of a new part in station_2. Again at this time two cases may happen:

- If a part to which a station_1 kanban is attached is available in $B_1$, it is instantaneously detached station_1 kanban and attached station_2 kanban. At the same time, the pair (part, station_2 kanban) is released in to $P_2$. The station_1 kanban
is transferred upstream to $K_1$ authorizing the release of two parts from both $P_{12}$ and $P_{22}$ simultaneously into $P_1$.

- If no part is available in $B_1$, station 2 kanban waits in $K_2$ until a newly finished part arrives in $B_1$.

The process is continuing similarly to the upstream stations in series to pull the parts along the sub-assembly lines as well as to pull the parts required for assembly stations ($P_{11}$ and $P_{21}$) through the fabrication lines.

The kanban control is a simple control mechanism that depends only on one parameter per work station, namely $K_i, i = 1, \ldots, N$. These parameters influence both the transfer of finished parts downstream through the system and the transfer of demands upstream through the system.

In a Kanban system the transfer of a finished part from $B_i$ into $P_{i+1}$ is totally synchronized with the transfer of a demand from $K_{i+1}$ (or $D$ if $i = N$) into $K_i$. The invariant of kanban mechanism of each stage can be expressed as follow.

$$Q(K_i) + Q(P_i) + Q(B_i) = K_i, \quad i = 1, \ldots, N$$

This also implies that both the WIP and the number of finished parts in each workstation $i$ are bounded by $K_i$.

### 2.2 CONWIP-controlled assembly system

#### 2.2.1 General concept

CONWIP (CONstant Work In Process) control system uses a single card type to control the total amount of WIP permitted in the entire line. It is a generalization of a
Kanban system and can be viewed as a single stage Kanban system. A CONWIP system behaves as follow: when a job order arrives to a CONWIP line, a card is attached to the job, provided cards are available at the beginning of the line. Otherwise, the job must wait in a backlog. When a job is processed at the final station, the card is removed and sent back to the beginning of the line, where it might be attached to the next job waiting in the backlog. No order can enter the line without its corresponding card. The primary difference between CONWIP and Kanban systems is that CONWIP pulls a job into the beginning of the line and the job goes with a kanban between workstations, while Kanban pulls jobs between all stations (Hopp and Spearman, 2001).

CONWIP mechanism maintains a WIP level upper bound for the entire system. When the preset WIP level is reached, no new jobs are authorized for release to the system before some job leaves. A CONWIP line can be seen as controlled by a single kanban cell encompassing all stations. CONWIP control is indeed considered as a single-station control.

Figure 2.3 shows the Activity Interaction Diagram of a single-product CONWIP controlled assembly system having an assembly line fed by two fabrication lines. The manufacturing/assembling processes at each stage are drawn as circles, the intermediate and output buffers as triangles, and raw material buffers are drawn as shaded triangles. In addition, solid lines represent material flows and the card movement is shown by the dotted lines. Queue $C$ contains CONWIP cards/signals.

The CONWIP policy operates as follows. When a customer demand arrives at the system (Queue $D$), it requests the release of a finished product from $B_2$ to the customer. At this time there are two possibilities:
- If a part is available in $B_2$, it is released immediately to the customer and the CONWIP card is detached from the part and transferred to queue $C$.

- Otherwise, the demand is backordered and waits in $D$ until a new part completes from the upstream stage arrives.

For other stations beside the last station, they will operate in the same way as push system, i.e. parts move downstream without any blocking.

The CONWIP control is a very simple control mechanism that depends only on one parameter for the entire system, the amount of CONWIP, $C$. It influences both the transfer of finished parts downstream and the transfer of demands upstream through the system. There is no demand transfer between each work station except the last and the first work station.

The production capacity or the maximum production rate of the system is affected only by the amount of CONWIP card, $C$. The total amount of parts in the system is bound by $C$ and can be expressed as follow.
\[ Q(C) + \sum Q(P_i) + \sum Q(B_i) = C, \quad i = 1, \ldots, N \]

where, \( C \) indicates the total circulating cards buffer; \( P_i \), the process at station \( i \), and \( B_i \), the output buffer at station \( i \). If a work station fails in a CONWIP line, the amount of material downstream of it will be gradually flushed out of the system by the demand process. These demand events will trigger the release of new raw parts into the system. When all CONWIP cards accumulate in front of the failed machine, the release of new jobs to the system will then stop.

CONWIP can be implemented by associating a single card with each part, authorizing its presence in the system. Whenever a part leaves the finished goods inventory, its card is detached and sent to the first production station, authorizing another part to enter the system. All other stations always authorized to work on any part released to the system, so passing card to these machines is not necessary.

In an assembly system operating under CONWIP, the fabrication lines begin a new job whenever a part is completed at the end of the assembly line. The way in which cards from the last station are released in the first station of the fabrication lines depends on the specific rule adapted by the system. In this research, for an assembly system operating under CONWIP, we define two types of card releasing rules which are discussed in the next section.

### 2.2.2 Shared and Distinct Card Buffer policies

In this section, we define two policies to release the cards in CONWIP-controlled assembly system. Figure 2.4 shows the two policies for CONWIP system in an assembly line with two sub-assemblies each of which fed by two fabrication lines.
In the first policy, called Shared Card Buffer (SCB), there is only one card buffer shared for all fabrication lines, so that available cards might be attached to new jobs whether in one of the fabrication lines, according to first-come-first-served sequence (Figure 2.4_a). The second policy (called Distinct Card Buffer, DCB) is to set separate card buffers for each fabrication line. According to this policy, a job is released in a fabrication line when there is an available card in the corresponding card buffer (Figure 2.4_b).
The main difference between these two schemes can be the average WIP level with the same throughput. In other words, the average WIP can be less in a DCB than in a SCB CONWIP system, providing the same total number of cards. The simulation results of comparison between these two policies will be given in the next chapter.
CHAPTER 3
ANALYSIS OF TWO CONWIP POLICIES

In this chapter, we provide performance comparisons between two CONWIP policies (SCB and DCB) discussed in the previous chapter. In the following, prior to simulation results, we present the details of the performance measures used in the comparisons.

3.1 Performance measures

In the simulation, the following three performance measures are used.

1. Throughput rate, \( TH \). This is measured by the average number of products produced per hour during the time period (in steady state).

\[
TH = \frac{\sum_{i=1}^{T} P_i}{T}
\]

where, \( P_i \) is the number of products produced in time \( i \), and \( T \) is the time period.

2. Total average WIP, \( TA\_WIP \). This is measured by the average number of parts in the whole production system during the time period. This includes the products being processed on the machines and stored in the buffers.

\[
TA\_WIP = \frac{\sum_{i=1}^{T} WIP_i}{T}
\]

where, \( WIP_i \) is the total WIP at the end of time \( i \), and \( T \) is the time period.

3. Average WIP, \( A\_WIP \). This is measured by the total average WIP at each station during the time period.

\[
A\_WIP = \frac{(TA\_WIP)}{N}
\]
where, $TA_{WIP}$ is the total average WIP and $N$ the number of workstations in the system.

### 3.2 Comparison of SCB and DCB CONWIP systems

This section gives the simulation results of comparing two defined policies (SCB and DCB) for a CONWIP-controlled assembly system discussed in Chapter 2. As we mentioned, the main difference between these two policies is WIP level with the same throughput. The simulation results show that the average WIP can be less in a DCB than in a SCB CONWIP system with the same throughput rate, providing the equivalent number of circulating cards.

Figure 3.2 shows the average WIP obtained by the two policies at different numbers of circulating cards. Considered model in the simulation experiments is an assembly system with three stages (see Figure 3.1). The third stage is an assembly line consists of two work stations fed by two sub-assembly lines in stage 2, each of which is fed by two fabrication lines in stage 1. Each line in the both stages 1 and 2 has three workstations. Therefore, in the system there are totally 20 workstations. The other assumptions for this model are those mentioned in Section 1.3.

The total numbers of circulating cards within the system are represented on the horizontal axis of Figure 3.2 which range from 20 to 30. The total number of work stations in the system defines the minimum feasible number of circulating cards to assign to the system (that is, the number 20 in the figure). In the initial state of this case (i.e. the case in which the number of cards equals 20), there is no available cards in queue $C$, because one card has been already attached to a part (or a container) at each work station. Similarly, for the case 30 in the initial state, there are ten available cards in
Figure 3.1: An assembly system with three stages

Figure 3.2: Comparison of SCB and DCB CONWIP policies (TH=2.07)
the queue \( C \) after assigning one card to a part (or a container) at each station. We found that having the amount of cards greater than 30 results in too excessive WIP. Hence, we limited the amount of circulating cards to be 30.

We ran each simulation program, SCB and DCB policies for 11 times (20 to 30) given the same number of circulating cards for each one. After reaching the steady state, two performance measures, \textit{average WIP} and \textit{throughput} are calculated. Steady state is to reach to a period of time during the process, such that, this period is repeated with its all components as the time proceeds. In this state, because the system is at a stationary state, the performance measures can be calculated as defined in Section 3.1.

In this experiment, the system provides the same throughput rate equal to 2.07 (parts per hour) at different numbers of cards, when the given distribution of process times is constant among all the cases, as follows.

\[
P_{11}^1 = 17, \ P_{12}^1 = 8, \ P_{13}^1 = 28, \ P_{21}^1 = 21, \ P_{22}^1 = 27, \ P_{23}^1 = 11, \ P_{11}^2 = 9, \ P_{12}^2 = 25, \ P_{13}^2 = 18, \ P_{21}^2 = 24, \ P_{22}^2 = 20, \ P_{23}^2 = 10, \ P_{11} = 26, \ P_{12} = 13, \ P_{13} = 10, \ P_{21} = 16, \ P_{22} = 22, \ P_{23} = 29, \ P_1 = 24, \ P_2 = 10 \text{ minutes.}
\]

The simulation was run with 40,000 time units and the process reaches to the steady state after 15,000 time units in average.

From Figure 3.2 the DCB policy provides less average WIP than SCB at the all different number of cards. It shows that for examined 11 cases, DCB CONWIP system gives 11.94% in average less WIP than SCB CONWIP system, where the both two policies give the same throughput level (equal 2.7 parts/hour) at all the cases. The average WIP becomes larger as the number of circulating cards within the system increases, where the rate of system throughput remains constant. Thus, as a consequence, the minimum WIP can be obtained by employing DCB policy, subject to being the
assigned total number of cards equivalent to the total number of workstations of the system.

The simulation result for another experiment is shown in Figure 3.3_b. The simulation model is the same as the previous one, only with a different distribution of process

![Figure 3.3: Comparison of SCB and DCB CONWIP policies](a)

![Figure 3.3: Comparison of SCB and DCB CONWIP policies](b)
times given the same number of circulating cards. For this case, Figure 3.3_a also shows the throughput rate obtained by the two policies at the corresponding number of cards.

In this case, not only the result of the previous case is holding true, but also throughput rate is higher in DCB than SCB CONWIP system. Thus, based on observations obtained at these two experiments, DCB CONWIP system is superior to the SCB with less average WIP and the same throughput rate (or even higher in some cases) providing the same number of circulating cards within the system.
In this chapter, we provide performance comparisons between Kanban and CONWIP control systems with respect to WIP as well as comparing them given the same total number of circulating cards within the system. In addition, the effect of card distribution in a Kanban system is also discussed. Performance measures used in the comparisons are those given in Section 3.1.

4.1 Performance of the two systems with the same number of cards

Spearman and Zazanis (1992) showed that in a single production line, a CONWIP system with \( N \) circulating card has better performance than a Kanban system with \( N \) cards. In this section we examine whether this result is hold for an assembly system as well or not. That is, we compare two Kanban and CONWIP system applied in an assembly system given the same number of circulating cards within the system.

Consider an assembly system fed by two fabrication lines with three stations for each fabrication lines as well as the assembly line (Figure 4.1). Table 4.1 gives the simulation results consist of systems throughput and average WIP of both Kanban and CONWIP systems, when the total number of circulating cards within the both systems is identical and equal to 13.
In Table 4.1, \( k_{ij} \) denotes the number of kanbans at \( i \)-th station of \( j \)-th fabrication line in the Kanban system. That is, \( k_{11}, k_{12} \) and \( k_{13} \) denote the number of kanbans at stations 1, 2 and 3 of the first fabrication line, respectively. Similarly, \( k_{21}, k_{22} \) and \( k_{23} \) denote the number of kanbans at stations 1, 2 and 3 of fabrication line 2, respectively. \( k_1 \) and \( k_2 \) also denote the number of kanbans at stations 1 and 2 of the assembly line, respectively.

Table 4.1 Average WIP and throughput in the both systems given the same number of cards

<table>
<thead>
<tr>
<th>Control system</th>
<th>TH</th>
<th>A_WIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kanban</td>
<td>3.75</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>(Kanbans distributions)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( k_{11}, k_{12}, k_{13}, k_{21}, k_{22}, k_{23}, k_1, k_2 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1, 3, 2, 1, 1, 1, 2, 1</td>
<td></td>
</tr>
<tr>
<td>CONWIP</td>
<td>3.75</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>(Total number of circulating cards)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td></td>
</tr>
</tbody>
</table>

From the table, two systems has the same rate of throughput (equal 3.75 parts per hour) and, average WIP equal 1.09 and 1.45 parts obtained by Kanban and CONWIP system, respectively. As a result, when the total number of cards in both Kanban and
CONWIP systems is equivalent, average WIP can be less in Kanban system than in CONWIP given the same level of throughput.

Since final demand is unlimited, the number of kanbans at the last station of the assembly line is not relevant in Kanban system. Thus, the last station (station 3) is not shown in the table.

4.2 Comparison between Kanban and CONWIP

In this section, we provide the performance comparisons between two Kanban and CONWIP controlled assembly systems. The control policies we compare are DCB CONWIP and LMT Kanban control system.

4.2.1 Simulation models

We construct four cases as simulation models (see Table 4.2 for specific parameters). In all cases, the processing times are deterministic at one part per unit time. The only difference among them is the number of lines at each stage, and hence, the total number of manufacturing/assembling stations at each case. On the other hand, the difference among these cases is the total number of stations in the system, which are 9, 7, 13 and 20 for cases 1, 2, 3 and 4 respectively. Case 1 is where an assembly system consists of three work stations is fed by two fabrication lines, each of which with three work stations. For the other cases, we consider an assembly system consists of three stages, where there are one assembly, two sub-assemblies and four fabrication lines in stages 1, 2, and 3, respectively. However, the number of manufacturing/assembling stations of each stage is as follows.
Case 2: only one station at each line of each stage.

Case 3: two stations at each line of stages 1 and 2, with only one station at the final stage.

Case 4: three stations at each line of stages 1 and 2, with two stations at the final stage.

The four cases are illustrated in Figure 4.2.

Table 4.2: Four cases for performance comparisons

<table>
<thead>
<tr>
<th></th>
<th>Case 1 (Figure 4.2_a)</th>
<th>Case 2 (Figure 4.2_b)</th>
<th>Case 3 (Figure 4.2_c)</th>
<th>Case 4 (Figure 4.2_d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-assembly lines, $M$</td>
<td>-</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total fabrication lines, $\sum n_i$ ($i = 1, \ldots, M$)</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Stations at the assembly line, $n$</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Stations at each sub-assembly line, $m_i$ ($i = 1, \ldots, M$)</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Stations at each fabrication line, $n_{ij}$ \begin{align*} i = 1, \ldots, M \ j = 1, \ldots, n_i \end{align*}</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Total number of work stations, $\sum_{i=1}^M \sum_{j=1}^{n_i} n_{ij} + \sum_{i=1}^M m_i + n$</td>
<td>9</td>
<td>7</td>
<td>13</td>
<td>20</td>
</tr>
</tbody>
</table>

For each case, the process times are randomly generated as positive numbers between (0, 20] time unit. This process is replicated ten times for each case to generate different process time distributions. For each generated distribution (sub-cases in the figures), then the simulation was run with 40,000 simulation time unit to obtain the performance measure, average WIP ($A_WIP$) in steady state. It is obvious that by changing the process time distribution at each sub-case, different throughput rate and average WIP may obtain. The results are shown in Figures 4.3, 4.4, 4.5 and 4.6.
(a) Case 1

(b) Case 2

(c) Case 3
4.2.2 Simulation results

Figures 4.3, 4.4, 4.5 and 4.6 show the simulation results for cases 1, 2, 3 and 4 respectively. In each figure, parts “a” and “b” show the system throughput rate (parts per hour) and average WIP level (parts) at ten different cases, respectively. On the other hand, part “b” of each figure shows the average WIP of both Kanban and CONWIP systems with respect to different process time distributions, given the same level of throughput in each case shown in the part “a” of the figure.

From the four figures, Kanban system provides better performance than CONWIP with a less $A_{WIP}$ level. In a precise description, $A_{WIP}$ levels obtained by Kanban system are 27.18%, 14.45%, 9.32% and 12.89% less in average than the corresponding values obtained by CONWIP system in the cases 1, 2, 3 and 4 respectively. It shows that for an assembly system, Kanban has better performance than
CONWIP control system. In other words, Kanban system provides a less WIP level in average than CONWIP system given the same level of system throughput.

Figure 4.3: Comparison between WIP and throughput in Kanban and CONWIP in case 1
Figure 4.4: Comparison between WIP and throughput in Kanban and CONWIP in case 2
Figure 4.5: Comparison between WIP and throughput in Kanban and CONWIP in case 3
Figure 4.6: Comparison between WIP and throughput in Kanban and CONWIP in case 4
However, as it can be inferred from the figures, in only rarely cases, CONWIP system provides less WIP level. For instance, in case 1, $A_{WIP}$ at the last sub-case is less in CONWIP than Kanban system, however, the difference between these two values is about 2.47% which is too slight in analogy with the other sub-cases. Also, this rarely case was happened in other three cases, and only once for each case. For those cases also the differences are too slight, equivalent 2.86% (sub-case 4), 7.25% (sub-case 7), and 1.05% (sub-case 3), in cases 2, 3 and 4 respectively. Nevertheless, as a consequence, Kanban control system outperforms CONWIP in average, providing a less average WIP and the same throughput rate.

Meanwhile, in a Kanban system, we cannot neglect the effect of card distribution on the system performance. On the other hand, kanbans distribution in a Kanban system as well as the number of circulating cards in a CONWIP system certainly influences the performance of system. The effect of card distribution in Kanban system and circumstance of setting a proper distribution of kanbans and a suitable number of circulating cards in CONWIP system are detailed in the following section.

### 4.3 The effect of card distribution in a Kanban system

As we mentioned in the previous section, kanbans distribution among the work stations of a Kanban system and also the number of circulating cards in a CONWIP system can affect the system performance, such that WIP may rise by increasing the number of cards (kanbans) in the system. In the simulation process, in fact, we found that for CONWIP system, choosing the total number of cards equivalent to the total number of stations achieves the minimum WIP level with the maximum feasible
throughput for the system. (for instance, 20 cards for case 4, where there are totally 20 manufacturing/assembling stations in the system, or 13 cards for case 3 and so on).

As a result, for CONWIP system, which we employed DCB policy, by assigning the minimum feasible number as circulating cards, by only one time running the simulation, the optimal solution can be obtained. On the other hand, by setting the total number of circulating cards equal to the total number of stations, optimal solution is obtained in the first run of simulation.

Assigning additional cards causes an increase in WIP, whereas throughput remains constant. For example, case 4 with 21 and 22 circulating cards obtains 1.043 and 1.09 parts as WIP, respectively, when the throughput is constant and equal to 2.06 (parts/hour), while 0.99 WIP can be obtained by only 20 cards having the same value of throughput.

For Kanban system, we found that for most cases, by assigning only one card at each station, the best performance (i.e. the maximum throughput and the minimum WIP) can be achieved. Therefore, in simulation, for all sub-cases of cases 2, 3 and 4, the minimum WIP was obtained with a vector of card distribution in which all elements are equal to one. That is $K = \{k_1, k_2, \ldots, k_N\} = \{1, 1, \ldots, 1\}$, where $k_i$ indicates the number of kanbans at station $i$, and $N$ indicates the total number of stations in the system. However, in some cases like sub-cases 2, 5, 7 and 10 of case 1, since by assigning only one kanban at each work station, the expected values for both WIP and throughput were not achieved, therefore, for each sub-cases, we firstly tried to find the optimal card distribution. Thus, the performance measures of these cases were obtained through the adapted card distributions.
As a result, kanbans distribution in a Kanban system can affect the system performance. i.e., a different WIP level can be achieved by a different card distribution.
In this study, we analyzed a single-product assembly system with unlimited demand at the end of the assembly line. For CONWIP system, we first introduced two methods for releasing the cards into the system. These two were defined as SCB and DCB. The results in Chapter 3 showed that DCB is superior to SCB CONWIP system with less average WIP and the same rate of throughput (even with higher throughput in some cases), providing the equivalent number of circulating cards.

Comparison between Kanban and CONWIP systems in Chapter 4 showed that Kanban system provides a less WIP level in average than CONWIP system given the same level of throughput. In most cases, optimized Kanban system (a system with adapted card distribution) outperforms CONWIP system with a lower WIP and the same level of throughput. However, only in rarely cases, CONWIP provides a less WIP level, whereas the difference is too slight and insignificant. In fact, investigating of this observation is a part of our future research.

This result is also true for the case that the same number of circulating cards is provided for the both systems. The result showed that when the total number of cards in both systems is equivalent, average WIP can be less in Kanban system than in CONWIP given the same level of throughput. This implies that the result of Spearman and Zazanis (1992) can not be valid for all kinds of assembly systems.

In addition, in a Kanban system, distribution of kanbans among the stations, and in a CONWIP system the number of circulating cards can affect the system performance such that, WIP might rise by increasing the number of cards. For CONWIP system,
setting the total number of circulating cards equal to the total number of stations may obtain the best performance (the minimum WIP). However, for Kanban system, in most cases by assigning only one card at each station, the minimum WIP can be achieved, while for some cases an adaptation of card distribution is necessary in order to get the optimal solution. In other words, choosing an appropriate distribution of kanbans may give the expected results. Finding the optimal card distribution is also a part of our future research.

Furthermore, another part of our future research is comparing our results with those obtained by Takahashi et al. (2005) which developing a unified model would be necessary to have a significant comparison.


ACKNOWLEDGEMENTS

I would like to thank my academic advisor, Professor Ryo Sato, for his continuous guidance and support through my studies in Japan. I am also grateful to all the members of the lab who are helping me mostly regarding to my Japanese language difficulties.