A STUDY ON WORKER COLLABORATION FOR BUCKET BRIGADE PRODUCTION LINES

(バケツリレー型生産ラインにおける作業者協調に関する研究)

Aditya Tirta Pratama

D 1 5 0 0 4 5

Production Systems Engineering Laboratory

Department of System Cybernetics - Graduate School of Engineering

Hiroshima University

A dissertation submitted to the Graduate School of Engineering – Hiroshima University for the degree of Doctor of Engineering

Hiroshima University - Japan

November 2018

Certification

This is to certify that the dissertation entitled:

A STUDY ON WORKER COLLABORATION FOR BUCKET BRIGADE PRODUCTION LINES

(バケツリレー型生産ラインにおける作業者協調に関する研究)

is a series of research works by **Aditya Tirta Pratama** during his doctoral study from October 1, 2015 to the November 1, 2018 in Production Systems Engineering Laboratory, Department of System Cybernetics, Graduate School of Engineering, Hiroshima University, Japan. This dissertation has been accepted as a part of requirements in conferring in a **Doctor of Engineering** degree to him.

Approved by Supervisor

Katsuhiko Takahashi, Dr. Eng.
Professor

Acknowledgement

بِسْمِ اللهِ الرَّحْمٰنِ الرَّحِيْمِ

In the name of Allah, the most beneficent and the most merciful

I testify that (there is) no god except God; One is He, no partner has He, and I testify that Muhammad is His servant and messenger.

First and foremost, praise is to Allah SWT, the Almighty, on whom we ultimately depend for substance and guidance.

I would like to express my sincere appreciation to my supervisor Prof. Katsuhiko Takahashi, Head of Production Systems Engineering Laboratory, Hiroshima University, for giving me the opportunity to do research and providing me with invaluable guidance, support, and encouragement throughout this research. He has taught me the methodology to carry out the research and to present the research works as clearly as possible. He had dedicated his time not only in advising and supervising my research work but also in developing my ability to become an independent scholar. It was a great privilege and honor to work and study under his guidance.

I would like to express my gratitude to Assoc. Prof. Katsumi Morikawa as my co-supervisor, Assoc. Prof. Daisuke Hirotani, and Asst. Prof. Keisuke Nagasawa for their constant support and constructive suggestions, which were determinant for the accomplishment of the research works.

I also would like to express my gratitude to another co-supervisor, Prof. Ichiro Nishizaki for his critical discussions and comments in which have improved this thesis so much.

I am extremely grateful to my parents for their love, prayers, caring and sacrifices for educating and preparing me for my futures. I must express my appreciation to Karina, my wife, and Altaf, my son, for their love, understanding, prayers, and continuing support and motivation to complete this research work. Also, I express my thanks to my parents in law, sister, brother in law, and sister in law for their moral's supports and valuable prayers.

I will always remember all of precious time which I spent with seniors and friends: Sumarsono-san, Abdillah-san, Imam-san, Ananta-san, Zulhaj-san, Yunus-san, Rizal-san, Jon-san, Arlyn-san, Agus-san, Baskoro-san, Ice-san, Chao-san, Sui-san, Fukada-san, Shirasu-san, Nishimura-san, and others. Many thanks for your helps and support in academic and non-academic life.

Aditya Tirta Pratama

Abstract

The development of production line continued during industrial revolution which was stimulated by the invention of steam engine technology by James Watt. Moreover, the productivity of workers at that time increased multiple time since the concept of interchangeable parts in production systems had been introduced. The fundamental of the mass production line was introduced by Henry Ford in 1913. He installed an assembly line that driven by conveyer belt where components will be moved from one station to next station while workers remain stationary at their respective stations. Nowadays, manufacturing companies are constantly trying to increase their productivity with the same amount of resources. The main challenge to manage the production line is to balance the work assignments, so there is no idle time due to the bottleneck in order to obtain low cost and high productivity. The bottleneck in a production line can cause the entire line to slow down or stop, and it affects the capacity of the whole production line. Balancing a production line is a procedure in which workloads are distributed evenly to each assembly station in the line so that each workstation has the same amount of the work. It can decrease the unused idle station capacity by reducing the operator idle time over the takt time.

One way to increase productivity in the serial or U-shaped assembly line is by increasing the number of workers. As the consequences, if more workers are added in the line, then more workers have to wait, and bottleneck will occur. Assembly line balancing problem (ALBP) is the term commonly used to refer to the decision process of assigning workloads to workstations in a serial production system. If the ALBP is utilized to balance the line, then the assembly line needs to be configured. Moreover, it is not guaranteed that a perfect balance line will be obtained.

The flexibility of the assembly system is used to improve the throughput rate of non-perfectly balance assembly line through work-sharing. The same task may be accomplished in different stations in different cycles when applying work-sharing. As a result, the division of workload among the stations is improved, and the cycle time is reduced. Work-sharing is closely related to the cross-trained studies since the tasks must be performed by cross-trained works due to the overlapping in the workers' capabilities. The Toyota Sewn System (TSS) and bucket brigades are the most common work-sharing system.

The bucket brigade is a self-balancing line in which each worker can move from one station to the next to continue working on a given part. Sequencing worker from slowest-to-fastest is the best policy for maximizing throughput on a continuous line. Meanwhile, throughput at discrete workstations may decrease due to blocking even though workers are properly sequenced. Most studies of bucket brigades in serial line and U-shaped line have been carried out based on the assumption that the work content is distributed continuously and uniformly over the entire line. However, for many assembly lines, the work content is neither continuously nor evenly distributed but is grouped in various proportions into discrete workstations.

The maximum possible throughput is not always achieved due to blocking conditions, although preemption or simply handing over task is allowed is the main problem of bucket brigade at discrete workstations. Workers may block each other, as each workstation can only accommodate one worker at one time. By utilizing cellular bucket brigades (CBB) to coordinate workers in a U-shaped line with discrete workstations, the throughput is significantly improved when the number of stations at each stage increases from one to two, but that there are diminishing returns if each stage is divided into more stations, then the performance may vary according to the situation.

The most famous application of bucket brigades is to coordinate workers to pick products for customer orders in distribution centers. The results show more effective work-sharing where the pick rates increase as a result of the absence of zone restriction by using bucket brigades. A case study of order picking by CBB, using data from a distributor of service parts in North America, and compares the average throughput of cellular and serial bucket brigades using a computer simulation. CBB can not only boost productivity but also save costs in terms of labor and wireless technology.

Teamwork or collaborative work can also be used to improve the performance of an assembly line that relies on workforce flexibility. A scenario at Compaq where teams of three workers built, tested and shipped computers at a single workstation and showed productivity and quality improvement as much as 25%. A prior study had compared assembly line design without collaboration to the parallel cell-based design of two single tasks with collaboration and introduced an inefficiency factor that rates the efficiency due to collaboration. Other study had compared four different worker coordination policies (no helping, floater, pairs, and complete helping) on a parallel assembly line under the assumption that the collaborative inefficiency reduces the productivity. The study tested collaborative efficiency factors at minor collaborative inefficiency in pair-working as 10% (with a collaborative coefficient of 0.9) and major inefficiency as 30% (with a collaborative coefficient of 0.7).

A method to counter halting, blocking, and starvation condition in serial line and U-shaped line by integrating bucket brigades and worker collaboration is proposed in this thesis. Since the increase of task speed can be obtained by using worker collaboration, then by integration of worker collaboration may decrease the idling of workers in some cases, and increase the performance of the production line. Prior assumptions are utilized to investigate and compare the performance of a production line in which the collaboration velocity is proportional to the sum of the individual worker velocities and is influenced by the collaboration coefficient under additive conditions (α = 1.0) and inefficient collaborative condition (α = 0.7 and α = 0.9).

The aim of this thesis is to determine the possible extended conditions for improvement and a procedure for achieving possibly higher throughput through worker collaboration. The performance of bucket brigades with and without worker collaboration can be compared at the serial line and U-shaped line. Moreover, a case study on migration from craft manufacturing to assembly line by integrating bucket brigade and worker collaboration based on prior assumption of serial-continuous line has been performed. Based on this thesis, worker collaboration can preserve the characteristics of self-balancing line and obtained performance improvement.

Keywords: bucket brigade, worker collaboration, collaboration coefficient, serial line, U-shaped line

Table of Content

List of Figures

List of Tables

List of Functions

Chapter 1 Introduction

1.1. Background

Most manufactured products were made individually from start to finish by hand before the industrial revolution. A worker created each part of a product based on their skills and tools, then assemble those parts into the final product. At that time, the craftsman team had an idea for improving capability and skills of using equipment or tools to meet the market demands. The development of production line continued during industrial revolution which was stimulated by the invention of steam engine technology by James Watt in 1769. Eli Whitney, in 1780, introduced the concept of interchangeable parts in production systems. The concept allowed the component/part to be created in other places where the size of parts has to meet the specific standard by considering some tolerance. Based on this concept, the productivity of workers at that time increased multiple times. Henry Ford started his automobile business in 1903, where each car was built and assembled by a highly skilled worker (craftsmen) at one location. At that time, if any part or component did not work or cannot be assembled with other parts or components, then the component will be repaired or rebuilt from the beginning until that component is appropriate. Based on this condition, the concept of standardization began to be used. In 1908, Ford modified the working process of the craftsman by specifying the specialization of the work on each task. This method proved to be efficient, but it has a disadvantage that the speed of tasks completion is not uniform then workers who completed the task faster often wait for other slower workers. The modern production line was initiated by Henry Ford in 1913. He installed moving assembly line for the mass production of Ford's model T. The assembly line was driven by conveyor belts where components will be moved from one station to the next station while the workers remain stationary at their respective stations. The results can significantly reduce the production time from 12 hours to 93 minutes by dividing the process into 45 steps. Therefore, this system is known as the mass production system.

Nowadays the mass production assembly line continues to evolve which involves making many copies of products very quickly, and by using assembly line technique to send partially complete products to workers who each work on an individual step. According to Miltenburg and Wijngaard (1994), the assembly line can be divided into two main groups based on the shape of the line: straight and U-shaped. The straight or serial line has an advantage since it has easy access from both sides for both material and workers. On the other hand, if the serial line is too long, then it may reach the limit of the building you have. Managing and supervising the line will involve more waste for the supervisor and possibly also for the workers due to walking distances. While the advantage of the U-shaped line is the ability of workers to tend to multiple processes within the line. Breakdowns and other problem may be fixed faster than in the other lines. If demand is very high, by putting a worker at every station, then the total output goes up, while if demand is lower, then reduce more workers from the line until at the end only single worker handles all the process and produce only a few items. U-shaped lines are popular in cellular manufacturing, due to the use of just-in-time and lean manufacturing, and have particular characteristics, such as: the entrance and exit of the line are close to each other, and workers can perform tasks and handle workpieces from both the front and the back of the line (Kucukkoc and Zhang, 2017). The superiority of the U-shaped line over the traditional serial line has been demonstrated and documented in various studies (e.g. Miltenburg, 2001; Aase et al., 2004).

On a production line, a worker can become starved (no part is available) or blocked (there is no room to place a complete part). There are two common methods for balancing production line: first, by distributing the workload among the different stations (Becker and Scholl, 2006), and second, by assigning storage space to different buffer (Gershwin and Schor, 2000). The main challenge to manage the production line is to balance the work assignments, so there is no idle time due to the bottleneck in order to obtain low cost and high productivity. According to Baudin (2002), the bottleneck in a production line causes the entire line to slow down or stop and it affects the capacity of the whole production line. Balancing a production line is a procedure in which workloads are distributed evenly to each assembly station in the line so that each workstation has the same amount of the work. It can decrease the unused idle station capacity by reducing the operator idle time over the takt time. Well-balanced workstations give various advantages in reducing wastes, such worker idleness, and need of changing operator, faulty product and stocks, and allows the company to reduce the price of their product by through the decrease in production cost of the unit.

According to Becker and Scholl (2006), assembly line balancing problem (ALBP) is the term commonly used to refer to the decision process of assigning workloads to workstations in a serial production system. They did a survey on problems and method in generalized assembly line balancing and found that the assembly line balancing research had traditionally focused on the simple assembly line balancing problem (SALBP) which had a restricting assumption. Common objectives of SALBP are minimizing the number of stations subject to a required throughput rate (denoted as SALBP-1) or minimizing the cycle time subject to a given number of stations (denoted as SALBP-2). Similar to the main challenge in the serial line, U-shaped line also needs to be balanced, thus reduce the idle time and obtain high productivity. U-shaped line balancing (ULB) was first studied by Miltenburg and Wijngaard (1994), who developed a dynamic programming (DP) formulation to minimize the number of workstations for a given cycle time. According to Bratcu and Dolgui (2005), the ALBP is Nondeterministic Polynomial-time (NP)-hard, meaning that the optimal line structure can be obtained, but it is sensitive to changes in the environment (i.e., short product life cycles, high demand for product variety, many models of products in small lot sizes, and short lead-times to the customer), and then the assembly line has to be configured or reconfigured. The assembly system must have flexibility in order to respond to the changes in the environment.

One way to increase productivity in the serial or U-shaped assembly line is by increasing the number of workers. As the consequences, if more workers are added in the line, then more workers have to wait, and bottleneck will occur. If the ALBP is utilized to balance the line, then the assembly line needs to be configured. Moreover, it is not guaranteed that a perfect balance line will be obtained. The flexibility of the assembly system is used to improve the throughput rate of non-perfectly balance assembly line through work-sharing. The same task may be accomplished in different stations in different cycles when applying work-sharing. As a result, the division of workload among the stations is improved, and the cycle time is reduced. Work-sharing is closely related to the cross-trained literature, since the tasks must be performed by cross-trained works due to the overlapping in the workers' capabilities. According to McClain et. al (2000), work-sharing is one way to reduce idle time, thus increased productivity. In the work-sharing, when workers are cross-trained, then it gives the system flexibility to respond process variability and allowing the line to be balanced by alternating which worker does a particular operation, effectively splitting the shared task. Several studies had explained the application of work-sharing in which related to cross-train. The range of task can start from single task per worker (no overlapping, no work-sharing) through several tasks per workers, up to fully cross-trained workers where workers are capable for performing all task in the line (Van Oyen et al., 2001; Hopp et al. 2004). Bartholdi and Eisenstein (1996a) introduced bucket brigades that rely on full cross-trained workers in continuous line. Hopp et al. (2004) also address the range of workstations allocate to each worker or work zone issue. On "Cheery picking", they suggested that one worker will assist all other stations, while on "2-skill Chaining", they proposed work-sharing between adjacent stations as each worker assists his neighbor. Each worker must finish the task before handing it to another worker when preemption is not allowed. In the case of preemption, the worker can take over the task in the middle of its performance (McClain et al., 2000). The Toyota Sewn System (TSS) and bucket brigades are the most common work-sharing system. According to Bartholdi and Eisenstein (1996a), a bucket brigade differs from the TSS in two ways. First, although the TSS and bucket brigades allow preemption, the bucket brigade does not restrict workers to the zones of the machines. Second, when a bucket brigade worker has finished an operation and finds that the next machine is being used, he must wait until the next worker finishes. In the TSS, a worker may leave and commence preemption or return to the beginning of his zone

Bartholdi and Eisenstein (1996a) showed that a bucket brigade is self-balancing, with the points where the item is transferred from one worker to the next worker determined by the worker's speed and tend to be stable. Sequencing workers from slowest-to-fastest is the best policy for maximizing throughput on a continuous line. Meanwhile, throughput at discrete workstations may decrease due to blocking even though workers are properly sequenced. Most studies of bucket brigades in serial and U-shaped line have been carried out based on the assumption that the work content is distributed continuously and uniformly over the entire line (e.g., Bartholdi and Eisenstein 1996a, 2005; Bartholdi et al. 1999, 2001, 2006; Armbruster and Gel 2006; Hirotani et al. 2006, Lim 2011). However, for many assembly lines, the work content is neither continuously nor evenly distributed, but is grouped in various proportions into discrete workstations. Lim and Yang (2009) studied the main problem of discrete workstations: that the maximum possible throughput is not always achieved due to blocking conditions, although preemption or simply handing over task is allowed. They found that workers may block each other, as each workstation can only accommodate one worker at one time. Lim (2011) introduced the idea of cellular bucket brigades (CBB) to coordinate workers on U-shaped lines; this eliminates the unproductive walk-back that is inherent in traditional bucket brigades. Lim and Wu (2014) analyzed the features of CBB on U-shaped lines with discrete workstations, and adapted the basic idea of CBB as introduced by Lim (2011) to coordinate workers on the U-shaped lines. They showed that throughput is significantly improved when the number of stations at each stage increases from one to two, but that there are diminishing returns if each stage is divided into more stations. They concluded that the performance of CBB might vary according to the situation.

The most famous application of bucket brigades is to coordinate workers to pick products for customer orders in distribution centers. The results show more effective work-sharing where the pick rates increase as a result of the absence of zone restriction by using bucket brigades (Bartholdi and Eisenstein, 1996b). In the production of garments, Bartholdi and Eisenstein (1996a) described the average production rate of a bucket brigade line staffed by standard workers spontaneously increases to the maximum possible under any way of organizing the workers. In the assembly of large-screen televisions, Villalobos et al. (1999a) explained that by implementing a 3-person feeding line, the sub-assembly work-in-process inventory shrank away until the portable conveyor was empty and no longer needed. The feeder line decreased the queue of waiting TV's until the feeder line was no longer a bottleneck during the next two hours. Villalobos et al. (1999b) explained the application of bucket brigades in the assembly of the automotive electrical harness. The assembly of the harness is labor intensive because the insertion of the cables' terminal into the connectors or the taping is automated hardly, in which the operator covers the outside of the wires' bundle with electrical tape. Bucket brigades can improve the production rate by about 10% and set new records for production in a single shift. Moreover, the work-in-process dropped from a peak of fifty harnesses to a constant six, which were worked by six workers. This, in turn reduced setup times when changing production to a different type of harness, which happened 1 until 4 times a shift. Lim (2012) provides a case study of order picking by CBB, using data from a distributor of service parts in North America, and compares the average throughput of cellular and serial bucket brigades using a computer simulation. This paper suggests that CBB can not only boost productivity but also save costs in terms of labor and wireless technology. The improvement in throughput due to a CBB can be as high as 25% over a serial bucket brigade for a team with 20 workers. CBB can be more productive than serial bucket brigades that are equipped with wireless technology for reducing travel even with fewer and slower workers.

Teamwork or collaborative work can be used to improve the performance of an assembly line that relies on workforce flexibility. Salas et al. (1992) have defined a team as a group of two or more people with specific or nonspecific roles or functions, who interact dynamically, interdependently and adaptively to target a common objective or mission. McGraw (1996) describes a scenario at Compaq where teams of three workers built, tested and shipped computers at a single workstation that showed improvements in productivity and quality of as much as 25%, although the operating costs were reported to be nearly four times higher than those of a conventional assembly line. With regard to multi-product scenarios with various product options, the teamworking experiments at Volvos Uddevalla and Kalmar plants are probably the most well-known (Engström and Medbo 1994; Ellegärd et al. 1992). Workers could collaborate on the same task, and each team of workers was assigned to do all or most of the assembly tasks on a particular vehicle. This plant showed an improvement in quality and a decrease in the total lead time, and it was also easier to handle requests for customization from customers. Most works in the literature have studied the impact of collaboration on the tandem queuing system where workers can work at the same task and have included the additive magnitude of the worker's collaboration/synergy, or $\alpha = 1.0$ (Andradóttir et al. 2001; Andradóttir and Ayhan, 2005; Andradóttir et al., 2011; Wang et al., 2015). Sengupta and Jacobs (2004) compared assembly line design without collaboration to the parallel cell-based design of two single tasks with collaboration. They introduced an inefficiency factor that rates the efficiency due to collaboration from no impact to a negative impact in which the productivity of each worker in the collaboration decreases. Peltokorpi et al. (2015) compared four different worker coordination policies (no helping, floater, pairs, and complete helping) on a parallel assembly line under the assumption that their collaborative inefficiency reduces the productivity. Their paper tests collaborative efficiency factors equivalent to the factors of Sengupta and Jacobs (2004), defining minor collaborative inefficiency in pair-working as 10% (with a collaborative coefficient of 0.9) and major inefficiency as 30% (with a collaborative coefficient of 0.7). They suggested the use of a complete helping policy in conditions of minor collaborative inefficiency and a pairs policy in conditions of major collaborative inefficiency.

Since halting, blocking, and starvation occur at bucket brigade in serial line and U-shaped line, then a method to counter those conditions by integrating bucket brigades and worker collaboration is proposed in this thesis. The use of worker collaboration may help to increase the task speed. The integration of worker collaboration may decrease the idling of workers in some cases, and increase the performance of the production line. Prior assumptions are utilized to investigate and compare the performance of a production line in the collaboration velocity is proportional to the sum of the individual worker velocities and is influenced by the collaboration coefficient. The aim of this thesis is to determine the possible extended conditions for improvement and a procedure for achieving possibly higher throughput through worker collaboration. The performance of bucket brigades with and without worker collaboration can be compared at serial and U-shaped line. Moreover, a case study on migration from craft manufacturing to assembly line by integrating bucket brigade and worker collaboration based on prior assumption of serial-continuous line by considering walk-back time and hand-off time has been performed. Based on this study, worker collaboration can preserve the characteristics of self-balancing line and obtained performance improvement.

1.2. Literature review

The literature that was reviewed in this thesis is detailed in this section under four topics: assembly line balancing, work-sharing system, bucket brigades, and worker collaboration. On the last part, we will discuss the gap that was identified in this section.

1.2.1 Assembly line balancing

Several numbers of workstations are positioned along a moving conveyor belt is the basic of an assembly line. Every workstation performs a value-added task where the tasks are performed by workers by using appropriate tools. The conveyor belts move according to a time and by repeating this process for several times, then the final product can be obtained at the last workstation. By using the principle of specialization and work division, high productivity of a mass production system can be achieved (Bukchin et al, 2002). Assembly line system has been explained by Ghosh and Gagnon (1989), Kriengkorakot and Pianthong (2007), and Sivasankaran and Shahabudeen (2014) as a set of different workstations, which usually have been fixed along the conveyer belt by allocating specific machines or operators.

Line balancing is arranging a production line so that there is a uniform flow of production from one station to the next. According to Falkenauer (2005), Assembly Line Balancing (ALB) or simply Line Balancing (LB) is the problem of assigning operations to workstations along with an assembly line, in such a way that the assignment is optimal in some sense. Line balancing is a successful tool to reduce bottleneck by balancing the task time of each station. As a result, there is no delay, and nobody is overburden with their task. Based on the theory of constraints (TOC) by Goldratt and Cox (1986), the capacity of bottleneck machines constrained the throughput of manufacturing systems. In most situations, the final throughput of manufacturing systems could be particularly improved if the bottleneck machines are well scheduled and controlled. Nowadays, the assembly lines move towards cellular manufacturing in terms of production variety. As a result, the utilization of special equipment and professional workers, which are able to perform more than one process, is increasing. This equipment and workers must be added to the line in a way by which high efficiency measures in order to benefit from continuous productions advantages. Baybars (1986) stated that the list of tasks to be done, the required task times to perform each task, and the precedence relations between tasks are analyzed while designing the line. The tasks are being grouped into stations, then the following goals are considered: (1) Minimization of the number of stations for a given cycle time. (2) Minimization of cycle time for a given number of stations. The decision problem of optimally balancing the assembly work among the workstations is pointed out as the assembly line balancing problem (ALBP) by Baskak (2008).

According to Becker and Scholl (2006), assembly line balancing problem (ALBP) is the term commonly used to refer to the decision process of assigning workloads to workstations in a serial production system. They did a survey on problems and method in generalized assembly line balancing and found that the assembly line balancing research had traditionally focused on the simple assembly line balancing problem (SALBP) which had restricting assumptions (e.g. no assignment restrictions besides the precedence constraints, one-sides stations, etc). Common objectives of SALBP are minimizing the number of stations subject to a required throughput rate (denoted as SALBP-1) or minimizing the cycle time subject to a given number of stations (denoted as SALBP-2). If the line efficiency is to be maximized, while both cycle time and the number of stations can be altered, the problem is recognized as SALBP-E (Boysen et al, 2007). A feasible balance for a given number of stations and a given cycle time is the objective of SALBP-F (Boysen et al, 2007). While the SALBP has been studied intensively in the literature, additional constraints coming from real-world applications have been considered rarely (Lapierre et al, 2006; Boysen et al, 2008).

Similar to the main challenge in the serial line, U-shaped line also needs to be balanced, thus reduce the idle time and obtain high productivity. U-shaped line balancing problem (UALBP) was first studied by Miltenburg and Wijngaard (1994), who developed a dynamic programming (DP) formulation for the single-model U-shaped line to minimize the number of workstations for a given cycle time. Miltenburg and Sparling (1995) developed three exact algorithms to solve the UALBP. Urban (1998) developed an integer linear programming formulation to solve small to medium-sized of UALBP with up to 45 tasks. Scholl and Klein (1999) developed a branch-and-bound procedure to solve, either optimally or sub-optimally, the problem with up to 297 tasks. Sparling and Miltenburg (1998) studied mix model U-shaped lines by developing a heuristic procedure for the U-shaped line in which different products were assembled simultaneously. Miltenburg (1998) proposed a DP formulation for a U-shaped line facility that consisted of numerous U-shaped lines connected by multiline stations. Sparling (1998) developed heuristic solution procedures for a U-shaped line facility consisting of individual U-shaped lines operating at the same cycle time and connected with multiline stations. Ajenblit and Wainwright (1998) developed a genetic algorithm, and Erel et al. (2001) proposed simulated annealing as solution methodologies for larger U-shaped line

The ALBP is Nondeterministic Polynomial-time (NP)-hard (Bratcu and Dolgui, 2005), meaning that the optimal line structure can be obtained, but it is sensitive to changes in the environment (i.e., short product life cycles, high demand for product variety, many models of products in small lot sizes, and short lead-times to the customer), and then the assembly line has to be configured or reconfigured.

As the conclusion, the main challenge of ALBP is to balance the work assignment, so there are no bottlenecks. Mathematical modelling and simulation have widely used to reduce the bottleneck in the assembly line. Those approaches can determine the approximate number of stations needed and reduce the cycle time on the line. However, this becomes tough due to know how much work is inherent and how to divide the work appropriately among the workers.

1.2.2 Work-sharing system

In order to increase productivity with the same amount of resources, manufacturing companies need to make their systems flexible to counter external demand variability, while dealing with the internal process variability. Reducing idle time of a limiting resource is the key to increased productivity. Work-sharing is one way to reduce idle time when labor is the limiting resource in a production facility (McClain et al., 2000). In the work-sharing, when workers are cross-trained, then it gives the system flexibility to respond process variability and allowing the line to be balanced by alternating which worker does a particular operation, effectively splitting the shared task. The range of task can start from single task per worker (no overlapping, no work-sharing) through several tasks per workers, up to fully cross-trained workers where workers are capable for performing all task in the line (Van Oyen et al., 2001; Hopp et al. 2004).

McClain et al. (1992) concluded that dynamic line balancing can increase efficiency even when inventory buffers are absent. McClain et al. (2000) analyzed work-sharing in a variety of situations including different worker to machine ratios, unequal workers, uncertain processing times, and handoffs with and without preemption. They concluded that worker sequencing is quite important, as slowest to fastest performs well in some situations and poorly in others. Their hypotheses consider work zones, inventory buffers and that there is complete dominance regarding workers' velocities. Askin and Chen (2006) studied the dynamic assignment in the traditional serial line model with partially cross-trained workers to maximize throughput. They analyzed the tradeoff between the cost and work-in-process inventory and cross-training in dynamic balancing systems. They also try to determine the best operating policies for shared tasks. They concluded that work-sharing improved output in the analyzed environments by 5.6% over static balanced assignments.

Hopp et al. (2004) studied two cross-training strategies for serial production systems with flexible servers. They stated that when the number of workers is equal to the number of stations, the primary benefits of workforce agility in this environment are variability buffering and capacity balancing in which provides a solution for worker idleness caused by processing times variability. Hopp et al. (2004) also address the range of workstations allocate to each worker or work zone issue. On "Cheery picking", they suggested that one worker will assist all other stations, while on "2-skill Chaining", they proposed work-sharing between adjacent stations as each worker assists his neighbor. Hopp and Van Oyen (2004) outline approach for accessing and classifying manufacturing and services with regard to their suitability for the utilization of the cross-trained workers. They define production agility as the ability to achieve heightened levels of efficiency and flexibility while meeting objectives for quality and customer service.

Sennott et al. (2006) modeled and analyzed serial production lines with specialists at each station and a single, cross-trained floating worker who can work at any station. They formulated a Markov Decision Process which models K-station production lines. The model includes holding costs, set-up costs and set-up times at each station. They performed a numerical study for two and three station lines. They concluded that problems with both specialists and cross-trained workers are extremely difficult to optimize, and that the burden of maximizing performance falls on the worker with the greatest flexibility.

Bartholdi and Eisenstein (1996a) introduced bucket brigades that rely on full cross-trained workers in continuous line. When preemption is not allowed, each worker must finish the task before handing it to another worker. On the other hand, the worker can take over the task in the middle of its performance (McClain et al., 2000). The Toyota Sewn System (TSS) and bucket brigades are the most common work-sharing system. According to Bartholdi and Eisenstein (1996a), a bucket brigade differs from the TSS in two ways. First, although the TSS and bucket brigades allow preemption, the bucket brigade does not restrict workers to the zones of the machines. Second, when a bucket brigade worker has finished an operation and finds that the next machine is being used, he must wait until the next worker finishes. In the TSS, a worker may leave and commence preemption or return to the beginning of his zone

As the conclusion, the work-sharing system able to increase the productivity by making a flexible system by considering the same amount of resource. The main characteristic of the work-sharing system is cross-trained workers that can respond and adapt quickly to the process variability and effectively balance the line by sharing tasks.

1.2.3 Bucket brigades

Bartholdi and Eisenstein (1996a) was the first scientific article that introduces the idea of bucket brigades. The idea is based on the Toyota Sewn System (TSS), an assembly line mostly used in the apparel industry. In a TSS, each worker receives a specific amount of work. When the last worker finishes with his task, he walks back to the worker behind him and continues with his task. This worker does the same to the picker behind him. In the end, as this process continues, the first worker is reached, and he must walk back to initiate a new amount of work. The TSS imposes no ordering on the workers, while the bucket brigade requires workers to be ordered from slowest to fastest is the main difference between the two procedures. The ordering of workers was introduced by Bartholdi and Eisenstein (1996a) to show that with it the flow line becomes a self-balancing system with respect to workload. Since the worker performs the same amount of work every time he receives a new order, then the fixed hand-over points indicate the workload is balanced (Bartholdi and Eisenstein, 1996a).

Bartholdi et al. (1999) studied the dynamics of two- and three-worker bucket brigade production lines and discussed the type of asymptotic behavior possible in practice as a function of the workers' relative speeds, which is assumed to be constant over the entire line. For two-worker bucket brigade production line, they concluded that the movements of workers would spontaneously converge to a fixed point balanced line with the optimal production rate and the movements of the workers would converge to a two-cycle balanced line with a suboptimal production rate. For three-worker bucket brigade production line, they defined four regions of possible asymptotic behavior. Region 1 is defined as one cycle or convergence to a fixed point with the optimal production rate. Regions 2 and 3 cover situations when workers are not ordered from slowest to fastest (thus blocking is present) and the positions of the workers would alternate between two and three cycle positions with suboptimal production rates. The fourth region is defined as region k where the systems in this region can converge to a k cycle for some values of $k>3$.

Bartholdi et al. (2001) addresses the case of stochastic processing times and proves a similarity between the deterministic and stochastic systems as the number of stations goes to infinity. Bartholdi and Eisenstein (2005) studied the real case in migrating from crafts manufacturing to assembly line by extending the Normative Model and assumed that walk-back times and hand-off times are significant. The adoption of bucket brigades resulted in a reduced number of tasks for each worker and higher overall productivity. Bartholdi et al. (2006) extend the ideas of bucket brigades to a network of sub-assembly lines so that all sub-assembly lines are synchronized to produce at the same rate and items are completed at regular, predictable intervals.

Armbruster and Gel (2006) studied a two-worker bucket brigade where one worker is faster than the other over some part of the production line and slower over another part of the line. They assumed deterministic processing times, continuous tasks and instantaneous walking speeds. The original no passing rule is modified as workers are allowed to pass each other. They concluded that if the order of the workers is switched when one passes another the bucket brigade self-organizes itself. Their conclusion is that the system may not always balance itself on a fixed point but rather to two stable positions where workers exchange jobs. Workers would hand over jobs at exactly two fixed locations that they visit periodically.

Hirotani et al. (2006) considered that blocking happens when the slower worker slows the process by preventing faster workers from continuing the process. They concluded that the positions of workers will not converge to a fixed point and then the production rate will decrease. Lim (2011) introduced the idea of cellular bucket brigades (CBB) to coordinate workers on U-shaped lines; this eliminates the unproductive walk-back that is inherent in traditional bucket brigades.

Most studies of bucket brigades in serial and U-shaped line have been carried out based on the assumption that the work content is distributed continuously and uniformly over the entire line (e.g., Bartholdi and Eisenstein 1996a, 2005; Bartholdi et al. 1999, 2001, 2006; Armbruster and Gel 2006; Hirotani et al. 2006, Lim 2011). However, for many assembly lines, the work content is neither continuously nor evenly distributed, but is grouped in various proportions into discrete workstations.

Lim and Yang (2009) studied the main problem of discrete workstations: that the maximum possible throughput is not always achieved due to blocking conditions, although preemption or simply handing over task is allowed. They found that workers may block each other, as each workstation can only accommodate one worker at one time. Lim and Wu (2014) analyzed the features of CBB on U-shaped lines with discrete workstations, and adapted the basic idea of CBB as introduced by Lim (2011) to coordinate workers on the U-shaped lines. They showed that throughput is significantly improved when the number of stations at each stage increases from one to two, but that there are diminishing returns if each stage is divided into more stations. They concluded that the performance of CBB may vary according to the situation.

The most famous application of bucket brigades is to coordinate workers to pick products for customer orders in distribution centers. The results show more effective work-sharing where the pick rates increase as a result of the absence of zone restriction by using bucket brigades (Bartholdi et al., 2001). Lim (2012) provides a case study of order picking by CBB, using data from a distributor of service parts in North America, and compares the average throughput of cellular and serial bucket brigades using a computer simulation. This paper suggests that CBB can not only boost productivity but also save costs in terms of labor and wireless technology. The improvement in throughput due to a CBB can be 25% higher than a serial bucket brigade for a team with 20 workers. CBB can be more productive than serial bucket brigades that are equipped with wireless technology for reducing travel although with fewer and slower workers.

As the conclusion, bucket brigades able to achieve better balance because it redistributes the work based, not on estimates (time-motion studies), but on the actual time of a particular worker to perform a particular task. However, it has weakness on blocking and starvation even if the workers are sequencing from slower-to-faster and the chance of blocking and starvation increase when the number of workers approaches the number of stations under discrete work stations.

1.2.4 Worker collaboration

Teamwork or collaborative work can be used to improve the performance of the assembly line that relies on workforce flexibility. Salas et al. (1992) have defined a team as a group of two or more people with specific or nonspecific roles or functions, who interact dynamically, interdependently and adaptively to target a common objective or mission. McGraw (1996) describes a scenario at Compaq where teams of three workers built, tested and shipped computers at a single workstation that showed improvements in productivity and quality of as much as 25%, although the operating costs were reported to be nearly four times higher than those of a conventional assembly line. With regard to multi-product scenarios with various product options, the teamworking experiments at Volvos Uddevalla and Kalmar plants are probably the most well-known (Engström and Medbo 1994; Ellegärd et al. 1992). Workers could collaborate on the same task, and each team of workers was assigned to do all or most of the assembly tasks on a particular vehicle. This plant showed an improvement in quality and a decrease in the total lead time, and it was also easier to handle requests for customization from customers.

Buzacott (1996) used queueing models to analyze the performance of collaborative teams and found that the mean job completion time was shorter for teams than for individuals. However, the improvement depends on several important factors including the variability level of task processing times, and the utilization of servers. Mandelbaum and Reiman (1998) examined the effectiveness of pooling servers into teams. They found that the pooling of tasks and servers may reduce the steady-state average sojourn times for some circumstances such as under light-traffic and low variability in pooled tasks. According to Hopp and Van Oyen (2004), a basic measure of collaboration efficiency is the relative percentage increase in average task speed (or labor productivity) that result from assigning multiple workers to the same task.

Andradóttir et al. (2001) used model assumption that the combined service rate is additive when multiple servers are assigned to the same task. Several servers can work together on the single customer, in which case the combined rate of the server team is proportional to the sum of rates of the individual servers. They considered α as a measure of the magnitude of server's collaboration/synergy. They studied worker coordination in a finite queuing system in order to obtain the near-optimal long-run average throughput. They suggest that workers should not idle but should help others when the processing times for each task are independent of the worker or, alternatively, when each worker processes at about the same speed on all tasks. In contrast, when the processing times depend both on the worker and on the task, the study suggests assigning a worker to each task in such a way that the product of the processing rates of the workers at their assigned tasks is maximized. This requires workers to be instructed to avoid idleness by working on tasks that will enable them to get back to work at their primary task as soon as possible, and that the worker processing rates do not vary a lot for the tasks that are not their primary ones.

Van Oyen et al. (2001) showed that collaborative teams are beneficial for systems with high variability. Under some circumstances, such as operational environments with low utilization, low variability, and a lack of balance, cooperative teams may not improve system performance unless collaborative efficiency is very high.

Andradóttir and Ayhan (2005) studied how the servers should be assigned dynamically to the station to obtain optimal long-run average throughput. They assumed that each server can work on only one job at a time, the several servers can work together on a single job, and the travel times between stations are negligible. As the conclusion, they proposed heuristic server-assignment policies that involve grouping all available servers into two or three teams and suggest to use three-team heuristic policy for achieving near-optimal long-run average throughput.

Andradóttir et al. (2011) considered tandem lines with finite buffers and flexible, heterogeneous servers that are synergistic in which they work more effectively in teams than on their own. They studied how the servers should be assigned dynamically to tasks in order to maximize the long-run average throughput. They showed that the optimal policy has servers working in teams of two or more at all times when there is no trade-off between server synergy and servers' special skills.

Most works in the literature have studied the impact of collaboration on the tandem queuing system where workers can work at the same task and have included the additive magnitude of the worker's collaboration/synergy, or α = 1.0 (Andradóttir et al. 2001; Andradóttir and Ayhan, 2005; Andradóttir et al., 2011; Wang et al., 2015).

Sengupta and Jacobs (2004) compared assembly line design without collaboration to the parallel cell-based design of two single tasks with collaboration. They introduced an inefficiency factor that rates the efficiency due to collaboration from no impact to a negative impact in which the productivity of each worker in the collaboration decreases.

Peltokorpi et al. (2015) compared four different worker coordination policies (no helping, floater, pairs, and complete helping) on a parallel assembly line under the assumption that their collaborative inefficiency reduces the productivity. Their paper tests collaborative efficiency factors equivalent to the factors of Sengupta and Jacobs (2004), defining minor collaborative inefficiency in pair-working as 10% (with a collaborative coefficient of 0.9) and major inefficiency as 30% (with a collaborative coefficient of 0.7). They suggested the use of a complete helping policy in conditions of minor collaborative inefficiency and a pairs policy in conditions of major collaborative inefficiency.

As a conclusion, it becomes extremely important to improve productivity and worker collaboration enables workers to be quicker and more effective in their work. Collaborative efficiency measures whether and how the grouping of workers on tasks improves productivity. It also one factor that affects the team structure that arises from worker competency synergies or an economy scale gained through the size of a team.

1.2.5 Research gap

One way to increase productivity in the serial or U-shaped assembly line is by increasing the number of workers. As the consequences, if more workers are added in the line, then more workers have to wait, and bottleneck will occur. Since the solution of ALBP is NP-hard, then the assembly line has to be configured or reconfigured to counter the change of environment. Moreover, it is not guaranteed that a perfect balance line will be obtained. Them, the assembly system must have flexibility in order to respond to the changes in the environment. The flexibility of the assembly system is used to improve the throughput rate of non-perfectly balance assembly line through work-sharing. Work-sharing is closely related to the cross literature, since the tasks must be performed by cross-trained works due to the overlapping in the workers' capabilities. A bucket brigade is one of the common work-sharing systems. A bucket brigade is self-balancing, with the points where the item is transferred from one worker to the next worker as determined by the worker's speed and tend to be stable. Sequencing workers from slowest-to-fastest is the best policy for maximizing throughput on a continuous line.

However, for many assembly lines, the work content is neither continuously nor evenly distributed, but is grouped in various proportions into discrete workstations. Literature that explores the impact of bucket brigade on discrete workstations is rare. Moreover, the study of a bucket brigade on the U-shaped line is scarce. In addition, the studies that integrate bucket brigade and worker collaboration is also limited. In worker collaboration, most studies only investigate the condition at the stochastic process by assuming collaboration coefficient is additive ($\alpha = 1.0$) or synergistic ($1 \leq \alpha < \infty$).

Since halting, blocking, and starvation occur at bucket brigade in serial line and U-shaped line, then a method to counter those conditions is proposed by integrating bucket brigades and worker collaboration. The use of worker collaboration may help to increase the task speed. The integration of worker collaboration may decrease the idling of workers in some cases, and increase the performance of the production line. Prior assumptions are utilized to investigate and compare the performance of a production line in which the collaboration velocity is proportional to the sum of the individual worker velocities and is influenced by the collaboration coefficient. The aim of the study is to determine the possible extended conditions for improvement and a procedure for achieving possibly higher throughput through worker collaboration. Moreover, the performance of bucket brigades with and without worker collaboration can be compared at serial and U-shaped line. In addition, a case study on migration from craft manufacturing to assembly line by integrating bucket brigade and worker collaboration based on prior assumption at serial-continuous line by considering walk-back time and hand-off time has been performed. Based on this thesis, worker collaboration can preserve the characteristics of self-balancing line and obtained performance improvement.

1.3. Problem statements

The research gap outlines problems in bucket brigades that can be addressed. The objective of this thesis is to study worker collaboration for a bucket brigade production line that accommodates discrete workstations, cross-trained workers, and collaboration coefficient.

The objective of this thesis can be described as follows:

- to study the impact on the integration of bucket brigades and worker collaboration by adopting assumptions based on prior studies in bucket brigades with discrete workstations.
- to identify the conditions for worker collaboration where it can produce higher performance than bucket brigade in serial line and U-shaped line with discrete workstations.
- to investigate worker collaboration based on the case of migrating from craftsman manufacturing to assembly lines at serial-continuous line by considering walk-back time and hand-off time.

Specific sets of research question that this thesis aims to be answered are:

- Can worker collaborate be integrated at bucket brigade production line? What are the capabilities and limitations?
- Is worker collaboration always obtained maximum throughput under any conditions in a production line?
- What kind of conditions for worker collaboration can obtain higher performance than bucket brigade?

1.4. Thesis outline

The thesis consists of five chapters. The research topics are mainly distributing among the chapters as follows:

a. Chapter 1 presents the background of the study, literature review, problem statements, and the thesis outlines.
b. Chapter 2 provides the study on the integrations of bucket brigades and worker collaboration on a serial line with discrete workstations is proposed to counter the blocking condition.
c. Chapter 3 provides the study on the integration of cellular bucket brigades (CBB) and worker collaboration on U-shaped line with discrete workstations is proposed to counter haling and/or blocking condition.
d. Chapter 4 presents the integration of bucket brigades and worker collaboration by considering walk-back times and hand-off times or preparation for collaboration times based on a prior study at serial-continuous line on migration process from craft manufacturing to an assembly line.
e. Chapter 5 presents the summary of the major achievements. In addition, the future research works are discussed in relation to this thesis.

Chapter 2 Integration of bucket brigades and worker collaboration on production line with discrete workstations

2.1. Introduction

In this chapter, the integration of bucket brigades and worker collaboration will be described by adopting prior studies and assumption of Lim and Yang (2009) to counter the blocking condition at discrete workstations. Moreover, the conditions that produce higher throughput and performance comparison of bucket brigade with and without worker collaboration are explained. A procedure has been developed for deriving throughput for the case including worker collaboration.

Most studies of bucket brigades have been carried out based on the assumption that the work content is distributed continuously and uniformly over entire line (e.g., Bartholdi and Eisenstein 1996a, 2005. Bartholdi et al. 1999, 2001, 2006, Armbruster and Gel 2006; Hirotani et al. 2006). In real conditions, the work content is grouped in various proportions at discrete workstations. Lim and Yang (2009) studied the main problem of bucket brigades in discrete workstations that the maximum throughput is not always be achieved due to blocking conditions, although preemption or simply handing over task is allowed. They found that workers may block each other, as each workstation can only accommodate one worker at one time.

Worker collaboration can be utilized to offset the decrease in performance as a result of the blocking condition. The experiment of worker collaboration by Compaq at one of its assembly lines showed that there was an improvement in productivity and quality, although the operating costs increase (McGraw, 1996). Andradóttir et al. (2001) used the assumption that when multiple servers are assigned to the same task, their combined service rate is additive. These authors use α as a measure of the magnitude of the servers' collaboration/synergy. The magnitude of the server's collaboration/synergy (α) can be calculated from the ratio between the combined rate of the server team and the sum of rates of the individual servers. If the combined rate of the server team equal with the sum of the rates if the individual servers, then the servers are additive ($\alpha = 1.0$). If the combined rate of the server team is less than the sum of the rates if the individual servers, then $\alpha < 1.0$ and the servers collaboration/synergic slows the processing. If the successor has finished with his item, he then walks to the predecessor's position to work collaboratively. A maximum of two workers can collaborate on the same task (or at the same workstation), so the worker's idle time due to blocking can be minimized. Since the work content of the product at each station is deterministic, then based on the analysis of the deterministic system shows that the working velocity and work content distribution along the production line are the most important parameters related to throughput.

This chapter is structured into the following sections. The first section presents introduction. The second section explains the production line model along with the general rules and assumptions. The third section explains the behavior analysis for the larger production line and followed with procedures to define throughput of the bucket brigades with worker collaboration. The fourth section explains the numerical calculation for a small production line and m-workstation and n-worker production line. Finally, the last section summarizes this chapter by presenting the managerial implication and explaining the conclusion regarding bucket brigades with and without worker collaboration.

2.2. Production line

The production line model and assumptions for bucket brigades without worker collaboration are adopted from Lim and Yang (2009). They considered a production line in which each instance of a product is progressively assembled in the same sequence of m stations. The work content of the product at station j is deterministic and is denoted as s_j, and the total work content is normalized to 1 so that $\sum_{j=1}^{m} s_j = 1$. Workers are indexed from 1 to n and remain in this sequence along the production line in the direction of production flow and each worker works with constant and deterministic velocity v_i. Workers $i-1$ and $i+1$ are the predecessor and successor, respectively, of worker i. Each worker i is cross-trained to work in zone Z_i, a set of adjacent stations along the line. Worker i is fully cross-trained if Z_i contains all stations on the line. A worker $i < n$ will be blocked if he finishes his work at station j while worker $i+1$ is still working at the next station $j+1 \in Z_i$. The blocked worker remains idle until the next station becomes available. A worker $i < n$ will be halted if he finishes his work at all stations in Z_i before he can hand off his item to worker $i+1$. The halted worker remains idle until the successor takes over his item. A worker $i > 1$ will be starved if he reaches the beginning of his zone before worker $i-1$ can hand over the item to him. The starved worker remains idle until his predecessor hands over an item. The production line can be conceptually represented by a line with length equal to 1 as shown in Figure 2.1.

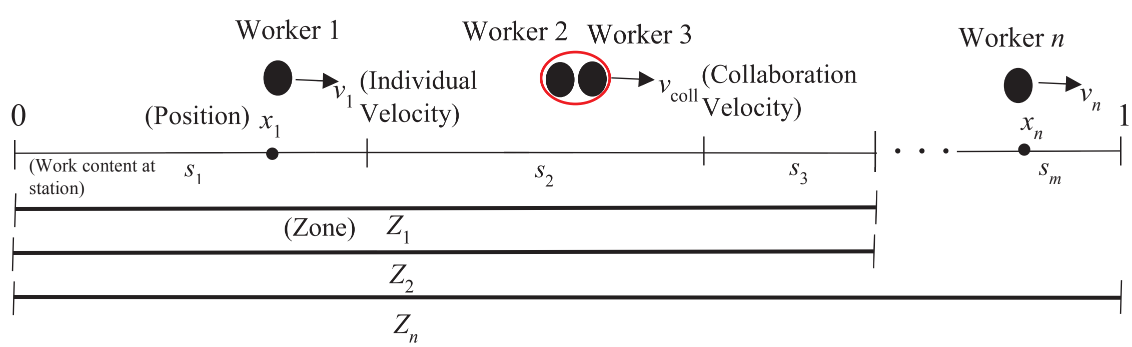


Figure 2.1. Conceptual representation of the total work content of a product as a line segment that is partitioned into intervals by workstations (s_m). The position, velocity, and working zone of worker i are denoted as x_i, v_i, and Z_i, respectively. x_i also represents the cumulative fraction of completed work content of an item.

In a bucket brigade without worker collaboration, when the last worker (worker n) finishes work on his item, he then walks back to get the item from worker $n-1$, who in turn walks back to get the item from worker $n-2$, and so on until worker 1 initiates a new item. Each worker i works along the line with constant velocity v_i within zone Z_i, except when the workers are blocked, halted, starved, and/or working collaboratively.

Worker collaboration at a collaborative station begins when the successor and predecessor can work at any place in the station; they work collaboratively until the task is complete at the end of the station. A collaborative station is defined as a station that allows multiple workers to work together by sharing spaces and tools to complete an item. At a station, a worker will process an item as individual work and/or partial work will be performed by collaboration without any loss of work. At most two workers can work together on the same task, in which case the combined velocity of a team is proportional to the sum of the velocities of the individual workers. Worker collaboration cannot be established at the last station because only the last worker can work at the last station. The collaborative velocity is $v_{coll}(i) = \alpha_i(v_i + v_{i+1})$ and must be higher than the minimum worker velocity ($v_{coll}(i) > \min\{v_i, v_{i+1}\}$). α_i is a measure or coefficient of the collaboration or synergy between worker i and worker $i+1$, defined as $0 < \alpha_i \leq 1$.

Table 2.1. Behavior rules independently followed by each worker.

<table>
<tr><td colspan="2">Forward rule: Work along the line until one of the following events occurs:</td></tr>
<tr><td>Without collaboration</td><td>With collaboration</td></tr>
<tr><td>• Your item is taken by your successor.</td><td>• You complete the collaborative work with your successor at the end of the collaborative station (intersection zone).
• You and your co-worker are intercepted by the next downstream worker at a collaborative station.</td></tr>
<tr><td colspan="2">• You are halted; in this case, wait until you pass your item to your successor.
• You are blocked; in this case, wait until the next workstation is available.
• You complete your item at the end of the line.
Then follow the backward rule.</td></tr>
</table>

<table>
<tr><td colspan="2">Backward rule: Walk back until one of the following events occurs:</td></tr>
<tr><td>Without collaboration</td><td>With collaboration</td></tr>
<tr><td>• You encounter your predecessor; in this case, take over his item.</td><td>• You encounter your predecessor; in this case, begin to work collaboratively.
• You meet with the upstream pair at a collaborative station (intersection zone); in this case, intercept and continue to work collaboratively with your predecessor until the end of the collaborative station.</td></tr>
<tr><td colspan="2">• You are starved; in this case, wait until you receive an item from your predecessor.
• You reach the start of the line; in this case, begin a new item.
Then follow the forward rule.</td></tr>
</table>

The work content is preemptible when an item is handed off without any loss of work. In the production line, the time taken to process an item is significantly longer than the time taken to hand over the item and the time taken to walk back along the entire length of the line. Therefore, each worker spends negligible time handing over the item and walking back to the predecessor or the beginning of his zone. Table 2.1 explains the forward and backward rules that must be followed by each worker.

2.3. Behavior analysis

This section explains the behavior of bucket brigades with worker collaboration on a general production line with discrete workstations. The condition will be focused on fully cross-trained workers utilizing slowest-to-fastest sequencing, which is based on the most reasonable condition and most of the works in the literature.

2.3.1 Behavior of worker collaboration

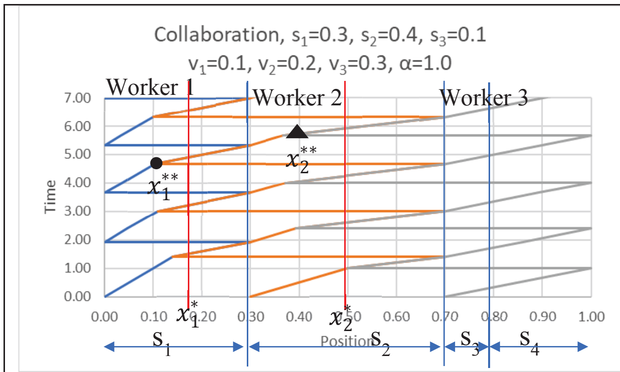
Figure 2.2 gives four examples of time charts for a four-station, three-worker line with similar velocity conditions and a collaboration coefficient $\alpha = 1.0$. The collaboration meeting point between Worker 1 and Worker 2 is indicated by a solid black circle, and the collaboration meeting point between Worker 2 and Worker 3 is indicated by a solid black triangle. The vertical line in which time elapses without any work progress indicates the worker's idle time. The behavior of worker collaboration can be divided into single-orbit and multi-orbit cyclic behavior. Single-orbit cyclic behavior means that each collaboration meeting point is always at the same station in every iteration. Multi-orbit cyclic behavior means that the collaboration meeting points move between the downstream and upstream stations alternately in every iteration.

Maximum throughput can be defined as the throughput of the bucket brigade's line without idle time. The necessary condition for achieving the maximum throughput with worker collaboration is no idleness occurring and $\alpha = 1.0$. The throughput decreases when idling occurs on the bucket brigade line, whereas by using worker collaboration with $\alpha < 1.0$ and elimination of idling, the throughput may be higher than that of the bucket brigade but still lower than the maximum possible throughput.

x_i^* defines as the fixed point of a bucket brigade where workers maintain balance by repeating the respective portion of the work content for each item produced, x_i^{**} as the collaboration meeting point at which a pair of workers will start collaboration, and $j^*(i)$ as the smallest index of a station within which the fixed point of the bucket brigade falls.

Figure 2.2a shows single-orbit cyclic behavior without blocking where the collaboration meeting points are unique and are at the same station as the fixed points of bucket brigade. In single orbit cyclic behavior, each pair of workers always carries out collaborative work at the same station repeatedly. Multi-orbit cyclic behavior without blocking is shown in Figure 2b where the collaboration meeting points move between the upstream and downstream stations in every iteration.

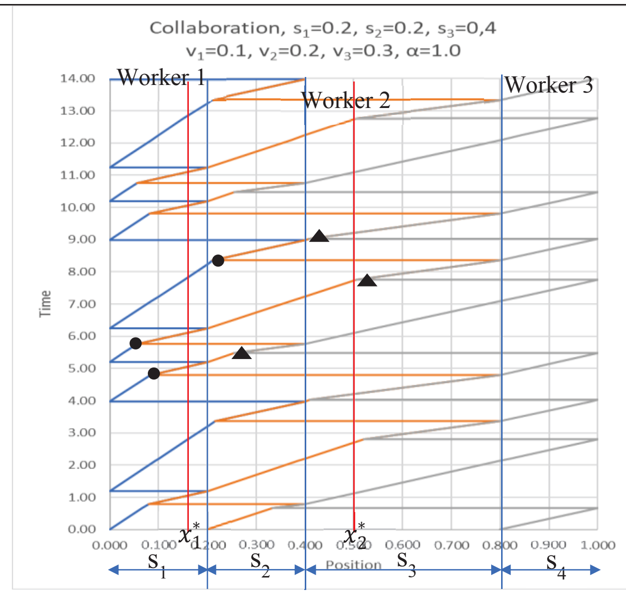
Figure 2.2c shows single-orbit cyclic behavior with blocking. Since all fixed points of the bucket brigade are located at a single station, the upstream worker is blocked when he finishes his work earlier, while others are still working at the next station. Two workers always meet and start collaboration at the same point in every iteration. Multi-orbit cyclic behavior with blocking is shown in Figure 2.2d. The collaboration meeting points move between the upstream and downstream stations. The upstream worker is blocked when he has finished his work because the next station is still being operated by other workers.



$x_1^* = 0.1667 \rightarrow j^*(1) = 1$

$x_2^* = 0.5 \rightarrow j^*(2) = 2$

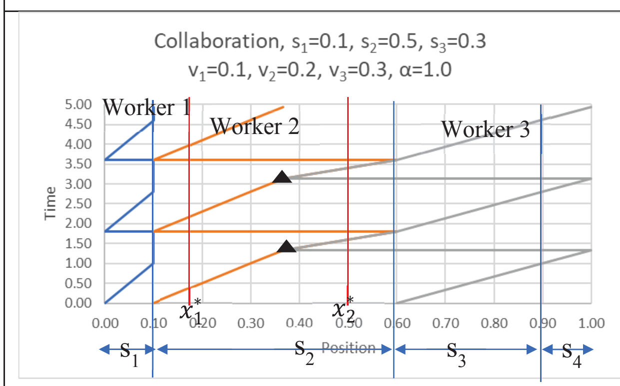
a. Single-orbit cyclic behavior without blocking



$x_1^* = 0.1667 \rightarrow j^*(1) = 1$

$x_2^* = 0.5 \rightarrow j^*(2) = 3$

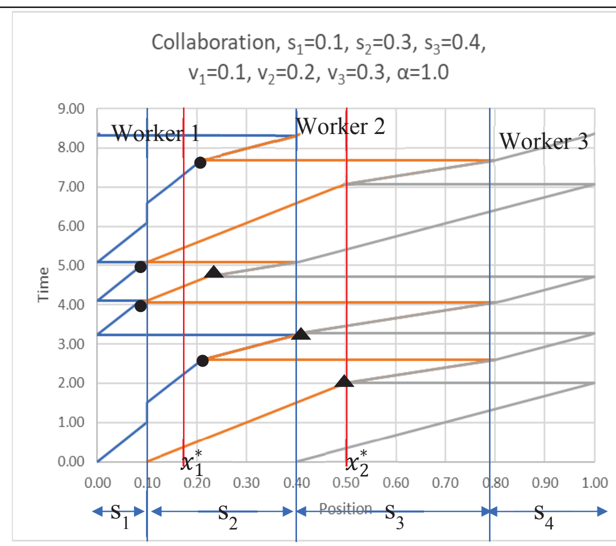
b. Multi-orbit cyclic behavior without blocking



$x_1^* = 0.1667 \rightarrow j^*(1) = 2$

$x_2^* = 0.5 \rightarrow j^*(2) = 2$

c. Single-orbit cyclic behavior with blocking



$x_1^* = 0.1667 \rightarrow j^*(1) = 2$

$x_2^* = 0.5 \rightarrow j^*(2) = 3$

d. Multi-orbit cyclic behavior with blocking

Figure 2.2. Time chart for four-station, three-worker production lines where $v_1 = 0.1$, $v_2 = 0.2$, $v_3 = 0.3$, and $\alpha = 1.0$ (●: collaboration between workers 1 and 2; ▲: collaboration between workers 2 and 3).

The analysis of multi-orbit cyclic behavior is neglected for several reasons. Multi-orbit cyclic behavior is hard to identify because the system does not converge into single-orbit cyclic behavior. A similar behavior is expected to occur on larger production lines, and the movement of collaboration meeting points will be hard to identify. Furthermore, the number of configurations with multi-orbit cyclic collaboration behavior will be smaller than the number of configurations with single-orbit cyclic collaboration behavior.

2.3.2 Single-orbit cyclic behavior

The complexity of the analysis to achieve higher throughput on a line with *m* stations and *n* workers increases rapidly with *m* and *n*. Based on Figure 2.2a, a production line can obtain higher throughput with single-orbit cyclic behavior by utilizing worker collaboration if the meeting point for collaborative work is always at the same point in the next iteration. Furthermore, there is no idleness due to blocking, halting, or starvation when collaboration occurs.

Based on Figure 2.3, with the same definition of x_i^*, x_i^{**}, and $j^*(i)$, the single-orbit cyclic behavior without blocking will be achieved if all workers start the collaborative work at each collaboration meeting point (x_i^{**}) obtained without any loss or blocking condition. The obtained collaboration meeting points for each pair of workers can be derived simultaneously based on the mathematical formulation developed in this section.

Assume that all expected collaboration stations are the stations where the fixed points of bucket brigades are located and that the collaboration meeting points for different pairs of workers occur at different collaboration stations. If all collaboration meeting points (x_i^{**}) are obtained and all workers start collaborative work at the obtained points, then single-orbit cyclic behavior can be achieved. Below, the single-orbit cyclic behavior based on those assumptions is derived.

When worker *n* and worker *n* – 1 have just finished the collaborative work at the intended collaboration station, worker *n* starts the individual work while worker *n* – 1 will collaborate with worker *n* – 2 at the upstream collaboration station as shown in Figure 2.3a. The inequality $\frac{\left(\sum_{j=1}^{j^*(n-2)} s_j - x_{n-2}^{**}\right)}{\alpha_{n-2}\sum_{j=n-2}^{n-1} v_j} < \frac{\sum_{j=1}^{j^*(n)} s_j - \sum_{j=1}^{j^*(n-1)} s_j}{v_n}$ expresses that the collaboration time for worker *n* – 2 and worker *n* – 1 at the expected collaboration station $j^*(n-2)$ is shorter than the individual processing time by worker *n*. After finishing collaboration, worker *n* – 1 starts individual work while worker *n* has already started his work. If this condition is not satisfied, worker *n* will finish earlier at the end of the line and then interrupt the collaboration process and continue the collaborative work with worker *n* – 1 at collaboration station $j^*(n-2)$, while worker *n* – 2 will go upstream to collaborate with worker *n* – 3 or introduce a new item.

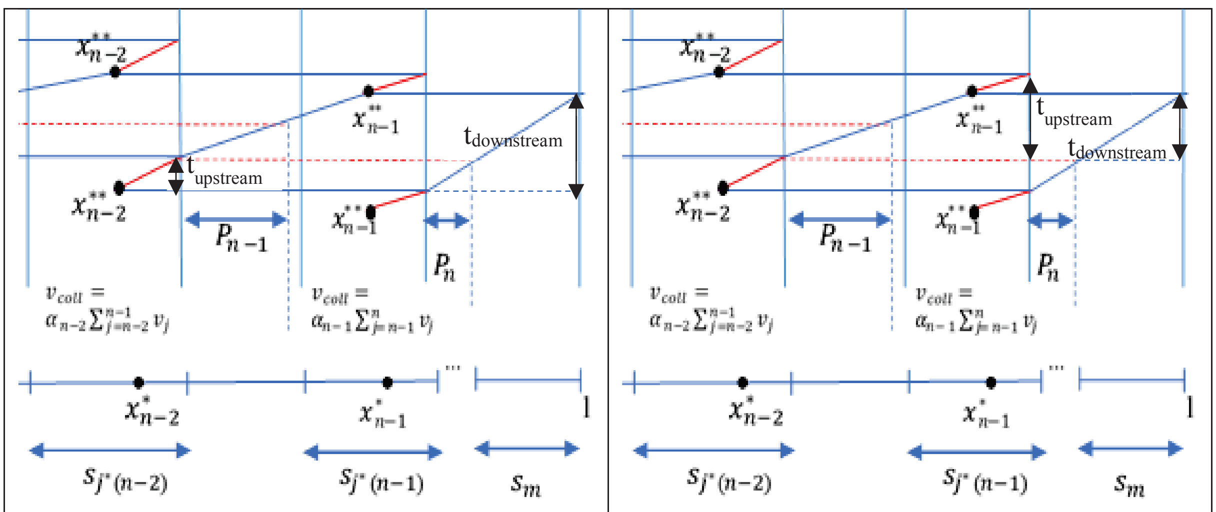
Based on the inequality condition, the position of worker *n* (P_n) after worker *n* – 1 and worker *n* – 2 have finished collaborating is determined.

$$P_n = \frac{\left(\sum_{j=1}^{j^*(n-2)} s_j - x_{n-2}^{**}\right) v_n}{\alpha_{n-2} \sum_{j=n-2}^{n-1} v_j} \tag{2.1}$$

When worker $n-2$ and worker $n-1$ have just finished collaborating, worker $n-1$ starts individual work while worker n has already begun his work as shown in Figure 2.3b. The inequality $\frac{\left(\sum_{j=1}^{j^*(n-1)} s_j - \sum_{j=1}^{j^*(n-2)} s_j\right)}{v_{n-1}} \geq \frac{\left(1-\sum_{j=1}^{j^*(n-1)} s_j\right) - P_n}{v_n}$ expresses that the processing time by worker $n-1$ must be longer than or equal to the processing time by worker n. Worker n will go to support worker $n-1$ at a collaboration station. If this condition is not satisfied, then worker $n-1$ will be halted until worker n finishes with his item at the end of the line and takes over the item from worker $n-1$.

Based on the inequality condition, the collaboration meeting point for worker n and worker $n-1$ (x_{n-1}^{**}) can be defined as the individual processing time for worker n multiplied by the velocity of worker $n-1$ added to the length of work contents at $j^*(n-2)$.

$$x_{n-1}^{**} = \frac{\left(\left(1-\sum_{j=1}^{j^*(n-1)} s_j\right) - P_n\right) v_{n-1}}{v_n} + \sum_{j=1}^{j^*(n-2)} s_j \tag{2.2}$$



(a) $t_{upstream}$: collaboration processing time by workers $n-2$ and $n-1$ $\left[\frac{\left(\sum_{j=1}^{j^*(n-2)} s_j - x_{n-2}^{**}\right)}{\alpha_{n-2}\sum_{j=n-2}^{n-1} v_j}\right]$

$t_{downstream}$: individual processing time by worker n $\left[\frac{\sum_{j=1}^{j^*(n)} s_j - \sum_{j=1}^{j^*(n-1)} s_j}{v_n}\right]$

(b) $t_{upstream}$: individual processing time by worker $n-1$ $\left[\frac{\left(\sum_{j=1}^{j^*(n-1)} s_j - \sum_{j=1}^{j^*(n-2)} s_j\right)}{v_{n-1}}\right]$

$t_{downstream}$: individual processing time by worker n $\left[\frac{\left(1-\sum_{j=1}^{j^*(n-1)} s_j\right) - P_n}{v_n}\right]$

Figure 2.3. Model of the relationship between the fixed point of a bucket brigade (x_i^*), the index of the station where the fixed point of the bucket brigade falls ($j^*(i)$), and the collaboration meeting point (x_i^{**}).

By defining x_{n-1}^{**} as the collaboration meeting point for worker n and worker $n-1$, if all necessary conditions are satisfied without any loss, then the equilibrium condition will be obtained:

$$\frac{\left(\sum_{j=1}^{j^*(n-2)} s_j - x_{n-2}^{**}\right)}{\alpha_{n-2}\sum_{j=n-2}^{n-1} v_j} + \frac{\left(x_{n-1}^{**} - \sum_{j=1}^{j^*(n-2)} s_j\right)}{v_{n-1}} + \frac{\left(\sum_{j=1}^{j^*(n-1)} s_j - x_{n-1}^{**}\right)}{\alpha_{n-1}\sum_{j=n-1}^{n} v_j} = \frac{\left(\sum_{j=1}^{j^*(n-1)} s_j - x_{n-1}^{**}\right)}{\alpha_{n-1}\sum_{j=n-1}^{n} v_j} + \frac{\left(1-\sum_{j=1}^{j^*(n-1)} s_j\right)}{v_n} \quad (2.3)$$

Based on Equation 2.3, the total time on the left side must be equal to the total time on the right side. The left side indicates the collaboration time for worker $n-2$ and worker $n-1$, the individual processing time for worker $n-1$, and the collaboration time for worker $n-1$ and worker n. The right side indicates the collaboration time for worker $n-1$ and worker n and the processing time for worker n. Equation 2.3 ensures that the cycle time will be the same for all workers without any loss, and then worker n and worker $n-1$ will always start collaboration at the same position of x_{n-1}^{**} in every iteration.

The non-cyclic condition may occur if the conditions for cyclic behavior are not satisfied. Consider the situation in which the expected collaboration of worker n and worker $n-1$ at station $j^*(n-1)$ is obtained. If $\frac{\left(\sum_{j=1}^{j^*(n-2)} s_j - \sum_{j=1}^{j^*(n-3)} s_j\right)}{v_{n-2}} \geq \frac{\left(\sum_{j=1}^{j^*(n-1)} s_j - x_{n-1}^{**}\right)}{\alpha_{n-1}\sum_{j=n-1}^{n} v_j} + \frac{\left(x_{n-1}^{**} - \sum_{j=1}^{j^*(n-1)} s_j\right)}{v_{n-2}}$, then the next expected collaboration will take place at station $j^*(n-2)$. If this condition is not satisfied, worker $n-2$ will be blocked at the end of station $j^*(n-2)$ or each pair of collaborative workers will shift to the next downstream station to prevent the blocking condition. Due to non-cyclic movement, the next expected meeting point will be hard to determine.

2.3.3 Procedure to determine throughput

A procedure to determine the worker collaboration throughput with m stations and n workers in accordance with Section 2.3.2 is proposed. Figure 2.4 shows the proposed procedure to determine the throughput of bucket brigades with worker collaboration by considering the collaboration coefficient. As seen in Figure 2.4, with the same definitions of x_i^*, x_i^{**}, and $j^*(i)$, the expected collaboration station and propose condition 1 is determined as follows:

$$j^*(1) < j^*(2) < \cdots < j^*(n-1) < m \quad (2.4)$$

Equation 2.4 ensures that:

1. No two neighboring collaboration locations can be at the same station. If there are two or more neighboring collaboration locations at the same station, then the predecessor will always be blocked by successor workers.
2. No collaboration occurs at station m. Only the last worker can work at station m.

In the next step of Figure 2.4, the collaboration meeting point for each pair of workers is determined. By substituting Equations 2.1 and 2.2, x_{n-2}^{**} as the collaboration meeting point for worker $n-2$ and worker $n-1$ is determined.

$$x_{n-2}^{**} = \sum_{j=1}^{j^*(n-2)} s_j + \frac{\left(x_{n-1}^{**} - \sum_{j=1}^{j^*(n-2)} s_j\right)\alpha_{n-2}\sum_{j=n-2}^{n-1} v_j}{v_{n-1}} - \frac{\left(1-\sum_{j=1}^{j^*(n-1)} s_j\right)\alpha_{n-2}\sum_{j=n-2}^{n-1} v_j}{v_{n-1}} \quad (2.5)$$

Then, by substituting Equations 2.3 and 2.5, x^{**}_{n-1} as the meeting point for collaboration between worker n and worker $n-1$ is determined.

$$x^{**}_{n-1} = \frac{\left(1-\sum_{j=1}^{j^*(n-1)} s_j\right)\left(\alpha_{n-1}\sum_{j=n-1}^{n} v_j\right)\left(\alpha_{n-2}\sum_{j=n-2}^{n-1} v_j\right)+\left(\sum_{j=1}^{j^*(n-1)} s_j\right)(v_{n-1})(v_{n-2})}{v_{n-1}\left(v_{n-2}+\alpha_{n-1}\sum_{j=n-1}^{n} v_j\right)} \tag{2.6}$$

Assume that all collaboration coefficients are additive such that $\alpha_i = 1.0$; then the relationship between the fixed point of the bucket brigade and the collaboration meeting point is as follows:

$$x^{**}_{n-1} = \left(\sum_{j=1}^{j^*(n-1)} s_j\right) x^*_{n-2} + \frac{\left(1-\sum_{j=1}^{j^*(n-1)} s_j\right)\left(\sum_{j=n-1}^{n} v_j\right) x^*_{n-1}}{v_n} \tag{2.7}$$

Based on single-orbit cyclic behavior and the equilibrium condition, the collaboration meeting point of the next upstream pair can be determined for $i = 3, \ldots, (n-1)$ as follows:

$$x^{**}_{n-i} = \sum_{j=1}^{j^*(n-i)} s_j + \frac{\left(x^{**}_{n-(i-1)}-\sum_{j=1}^{j^*(n-i)} s_j\right)\alpha_{n-i}\left(\sum_{j=n-i}^{n-(i-1)} v_j\right)}{v_{n-(i-1)}} - \frac{\left(\sum_{j=1}^{j^*(n-(i-2))} s_j - x^{**}_{n-(i-2)}\right)\alpha_{n-i}\left(\sum_{j=n-i}^{n-(i-1)} v_j\right)}{\alpha_{n-(i-2)}\sum_{j=n-(i-2)}^{n-(i-3)} v_j}$$
$$- \frac{\left(x^{**}_{n-(i-2)}-\sum_{j=1}^{j^*(n-(i-1))} s_j\right)\alpha_{n-i}\left(\sum_{j=n-i}^{n-(i-1)} v_j\right)}{v_{n-(i-2)}} \tag{2.8}$$

Halting can occur if the processing time for the last worker is longer than the collaboration time for worker $n-1$ and worker $n-2$ and the processing time for worker $n-1$. Thus, the no halting condition can be derived as follows:

$$\frac{\left(1-\sum_{j=1}^{j^*(n-1)} s_j\right)}{v_n} < \frac{\left(\sum_{j=1}^{j^*(n-2)} s_j - x^{**}_{n-2}\right)}{\alpha_{n-2}\sum_{j=n-2}^{n-1} v_j} + \frac{\left(\sum_{j=1}^{j^*(n-1)} s_j - \sum_{j=1}^{j^*(n-2)} s_j\right)}{v_{n-1}} \tag{2.9}$$

On a larger production line, blocking may occur when the collaboration time for a downstream pair is longer than the collaboration time for the next upstream pair. Under the blocking condition, after the collaboration between worker $n-3$ and worker $n-4$ has finished, worker $n-3$ will do individual work at the downstream station and will be blocked at the end of the downstream station, because worker $n-1$ and worker $n-2$ are still performing collaboration. Condition 2 ensures that the no-blocking condition exists for $i = 1, \ldots, n-1$.

$$\frac{\left(\sum_{j=1}^{j^*(n-(i+1))} s_j - x^{**}_{n-(i+1)}\right)}{\alpha_{n-(i+1)}\sum_{j=n-(i+1)}^{n-i} v_j} + \frac{\left(x^{**}_{n-(i+1)}-\sum_{j=1}^{j^*(n-(i+2))} s_j\right)}{v_{n-(i+1)}}$$
$$< \frac{\left(\sum_{j=1}^{j^*(n-(i+3))} s_j - x^{**}_{n-(i+3)}\right)}{\alpha_{n-(i+3)}\sum_{j=n-(i+3)}^{n-(i+2)} v_j} + \frac{\left(\sum_{j=1}^{j^*(n-(i+2))} s_j - \sum_{j=1}^{j^*(n-(i+3))} s_j\right)}{v_{n-(i+2)}} \tag{2.10}$$

The cycle time (CT) of single-orbit cyclic behavior for worker collaboration on an m-station and n-worker line without loss can be determined as follows:

$$CT = \frac{\left(\sum_{j=1}^{j^*(n-1)} s_j - x^{**}_{n-1}\right)}{\alpha_{n-1}\sum_{j=n-1}^{n} v_j} + \frac{\left(1-\sum_{j=1}^{j^*(n-1)} s_j\right)}{v_n} \tag{2.11}$$

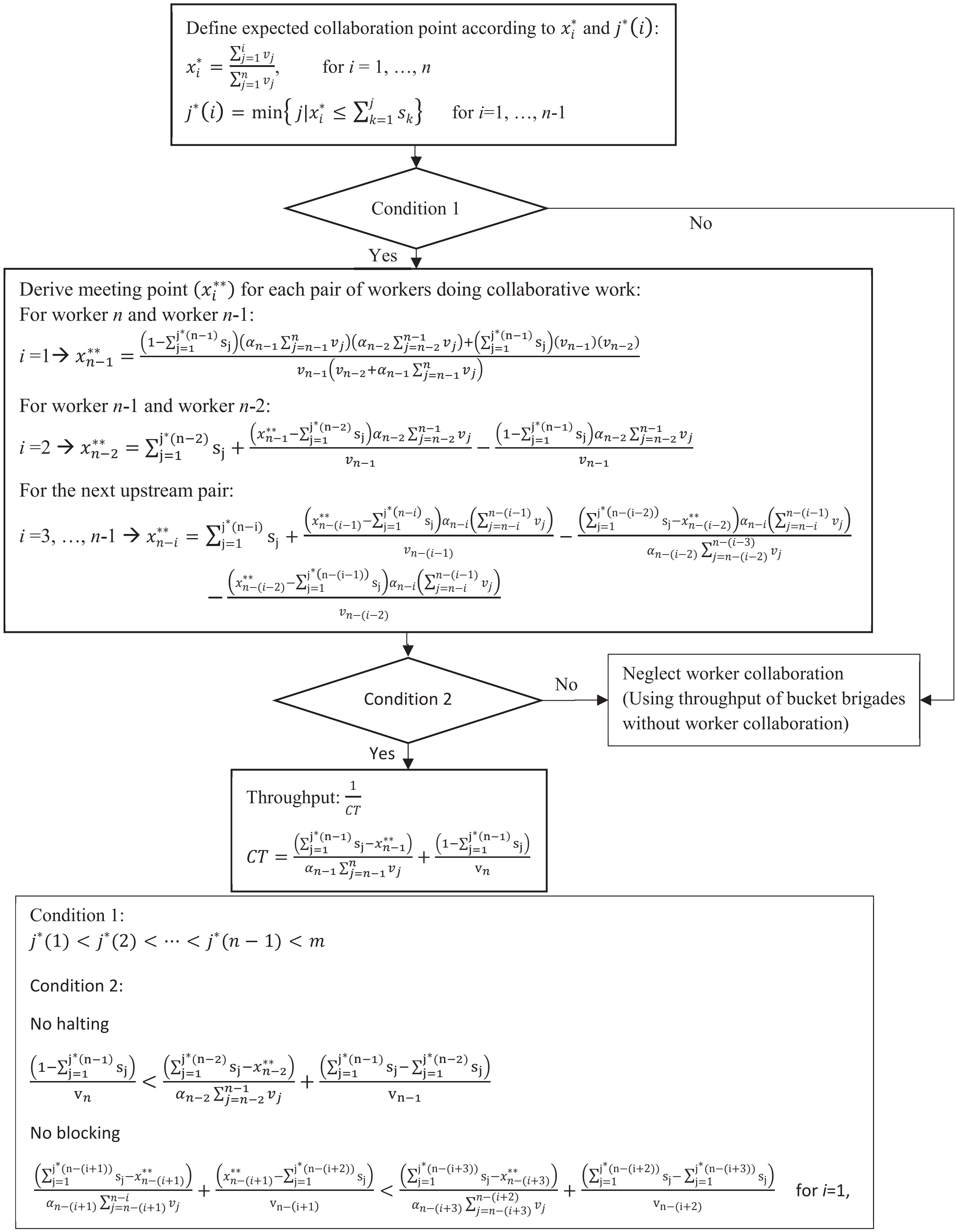


Figure 2.4. Proposed procedure to determine the throughput of bucket brigades with worker collaboration on an m-station, n-worker line by considering the collaboration coefficient (α).

Based on Figure 2.4, if one of those conditions is not satisfied, then a line might sustain single-orbit cyclic behavior with the halting or blocking condition. In this condition, the movement of bucket brigades without worker collaboration will be utilized. A computational calculation to determine the throughput of bucket brigades without worker collaboration has been developed, not only under the condition in which the maximum throughput possible can be achieved but also under the blocking and halting conditions. The computational calculation is developed based on the iteration process by comparing the processing time among workers in accordance with the fixed points and work content at each station.

2.4. Performance analysis

In this section, two performance comparisons between bucket brigades with and without worker collaboration are presented. First, by considering a three-station, two-worker production line with two conditions: slowest-to-fastest sequencing and fastest-to-slowest sequencing. Most studies in the literature state that sequencing workers from slowest-to-fastest leads to superior performance compared to fastest-to-slowest sequencing. The two-worker sequences are considered to observe the usability of worker collaboration when there is variability in the work content. As a result, the characteristics of the regions with fully and partially cross-trained workers are shown. Second, the performance analysis considers fully trained workers, slowest-to-fastest sequencing, and variation of the collaboration coefficient index. The main focus is the behavior that achieves higher throughput according to Section 2.3.2.

2.4.1 Three-station, two-worker production line

Figures 2.5 and Figure 2.6 show the regions of a production line in work content distribution with fully or partially cross-trained workers and slowest-to-fastest and fastest-to-slowest sequencing, respectively. The horizontal and vertical axes correspond to s_1 and s_2, respectively. Each point on the diagram represents the distribution of work content at the workstations. The feasible region is $s_2 < 1 - s_1$, and the behavior in each region can be summarized as follows:

Region 1: The predecessor is always halted at point $s_1 + s_2$ because the work content at the first two stations is small, so the predecessor can finish his work at these stations before the successor arrives to collaborate.

Region 2: The meeting point for collaboration is located at station 2. There is no blocking, so the maximum throughput possible may be achieved if $\alpha = 1.0$.

Region 3: The first and second collaborations are located at stations 1 and 2, respectively. After finishing collaboration at station 1, the predecessor will be blocked at point s_1.

Region 3a: The collaboration meeting point is located at station 1. After finishing collaboration, the predecessor will be blocked at point s_1 and halted at point $s_1 + s_2$.

Region 4: The first and second collaborations are located at stations 1 and 2, respectively. The maximum throughput possible may be achieved if α = 1.0.

Region 4a: The collaboration is located at station 1. After finishing collaboration, the predecessor will be halted at point $s_1 + s_2$.

Region 5: The meeting point for collaboration is located at station 1. With fully cross-trained workers, there is no blocking, so the maximum throughput possible may be achieved if α = 1.0. Meanwhile, with partially cross-trained workers, the successor is always starved at point s_1.

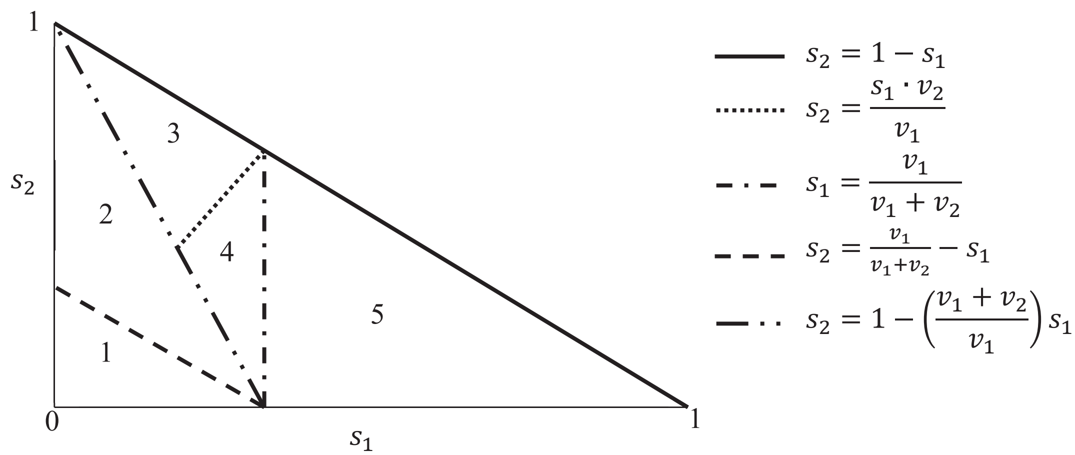


Figure 2.5. Regions of the production line in work content distribution with fully or partially cross-trained workers and slowest-to-fastest sequencing.

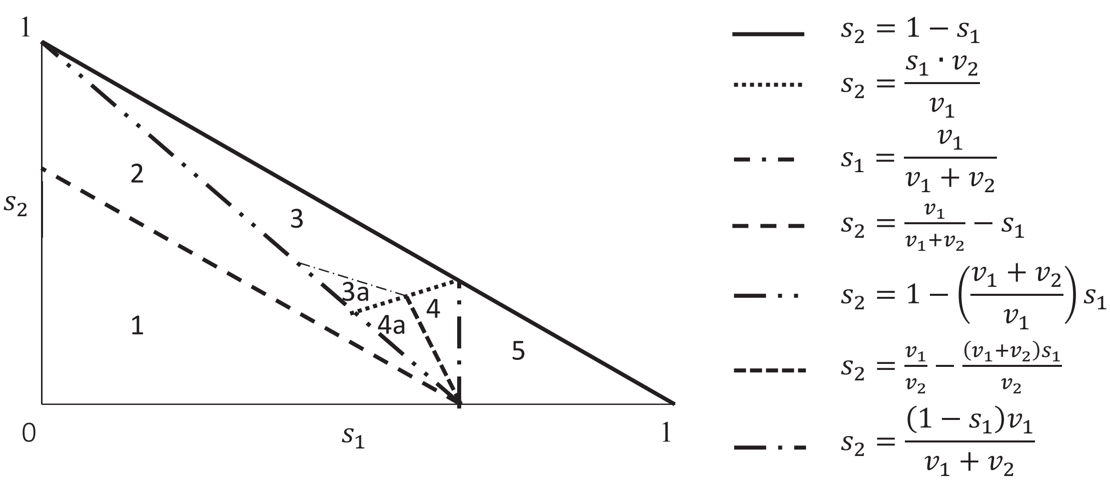


Figure 2.6. Regions of the production line in work content distribution with fully or partially cross-trained workers and fastest-to-slowest sequencing.

Figure 2.7 shows the impact of worker collaboration with fully and partially cross-trained workers and slowest-to-fastest and fastest-to-slowest sequencing. Figures 2.7a, 2.7b, and 2.7c show the percentage difference in throughput between bucket brigades with and without worker collaboration for α = 0.7, α = 0.9, and α = 1.0, respectively. Based on these figures, regions 2, 4, and 5 are most affected by the increase in α. The workers' collaborative performance can be equal to or better than their performance without worker collaboration at $\alpha = 1.0$.

Figure 2.7d shows the percentage difference in throughput between bucket brigades with and without worker collaboration with fully cross-trained workers, fastest-to-slowest sequencing, and $\alpha = 1.0$. Although region 1 is the largest compared to the other regions, worker collaboration still has a significant impact on increasing the performance when blocking occurs, which is represented in the parts of regions 2 and 5.

Figures 2.7e and 2.7f show the percentage difference in the throughput of bucket brigades with and without worker collaboration with partially cross-trained workers at $\alpha = 1.0$ for slowest-to-fastest and fastest-to-slowest sequencing, respectively. In region 5, the successor will be starved in front of s_2 while the predecessor is still working on s_1. Worker collaboration can only increase the performance in the part of region 2.

Based on Figure 2.7, with fully cross-trained workers, better performance is achieved with worker collaboration than without it in regions 2 and 5. Meanwhile, with partially cross-trained workers, worker collaboration only performs better in region 2 due to the starvation condition in region 5.

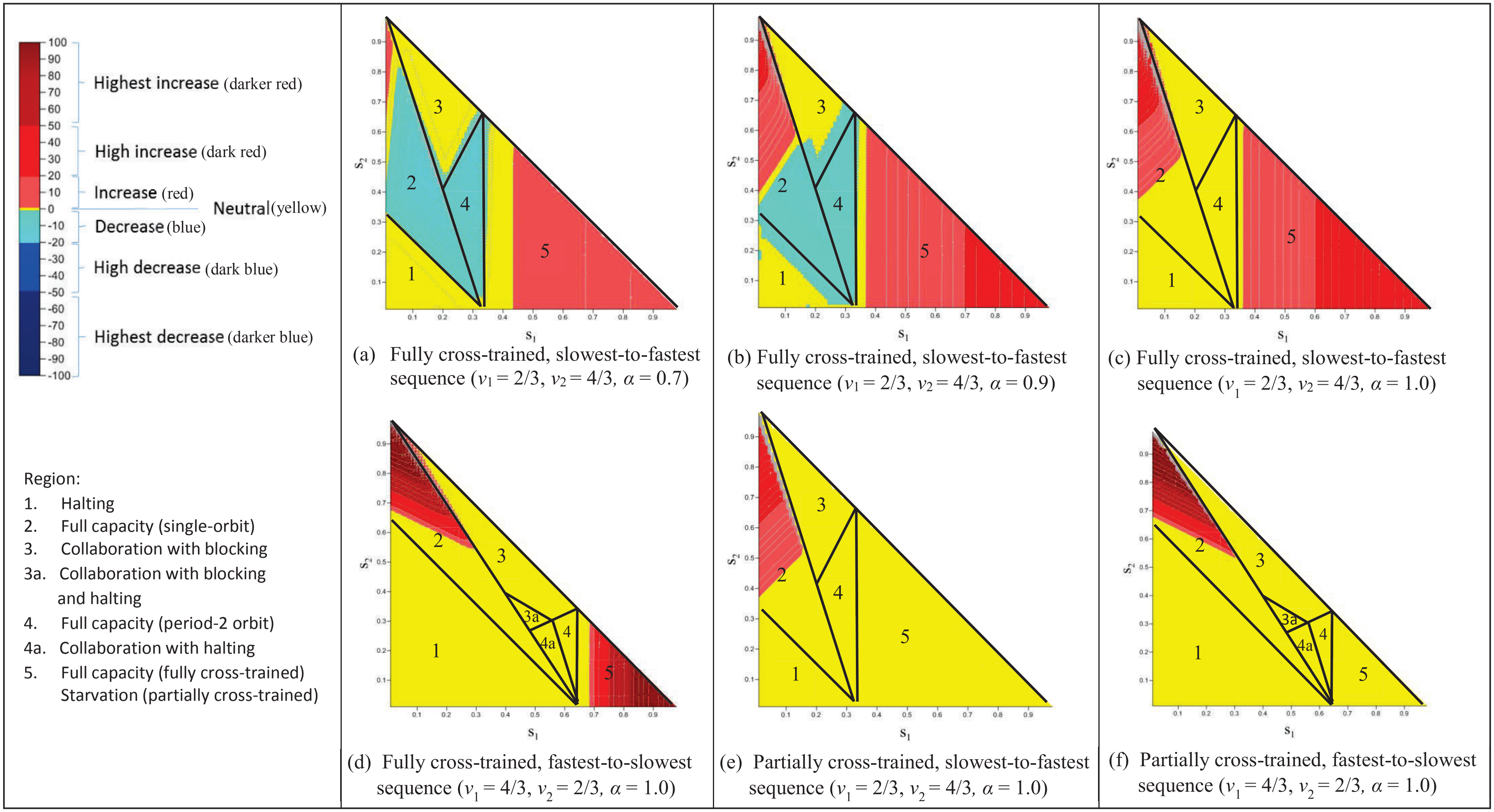


Figure 2.7. Percentage difference in throughput between bucket brigades with and without worker collaboration for different parameters.

Table 2.2. Performance comparison of bucket brigades with and without worker collaboration considering variation of the collaboration coefficient (α).

Number of workstations	Number of workers	Total number of configurations	Set of worker velocity variations	Collaboration coefficient	Average number of configurations without idleness			Average number of configurations with idleness	
					Bucket brigade without collaboration (maximum throughput)	Bucket brigade with collaboration		Bucket brigade without collabo- ration	Bucket brigade with collaboration
						Maximum throughput	Not achieving maximum throughput		
4	3	969	50	0.7	37.34	0	209.54	931.66	759.46
				0.9		0	270.04		698.96
				1.0		292.08	0		676.92
5	4	3876	50	0.7	17.8	0	272.76	3858.2	3603.24
				0.9		0	383.74		3492.26
				1.0		447.84	0		3428.16

2.4.2 A larger production line with *m*-station and *n*-worker

The workstation configurations are derived from all possible work contents that can be accommodated by each station. The work content of the product at each station is deterministic and the total work content is normalized to 1. For each station, a work-content multiplication factor of 0.05 is applied; that is, the first configuration is $s_1 = 0.05$, $s_2 = 0.05$, $s_3 = 0.05$, and $s_4 = 0.85$, the second configuration is $s_1 = 0.05$, $s_2 = 0.05$, $s_3 = 0.1$, and $s_4 = 0.8$, and so on. Worker velocities are generated by a uniform random number with a range of 0.1 to 1.0, sorted from the lowest to the highest value to represent the sequence of workers on the production line.

Table 2.2 shows a performance comparison of bucket brigades with and without worker collaboration at an *m*-workstation, *n*-worker line by considering the variation of the collaboration coefficient (α). For a four-workstation, three-worker line, there are 969 work content configurations, comprising 37.34 configurations for bucket brigades with maximum throughput (no idling) and 931.66 configurations for bucket brigades with idling. Worker collaboration with $\alpha < 1.0$ cannot achieve maximum throughput but can decrease the number of configurations with idling compared to the bucket brigade: 759.46 and 698.96 for $\alpha = 0.7$ and $\alpha = 0.9$, respectively. However, worker collaboration can increase the number of configurations with the maximum throughput at $\alpha = 1.0$: 292.08 configurations compared to 37.34 configurations when using bucket brigades.

For a five-workstation, four-worker line, the number of combinations of work contents increases to 3876 configurations, but the number of bucket brigades with maximum throughput (no idling) decreases to 17.8 configurations, and the number of bucket brigades with idling increases to 3858.2 configurations. Utilizing worker collaboration can decrease the number of configurations with idling, and though it cannot achieve maximum throughput at $\alpha < 1.0$, it can increase the number of configurations with the maximum throughput at $\alpha = 1.0$. The application of worker collaboration with $\alpha < 1.0$ cannot achieve maximum throughput but can decrease the number of configurations with idling compared to the bucket brigade: 3603.24 and 3492.26 for $\alpha = 0.7$ and $\alpha = 0.9$, respectively. At $\alpha = 1.0$, however, worker collaboration can increase the number of configurations with the maximum throughput: 447.84 configurations compared to 17.8 configurations when using bucket brigades.

Based on Table 2.2, worker collaboration can effectively reduce the number of configurations with idling that may occur when using bucket brigades. If the number of stations and the number of workers increase, then without worker collaboration the number of configurations with the maximum throughput will decrease. However, by utilizing worker collaboration at $\alpha < 1.0$, maximum throughput cannot be achieved, but the number of configurations without idling is higher than for the case without worker collaboration. The maximum throughput can be obtained by worker collaboration only at $\alpha = 1.0$.

2.5. Summary

When worker collaboration at discrete workstations can achieve its full production capacity is the desired condition. Cyclic behavior and the equilibrium condition for worker collaboration can be achieved if each pair of workers always starts the collaboration at the same meeting point in every iteration; then the characteristics of a self-balancing line can still be preserved, and a performance improvement can be obtained.

To obtain the desired condition in a system with changeable size, workers need to have the flexibility to work at any station, and the work content needs to be adjustable across all stations. However, in practical cases, it is difficult and expensive to train workers to be flexible, and task allocation cannot be adjustable. Another limitation is that a station must be able to accommodate two or more workers simultaneously and the work content must be able to be divided among the workers at any time. Moreover, the condition where a downstream worker can join and assist the upstream worker with an additive collaboration coefficient is rare. If a single task is processed by multiple workers at the same time, the collaborative processing time might be faster or slower than the sum of the processing time by individual workers.

This chapter focuses on how to improve the bucket brigade's performance with discrete workstations by integrating worker collaboration. Possible extended conditions for improvement and a procedure for achieving a possibly higher throughput have been described. By analyzing the single-orbit cyclic behavior of worker collaboration, the characteristics and throughput formulation can be obtained.

On a three-station, two-worker line and an m-station, n-worker line with fully cross-trained workers and slowest-to-fastest sequencing, the bucket brigade with worker collaboration almost always outperforms that without worker collaboration. When the collaboration coefficient is not additive, two workers can process the same task less than twice as fast as one worker, but worker collaboration can still effectively contribute some performance improvement.

Most of the results depend only on the assumptions that each worker works at a constant work velocity that is associated with the working zone, walking back is instantaneous, and handover time is neglected. Relaxing those assumptions would be an interesting topic for future research.

A case study of worker collaboration in the order picking process at a warehouse is suggested. Workers are flexible in that they may work at any shelf, task allocation can be adjusted, and the shelf (station) can accommodate two workers, then evaluate the behavior and performance of worker collaboration in this type of setting.

Chapter 3 Cellular bucket brigades with worker collaboration on U-shaped line with discrete workstations

3.1. Introduction

This chapter explains a worker collaboration approach to counter the blocking and halting condition for U-shaped lines with fewer workers than the number of stations, where the work content at each station is deterministic and using prior assumption of cellular bucket brigade (CBB) at discrete workstation (Lim and Wu, 2014). A maximum of two workers can work collaboratively on the same task (at the same station), and thus each worker's idle time due to blocking and halting can be minimized. Furthermore, the conditions of worker collaboration on the U-shaped lines are defined and the performance of CBB against worker collaboration is compared for different collaboration coefficients.

Lim (2011) has introduced the idea of CBB to coordinate worker on U-shaped lines. CBB is used to improve the efficiency of bucket brigade for a long assembly line by eliminating the unproductive walk-back that is inherent in traditional bucket brigades. Lim (2011) shows that a CBB, even with fewer workers, can be significantly (30%) more productive than its traditional counterpart if the aisle is sufficiently narrow. Lim and Wu (2014) have analyzed the features of CBB with discrete workstations and concluded that CBB may perform differently in different situations, due to the blocking and halting of workers. The system always converges to a fixed point or a period-2 orbit for a given work content distribution.

The integration of worker collaboration may decrease the idling of workers in some cases, and increase the performance of production line. The team working experiments at Volvo's Uddevalla and Kalmar plants are probably the most well-known (Engström and Medbo 1994; Ellegärd et al. 1992). Workers could collaborate on the same task, and each team of workers was assigned to do all or most of the assembly tasks on a particular vehicle. This plant showed an improvement in quality and a decrease in the total lead time, and it was also easier to handle requests for customization from customers. In addition, Andradóttir et al. (2001) introduced collaboration coefficient (α) as a measure of the magnitude of the servers' collaboration/synergy. The study of worker collaboration will be related to additive conditions ($\alpha = 1.0$) and inefficiency collaborative conditions ($\alpha = 0.7$ and $\alpha = 0.9$).

This chapter is structured into the following sections. The first section presents introduction. The second section presents the model of U-shaped production line especially definition of a three-station, two-worker U-shaped line, with worker collaboration movement rules and condition classification. The third section explains the numerical analysis by comparing the performance of CBB and worker collaboration for different collaboration coefficients and working velocities. Finally, the last section summarizes this chapter by presenting managerial implications and conclusion regarding CBB and worker collaboration.

3.2. U-shaped production line

There are two parts that will be presented in this section. The first presents the definition of the model and movement rules for collaborative work, and second describes the classification and throughput formulation of worker collaboration.

3.2.1 Model definition

Lim and Wu (2014) have defined the general assumptions of the U-shaped line with discrete workstations. They assume that a U-shaped line may consist of multiple stations at each stage and work by two workers. They have shown that on a U-shaped line with one station at each stage, blocking and/or halting conditions still occur even if workers are sequenced properly; these are caused by imbalances arising when one stage has more work content than the other stages. They also analyzed the impact of multiple stations at each stage, and showed that increasing the number of stations can reduce the time for which workers are blocked, and thus increase the average throughput. However, if each stage is further divided into more stations, this gives rise to a continuous line, and throughput soon becomes constant.

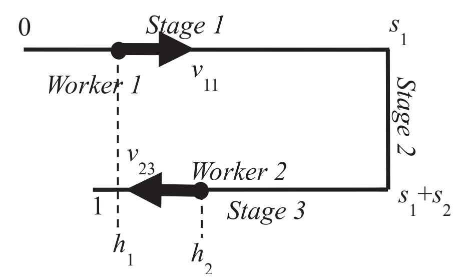


Figure 3.1. A conceptualized U-shaped line with length 1. W_1 works at Stage 1 and W_2 at Stage 3. The horizontal position h_i is determined by projecting the point where each worker i is located on the horizontal axis.

The same assumptions of the U-shaped production line made by Lim and Wu (2014) are adopted and limit these assumptions only for a three-station system where the highest rates of blocking and/or halting occur. Consider a U-shaped production line that consists of three stages. Stages 1 and 3 are separated by an aisle, and Stage 2 spans across the aisle. That is, Stage 1 consists of a station located on one side of the aisle; stage 2 has a station located across the aisle; and Stage 3 consists of a station located on the other side of the aisle. Since each stage in the U-shaped line consists of only one station, then the work content on each stage j is deterministic; it is denoted as s_j and the total work content is normalized to 1. The U-shaped line is worked by W_1 and W_2. Each worker is cross-trained to work on any stage of the U-shaped line, and workers continuously move along a station as they progressively work at the station. W_i works with a constant and deterministic velocity v_{ij} at stage j, for i=1,2 and j=1,2,3. The travel time between stations is short compared to the time required to process an item; therefore, the time to walk from one stage to another is instantaneous is assumed, and hand-off time is neglected.

With CBB, each item in the U-shaped line is initiated at the start of stage 1, specifically by W_1. The item is passed to W_2 at some point during Stage 1. W_2 then finishes the remaining work of Stage 1 and continues to assemble the item at Stage 3 before passing it back to W_1 at Stage 3. W_1 then completes the item at the end of Stage 3. When W_1, who is working on Stage 1, meets with W_2, who is working on Stage 3, their horizontal position coincides, and a hand-off takes place between the two workers; each worker relinquishes the item, walks across the aisle and takes over the other's item. After the hand-off, W_1 works on Stage 3, while W_2 proceeds with Stage 1. At most, one worker is allowed to work at a station at any one time. As a result, a worker may be idle at the end of the station while a colleague is still working at the next station. When the hand-off occurs, the arriving worker takes over the task without stopping the process is assumed, then the work content is preemptible without any loss of work. Figure 3.1 shows a conceptualized U-shaped line of length 1. The start and end of the path are represented by points 0 and 1, respectively; the intervals $[0,s_1]$, $[s_1,s_1+s_2]$, and $[s_1+s_2,1]$ correspond to the work content at Stages 1, 2, and 3, respectively; and the horizontal line segments $[0,s_1]$ and $[s_1+s_2,1]$ are parallel to each other, while the line segment $[s_1,s_1+s_2]$ is perpendicular to them.

Table 3.1. Movement rules for worker collaboration on a U-shaped line

<table>
<tr><th>Type</th><th>Individual Work</th><th>Collaborative work</th></tr>
<tr><td>1</td><td>• Work individually until the end of the stage, then go to another worker's position to collaborate.
• If you are intercepted by another worker, then terminate your work at the current stage and start collaborating</td><td rowspan="2">• Complete collaborative work at the end of the current stage, and then go to your next new position (*) for individual work.
• Worker 2 has priority in determining the next new position (*), followed by Worker 1.
* The next new position of Worker 2 is in front of Stage 2 if possible; otherwise, it is in front of Stage 3
* The next new position of Worker 1 is in front of Stage 3 if possible; otherwise, it is in front of Stage 1</td></tr>
<tr><td>2</td><td>• Work individually until the end of the line or idling; then go to another worker's position to collaborate.
• If you are intercepted by another worker, then terminate your work at the current stage and start collaborating</td></tr>
</table>

For worker collaboration, several of the assumptions made in CBB are extended. One item at most can be processed by a maximum of two workers at a station at any given time, in the case of collaborative work. As a result, a worker may be idle at the end of the station while another colleague is still working at the next station, rather than being able to continue the individual task. The station can accommodate multiple workers working together simultaneously by sharing the space and tools required to complete an item. There is a buffer at the end of each stage; a worker can put an item into this buffer and then move to support another worker. A worker can also pick up an item from a buffer and then continue to process the item.

The collaborative velocity of a team is the sum of the velocities of the individual work, and is influenced by the worker collaboration coefficient. Since there are only two workers in the U-shaped line, the collaboration velocity is equal to $v_{coll}(j) = \alpha(v_{1j} + v_{2j})$ and must be higher than the minimum worker velocity at each stage $\left(v_{coll}(j) > \min\{v_{1j}, v_{2j}\}\right)$. α is a measure or coefficient of the collaboration or synergy between Worker 1 and Worker 2, and can be defined by $0 < \alpha \leq 1$. At a station, a worker will process an item in individual work and/or partial work of the item will be processed by collaboration. Collaborative work can start at any point at a station, and finish at the end of the station without any loss of work. Hand-off occurs only at the end of the station after finishing collaborative work. Table 3.1 summarizes the movement rules that must be followed by workers under the two types of worker collaboration.

3.2.2 Classification of worker collaboration

Before workers implementing the CBB or worker collaboration at the production line, an initial situation before the production line achieving the steady state is assumed as shown in Figure 3.2 and Figure 3.3. For initial situation, Worker 1 initiates the new item and continue to process the item along the production line, while Worker 2 will wait on the designated station. When they meet, Worker 1 hands off the item to Worker 2 and return to initiate new item. Since both workers have their own item to be processed, they can continue to process the item based on CBB or worker collaboration movement rules.

Figure 3.2 shows an example of CBB behavior, in which the line has a "long" Stage 1 and a "short" Stage 3. Worker 1 starts at Stage 1, while Worker 2 starts at Stage 2. When Worker 2 reaches the end of Stage 3, then work will be halted, since Worker 1 is still working on Stage 1, where $h_1 \neq h_2$. If x^* denotes the hand-off position between Worker 1 and Worker 2, then the halting condition before exchanging an item can be defined as $\frac{x^*}{v_{11}} > \frac{s_2}{v_{22}} + \frac{1-(s_1+s_2)}{v_{23}}$. After exchanging the item, Worker 2 continues to work at Stage 1, while Worker 1 will be blocked in front of Stage 1. The blocking condition after exchanging the item can be defined as $\frac{(1-(s_1+s_2))-(s_1 - x^*)}{v_{11}} < \frac{(s_1 - x^*)}{v_{21}}$. According to Lim and Wu (2014), this condition can be classified as Region 1, where Worker 1 is always blocked at point 0, and Worker 2 is always halted at point 1. The system will converge to a single fixed point at $x^* = s_1 - s_3$, and the cycle time of the system is $CT = \frac{x^*}{v_{11}} + \frac{\left(1-(s_1+s_2)\right)}{v_{21}}$.

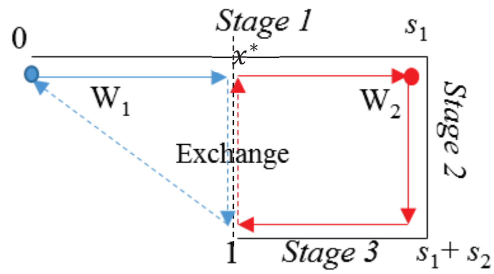


Figure 3.2. Operational principle of Cellular Bucket Brigade (CBB)

Lim and Wu (2014) have classified the other dynamic behaviors and the throughput of the system according to CBB rules. Based on the deterministic model, if the CBB's convergence condition $(1/v_{11} - 1/v_{13} \geq 1/v_{21} - 1/v_{23})$ is satisfied, then the system can be divided into five regions, where Regions 1 through 4 experience CBB behavior with blocking/halting, and neither blocking nor halting occurs in Region 5, since the work content of the three stages is balanced, allowing the system to avoid blocking and halting. Meanwhile, if the convergence condition for CBB is not satisfied $(1/v_{11} - 1/v_{13} < 1/v_{21} - 1/v_{23})$, the behavior of all regions remain the same except for Region 5, which now can be partitioned into seven regions (Regions 5a through 5g). All of the regions (Regions 1 through 5g) are dominated by blocking/halting or combinations of blocking and halting. The term $1/v_{i1} - 1/v_{i3}$ represents the extra work time needed by worker *i* to complete a unit of work at Stage 1 compared with Stage 3. Even though there is no idleness in Region 5, the throughput may be lower than for other regions. When each worker has a different work velocity at different stations, a worker may repeatedly work at a station where s/he is slow although there is no idleness in Region 5. Instead, a worker may repeatedly work on a station where s/he is fast, although a worker may be blocked or halted in the other regions. For details of the behavior and classification of CBB with three stations and two workers, see Lim and Wu (2014).

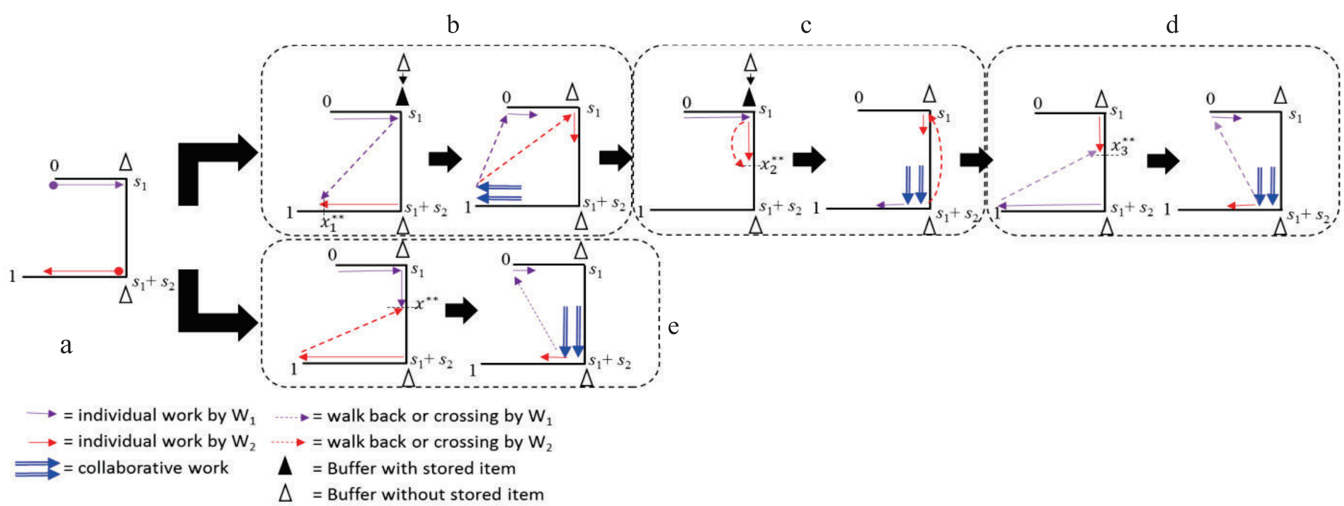


Figure 3.3. Operational principle of worker collaboration for types 1 and 2

Figure 3.3 shows the principle of worker collaboration for types 1 and 2. Figure 3.3a shows that Worker 1 starts at Stage 1, while Worker 2 starts at Stage 3. Worker 1 has finished at the end of Stage 1, while Worker 2 is still working on Stage 3; this can be expressed as $\frac{s_1}{v_{11}} < \frac{(1-(s_1+s_2))}{v_{23}}$. Figures 3.3b-d show the next movement of the worker for type 1 worker collaboration, while Figure 3.3e shows the next movement for type 2.

In Figure 3.3b, if Worker 1 reaches the end of Stage 1 earlier than Worker 2 finishes Stage 3, Worker 1 will put the item into the buffer and go to Worker 2's position for collaboration at Stage 3. Let x^{**} be defined as the meeting point for Workers 1 and 2 to start collaborative work at a station. The collaboration meeting point is located at Stage 3, and can be defined as $x_1^{**} = \mathrm{s}_1 + \mathrm{s}_2 + \frac{\mathrm{s}_1 \mathrm{v}_{23}}{\mathrm{v}_{11}}$. Figure 3.3c shows that after finishing the collaboration, Worker 1 will introduce a new item to Stage 1, while Worker 2 will take an item from the buffer and continue to work at Stage 2. Worker 1 reaches the end of Stage 1 earlier than Worker 2 on Stage 2, which can be expressed as $\frac{s_1}{v_{11}} < \frac{s_2}{v_{22}}$. Worker 1 puts the item into the buffer and goes to the position of Worker 2 for collaboration at Stage 2. The collaboration meeting point is located at Stage 2, and can be defined as $x_2^{**} = \mathrm{s}_1 + \frac{\mathrm{s}_1 \mathrm{v}_{22}}{\mathrm{v}_{11}}$. Figure 3.3d shows that after finishing the collaboration, Worker 1 will continue to work at Stage 3, while Worker 2 takes the item from the buffer and works at Stage 2. Worker 1 reaches the end of Stage 3 earlier than Worker 2 at Stage 2, which can be expressed as $\frac{(1-(s_1+s_2))}{v_{13}} < \frac{s_2}{v_{22}}$. Worker 1 goes to the position of Worker 2 for collaboration at Stage 2. The collaboration meeting point is located at Stage 2, and can be defined as $x_3^{**} = \mathrm{s}_1 + \frac{(1-(s_1+s_2))\mathrm{v}_{22}}{\mathrm{v}_{13}}$. After finishing the collaboration, Worker 1 introduces a new item, while Worker 2 works at Stage 3. The behaviors of this condition are shown as Class 1.1 in Table 3.2, and the cycle time of the system can be defined as $CT = \frac{2\mathrm{s}_1}{\mathrm{v}_{11}} + \frac{((\mathrm{s}_1+s_2)-x_2^{**})}{\alpha(\mathrm{v}_{12}+\mathrm{v}_{22})} + \frac{((\mathrm{s}_1+s_2)-x_3^{**})}{\alpha(\mathrm{v}_{12}+\mathrm{v}_{22})} + \frac{(1-(s_1+s_2))}{\mathrm{v}_{13}} + \frac{(1-x_1^{**})}{\alpha(\mathrm{v}_{13}+\mathrm{v}_{23})}$.

Figure 3.3e shows that when Worker 1 reaches the end of Stage 1, s/he can continue to work at the next stage, while Worker 2 still works at Stage 3. When Worker 2 has finished at the end of the line, and Worker 1 is still working on an item at Stage 2, this condition can be defined as $\frac{s_1}{v_{11}} + \frac{s_2}{v_{12}} \geq \frac{(1-(s_1+s_2))}{v_{23}}$. Worker 2 then goes to the position of Worker 1 for collaborative work at Stage 2. The collaboration meeting point is located at Stage 2, and can be defined as $x^{**} = \mathrm{s}_1 - \frac{\mathrm{s}_1 \mathrm{v}_{12}}{\mathrm{v}_{11}} + \frac{(1-(s_1+s_2))\mathrm{v}_{12}}{\mathrm{v}_{13}}$. After finishing the collaboration, Worker 1 introduces a new item, while Worker 2 continues to work on an item at Stage 3. The behaviors of this condition are shown as Class 2.2 in Table 3.3, and the cycle time of the system can be defined as $CT = \frac{\mathrm{s}_1}{\mathrm{v}_{11}} + \frac{(1-(s_1+s_2))}{\mathrm{v}_{23}} + \frac{((\mathrm{s}_1+s_2)-x^{**})}{\alpha(\mathrm{v}_{12}+\mathrm{v}_{22})}$. Tables 3.2 and 3.3 show the classification conditions for worker collaboration of types 1 and 2, respectively. Both tables are based on the assumptions and worker collaboration movement rules for a U-shaped line.

Table 3.2. Classification conditions for worker collaboration type 1

Type	Class	Conditions						Collaboration meeting point	Cycle time
		1	2	3	4	5	6		
1	1.1	$<$		$<$	$<$			$x_1^{**} = s_1 + s_2 + \frac{s_1 v_{23}}{v_{11}}; x_2^{**} = s_1 + \frac{s_1 v_{22}}{v_{11}}; x_3^{**} = s_1 + \frac{(1-(s_1+s_2))v_{22}}{v_{13}}$	$CT = \left(\frac{2s_1}{v_{11}} + \frac{((s_1+s_2)-x_2^{**})}{\alpha(v_{12}+v_{22})} + \frac{((s_1+s_2)-x_3^{**})}{\alpha(v_{12}+v_{22})} + \frac{(1-(s_1+s_2))}{v_{13}} + \frac{(1-x_1^{**})}{\alpha(v_{13}+v_{23})}\right)$
1	1.2	$<$		$<$	$\geq$			$x_1^{**} = s_1 + s_2 + \frac{s_1 v_{23}}{v_{11}}; x_2^{**} = s_1 + \frac{s_1 v_{22}}{v_{11}}; x_3^{**} = s_1 + s_2 + \frac{s_2 v_{13}}{v_{22}}$	$CT = \left(\frac{2s_1}{v_{11}} + \frac{((s_1+s_2)-x_2^{**})}{\alpha(v_{12}+v_{22})} + \frac{s_2}{v_{22}} + \frac{(1-x_1^{**})}{\alpha(v_{13}+v_{23})} + \frac{(1-x_3^{**})}{\alpha(v_{13}+v_{23})}\right)$
1	1.3	$<$		$\geq$	$<$			$x_1^{**} = s_1 + s_2 + \frac{s_1 v_{23}}{v_{11}}; x_2^{**} = \frac{s_2 v_{11}}{v_{22}}; x_3^{**} = s_1 + \frac{(1-(s_1+s_2))v_{22}}{v_{13}}$	$CT = \left(\frac{s_2}{v_{22}} + \frac{(s_1-x_2^{**})}{\alpha(v_{11}+v_{21})} + \frac{(1-(s_1+s_2))}{v_{13}} + \frac{((s_1+s_2)-x_3^{**})}{\alpha(v_{12}+v_{22})} + \frac{s_1}{v_{11}} + \frac{(1-x_1^{**})}{\alpha(v_{13}+v_{23})}\right)$
1	1.4	$<$		$\geq$	$\geq$			$x_1^{**} = s_1 + s_2 + \frac{s_1 v_{23}}{v_{11}}; x_2^{**} = \frac{s_2 v_{11}}{v_{22}}; x_3^{**} = s_1 + s_2 + \frac{s_2 v_{13}}{v_{22}}$	$CT = \left(\frac{s_1}{v_{11}} + \frac{(s_1-x_2^{**})}{\alpha(v_{11}+v_{21})} + \frac{2s_2}{v_{22}} + \frac{(1-x_1^{**})}{\alpha(v_{13}+v_{23})} + \frac{(1-x_3^{**})}{\alpha(v_{13}+v_{23})}\right)$
1	1.5	$\geq$		$<$	$<$			$x_1^{**} = \frac{(1-(s_1+s_2))v_{11}}{v_{23}}; x_2^{**} = s_1 + \frac{s_1 v_{22}}{v_{11}}; x_3^{**} = s_1 + \frac{(1-(s_1+s_2))v_{22}}{v_{13}}$	$CT = \left(\frac{s1}{v11} + \frac{((s_1+s_2)-x_2^{**})}{\alpha(v_{12}+v_{22})} + \frac{((s_1+s_2)-x_3^{**})}{\alpha(v_{12}+v_{22})} + \frac{(1-(s_1+s_2))}{v_{13}} + \frac{(1-(s_1+s_2))}{v_{23}} + \frac{(s_1-x_1^{**})}{\alpha(v_{12}+v_{22})}\right)$
1	1.6	$\geq$		$<$	$\geq$			$x_1^{**} = \frac{(1-(s_1+s_2))v_{11}}{v_{23}}; x_2^{**} = s_1 + \frac{s_1 v_{22}}{v_{11}}; x_3^{**} = s_1 + s_2 + \frac{s_2 v_{13}}{v_{22}}$	$CT = \left(\frac{s1}{v11} + \frac{(s_1-x_1^{**})}{\alpha(v_{11}+v_{21})} + \frac{(1-(s_1+s_2))}{v_{23}} + \frac{((s_1+s_2)-x_2^{**})}{\alpha(v_{12}+v_{22})} + \frac{s_2}{v_{22}} + \frac{(1-x_3^{**})}{\alpha(v_{13}+v_{23})}\right)$
1	1.7	$\geq$		$\geq$	$<$			$x_1^{**} = \frac{(1-(s_1+s_2))v_{11}}{v_{23}}; x_2^{**} = \frac{s_2 v_{11}}{v_{22}}; x_3^{**} = s_1 + \frac{(1-(s_1+s_2))v_{22}}{v_{13}}$	$CT = \left(\frac{s_2}{v_{22}} + \frac{(s_1-x_1^{**})}{\alpha(v_{11}+v_{21})} + \frac{(s_1-x_2^{**})}{\alpha(v_{11}+v_{21})} + \frac{(1-(s_1+s_2))}{v_{13}} + \frac{((s_1+s_2)-x_3^{**})}{\alpha(v_{12}+v_{22})} + \frac{(1-(s_1+s_2))}{v_{23}}\right)$
1	1.8	$\geq$		$\geq$	$\geq$			$x_1^{**} = \frac{(1-(s_1+s_2))v_{11}}{v_{23}}; x_2^{**} = \frac{s_2 v_{11}}{v_{22}}; x_3^{**} = s_1 + s_2 + \frac{s_2 v_{13}}{v_{22}}$	$CT = \left(\frac{(1-(s_1+s_2))}{v_{23}} + \frac{(s_1-x_1^{**})}{\alpha(v_{11}+v_{21})} + \frac{(s_1-x_2^{**})}{\alpha(v_{11}+v_{21})} + \frac{2s_2}{v_{22}} + \frac{(1-x_3^{**})}{\alpha(v_{13}+v_{23})}\right)$

Table 3.3. Classification conditions for worker collaboration type 2

Type	Class	Conditions						Collaboration meeting point	Cycle time
		1	2	3	4	5	6		
2	2.1	$<$	$<$					$x^{**} = s_1 + s_2 + \frac{s_1 v_{23}}{v_{11}} + \frac{s_2 v_{23}}{v_{12}}$	$CT = \left(\frac{s_1}{v_{11}} + \frac{s_2}{v_{12}} + \frac{(1-x^{**})}{\alpha(v_{13}+v_{23})}\right)$
2	2.2	$<$	$\geq$					$x^{**} = s_1 - \frac{s_1 v_{12}}{v_{11}} + \frac{(1-(s_1+s_2))v_{12}}{v_{23}}$	$CT = \left(\frac{s_1}{v_{11}} + \frac{(1-(s_1+s_2))}{v_{23}} + \frac{((s_1+s_2)-x^{**})}{\alpha(v_{12}+v_{22})}\right)$
2	2.3	$\geq$		$<$	$<$			$x_1^{**} = \frac{(1-(s_1+s_2))v_{11}}{v_{23}}; x_2^{**} = s_1 + \frac{s_1 v_{22}}{v_{11}}; x_3^{**} = s_1 + \frac{(1-(s_1+s_2))v_{22}}{v_{13}}$	$CT = \left(\frac{s1}{v11} + \frac{((s_1+s_2)-x_2^{**})}{\alpha(v_{12}+v_{22})} + \frac{((s_1+s_2)-x_3^{**})}{\alpha(v_{12}+v_{22})} + \frac{(1-(s_1+s_2))}{v_{13}} + \frac{(1-(s_1+s_2))}{v_{23}} + \frac{(s_1-x_1^{**})}{\alpha(v_{12}+v_{22})}\right)$
2	2.4	$\geq$		$<$	$\geq$			$x_1^{**} = \frac{(1-(s_1+s_2))v_{11}}{v_{23}}; x_2^{**} = s_1 + \frac{s_1 v_{22}}{v_{11}}; x_3^{**} = s_1 + s_2 + \frac{s_2 v_{13}}{v_{22}}$	$CT = \left(\frac{s1}{v11} + \frac{(s_1-x_1^{**})}{\alpha(v_{11}+v_{21})} + \frac{(1-(s_1+s_2))}{v_{23}} + \frac{((s_1+s_2)-x_2^{**})}{\alpha(v_{12}+v_{22})} + \frac{s_2}{v_{22}} + \frac{(1-x_3^{**})}{\alpha(v_{13}+v_{23})}\right)$
2	2.5	$\geq$		$\geq$		$<$	$<$	$x_1^{**} = \frac{(1-(s_1+s_2))v_{11}}{v_{23}}; x_2^{**} = s_1 + s_1 - \frac{s_1 v_{23}}{v_{11}} - \frac{s_2 v_{23}}{v_{22}} + -\frac{s_2 v_{23}}{v_{22}}$	$CT = \left(\frac{(1-(s_1+s_2))}{v_{23}} + \frac{(s_1-x_1^{**})}{\alpha(v_{11}+v_{21})} + \frac{s_1}{v_{11}} + \frac{s_2}{v_{12}} + \frac{(1-x_2^{**})}{\alpha(v_{13}+v_{23})}\right)$
2	2.6	$\geq$		$\geq$		$<$	$\geq$	$x_1^{**} = \frac{(1-(s_1+s_2))v_{11}}{v_{23}}; x_2^{**} = s_1 - \frac{s_1 v_{12}}{v_{11}} + \frac{s_2 v_{12}}{v_{22}} + \frac{(1-(s_1+s_2))v_{12}}{v_{23}}$	$CT = \left(\frac{2\times(1-(s_1+s_2))}{v_{23}} + \frac{(s_1-x_1^{**})}{\alpha(v_{11}+v_{21})} + \frac{s_2}{v_{22}} + \frac{((s_1+s_2)-x_2^{**})}{\alpha(v_{12}+v_{22})}\right)$
2	2.7	$\geq$		$\geq$		$\geq$		$x^{**} = \frac{s_2 v_{11}}{v_{22}} + \frac{(1-(s_1+s_2))v_{11}}{v_{23}}$	$CT = \left(\frac{s_2}{v_{22}} + \frac{(1-(s_1+s_2))}{v_{23}} + \frac{(s_1-x^{**})}{\alpha(v_{11}+v_{21})}\right)$

Cond.1 $\frac{s_1}{v_{11}} : \frac{(1-(s_1+s_2))}{v_{23}}$; Cond.2 $\frac{s_1}{v_{11}} + \frac{s_2}{v_{12}} : \frac{(1-(s_1+s_2))}{v_{23}}$; Cond.3 $\frac{s_1}{v_{11}} : \frac{s_2}{v_{22}}$; Cond.4 $\frac{(1-(s_1+s_2))}{v_{13}} : \frac{s_2}{v_{22}}$; Cond.5 $\frac{s_1}{v_{11}} : \frac{s_2}{v_{22}} + \frac{(1-(s_1+s_2))}{v_{23}}$; Cond.6 $\frac{s_1}{v_{11}} + \frac{s_2}{v_{12}} : \frac{s_2}{v_{22}} + \frac{(1-(s_1+s_2))}{v_{23}}$

3.3. Analysis and discussion

Consider a U-shaped line with a narrow aisle consisting of m=3 stations and n=2 workers, where each worker has different work velocities at different stages. Since each worker has a different work velocity at different stages, the throughput for one region might be lower than for others. A worker may be slow in working at a particular station, even though there is no idling, or may work quickly at a station, giving rise to idling; these two situations therefore produce different throughputs. These situations cannot be found on a U-shaped line where each worker has constant working velocity at all stations; here, possible maximum throughput can always be obtained if there is no idling.

The same concept of collaboration coefficient at additive condition (α = 1.0) and inefficient collaborative condition (α = 0.7 and α = 0.9) is adopted in this thesis which refers to Van Oyen et al. (2001) and Peltokorpi et al. (2015), respectively. By analyzing those conditions, the relation and tendency of α to impact of worker collaboration on CBB is determined. If the α increases and close to the additive condition, then the advantage of worker collaboration on CBB increases. Meanwhile if the α decreases and close to 0, then the advantage of worker collaboration on CBB decreases since the collaboration velocity becomes smaller than the velocity of the individual workers. The preliminary analysis at α = 0.5 shows that worker collaboration improvement is limited only in Region 1, while if the α is less than 0.5, the worse performance will be obtained, and no area can be improved by worker collaboration.

The throughput and region classification in the CBB system will be explained in the following sub-section; then the region classification to demonstrate the impact of worker collaboration on CBB is utilized, by assuming an additive worker collaboration coefficient (α = 1.0) and an inefficiency collaboration coefficient (α = 0.7 and α = 0.9). In the second sub-section, using the same assumption of a collaboration coefficient, the performance of CBB and both types of worker collaboration are compared with random working velocities, corresponding to a numerical calculation of the relative difference in throughput between CBB and both types of worker collaboration.

3.3.1 Impact of worker collaboration in each CBB region

Based on Section 3.2 and in accordance with Lim and Wu (2014), the CBB regions will depend on the convergence condition. Figure 3.4 and Figure 3.5 show the throughput and region of CBB when the convergence condition $(1/v_{11} - 1/v_{13} \geq 1/v_{21} - 1/v_{23})$ is satisfied and the convergence condition is not satisfied, respectively. In Figure 3.4a, the working velocities is set at v_{11}=0.8, v_{13}=1.2, v_{21}=1.2, v_{23}=0.8, v_{12}=v_{22}=1, while in Figure 3.5a, the working velocities is set at v_{11}=1.2, v_{13}=0.8, v_{21}=0.8, v_{23}=1.2, and v_{12}=v_{22}=1. Since there are blocking and/or halting conditions within a region, then the throughput in each region will have a different expression. The red scale indicates the highest throughput in a region, while the blue scale indicates the lowest.

If the convergence condition is satisfied, the system can be partitioned into five regions as designated by Lim and Wu (2014), shown in Figure 3.4b and the behavior of the system can be described as follows:

Region 1: At the fixed point, Worker 1 is always blocked at point 0 and Worker 2 is always halted at point 1 at each iteration; **Region 2:** At the fixed point, Worker 1 is blocked at point 0 at each iteration; **Region 3:** At the fixed point, Worker 2 is blocked at point s_1+s_2 at each iteration; **Region 4:** At the fixed point, Worker 1 is halted at point s_1 at each iteration; **Region 5:** Neither blocking nor halting occurs.

If the convergence condition is not satisfied, the system can be divided into eleven regions as designated by Lim and Wu (2014), shown in Figure 3.5b. The behavior remains the same for Region 1 to 4, while Region 5 can be partitioned into seven sub-regions as follows:

Region 5a: The system converges to a period-2 orbit, where Worker 1 is blocked at point 0 at every other iteration; **Region 5b:** The system converges to a period-2 orbit, where Worker 2 is blocked at point s_1+s_2 at every other iteration; **Region 5c:** The system converges to a period-2 orbit, where Worker 1 is halted at point $s_1$1 at every other iteration; **Region 5d:** The system converges to a period-2 orbit, where Worker 1 is blocked at point 0 at one iteration and Worker 2 is halted at point 1 at the next iteration; **Region 5e:** The system converges to a period-2 orbit, where Worker 1 is blocked at point 0 at one iteration and Worker 2 is blocked at point s_1+s_2 at the next iteration; **Region 5f:** The system converges to a period-2 orbit, where Worker 1 is halted at point s_1 at one iteration and Worker 2 is blocked at point s_1+s_2 at the next iteration; **Region 5g:** The system converges to a period-2 orbit, where Worker 1 is first blocked at point 0 and then halted at point s_1 at one iteration, and Worker 2 is halted at point 1 at the next iteration.

Using the obtained CBB regions, the impact of worker collaboration on each CBB region can be analyzed based on the relative difference in throughput between CBB and both types of worker collaboration. Figure 3.6 shows this performance comparison when CBB's convergence condition is satisfied. For this condition, the CBB system converges to a fixed point with blocking and/or halting, and can be partitioned into Regions 1 through 5, as shown in Figure 3.6. Regions 1 through 4 have blocking/halting conditions, while Region 5 has a balance condition. Figures 3.6a-c show the performance comparison based on the relative difference in throughput between CBB and worker collaboration of type 1, for $\alpha = 0.7$, $\alpha = 0.9$, and $\alpha = 1.0$, respectively. Figure 3.6d-f show the performance comparison based on the relative difference in throughput between CBB and worker collaboration of type 2, for $\alpha = 0.7$, $\alpha = 0.9$, and $\alpha = 1.0$, respectively.

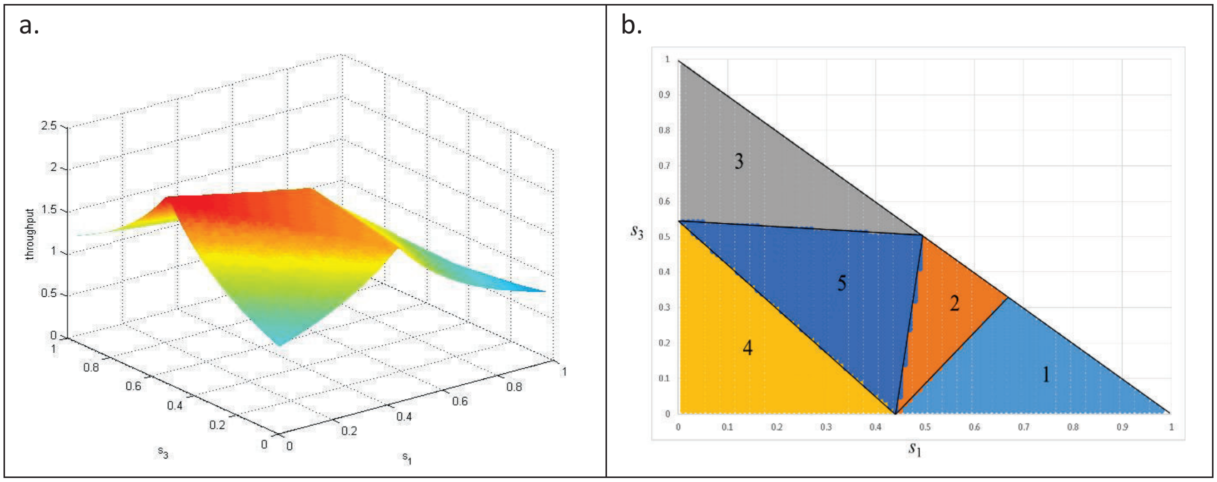


Figure 3.4. Throughput and region of CBB when the convergence condition is satisfied (v_{11}=0.8, v_{13}=1.2, v_{21}=1.2, v_{23}=0.8, v_{12}=v_{22}=1)

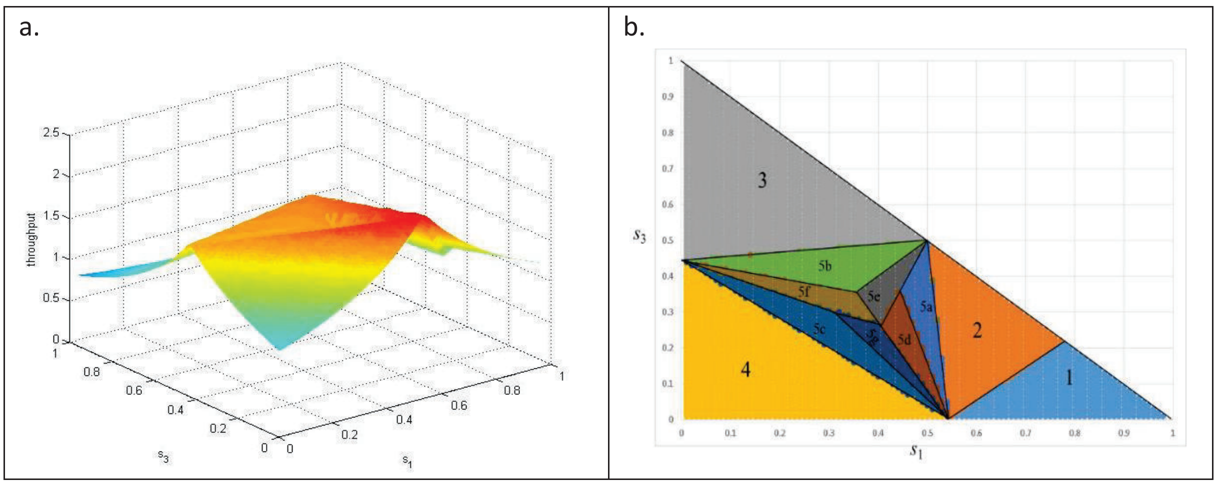


Figure 3.5. Throughput and region of CBB when the convergence condition is not satisfied (v_{11}=1.2, v_{13}=0.8, v_{21}=0.8, v_{23}=1.2, v_{12}=v_{22}=1)

Comparing Figures 3.6a and 3.6d, it can be seen that both types of worker collaboration are dominated by an area with decreasing performance, almost entirely within the CBB regions. Both types of worker collaboration can only improve the throughput of CBB, especially in Regions 1 to 4 when α = 0.7.

Increasing the collaboration coefficient can improve the performance of worker collaboration significantly in certain regions. When the collaboration coefficient increases, the area with decreased performance shrinks, while the area with equal or increased performance expands, as shown in Figures 3.6b and 3.6e for types 1 and 2 with α = 0.9, and Figures 3.6c and 3.6f for types 1 and 2 with α = 1.0, respectively.

Based on Figures 3.6c and 3.6f, and by calculating the number of configurations with a positive relative difference, it can be shown that worker collaboration type 1 covers 70.17% of all CBB regions, while type 2 covers 57.74% of all CBB regions. Both worker collaborations achieve the maximum relative difference in Region 1. Type 1 achieves a maximum relative difference of 143.52%, while type 2 reaches

142.47%. Based on Figures 3.6c and 3.6f, the performance of type 1 is superior to type 2, especially in Regions 1 through 4, while CBB is superior to both types in Region 5.

In the case where each worker has a constant working velocity at all stations, then the variable of working velocity will satisfy the convergence condition for CBB. The halting/blocking condition or combinations of blocking and halting can still occur only in Regions 1 through 4, while the maximum possible throughput can be obtained in Region 5, where neither blocking nor halting occurs. Since worker collaboration is utilized to eliminate the blocking/halting condition, then the maximum throughput in Regions 1 through 5 can be obtained for both types of worker collaboration with an additive collaboration coefficient.

Figure 3.7 shows a performance comparison in terms of the relative difference in throughput between CBB and both types of worker collaboration, where the convergence condition for CBB is not satisfied. In this situation, the CBB system converges to a fixed point or a period of 2-orbit, with blocking and/or halting, and can be partitioned into Regions 1 through 5g, as shown in Figure 3.7. Figures 3.7a-c show performance comparisons based on the relative difference between CBB and worker collaboration type 1, for $\alpha = 0.7$, $\alpha = 0.9$, and $\alpha = 1.0$, respectively. Figure 3.7d-f show performance comparisons based on the relative difference between CBB and worker collaboration type 2, for $\alpha = 0.7$, $\alpha = 0.9$, and $\alpha = 1.0$, respectively.

Comparing Figures 3.7a and 3.7d, it can be seen that type 2 worker collaboration gives a smaller region with decreased performance compared to type 1, when $\alpha = 0.7$. Type 1 shows worse performance in terms of throughput for almost all of the CBB regions when $\alpha = 0.7$, as shown in Figure 3.7a.

The impact on the increase of collaboration coefficient has a significant relation on performance improvement of worker collaboration compared with CBB. When the collaboration coefficient for both types of worker collaboration increases, the area with decreasing performance shrinks, while the area with equal or increased performance expands, as shown in Figures 3.7b and 3.7e for types 1 and 2 for $\alpha = 0.9$, and Figures 3.7c and 3.7f for types 1 and type 2 for $\alpha = 1.0$, respectively.

Based on Figures 3.7c and 3.7f, using the workers' velocity profile with an additive collaboration coefficient and calculating the number of configurations which have a positive relative difference, type 2 worker collaboration represents 99.09% of all CBB regions, while type 1 represents 98.31% of all CBB regions. Both types achieve a maximum relative difference in Region 3. Type 2 achieves a maximum relative difference of 145.89%, while type 1 achieves 144.95%. Based on Figures 3.7c and 3.7f, the performance of type 2 is superior to type 1.

3.3.2 Performance comparison for random working velocities

In this section, the performance of CBB and both types of worker collaboration is compared for random working velocities, by considering an additive worker collaboration coefficient ($\alpha = 1.0$) and an inefficiency collaboration coefficient ($\alpha = 0.7$ and $\alpha = 0.9$). Tables 3.4 and 3.5 show numerical results for the relative difference in throughput between CBB and worker collaboration when CBB's convergence condition is satisfied and unsatisfied, respectively. In these tables, work content multiplication factors of 0.01 is applied for each station. For instance, the first possible configuration is s_1=0.01, s_2=0.01 and s_3=0.98; the second is s_1=0.01, s_2=0.02 and s_3=0.97; and so on. Since zero work content at a station is neglected, there are 4851 possible configurations. There are 10 sets of scenarios for working velocity, where a uniform random number generator to generate working velocities is used; each worker then has different velocities at different stations. Based on both tables, an increase in collaboration coefficient has a significant impact on the increase in performance of worker collaboration compared with CBB.

Based on Table 3.4, in which the CBB convergence condition is satisfied, the CBB system is partitioned into five regions, where Regions 1 through 4 are dominated by blocking and/or halting, while Region 5 experiences neither blocking nor halting. Regions 1 through 4 show the most significant improvement that can be achieved by both worker collaboration, as indicated by the maximum relative difference and the average number of configurations with a positive relative difference. In Region 1, both types of worker collaboration achieve the highest number of configurations with a positive relative difference and maximum relative difference. For α = 0.7, type 1 worker collaboration achieves 890.9 out of 929 (or 95.90%) configurations with a positive relative difference and a maximum relative difference of 679.52%, while type 2 achieves 909.6 out of 929 (or 97.91%) configurations with a positive relative difference and a maximum relative difference of 676.65%. For α = 0.9, type 1 achieves 924.5 of 929 (or 99.52%) configurations with a positive relative difference and a maximum relative difference of 893.81%, while type 2 achieves 928.5 of 929 (or 99.95%) configurations with a positive relative difference and a maximum relative difference of 884.36%. For α = 1.0, type 1 achieves 927.3 of 929 (or 99.82%) configurations with a positive relative difference and a maximum relative difference of 999.77%, while type 2 achieves 929 of 929 (or 100%) configurations with a positive relative difference and a maximum relative difference of 986.58%. In Region 1, the CBB system corresponds to "more work" at Station 1 and "less work" at Station 3, where Worker 1 is always blocked at point 0 and Worker 2 is always halted at point 1 at each iteration.

In Region 5, however, both types of worker collaboration show worse performance than CBB based on the average number of configurations with a positive relative difference and the maximum relative difference. For α = 0.7, type 1 achieves 143.4 of 923.9 (or 15.52%) configurations with a positive relative difference and a maximum relative difference of 7.71%, while type 2 achieves 114.8 of 923.9 (or 12.43%) configurations with a positive relative difference and a maximum relative difference of 10.32%. For α = 0.9, type 1 achieves 251.5 of 923.9 (or 27.22%) configurations with a positive relative difference and a maximum relative difference of 16.79%, while type 2 achieves 134.8 of 923.9 (or 14.59%) configurations with a positive relative difference and a maximum relative difference of 17.43%. For α = 1.0, type 1 achieves 297.3 of 923.9 (or 32.18%) configurations with a positive relative difference and a maximum relative difference of 20.87%, while type 2 achieves 146 of 923.9 (or 15.80%) configurations with a positive relative difference and a maximum relative difference of 20.55%.

As shown in Table 3.4, type 1 almost always outperforms type 2; this is indicated by the total of the average number of configurations with a positive relative difference and maximum relative difference, especially for Regions 1 through 4. However, CBB has better performance in Region 5 than worker collaboration of both types. For an additive collaboration coefficient, type 1 can improve 78.33% of all CBB regions, with the maximum relative difference of 999.77% in Region 1, while type 2 can improve 56.58% of all CBB regions, with a maximum relative difference of 986.58 in Region 1.

As shown in Table 3.5, when the CBB regions are dominated by blocking and/or halting conditions, then both types of worker collaboration can be applied to counter these conditions. When $\alpha < 1.0$, type 1 has a lower performance than type 2 for several regions, as indicated by the average number of configurations with a positive relative difference and a maximum relative difference. For $\alpha = 0.7$, type 1 can improve 82.31% of all CBB regions with a maximum relative difference of 271.02% in Region 3, while type 2 can improve 87.54% of all CBB regions with a maximum relative difference of 342.08% in Region 3. For $\alpha = 0.9$, type 1 can improve 93.43% of all CBB regions with a maximum relative difference of 374.26% in Region 3, while type 2 can improve 94.32% of all CBB regions with a maximum relative difference of 383.23% in Region 3. In Region 3, the CBB system corresponds to "less work" at Station 1 and "more work" at Station 3, where Worker 2 is always blocked at point s_1+s_2 at each iteration.

Furthermore, type 1 outperforms type 2 for $\alpha = 1.0$, as indicated by the total average number of configurations with a positive relative difference and the maximum relative difference. Type 1 can improve 97.21% of all CBB regions with a maximum relative difference of 425.43% in Region 3, while type 2 can improve 96.64% of all CBB regions with a maximum relative difference of 433.26% in Region 3.

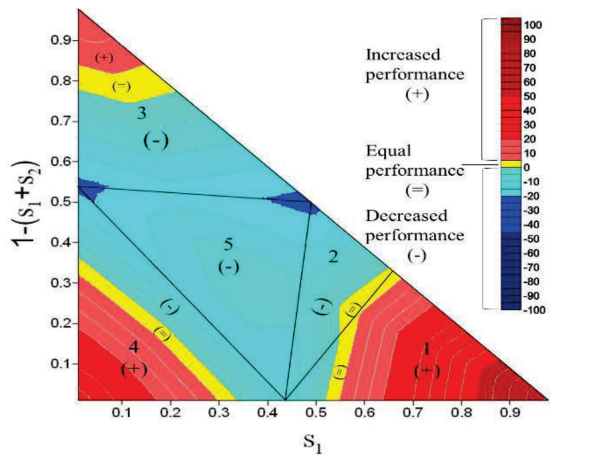
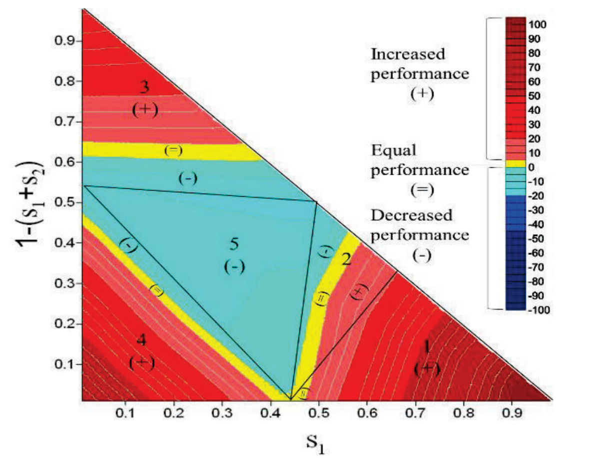
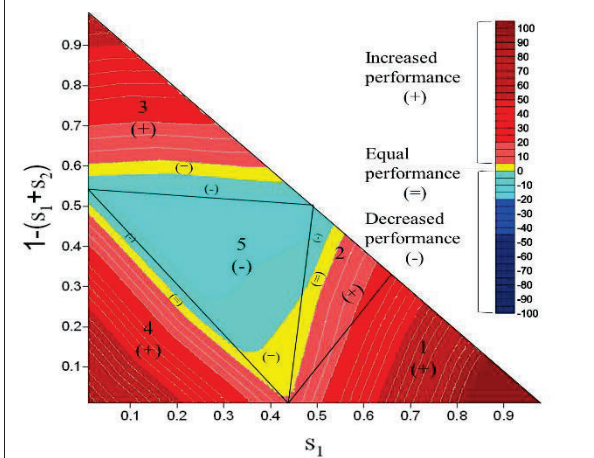
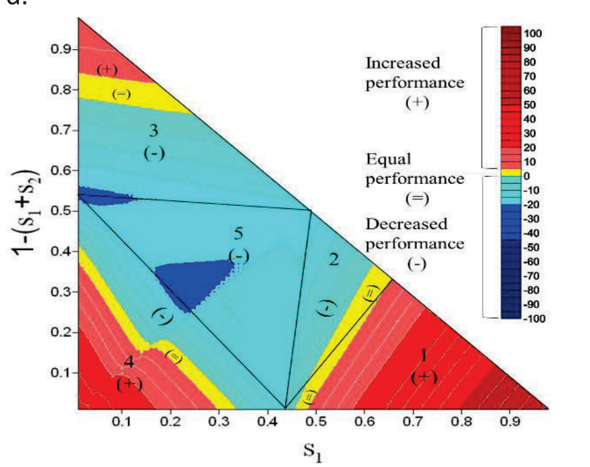
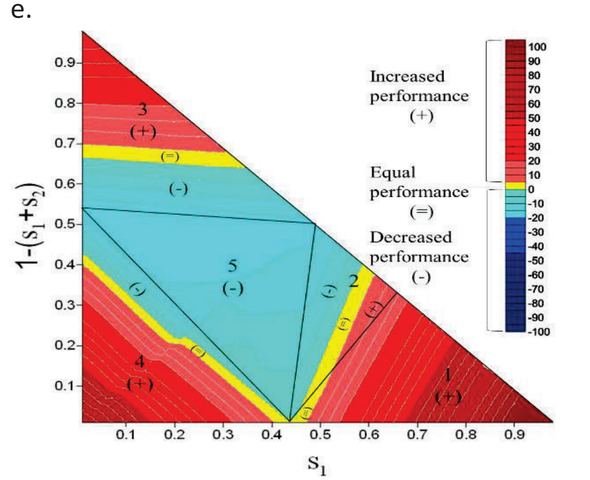
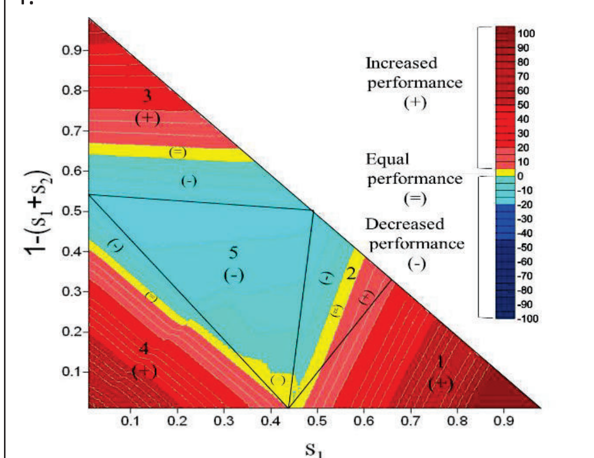
Cond. / Coll.	$1/v_{11} - 1/v_{13} \geq 1/v_{21} - 1/v_{23}$ (v_{11}=0.8, v_{13}=1.2, v_{21}=1.2, v_{23}=0.8, v_{12}=v_{22}=1, α=0.7)	$1/v_{11} - 1/v_{13} \geq 1/v_{21} - 1/v_{23}$ (v_{11}=0.8, v_{13}=1.2, v_{21}=1.2, v_{23}=0.8, v_{12}=v_{22}=1, α=0.9)	$1/v_{11} - 1/v_{13} \geq 1/v_{21} - 1/v_{23}$ (v_{11}=0.8, v_{13}=1.2, v_{21}=1.2, v_{23}=0.8, v_{12}=v_{22}=1, α=1.0)
Type 1	a. 	b. 	c. 
Type 2	d. 	e. 	f. 

Figure 3.6. Relative difference in throughput for CBB and worker collaboration when the CBB convergence condition is satisfied (three-station, two-worker U-shaped line)

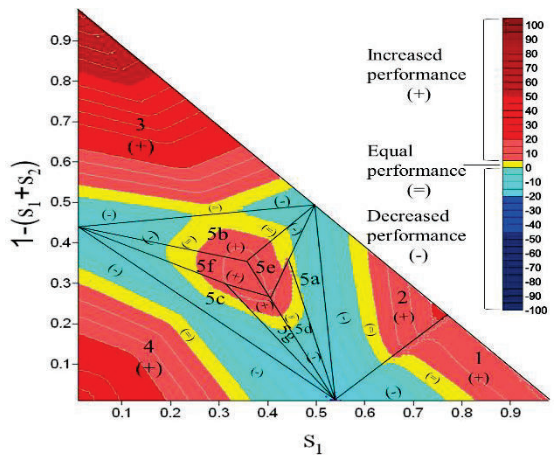
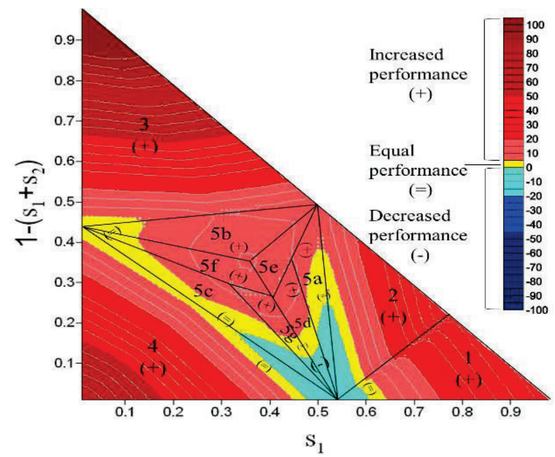
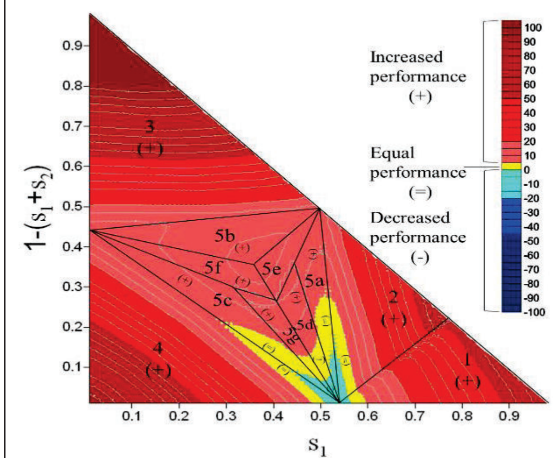
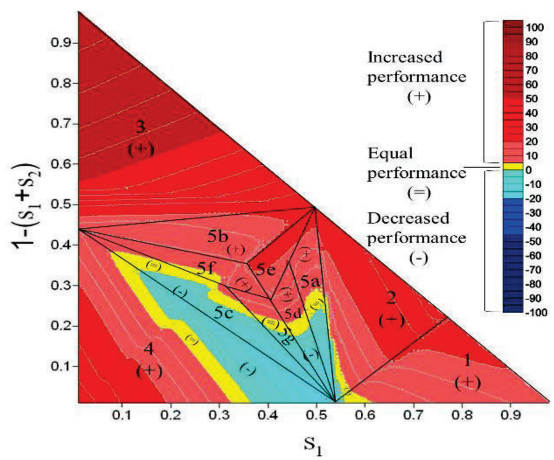
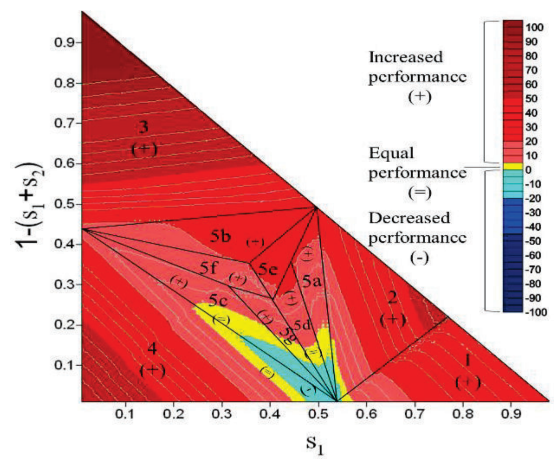
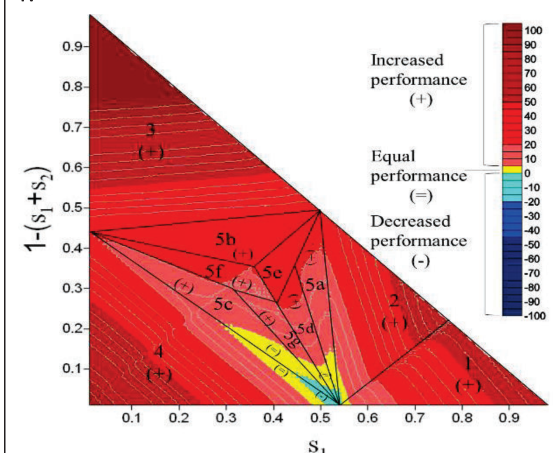
<table>
<tr><th>Cond. / Coll.</th><th>$1/v_{11} - 1/v_{13} < 1/v_{21} - 1/v_{23}$
(v_{11}=1.2, v_{13}=0.8, v_{21}=0.8, v_{23}=1.2, v_{12}=v_{22}=1, α=0.7)</th><th>$1/v_{11} - 1/v_{13} < 1/v_{21} - 1/v_{23}$
(v_{11}=1.2, v_{13}=0.8, v_{21}=0.8, v_{23}=1.2, v_{12}=v_{22}=1, α=0.9)</th><th>$1/v_{11} - 1/v_{13} < 1/v_{21} - 1/v_{23}$
(v_{11}=1.2, v_{13}=0.8, v_{21}=0.8, v_{23}=1.2, v_{12}=v_{22}=1, α=1.0)</th></tr>
<tr><td>Type 1</td><td>a.

</td><td>b.

</td><td>c.

</td></tr>
<tr><td>Type 2</td><td>d.

</td><td>e.

</td><td>f.

</td></tr>
</table>

Figure 3.7. Relative difference in throughput for CBB and worker collaboration when the CBB convergence condition is not satisfied (three-station, two-worker U-shaped line)

Table 3.4. Numerical result of relative difference in throughput between CBB and worker collaboration when the CBB convergence condition is satisfied (three-station, two-worker U-shaped line)

Collaboration coefficient	Region of CBB	Relative difference (%)					
		Worker collaboration (type 1)			Worker collaboration (type 2)		
		Average	Min	Max	Average	Min	Max
0.7	Reg 1	251.61	-4.84	679.52	234.67	-3.22	676.65
	Reg 2	0.87	-18.44	16.67	-8.69	-23.45	5.43
	Reg 3	-2.36	-29.15	30.10	-6.36	-37.62	27.17
	Reg 4	28.08	-16.28	86.79	28.76	-24.10	95.40
	Reg 5	-10.22	-28.25	7.71	-21.07	-37.91	10.32
0.9	Reg 1	316.06	9.30	893.81	282.95	0.94	884.36
	Reg 2	10.98	-7.27	28.93	-5.57	-20.65	8.28
	Reg 3	12.94	-19.91	58.77	4.22	-33.93	53.42
	Reg 4	48.69	-5.04	135.25	42.93	-16.44	132.90
	Reg 5	-4.02	-19.01	16.79	-17.78	-34.37	17.43
1.0	Reg 1	345.06	14.92	999.77	304.06	1.54	986.58
	Reg 2	15.07	-2.83	34.01	-4.38	-19.77	10.41
	Reg 3	19.67	-16.99	72.68	8.83	-32.98	67.28
	Reg 4	57.77	-0.88	158.93	48.96	-14.04	155.24
	Reg 5	-1.59	-16.06	20.89	-16.52	-33.51	20.55

Collaboration coefficient	Region of CBB	Average number of CBB configurations	Average number of configurations with the positive relative difference (%)	
			Worker collaboration (type 1)	Worker collaboration (type 2)
0.7	Reg 1	929.0	890.9 (95.90)	909.6 (97.91)
	Reg 2	365.9	179.3 (49.00)	52.6 (14.38)
	Reg 3	1610.1	633.7 (39.36)	589.5 (36.61)
	Reg 4	1022.1	753.0 (73.67)	737.1 (72.12)
	Reg 5	923.9	143.4 (15.52)	114.8 (12.43)
	Total	4851.0	2600.3 (53.60)	2403.6 (49.55)
0.9	Reg 1	929.0	924.5 (99.52)	928.5 (99.95)
	Reg 2	365.9	287.6 (78.60)	74.6 (20.39)
	Reg 3	1610.1	1082.2 (67.21)	660.5 (41.02)
	Reg 4	1022.1	870.8 (85.20)	789.6 (77.25)
	Reg 5	923.9	251.5 (27.22)	134.8 (14.59)
	Total	4851.0	3416.6 (70.43)	2588.0 (53.35)
1.0	Reg 1	929.0	927.3 (99.82)	929.0 (100.00)
	Reg 2	365.9	330.1 (90.22)	95.5 (26.10)
	Reg 3	1610.1	1332.4 (82.75)	763.2 (47.40)
	Reg 4	1022.1	912.7 (89.30)	810.9 (79.34)
	Reg 5	923.9	297.3 (32.18)	146.0 (15.80)
	Total	4851.0	3799.8 (78.33)	2744.6 (56.58)

Table 3.5. Numerical results for relative difference in throughput between CBB and worker collaboration when the CBB convergence condition is not satisfied (three-station, two-worker U-shaped line)

Collaboration coefficient	Region of CBB	Relative difference (%)					
		Worker collaboration (type 1)			Worker collaboration (type 2)		
		Average	Min	Max	Average	Min	Max
0.7	Reg 1	12.18	-14.91	53.40	24.22	-1.73	61.24
	Reg 2	-0.52	-21.40	20.85	21.85	-5.43	43.52
	Reg 3	115.34	-12.87	271.02	182.13	5.84	342.08
	Reg 4	37.08	-11.88	95.15	50.16	-12.64	107.69
	Reg 5a	-8.93	-19.93	-1.21	11.65	-6.27	22.47
	Reg 5b	18.39	-11.44	42.61	38.81	3.85	91.22
	Reg 5c	4.51	-13.55	15.26	13.24	-14.19	57.40
	Reg 5d	8.42	-17.01	25.37	21.60	-12.59	49.92
	Reg 5e	15.07	-8.61	42.66	38.18	13.87	71.47
	Reg 5f	25.49	4.43	46.67	32.56	1.64	77.75
	Reg 5g	21.82	-11.98	49.87	19.28	-11.98	47.34
0.9	Reg 1	33.65	-4.16	94.13	42.21	4.00	98.58
	Reg 2	14.27	-11.29	46.03	29.89	-1.82	57.87
	Reg 3	151.75	1.35	374.26	212.33	14.44	383.23
	Reg 4	60.21	0.31	148.49	75.52	-0.44	151.01
	Reg 5a	2.09	-9.88	11.92	16.21	-1.68	27.09
	Reg 5b	28.03	2.09	52.35	49.14	12.71	105.56
	Reg 5c	13.37	-2.53	22.58	24.64	-3.07	76.49
	Reg 5d	16.98	-8.21	35.80	29.06	-2.47	56.56
	Reg 5e	25.55	7.55	49.65	45.72	22.60	78.97
	Reg 5f	32.79	12.53	55.01	43.95	10.51	93.02
	Reg 5g	29.29	-1.43	57.78	27.11	-1.43	56.66
1.0	Reg 1	43.38	0.24	114.11	50.05	4.68	117.35
	Reg 2	20.63	-7.82	57.63	33.07	-0.61	66.85
	Reg 3	167.99	7.26	425.43	225.34	17.28	433.26
	Reg 4	70.45	5.41	174.79	86.90	4.67	178.02
	Reg 5a	6.67	-6.44	18.02	17.95	-0.12	29.11
	Reg 5b	31.87	7.89	56.26	53.31	15.82	112.25
	Reg 5c	16.88	2.10	25.64	29.35	1.60	85.55
	Reg 5d	20.35	-4.94	41.10	32.00	0.93	60.00
	Reg 5e	29.77	13.99	52.35	48.64	25.68	81.90
	Reg 5f	35.60	15.71	58.28	48.61	13.64	100.82
	Reg 5g	32.15	2.93	60.78	30.14	2.93	60.25

Collaboration coefficient	Region of CBB	Average number of CBB configurations	Average number of configurations with the positive relative difference (%)	
			Worker collaboration (type 1)	Worker collaboration (type 2)
0.7	Reg 1	411.1	319.2 (77.65)	400.7 (97.47)
	Reg 2	305.3	158.1 (51.79)	267.7 (87.68)
	Reg 3	1923.4	1838.4 (95.58)	1834.4 (95.37)
	Reg 4	1193.5	954.0 (79.93)	961.2 (80.54)
	Reg 5a	61.0	4.7 (7.70)	25.4 (41.64)
	Reg 5b	205.3	157.0 (76.47)	158.8 (77.35)
	Reg 5c	167.3	88.4 (52.84)	90.7 (54.21)
	Reg 5d	88.4	39.9 (45.14)	71.9 (81.33)
	Reg 5e	137.3	113.7 (82.81)	128.7 (93.74)
	Reg 5f	209.6	193.3 (92.22)	180.7 (86.21)
	Reg 5g	148.8	126.2 (84.81)	126.4 (84.95)
	Total	4851.0	3992.9 (82.31)	4246.6 (87.54)
0.9	Reg 1	411.1	394.6 (95.99)	411.1 (100.00)
	Reg 2	305.3	247.7 (81.13)	298.1 (97.64)
	Reg 3	1923.4	1891.7 (98.35)	1879.4 (97.71)
	Reg 4	1193.5	1127.0 (94.43)	1106.8 (92.74)
	Reg 5a	61.0	25.5 (41.80)	43.7 (71.64)
	Reg 5b	205.3	179.9 (87.63)	176.9 (86.17)
	Reg 5c	167.3	119.7 (71.55)	107.4 (64.20)
	Reg 5d	88.4	67.8 (76.70)	83.7 (94.68)
	Reg 5e	137.3	133.5 (97.23)	133.5 (97.23)
	Reg 5f	209.6	202.4 (96.56)	192.8 (91.98)
	Reg 5g	148.8	142.3 (95.63)	142.3 (95.63)
	Total	4851.0	4532.1 (93.43)	4575.7 (94.32)
1.0	Reg 1	411.1	404.0 (98.27)	411.1 (100.00)
	Reg 2	305.3	281.8 (92.30)	302.3 (99.02)
	Reg 3	1923.4	1917.1 (99.67)	1906.1 (99.10)
	Reg 4	1193.5	1163.9 (97.52)	1143.6 (95.82)
	Reg 5a	61.0	46.1 (75.57)	53.6 (87.87)
	Reg 5b	205.3	199.6 (97.22)	186.7 (90.94)
	Reg 5c	167.3	136.2 (81.41)	117.6 (70.29)
	Reg 5d	88.4	78.1 (88.35)	85.8 (97.06)
	Reg 5e	137.3	137.3 (100.00)	137.1 (99.85)
	Reg 5f	209.6	206.4 (98.47)	199.1 (94.99)
	Reg 5g	148.8	145.2 (97.58)	145.2 (97.58)
	Total	4851.0	4715.7 (97.21)	4688.2 (96.64)

3.4. Summary

Lim and Wu (2014) have explained that CBB can maximize the productivity of the U-shaped line with discrete workstations by choosing the worker sequence properly and preserve the productivity by allowing the workers dynamically to share the work. However, CBB shows a drawback where blocking and/or halting condition can occur in case of different amount work content distribution. This chapter puts forward another possibility for overcoming the impact of blocking/halting in CBB through the use of worker collaboration, where each worker has different work velocities at different stations. For a three-station, two-worker system, CBB always converges to a fixed point or period-2 orbit for a given work content distribution, when blocking and/or halting may occur. Numerical analysis shows that worker collaboration can effectively improve the performance of CBB in a region where blocking and/or halting occurs.

Based on the analysis of a three-station, two-worker U-shaped line where each worker has a different working velocity for each station, the worker collaboration condition with several sets of random worker velocities is tested, with the CBB convergence condition satisfied and unsatisfied (as defined by Lim and Wu (2014)). When the CBB convergence condition is satisfied, both types of worker collaboration perform well in countering blocking and/or halting in Regions 1 through 4. In a region where the U-shaped line is balanced, without blocking and/or halting, CBB shows higher performance than both types of worker collaboration. When the CBB convergence condition is not satisfied, then all regions of CBB are dominated by blocking and/or halting conditions. Both types of worker collaboration almost always outperform CBB in this case. In addition, α is strongly related to the performance of both types of worker collaboration to counter the blocking and/or halting in certain regions. By increasing the α, there is a tendency that area with increased performance expands and throughput relative difference also increases. Meanwhile, by decreasing α, then the performance worker collaboration on CBB becomes worse. The area with increased performance shrinks and throughput relative difference also decreases.

Based on the analysis of a three-station, two-worker U-shaped line, a manager can directly use those results to boost the productivity in the real implementation. Moreover, workers can easily adopt and follow the rules, therefore it can be implemented in practical condition. If a balanced U-shaped line can be obtained by CBB, then worker collaboration can be neglected since CBB shows higher performance than worker collaboration. A manager should do a preliminary check whether CBB or worker collaboration can give better performance since worker collaboration almost always outperform than CBB in halting/blocking case. In addition, a manager can still utilize those results even though each stage consists of multiple stations. The characteristic of self-balancing line can still be preserved, and the performance improvement can be obtained with discrete workstation by integrating worker collaboration. Although increasing the number of stations can reduce the idling time and increase the average throughput, blocking/halting conditions may still occur, and the performance might be improved by using worker collaboration.

Ideally, a condition that worker collaboration can give better performance than cellular bucket brigade is desired in a system with changeable size, then workers need to have flexibility to work at any station, and the work content needs to be adjustable across all stations. However, it is difficult and costly to train workers to be flexible, and task allocation is not easy to adjust. Another constraint is the additive rate of the collaboration coefficient. In practice, if a single task is processed by multiple workers at the same time, the collaborative processing time may be slower or faster than the total processing time for the individual workers.

Most of the results depend only on the assumptions that handover time is neglected and walking back is instantaneous. Relaxing those assumptions would be an interesting topic for future research. In addition, by conducting a case study of worker collaboration in order picking process at a warehouse is recommended. Analyzing the behavior and performance of worker collaboration would be an interesting topic for future study. In order picking process, workers are flexible to work at any shelf, task allocation of each worker can be adjusted, and the shelf can accommodate two workers to work collaboratively to fulfill the order list.

Chapter 4 Migrate from craft manufacturing to assembly line by integrating bucket brigades and worker collaboration

4.1. Introduction

In this chapter, the behavior of worker collaboration based on the prior case study on migration process from craft manufacturing to assembly line by Bartholdi and Eisenstein (2005) has been investigated. Moreover, the performance comparison of bucket brigade with and without worker collaboration based on the identified conditions at a continuous assembly line with various proportion of work content has been analyzed by considering walk-back time and hand-off time or time for preparing collaboration. Bucket brigade is self-balancing production lines which it involves hand-offs and walk-backs to assemble a product. These movements include an exchange of works, packing up tools and rolls the toolbox to the upstream worker, which can be time-consuming in practice. In addition, each worker is partially cross-trained with limited work content, then throughput may decrease due to the halting condition. A special movement to counter the halting condition is proposed by utilizing worker collaboration such that first worker can collaborate on the same task with the last worker.

Bartholdi and Eisenstein (2005) has studied the trade-off in migrating process of TUG™ from craft manufacturing to assembly line by implementing bucket brigade. They had made several adjustments to ensure that bucket brigade can work in TUG™ environment. TUG™ is a company that assembles about 10 models of industrial tractor of type commonly used at airports to pull luggage trains. Each tractor was built by a single person from start to finish, then each worker (1) had to know how to build a tractor from start to finish and (2) have a complete set of expensive tools. The requirement (1) meant that it took months for a new employee to become proficient, but the requirement (2) narrowed the pool of available labor because each worker was expected to provide his own tools. The company faced problem in how to increase production quickly when it was so hard to train and retain workers. In addition, there was no formalization of task primitives, no work content models, and no work standards on which to base any sort of traditional assembly line.

Worker collaboration is one way to improve the performance of assembly line through workforce flexibility. Van Oyen et al., (2001) showed that collaborative teams are beneficial for systems with high variability. Under some circumstances, such as operational environments with low utilization, low variability, and a lack of balance, cooperative teams may not improve system performance unless collaborative efficiency is very high. Peltokorpi et al. (2015) utilized the efficiency factor in collaboration by compared four different worker coordination policies (no helping, floater, pairs, and complete helping) on a parallel assembly line and showed that productivity of the line can be reduced due to inefficiency factor in collaboration.

This chapter consists of several sections that can be described as follows: the first section is the introduction of this chapter, the second section presents the model and assumptions of production line based on the condition of bucket brigade at TUG™. In addition, the movement rules for worker collaboration will be described in this section. The third section discusses the mathematical model of bucket brigades, worker collaboration type 1, and worker collaboration type 2 based on mixed integer programming. Behavior analysis and performance comparison of 3-worker production line are explained on the fourth section. Moreover, the special movement will be introduced in this section. Finally, fifth section will conclude this chapter.

4.2. The production line

This section will explain the condition of bucket brigades at TUG™, model assumption of the production line, and movement rules.

4.2.1 Condition of bucket brigade at TUG™

Several adjustments were needed for bucket brigade can work in the TUG™ environment (Bartholdi and Eisenstein, 2005). It was not possible to move tractors-in-process from station to station because it required special purpose material-handling equipment. Consequently, the workers must move from tractor to tractor. Four workstations are clustered around a shared crane and each worker independently assembles a tractor. Figure 4.1 shows the successive snapshots of the four-worker bucket brigade at TUG™.

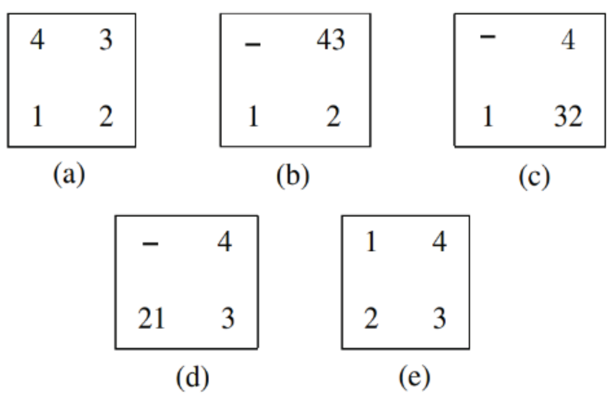


Figure 4.1. Successive snapshots of the four-worker bucket brigade at TUG™ (Bartholdi and Eisenstein, 2005).

Figure 4.1a shows that each of the four workers is assembling a tractor. Figure 4.1b shows that when Worker 4 finishes his tractor, then he pushes his tools to the predecessor and take over the tractor from Worker 3. Figure 4.1c shows that Worker 4 takes over the tractors from Worker 3, then Worker 3 packs up his tools and take over the tractor from Worker 2. Figure 4.1d shows that Worker 2 takes over the tractor from Worker 1, and Figure 4.1e shows that Worker 1 as the slowest worker, moves his tools to the empty area vacated by the tractor newly completed by Worker 4 and begins assembling the new tractor. Because each worker has his own workstation, then a slower worker may pass a faster worker. Each worker must gather his tools and push his tools to the assembly area of his predecessor, which takes 3 to 5 minutes. The time to hand-off work from one worker to another takes 10 to 20 minutes by assuming the downstream worker must understand exactly what remains to be completed.

4.2.2 Model Assumption

Bartholdi and Eisenstein (2005) has been described the general model assumption of bucket brigade at TUG™. Because worker collaboration is necessary to improve the performance of bucket brigades, the assumption of bucket brigade is extended to understand the effects to the production line.

Consider a continuous production line with the nominal work content of a product is a constant and normalized the total work content to 1. Since the hand-off and walk-back times are significant in the bucket brigade, then the same conditions will be applied for worker collaboration. The time required by the upstream worker to relinquish an item or preparing for collaboration with the downstream worker is a constant $h_i \geq 0$ and the time required for worker *i* to pack up tools and walk back to his predecessor is a constant $b_i \geq 0$. Special movement in worker collaboration that first worker can collaborate with the last worker is introduced, then the walk-back time of the first worker before and after collaboration can be neglected.

Each worker i=1, …, n is characterized by a distinct, constant work velocity v_i and workers are always sequenced slowest-to-fastest. In addition, each worker *i* is partially cross-trained where his work content overlaps with work content of the upstream worker where the amount of work contents which is covered by each worker, and is represented with B_i. A worker $i < 1$ will be halted if he finishes his work at the end of his covered work content before he can hand off his item to worker $i + 1$. The halted worker remains idle until the successor takes over his item. A worker $i > 1$ will be starved if he reaches the beginning of his covered work content before worker $i - 1$ can hand over the item to him. The starved worker remains idle until his predecessor hands over an item.

Worker collaboration begins when the successor and predecessor can work at any point inside the covered work content of the predecessor, they work collaboratively until the task is complete at the end of the covered work content of the predecessor. Collaborative work defines as multiple workers to work together by sharing spaces and tools to complete an item. A worker will process an item as individual work and/or partial work will be processed by collaboration without any loss of work. The collaborative velocity is equal to $v_{coll}(i) = \alpha(v_i + v_{i+1})$ and must be higher than the minimum worker velocity ($v_{coll}(i) > min\{v_i, v_{i+1}\}$). α is a measure or coefficient of the collaboration or synergy between worker i and worker i + 1 that can be defined by $\max_i \left(\frac{min\{v_i, v_{i+1}\}}{(v_i + v_{i+1})}\right) < \alpha \leq 1$ for i=1,…,n-1. The inefficiency of α can be caused by work for preparing collaboration between two workers. The conceptual representation of the assembly line is shown in Figure 4.2.

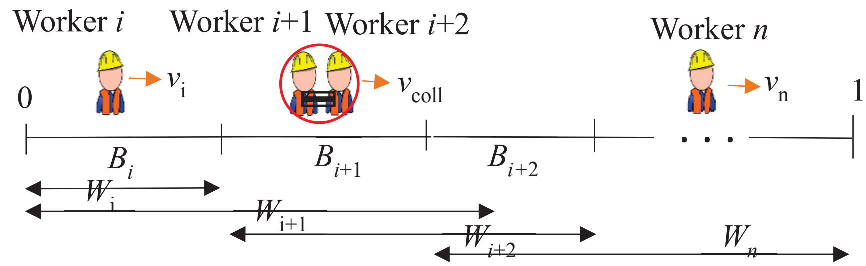


Figure 4.2. Conceptual representation of the assembly line

4.2.3 Movement rules

Figure 4.3a, Figure 4.3b, and Figure 4.3c show the time chart of no-idling condition on bucket brigade, worker collaboration type 1, and worker collaboration type 2, respectively. On these conditions, the assembly line is balanced, then each worker repeats the same interval of work content on the successive item. If the workers begin at the fixed point or collaboration point, then after completion, they will walk back to exactly the same position to begin work on the subsequent item. In no-idling condition, the performance of bucket brigades and worker collaboration type 1 can be equal, while throughput can increase in worker collaboration type 2 since the time for preparing collaboration is embedded to collaboration coefficient. The same value for all hand-off times or preparation of collaboration times and walk-back times are assumed where $h_1=h_2=h_i=h$ and $b_1=b_2=b_i=b$.

On worker collaboration type 1, when both workers meet at any point, they wait until the preparation for collaboration is complete, then both workers start the collaborative work until the end of covered work content by the upstream worker. After collaborative work, the upstream worker packs up the tools and walks back to the upstream point, while downstream worker continues to process the item. Meanwhile, on worker collaboration type 2, the time for preparing collaboration is embedded as part of the inefficiency of collaboration coefficient is assumed. When both workers meet at any point, they start the collaborative work until the end of covered work content by the upstream worker. After collaborative work, the upstream worker packs up the tools and walks back to the upstream point, while downstream worker continues to process the item.

According to Figure 4.3a and the snapshot on Figure 4.1, when Worker 3 has finished with his item at the end of the line, he packs up his tools and walk-back to Worker 2 to receive an item. Walk-back time is a time need for packing up the tools and walk-back to predecessor. When Worker 3 and Worker 2 meet at a certain point, they review and agree on what work remains to complete the item. When Worker 3 understands exactly what remains to be done, he takes the responsibility to complete the item. The time need for worker to review and understand his responsibility is called by hand-off time. After handing over the idem, Worker 3 continues to process the item, while Worker 2 packs-up his tools and walk-back to Worker 1, until Worker 1 initiates new item.

Based on Figure 4.3b, when Worker 3 has finished with his item at the end of the line, he packs up his tools and walk-back to Worker 2 to start collaborative work. Similar to Figure 4.3a, the time need for a worker to packs-up his tools and walk-back to predecessor is called by walk-back time. When Worker 3 and Worker 2 meet at the certain point, they will review the remaining tasks and start collaborative until the end of the work content of Worker 2. Both workers idle for certain time as time for preparing collaboration. After finishing collaborative work, Worker 2 packs-up his tools and walk-back to Worker 1, while Worker 3 continue to process the item. Worker 1 and Worker 2 do the same activities, until Worker 1 initiates a new item.

Based on Figure 4.3c, when Worker 3 has finished with his item at the end of the line, he packs up his tools and walk-back to Worker 2 to start collaborative work. Similar to Figure 4.3a, the time need for a worker to packs-up his tools and walk-back to predecessor is called by walk-back time. When Worker 3 and Worker 2 meet at the certain point, the time for both workers to prepare collaboration can be neglected. In this condition, the time for preparing collaboration is embedded into inefficiency of collaboration coefficient. After finishing collaborative work, Worker 2 packs-up his tools and walk-back to Worker 1, while Worker 3 continue to process the item. Worker 1 and Worker 2 do the same activities, until Worker 1 initiates a new item.

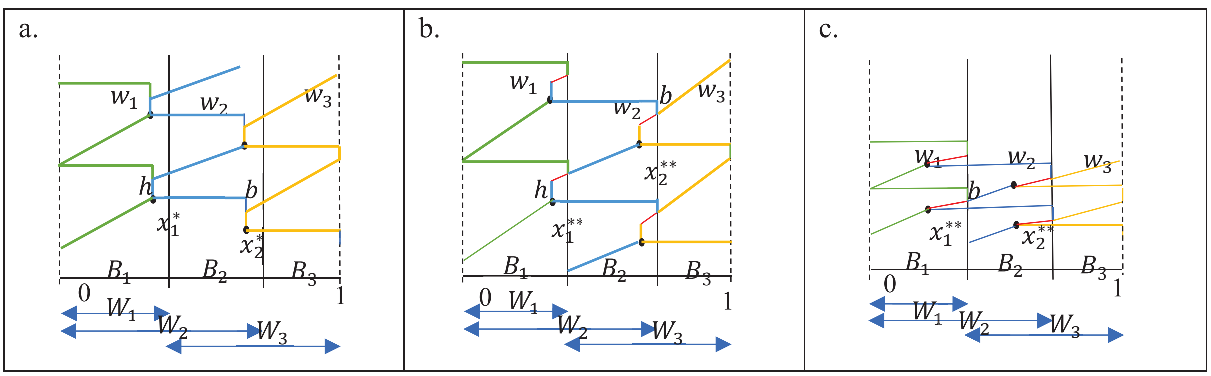


Figure 4.3. No-idling condition: a. bucket brigade, b. worker collaboration type 1, c. worker collaboration type 2

The bucket brigades' movement rule is modified to accommodate worker collaboration condition. Under bucket brigade with worker collaboration, each worker follows these rules:

Work forward: Continue to assemble your item as quickly as possible. If you are pre-empted by your successor, start the collaborative work. If you are the first worker, walk to begin collaborative work with the last worker. If you are not the first worker, finish your work content then wait.

Wait: If you are the last worker, remove your finished item from the assembly area, then walk back to initiate collaborative work. If you are not the last worker, then wait until your successor takes over your item and then walk back to get more work.

Walk back: If you are the first worker, walk back to begin introducing a new item. If you are not the first worker, walk back to the upstream worker and start the collaboration. In either case, begin to work forward.

4.3. Mathematical model of bucket brigades and worker collaboration

In this section, based on section 4.2, the mixed integer programming model has been developed to determine cycle time of bucket brigades, worker collaboration type 1, and worker collaboration type 2 for n-worker line.

Figure 4.4 shows the illustration of bucket brigade with no-idling condition for *n*-worker line. Thus, the objective function is to minimize from the maximum of cycle time (CT) given by *n*-workers and can be expressed as follows:

$$\text{Minimum} \left[\max_{j} \{CT_j\}\right] \quad \text{for } j=1,\dots,n \tag{4.1}$$

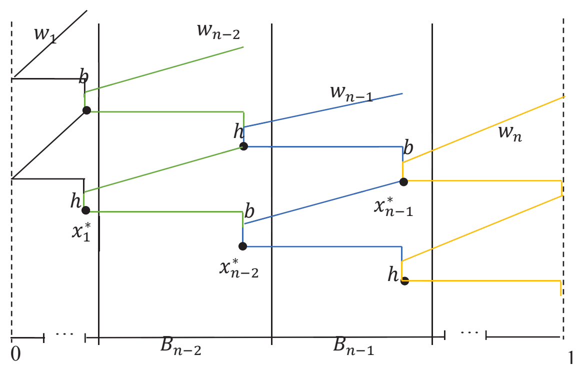


Figure 4.4. Bucket brigades for *n*-worker line (no-idling condition)

Since the objective function is based on the cycle time from each worker, the constrains of each worker cycle time can be expressed as follows:

$$CT_1 \geq b + h + \frac{x_1^*}{v_1} \tag{4.2}$$

$$CT_i \geq b + h + h + \frac{(x_i^* - x_{i-1}^*)}{v_i} \quad \text{for } i=2,\dots,n\text{-}1 \tag{4.3}$$

$$CT_n \geq \frac{(1 - x_{n-1}^*)}{v_n} + b + h \tag{4.4}$$

In addition, the equilibrium between each pair of workers is expanded by inserting idle time for each for each worker, which represents as β_i, then the equilibrium condition for each pair of workers will be restricted by β_i. The equilibrium constrains for each pair of workers by considering idle time (β_i) can be expressed as follows:

For *i*=1

$$b + h + \frac{x_1^*}{v_1} + \beta_1 = \frac{(x_2^* - x_1^*)}{v_2} + b + h + h + \beta_2 \tag{4.5}$$

For *i*=2,…,*n*-2

$$\frac{(x_i^* - x_{i-1}^*)}{v_i} + b + h + h + \beta_i = \frac{(x_{i+1}^* - x_i^*)}{v_{i+1}} + b + h + h + \beta_{i+1} \tag{4.6}$$

For i=n

$$b + h + h + \frac{(x^*_{n-1} - x^*_{n-2})}{v_{n-1}} + \beta_{n-1} = \frac{(1 - x^*_{n-1})}{v_n} + b + h + \beta_n \quad (4.7)$$

$$\beta_i \geq 0 \quad (4.8)$$

Next constrains are the location of bucket brigades fixed point as follows:

$$0 \leq x^*_1 \leq B_1 \quad (4.9)$$

$$\sum_{i=1}^{i-1} B_i \leq x^*_i \leq \sum_{i=1}^{i} B_i \qquad \text{for } i=2,\ldots,n\text{-}1 \quad (4.10)$$

A non-linear equation is added as follows:

$$\beta_i \left(x^*_{i-1} - \sum_{j=1}^{i-2} B_j \right) = 0 \quad (4.11)$$

Equation 4.11 expresses that when fixed point x^*_{i-1} at minimum of work content, then idle time is allowed. Then, the binary variable y_i is introduced as follows:

$$y_i \in \{0,1\} \quad (4.12)$$

The new relationship can be defined based on Equation 4.11 and Equation 4.12 as follows:

$$x^*_{i-1} - \sum_{j=1}^{i-2} B_j \geq 0 \qquad \text{for } i=2,\ldots,n \quad (4.13)$$

$$x^*_{i-1} - \sum_{j=1}^{i-2} B_j + y_i - 1 \leq 0 \qquad \text{for } i=2,\ldots,n \quad (4.14)$$

If $y_i = 0$, then Equation 4.14 will be useless, while Equation 4.13 is already accommodated by Equation 4.10. If $y_i = 1$, then $\beta_i > 0$ and Equation 4.13 and Equation 4.14 can be interpreted as $x^*_{i-1} - \sum_{j=1}^{i-2} B_j = 0$.

The condition Equation 4.13 can be expressed by following constraint:

$$My_i - \beta_i \geq 0 \qquad \text{for } i=2,\ldots,n \quad (4.15)$$

where M is large positive value.

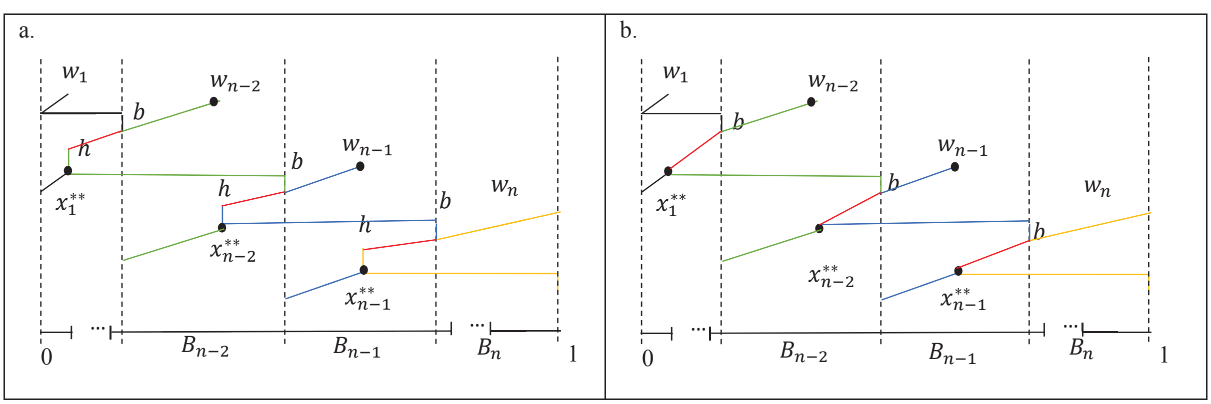


Figure 4.5. Worker collaboration at no-idling condition for n-worker line: a. type 1, b. type 2

Figure 4.5a and Figure 4.5b show the illustration of worker collaboration n-worker line at no-idling condition for type 1 and type 2, respectively. Based on the Figure 4.5 and by considering similar approach of mixed integer programing of bucket brigade mathematical model, the formulation of worker collaboration type 1 and type 2 for n-worker line can be expressed at Table 4.1.

On Table 4.1, Equation 4.16 and Equation 4.29 are the objective functions of worker collaboration type 1 and type 2 based on the minimum of the maximum cycle time given by n-worker, respectively. The constrains of each worker cycle time for worker collaboration type 1 are expressed in Table 4.1 at Equation 4.17, Equation 4.18, and Equation 4.19, while for worker collaboration type 2 are expressed in Table 4.1 at Equation 4.30, Equation 4.31, and Equation 4.32. The equilibrium of worker collaboration type 1 by each pair of workers by considering idle time (β_i) are defined in Table 4.1 at Equation 4.20, Equation 4.21, and Equation 4.22. Meanwhile, for worker collaboration type 2 are define in Table 4.1 at Equation 4.33, Equation 4.34, and Equation 4.35. Both type of worker collaboration has similar constraints for each collaboration point and idle time that are mentioned at Equation 4.23, Equation 4.24, Equation 4.25, Equation 4.36, Equation 4.37, and Equation 4.38. For non-linear programing, worker i can idle only when collaboration point x_{i-1}^{**} at the minimum work content and can be expressed at Equation 4.26 through Equation 4.28 and Equation 4.39 through Equation 4.41 for worker collaboration type 1 and type 2, respectively.

Table 4.1. Mathematical model of worker collaboration (type 1 and type 2)

Worker collaboration type 1		Worker collaboration type 2	
Minimize $\left[\genfrac{}{}{0pt}{}{max}{j}\{CT_j\}\right]$ for j=1,…,n	(4.16)	Minimize $\left[\genfrac{}{}{0pt}{}{max}{j}\{CT_j\}\right]$ for j=1,…,n	(4.29)
Subject to:		Subject to:	
$CT_1 - \frac{x_1^{**}}{v_1} - \frac{B_1 - x_1^{**}}{\alpha(v_1+v_2)} \geq h + b$	(4.17)	$CT_1 - \frac{x_1^{**}}{v_1} - \frac{B_1 - x_1^{**}}{\alpha(v_1+v_2)} \geq b$	(4.30)
for i=2,…,n-2		for i=2,…,n-2	
$CT_i - \frac{\left(x_i^{**} - \sum_{j=1}^{i-1} B_j\right)}{v_i} - \frac{\left(\sum_{j=1}^{i} B_j - x_i^{**}\right)}{\alpha(v_i+v_{i+1})} - \frac{\left(\sum_{j=1}^{i-1} B_j - x_{i-1}^{**}\right)}{\alpha(v_{i-1}+v_i)} \geq h + b + h$	(4.18)	$CT_i - \frac{\left(x_i^{**} - \sum_{j=1}^{i-1} B_j\right)}{v_i} - \frac{\left(\sum_{j=1}^{i} B_j - x_i^{**}\right)}{\alpha(v_i+v_{i+1})} - \frac{\left(\sum_{j=1}^{i-1} B_j - x_{i-1}^{**}\right)}{\alpha(v_{i-1}+v_i)} \geq b$	(4.31)
$CT_n - \frac{\left(\sum_{j=1}^{n-1} B_j - x_{n-1}^{**}\right)}{\alpha(v_{n-1}+v_n)} \geq \frac{B_n}{v_n} + b + h$	(4.19)	$CT_n - \frac{\left(\sum_{j=1}^{n-1} B_j - x_{n-1}^{**}\right)}{\alpha(v_{n-1}+v_n)} \geq \frac{B_n}{v_n} + b$	(4.32)
for i=1		for i=1	
$\frac{x_1^{**}}{v_1} - \frac{(x_2^{**} - B_1)}{v_2} - \frac{\left(\sum_{j=1}^{2} B_j - x_2^{**}\right)}{\alpha(v_2+v_3)} + \beta_1 - \beta_2 = h$	(4.20)	$\frac{x_1^{**}}{v_1} - \frac{(x_2^{**} - B_1)}{v_2} - \frac{\left(\sum_{j=1}^{2} B_j - x_2^{**}\right)}{\alpha(v_2+v_3)} + \beta_1 - \beta_2 = 0$	(4.33)
for i=2,…,n-2		for i=2,…,n-2	
$\frac{\left(\sum_{j=1}^{i-1} B_j - x_{i-1}^{**}\right)}{\alpha(v_{i-1}+v_i)} + \frac{\left(x_i^{**} - \sum_{j=1}^{i-1} B_j\right)}{v_i} - \frac{\left(x_{i+1}^{**} - \sum_{j=1}^{i} B_j\right)}{v_{i+1}} - \frac{\left(\sum_{j=1}^{i+1} B_j - x_{i+1}^{**}\right)}{\alpha(v_{i+1}+v_{i+2})} + \beta_i - \beta_{i+1} = 0$	(4.21)	$\frac{\left(\sum_{j=1}^{i-1} B_j - x_{i-1}^{**}\right)}{\alpha(v_{i-1}+v_i)} + \frac{\left(x_i^{**} - \sum_{j=1}^{i-1} B_j\right)}{v_i} - \frac{\left(x_{i+1}^{**} - \sum_{j=1}^{i} B_j\right)}{v_{i+1}} - \frac{\left(\sum_{j=1}^{i+1} B_j - x_{i+1}^{**}\right)}{\alpha(v_{i+1}+v_{i+2})} + \beta_i - \beta_{i+1} = 0$	(4.34)
for i=n		for i=n	
$\frac{\left(\sum_{j=1}^{n-2} B_j - x_{n-2}^{**}\right)}{\alpha(v_{n-2}+v_{n-1})} + \frac{\left(x_{n-1}^{**} - \sum_{j=1}^{n-2} B_j\right)}{v_{n-1}} + \beta_{n-1} - \beta_n = \frac{B_n}{v_n} - h$	(4.22)	$\frac{\left(\sum_{j=1}^{n-2} B_j - x_{n-2}^{**}\right)}{\alpha(v_{n-2}+v_{n-1})} + \frac{\left(x_{n-1}^{**} - \sum_{j=1}^{n-2} B_j\right)}{v_{n-1}} + \beta_{n-1} - \beta_n = \frac{B_n}{v_n}$	(4.35)
$0 \leq x_1^{**} \leq B_1$	(4.23)	$0 \leq x_1^{**} \leq B_1$	(4.36)
$\sum_{i=1}^{i-1} B_i \leq x_i^{**} \leq \sum_{i=1}^{i} B_i$ for i=2,…,n-1	(4.24)	$\sum_{i=1}^{i-1} B_i \leq x_i^{**} \leq \sum_{i=1}^{i} B_i$ for i=2,…,n-1	(4.37)
$\beta_i \geq 0$ for i=1,…,n	(4.25)	$\beta_i \geq 0$ for i=1,…,n	(4.38)
Non-linear programming: Worker i can idle only when collaboration point x_{i-1}^{**} at the minimum work content		Non-linear programming: Worker i can idle only when collaboration point x_{i-1}^{**} at the minimum work content	
$x_{i-1}^{**} - \sum_{j=1}^{i-2} B_j + y_i - 1 \leq 0$ for i=2,…,n	(4.26)	$x_{i-1}^{**} - \sum_{j=1}^{i-2} B_j + y_i - 1 \leq 0$ for i=2,…,n	(4.39)
$My_i - \beta_i \geq 0$ for i=2,…,n	(4.27)	$My_i - \beta_i \geq 0$ for i=2,…,n	(4.40)
$y_i \in \{0,1\}$	(4.28)	$y_i \in \{0,1\}$	(4.41)

4.4. Analysis of production line

In this section, the 3-worker production line is analyzed to simplify the behavior of bucket brigades and worker collaboration under various work content. A similar behavior will occur on the larger production line is expected where halting and starvation condition tend to increase under various work content.

4.4.1 Conditions and regions

Based on section 4.3, the regions of the production line from bucket brigades, worker collaboration type 1, and worker collaboration type 2 are determined as shown on Figure 4.6. The horizontal and vertical axis correspond to B_1 and B_2, respectively. Each point on the diagram represents the distribution of work content along the production line. The regions of the production line with bucket brigade in the work content distribution on Figure 4.6a can be described as follows: in **region 1**, Worker 1 and Worker 2 are always halted for every iteration. In **region 2**, Worker 2 and Worker 3 able to exchange an item, while Worker 1 is always halted in every iteration. In **region 3**, Worker 2 is always halted after receiving an item from Worker 1 for every iteration. In **region 4**, the last worker is always starved, and in **region 5**, no-idling condition, then possible maximum throughput by considering hand-offs and walk-backs can be achieved.

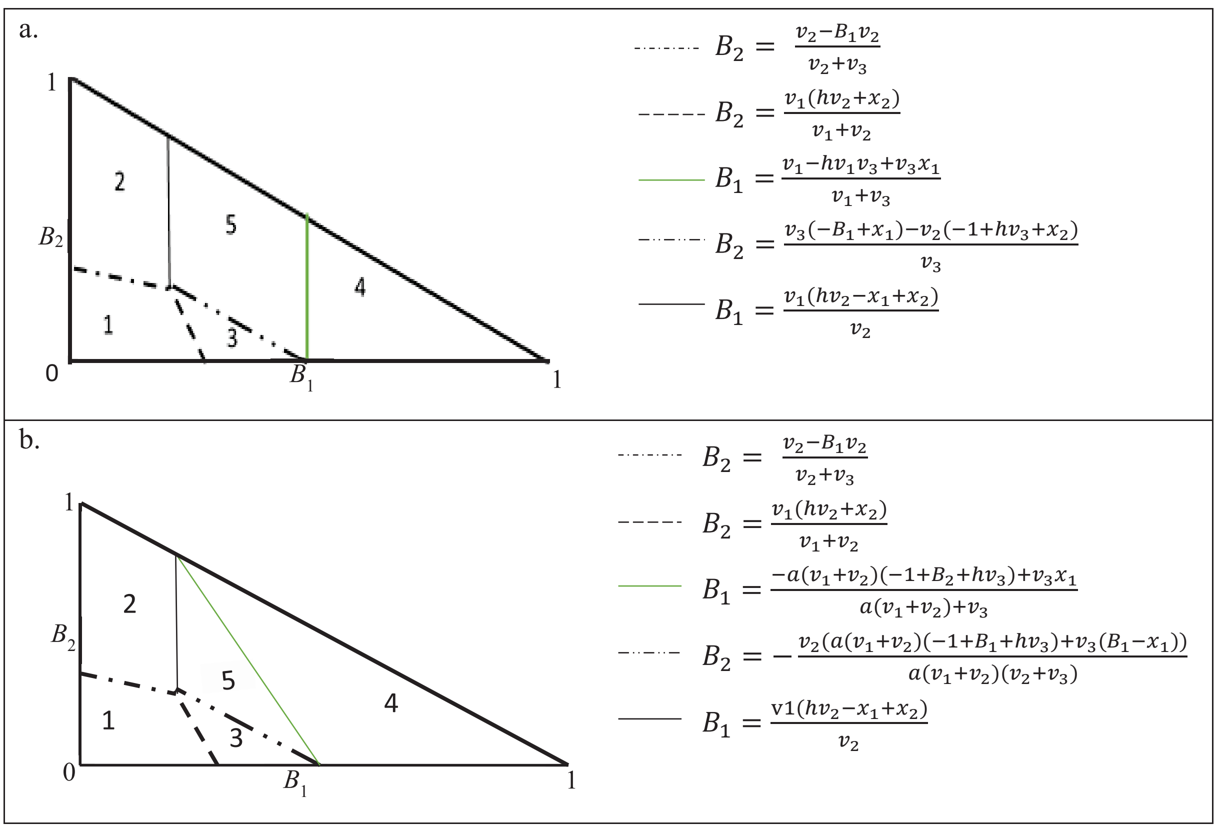


Figure 4.6. Region of three-worker line: a. bucket brigade, b. worker collaboration (type 1 and type 2)

The region of production line with worker collaboration in work content distribution on Figure 4.6b can be described as follows: in **region 1**, Worker 1 and Worker 2 are always halted for every iteration. In

region 2, Worker 1 is always halted when Worker 2 and Worker 3 perform collaborative work in each iteration. In **region 3**, when Worker 1 and Worker 2 have finished collaborative work, Worker 2 will be halted in every cycle, since Worker 3 is still processing an item at his work content. In **region 4**, Worker 3 finishes with his item earlier than collaborative work of Worker 1 and Worker 2. In each iteration, Worker 3 will always be starved. Finally, in **region 5**, no-idling condition, then possible maximum throughput by considering time for preparing collaboration and walk-back time can be obtained.

4.4.2 Performance comparison

For this section, the performance of bucket brigades and both types of worker collaboration is compared when v_1=0.2, v_2=0.3, v_3=0.5, h=0.08, and b=0.02 at variable collaboration coefficient (α = 0.7, 0.9, and 1.0).

Figure 4.7a, Figure 4.7b, Figure 4.7c, Figure 4.7d, Figure 4.7e, and Figure 4.7f show the performance comparison by throughput relative difference of bucket brigade and worker collaboration (type 1 and type 2) at α = 0.7, 0.9, and 1.0, respectively. The horizontal and vertical axis represents the B_1 and B_2, respectively. The red color indicates the regions with increased performance, while the blue color indicates the regions with decreased performance. In those figures, the regions of bucket brigade which have been explained in the previous section are utilized to analyze the impact of worker collaboration on each region.

Figure 4.7a and Figure 4.7b show the performance comparison by throughput relative difference of bucket brigade and worker collaboration type 1 and type 2 at α = 0.7, respectively. Figure 4.7a shows the minimum relative difference is -41.16% in region 4 and maximum relative difference 0 in region 1 and region 3, while Figure 4.7b shows the minimum relative difference is -37.43% in region 4 and the maximum relative difference is 8.56% in region 5. Both figures show that worker collaboration has equal performance toward bucket brigade only in region 1. By comparing the performance of worker collaboration type 1 and type 2 toward bucket brigade, worker collaboration type 2 shows better performance than type 1 in part of region 2, region 3, and region 5 as shown of Figure 4.7b.

Figure 4.7c and Figure 4.7d show the performance comparison by throughput relative difference of bucket brigade and worker collaboration type 1 and type 2 at α = 0.9, respectively. Figure 4.7c shows the minimum relative difference is -30.33% in region 4 and the maximum relative difference is 0 in region 1 and region 3, while Figure 4.7d shows the minimum relative difference is -24.53% in region 4 and the maximum relative difference is 9.79% in region 5. Both figures show that worker collaboration has equal performance toward bucket brigade only in region 1. By comparing the performance of worker collaboration type 1 and type 2 toward bucket brigade, worker collaboration type 2 shows better performance than type 1 in region 3 and in part of region 2 and region 5 as shown of Figure 4.7d.

Figure 4.7e and Figure 4.7f shows the performance comparison by throughput relative difference of bucket brigade and worker collaboration type 1 and type 2 at α = 1.0, respectively. Figure 4.7e shows the minimum relative difference is -24.95% in region 4 and the maximum relative difference is 0.74% in region 2, while Figure 4.7f shows the minimum relative difference is -17.96% in region 4 and the maximum relative difference is 11.73% in region 1. On Figure 4.7e, worker collaboration type 1 has equal performance toward bucket brigades on region 1, region 2, region 3, and in part of region 5, while worker collaboration type 2 shows equal performance toward bucket brigade only on region 1 as shown in Figure 4.7f. By comparing the performance of worker collaboration type 1 and type 2 toward bucket brigade, worker collaboration type 2 shows better performance than type 1 in region 2, region 3, and in part of region 4 and region 5 as shown of Figure 4.7f.

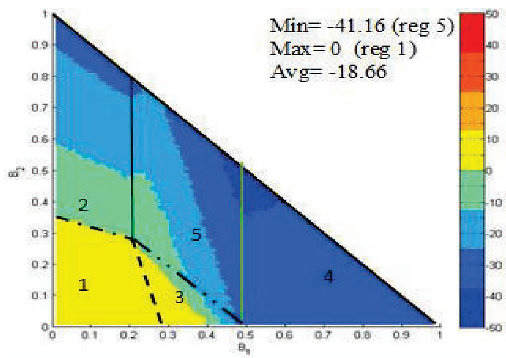
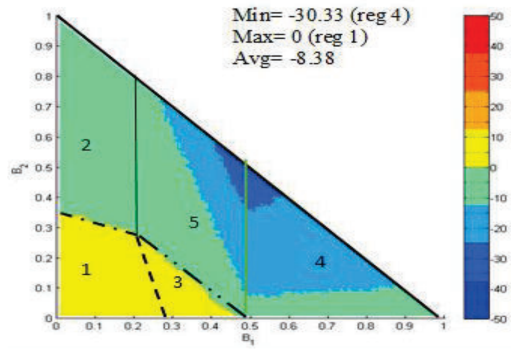
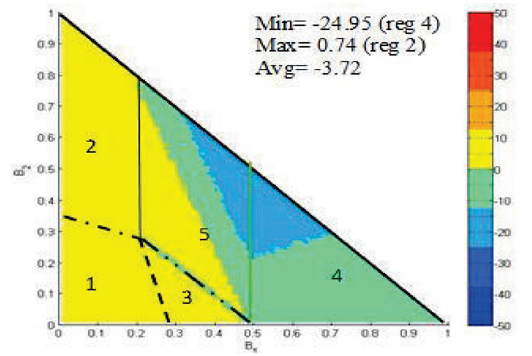
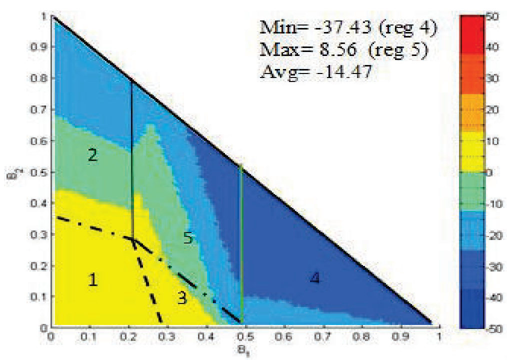
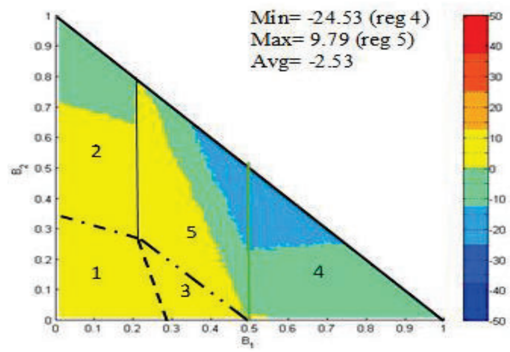
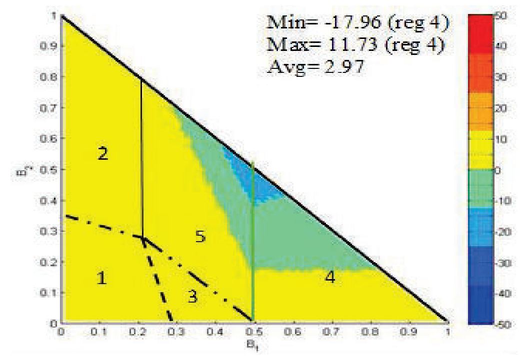
Worker collaboration	Collaboration coefficient (α)		
	0.7	0.9	1.0
Type 1	a. 	c. 	e. 
Type 2	b. 	d. 	f. 

Figure 4.7. Throughput relative difference between bucket brigades and worker collaboration for difference α (v_1=0.2, v_2=0.3, v_3=0.5, h=0.08 and b=0.02)

By assuming additive collaboration ($\alpha = 1.0$), the division of regions according to performance can be illustrated in Figure 4.8. Figure 4.8a and Figure 4.8b show the impact of worker collaboration type 1 and type 2, respectively. Worker collaboration type 1 will obtain equal performance or decrease performance in various work content as shown on Figure 4.8a, while worker collaboration type 2 will obtain increase performance at most of configurations as shown on Figure 4.8b.

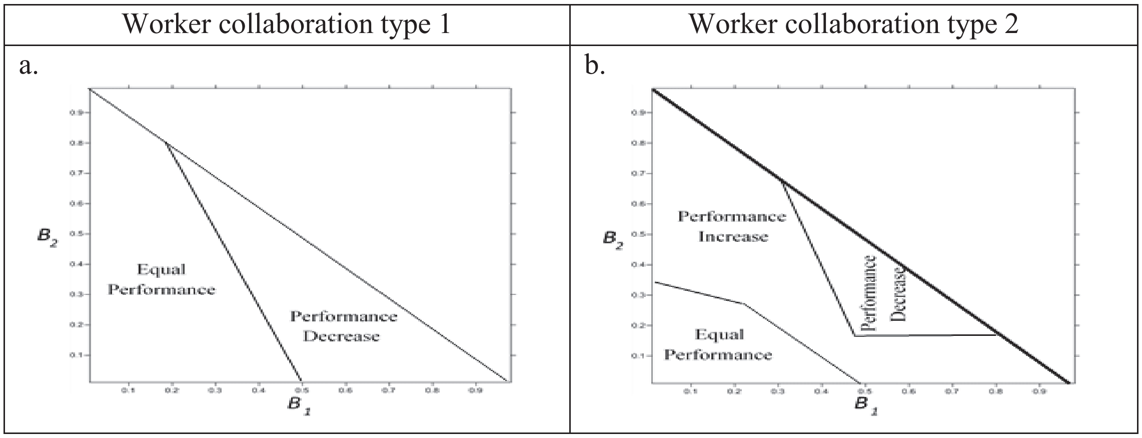


Figure 4.8. Division of worker collaboration region according to performance: a. worker collaboration type 1, b. worker collaboration type 2.

4.4.3 Special movement

Based on the performance comparison result between bucket brigade and worker collaboration (type 1 and type 2) at previous section, the movement modification as mention on the section 4.2.2 will be proposed to increase the performance of worker collaboration.

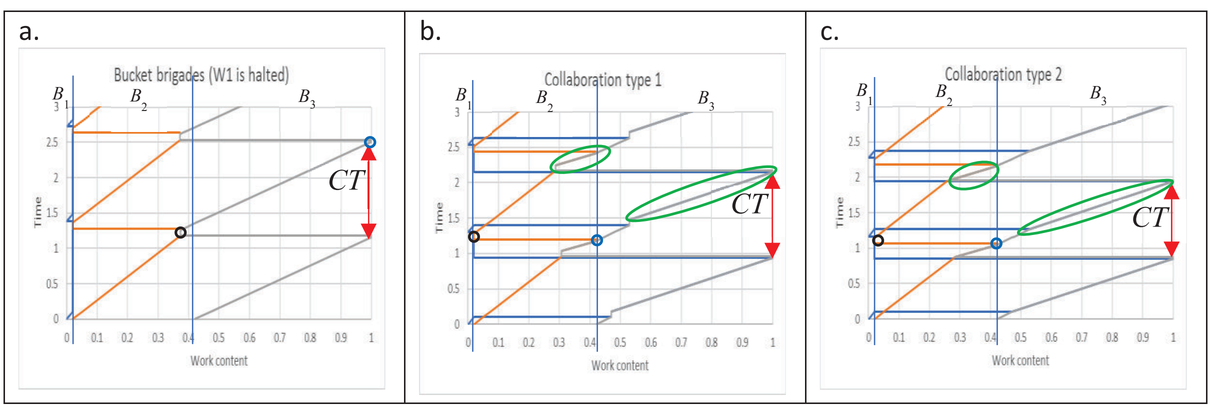


Figure 4.9. Time chart at three-worker production line: a. bucket brigade, b. worker collaboration with special movement type 1, c. worker collaboration with special movement type 2.

Figure 4.9a, Figure 4.9b, and Figure 4.9c show the example of time chart from bucket brigade, worker collaboration with special movement for type 1 and type 2, respectively. The horizontal axis and vertical axis represent the work content and time, respectively. The diagonal line represents the processing workers according to their velocities, while straight line represents walking back and take over motion.

The black circle indicates hand-off time or preparation for collaboration time, while the blue circle indicates the packing up toolbox and walk-back time. The green circle on Figure 4.9b and Figure 4.9c indicate the length of collaboration movement by two workers.

On Figure 4.9a, Worker 1 is always halted in every iteration. When Worker 3 has finished with his item, he packs up his tools and walks back to take over Worker 2. Worker 1 waits after introducing new item until Worker 2 can take over his item. Figure 4.9b and Figure 4.9c show the special movement at worker collaboration type 1 and type2, respectively. When the first worker is halted, and the last worker works individually, then the first worker can support the last worker to finish his work by collaboration. After finishing collaboration, the first worker returns to his station and wait until Worker 2 comes to take over his item, while Worker 3 collaborates with Worker 2 until the end of work content of Worker 2. After fishing collaborative work, Worker 2 takes over the item from the first worker, then the first worker can initiate new item, while the last worker continues to process the item. In the worker collaboration type 1, there is time to prepare the collaborative work, while the time for preparing collaboration is embedded to collaboration coefficient in the worker collaboration type 2. Based on this special movement, the new regions for worker collaboration type 1 and type 2 for 3-worker line can be defined as shown Figure 4.10.

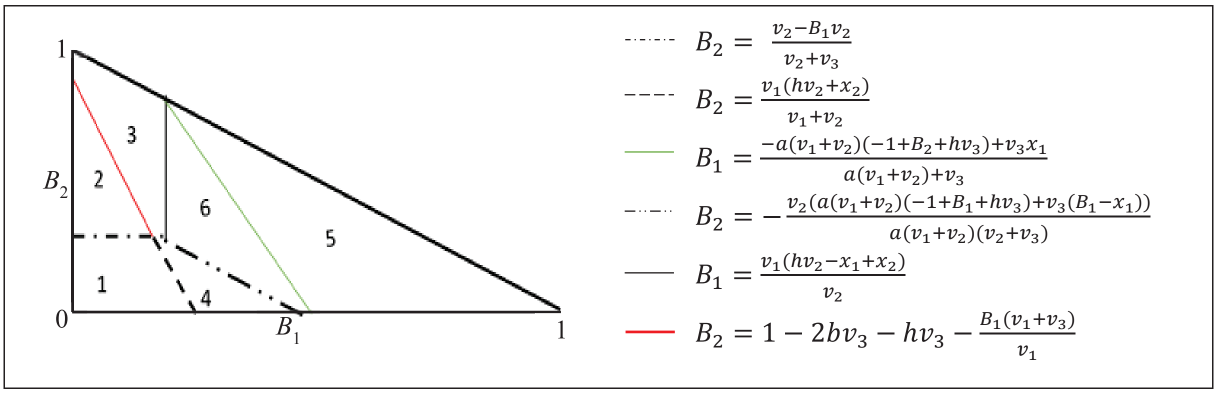


Figure 4.10. Region of worker collaboration with special movement for 3-worker line (type 1 & type 2)

The regions of the production line with worker collaboration in work content distribution on Figure 4.10 can be described as follows: in **region 1**, by using special movement, the first worker can support the last worker collaboratively, but Worker 2 is always halted in every iteration. In **region 2**, by using special movement, the first worker can support the last worker collaboratively. After finishing collaboration, the last worker will collaborate with Worker 2, while Worker 1 will be halted. In **region 3**, Worker 2 and Worker 3 collaborate to finish an item, while Worker 1 is always halted in every iteration. In **region 4**, after finishing collaboration, Worker 2 is always halted in every iteration. In **region 5**, when the last worker finishes with his item, Worker 1 and Worker 2 still collaborate for processing an item, then the last worker is always starved in every iteration. In **region 6**, no idling condition by using collaboration, then possible maximum throughput by considering hand-offs and walk-backs can be obtained. Based on Figure 4.10, the new conditions of worker collaboration type 1 and type 2 for 3-worker line that caused by special movement can be defined on Table 4.2.

Figure 4.11a, Figure 4.11b, Figure 4.11c, Figure 4.11d, Figure 4.11e, and Figure 4.11f show the performance comparison by throughput relative difference of bucket brigade and worker collaboration (type 1 and type 2) with special movement at α = 0.7, 0.9, and 1.0, respectively. The horizontal and vertical axis represents the B_1 and B_2, respectively. The red color indicates the regions with increased performance, while the blue color indicates the regions with decreased performance. In those figures, the regions of bucket brigade which have been explained in the previous section is utilized to analyze the impact of worker collaboration on each region.

Figure 4.11a and Figure 4.11b show the performance comparison by throughput relative difference of bucket brigade and worker collaboration type 1 and type 2 at α = 0.7, respectively. Figure 4.11a shows the minimum relative difference is -41.16% in region 4 and maximum relative difference 0 in region 3, while Figure 4.11b shows the minimum relative difference is -37.43% in region 4 and the maximum relative difference is 11.33% in region 2. Both figures show that worker collaboration has equal performance toward bucket brigade only in region 3. By comparing the performance of worker collaboration type 1 and type 2 toward bucket brigade, worker collaboration type 2 shows better performance than type 1 in part of region 2 and region 5 as shown of Figure 4.11b.

Figure 4.11c and Figure 4.11d show the performance comparison by throughput relative difference of bucket brigade and worker collaboration type 1 and type 2 at α = 0.9, respectively. Figure 4.11c shows the minimum relative difference is -30.33% in region 4 and the maximum relative difference is 16.34% in region 1, while Figure 4.11d shows the minimum relative difference is -24.53% in region 4 and the maximum relative difference is 27.35% in region 1. Both figures show that worker collaboration has equal performance toward bucket brigade only in region 3. By comparing both figures, worker collaboration type 1 shows better performance toward bucket brigade on part of region 1 and region 2 as shown in Figure 4.11c, while worker collaboration type 2 shows better performance toward bucket brigade on region 1 and part of region 2 and region 5 as shown in Figure 4.11d.

Figure 4.11e and Figure 4.11f shows the performance comparison by throughput relative difference of bucket brigade and worker collaboration type 1 and type 2 at α = 1.0, respectively. Figure 4.11e shows the minimum relative difference is -24.95% in region 4 and the maximum relative difference is 26.49% in region 1, while the minimum relative difference is -17.96% in region 4 and the maximum relative difference is 38.13% in region 1. On Figure 4.11e, worker collaboration type 1 has equal performance toward bucket brigades on region 3 and in part of region 2 and region 5, while worker collaboration type 2 shows equal performance toward bucket brigade only on region 3 as shown in Figure 4.11f. Moreover, worker collaboration type 1 shows better performance toward bucket brigades in part of region 1 and region 2 as shown in Figure 4.11e, while worker collaboration type 2 has better performance toward bucket brigades on region 1, region 2, and in part of region 4 and region 5 as shown in Figure 4.11f.

Table 4.2. Conditions of worker collaboration with special movement (type 1 and type 2)

Region	Worker collaboration type 1		Worker collaboration type 2	
	Condition	Cycle time	Condition	Cycle time
1	$\frac{B_1}{v_1}+b \le \frac{B_2}{v_2}+2b+h+\frac{\left(1-(B_1+B_2)+\left(\frac{B_2}{v_2}+b+h\right)v_3\right)}{v_3}$ $\frac{B_1}{v_1}+2b+h \le \frac{(1-(B_1+B_2))}{v_3}$ $\frac{B_2}{v_2}+b+h < \frac{(x_3^{**}-(B_1+B_2))}{v_3}+h+\frac{(1-x_3^{**})}{\alpha(v_1+v_3)}+b$	$CT=\frac{(x_3^{**}-(B_1+B_2))}{v_3}+b+h+\frac{(1-x_3^{**})}{\alpha(v_1+v_3)}$	$\frac{B_1}{v_1}+b \le \frac{B_2}{v_2}+2b+h+\frac{\left(1-(B_1+B_2)+\left(\frac{B_2}{v_2}+b+h\right)v_3\right)}{v_3}$ $\frac{B_2}{v_2}+b+h \le \frac{(1-(B_1+B_2))}{v_3}+b$	$CT=\frac{(x_3^{**}-(B_1+B_2))}{v_3}+b+h+\frac{(1-x_3^{**})}{\alpha(v_1+v_3)}$
2	$\frac{B_1}{v_1}+b \le \frac{(x_2^{**}-B_1)}{v_2}+h+\frac{((B_1+B_2)-x_2^{**})}{\alpha(v_2+v_3)}+b$ $\frac{B_1}{v_1}+2b+h \le \frac{(1-(B_1+B_2))}{v_3}$ $\frac{B_2}{v_2}+b+h > \frac{(x_3^{**}-(B_1+B_2))}{v_3}+h+\frac{(1-x_3^{**})}{\alpha(v_1+v_3)}+b$	$CT=\frac{((B_1+B_2)-x_2^{**})}{\alpha(v_2+v_3)}+b+2h+\frac{(x_3^{**}-(B_1+B_2))}{v_3}+\frac{(1-x_3^{**})}{\alpha(v_1+v_3)}$	$\frac{B_1}{v_1}+b \le \frac{(x_2^{**}-B_1)}{v_2}+\frac{((B_1+B_2)-x_2^{**})}{\alpha(v_2+v_3)}+b$ $\frac{B_1}{v_1}+2b+h \le \frac{(1-(B_1+B_2))}{v_3}$ $\frac{B_2}{v_2}+b+h > \frac{(x_3^{**}-(B_1+B_2))}{v_3}+\frac{(1-x_3^{**})}{\alpha(v_1+v_3)}+b$	$CT=\frac{((B_1+B_2)-x_2^{**})}{\alpha(v_2+v_3)}+b+\frac{(x_3^{**}-(B_1+B_2))}{v_3}+\frac{(1-x_3^{**})}{\alpha(v_1+v_3)}$
3	$\frac{B_1}{v_1}+b \le \frac{(x_2^{**}-B_1)}{v_2}+h+\frac{((B_1+B_2)-x_2^{**})}{\alpha(v_2+v_3)}+b$ $\frac{B_1}{v_1}+2b+h > \frac{(1-(B_1+B_2))}{v_3}$ $\frac{B_2}{v_2}+b+h > \frac{(1-(B_1+B_2))}{v_3}+b$	$CT=b+h+\frac{((B_1+B_2)-x_2^{**})}{\alpha(v_2+v_3)}+\frac{(1-(B_1+B_2))}{v_3}$	$\frac{B_1}{v_1}+b \le \frac{(x_2^{**}-B_1)}{v_2}+\frac{((B_1+B_2)-x_2^{**})}{\alpha(v_2+v_3)}+b$ $\frac{B_2}{v_2}+b+h > \frac{(1-(B_1+B_2))}{v_3}+b$	$CT=b+\frac{((B_1+B_2)-x_2^{**})}{\alpha(v_2+v_3)}+\frac{(1-(B_1+B_2))}{v_3}$
4	$\frac{B_1}{v_1}+b > \frac{B_2}{v_2}+b+h$ $b+h+\frac{(B_1-x_1^{**})}{\alpha(v_1+v_2)}+\frac{B_2}{v_2} \le \frac{(1-(B_1+B_2))}{v_3}+b$	$CT=\frac{(1-(B_1+B_2))}{v_3}+b+h$	$\frac{B_1}{v_1}+b > \frac{B_2}{v_2}+b+h$ $b+\frac{(B_1-x_1^{**})}{\alpha(v_1+v_2)}+\frac{B_2}{v_2} \le \frac{(1-(B_1+B_2))}{v_3}+b$	$CT=\frac{(1-(B_1+B_2))}{v_3}+b+h$
5	$\frac{B_1}{v_1}+b > \frac{B_2}{\alpha(v_1+v_2)}+b+h$ $b+h+\frac{(B_1-x_1^{**})}{\alpha(v_1+v_2)} > \frac{(1-(B_1+B_2))}{v_3}+b$	$CT=b+h+\frac{x_1^{**}}{v_1}+\frac{(B_1-x_1^{**})}{\alpha(v_1+v_2)}$	$\frac{B_1}{v_1}+b > \frac{B_2}{\alpha(v_2+v_3)}+b$ $b+\frac{(B_1-x_1^{**})}{\alpha(v_1+v_2)} > \frac{(1-(B_1+B_2))}{v_3}+b$	$CT=b+\frac{x_1^{**}}{v_1}+\frac{(B_1-x_1^{**})}{\alpha(v_1+v_2)}$
6	$\frac{B_1}{v_1}+b > \frac{(x_2^{**}-B_1)}{v_2}+h+\frac{((B_1+B_2)-x_2^{**})}{\alpha(v_2+v_3)}+b$ $b+h+\frac{(B_1-x_1^{**})}{\alpha(v_1+v_2)}+\frac{B_2}{v_2} > \frac{(1-(B_1+B_2))}{v_3}+b$	$CT=b+h+\frac{((B_1+B_2)-x_2^{**})}{\alpha(v_2+v_3)}+\frac{(1-(B_1+B_2))}{v_3}$	$\frac{B_1}{v_1}+b > \frac{(x_2^{**}-B_1)}{v_2}+\frac{((B_1+B_2)-x_2^{**})}{\alpha(v_2+v_3)}+b$ $b+\frac{(B_1-x_1^{**})}{\alpha(v_1+v_2)}+\frac{B_2}{v_2} > \frac{(1-(B_1+B_2))}{v_3}+b$	$CT=b+\frac{((B_1+B_2)-x_2^{**})}{\alpha(v_2+v_3)}+\frac{(1-(B_1+B_2))}{v_3}$

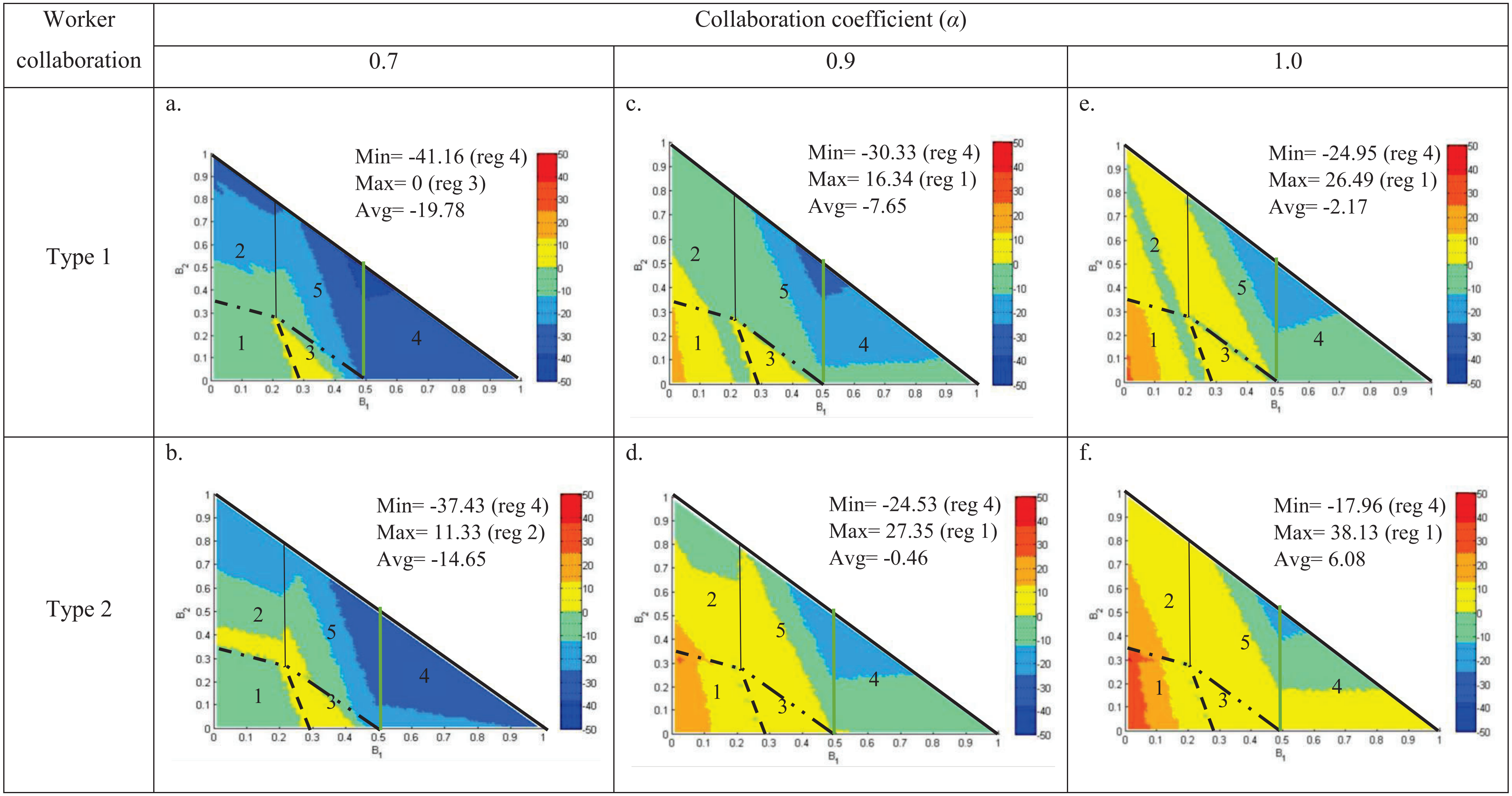


Figure 4.11. Throughput relative difference between bucket brigades and worker collaboration with special movement for difference α (v_1=0.2, v_2=0.3, v_3=0.5, h=0.08 and b=0.02)

By assuming additive collaboration ($\alpha = 1.0$), the division of regions according to performance of worker collaboration with special movement can be illustrated in Figure 4.12. Figure 4.12a shows that there is increase performance by utilizing special movement on worker collaboration type 1, and Figure 4.12b shows that by using special movement on worker collaboration type 2, area with increase performance can be expanded. Although the special movement has been introduced to counter the halting condition, there is decreasing performance in region 1 and region 2 by utilizing worker collaboration type 1. This condition happens when the length for collaboration by Worker 1 and Worker 3 is too short compared to individual work by Worker 2 or collaborative work between Worker 2 and Worker 3, then Worker 1 is still idle for a longer period.

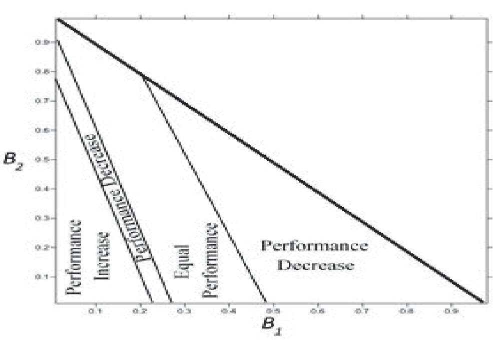
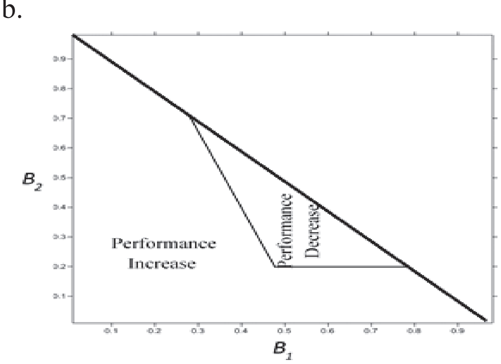
	Worker collaboration type 1	Worker collaboration type 2
With special movement	a. 	b. 

Figure 4.12. Division of worker collaboration region according to performance: a. worker collaboration with special movement type 1, b. worker collaboration with special movement type 2

4.5. Summary

In this chapter, the mathematical model for bucket brigades and both types of worker collaboration have been defined. Based on the mixed integer programming, the objective function of each mathematical model is minimizing the maximum cycle time given by n-worker. The constraints are according to equilibrium condition from each pair of workers by assuming the presence of idling time. In addition, non-linear programing is introduced where Worker i can idle only when fixed point or collaboration point at the minimum work content. Based on these mathematical models for 3-worker production line, worker collaboration type 1 gives equal or worse performance than bucket brigade. Meanwhile, worker collaboration type 2 can improve performance of bucket brigade in several configurations and equal or worse performance at other configurations.

This chapter has shown the other possibility to overcome the impact of halting in bucket brigades by using worker collaboration. Based on the analysis of 3-worker production line, by introducing special movement, worker collaboration can suppress the halting condition and improve the performance of bucket brigade. Moreover, by integration the time for preparing collaboration into collaboration coefficient, the performance of worker collaboration significantly increases and able to counter the halting condition.

On partially cross-trained workers condition, worker collaboration can transform no-idling condition into starvation condition, then throughput can decrease. In addition, introducing special movement can decrease the performance when the length for collaboration by Worker 1 and Worker 3 is too short compared to individual work by Worker 2 or collaborative work between Worker 2 and Worker 3. Then worker 1 will be idle for some time after finishing collaboration. The performance of special movement can become worse is expected when more workers in the line. The occurrence of halting condition will increase, then special movement of worker collaboration will not be significant for increasing the performance of bucket brigade.

There is an unfair situation at worker collaboration type 2 in which collaboration time can be smaller than actual time for preparing collaboration. Future work can be carried out to determine the relationship between the time for preparing collaboration and collaboration coefficient. In addition, this chapter only considers a production line with 3-worker. By expanding the study to a larger production line, then by evaluating the behavior and developing a general procedure to determine the performance of bucket brigades and worker collaboration at larger production line will be an interesting topic.

Chapter 5 Conclusions

The main purpose of the research work was to study the integration of worker collaboration for bucket brigade production line with discrete workstations. The approach taken was by defining the behavior of worker collaboration on various worker velocity, work content, and collaboration coefficient, then analyze the performance of bucket brigade with and without worker collaboration through numerical calculation.

In chapter two, worker collaboration can boost productivity when integrated by bucket brigade production line at serial line with discrete workstations. Bucket brigade with worker collaboration almost always outperform than without worker collaboration, especially as an approach to counter the blocking condition. Worker collaboration can obtain maximum throughput only at collaboration coefficient is additive and no-idling at production line. Worker collaboration at serial line with discrete workstations can obtain its fully capacity when each pair of workers has cyclic behavior and equilibrium condition can be achieved. Each pair of workers always start the collaborative work at the same meeting point in every iteration.

In chapter three, worker collaboration uses to counter the drawback of cellular bucket brigade (CBB) where halting and/or blocking conditions occur at U-shaped production line with discrete workstations. The numerical analysis shows that worker collaboration can effectively improve the performance of CBB where blocking and/or halting occurs. Since the maximum capacity on U-shaped line can be obtained under balanced condition of CBB, then worker collaboration can be neglected.

In chapter four, worker collaboration can improve the performance of bucket brigades by introducing special movement where first worker has ability to support the work of the last worker collaboratively. In addition, by assuming hand-off times as embedded part of collaboration coefficient, worker collaboration can increase the performance of bucket brigades in several work content configurations.

Collaboration coefficient (α) is strongly related to the obtained higher performance by utilizing worker collaboration. Based on the numerical calculation on serial line and U-shaped line with discrete workstation, the area with increase performance can be expanded by significantly increase the collaboration coefficient.

Workers can easily adopt and follow the rules of worker collaboration, therefore it can be implemented in practical condition. In addition, the characteristics of a self-balancing line can still be preserved, and a performance improvement can be obtained. Worker collaboration has a limitation that related to the conditions of cross-trained workers. Worker collaboration can give better performance than bucket brigades system with changeable size, then workers need to have flexibility to work at any positions and task allocation is adjustable. It is difficult and costly to train workers to be flexible and task allocation will not easy to be adjusted. In practice, the additive rate of collaboration coefficient is rare. If a single task is processed by multiple workers at the same time, the collaborative processing time may be slower or faster than the total processing time of individual worker.

Conducting a case study of worker collaboration would be an interesting topic for future study. A case study on order picking process at serial line and U-shaped line by assuming shelf as discrete workstation where workers are flexible to work at any shelf, task allocation of each worker can be adjusted, and any shelf can accommodate two workers to work collaboratively to fulfill the order lists. In addition, a stochastic model to analyze the performance of bucket brigade with worker collaboration can be an alternative topic for future study. The worker collaboration condition at fully and partially cross-trained workers with general demand and service process to obtain the minimum cycle time. The collaboration coefficient (α) is assumed to be disproportionally constant to the size of team and station. By allowing α depends only on the team size, then the optimal team size might be obtained, or by allowing α depends only on the size of the station, then the collaboration might not be equally beneficial for all tasks.

References

Aase, G. R., Olson, J. R., and Schniederjans, M. J. (2004). U-shaped assembly line layouts and their impact on labor productivity: An experimental study. *European Journal of Operational Research*, **156**(3), 698-711.

Ajenblit, D. A., and Wainwright, R. L. (1998). Applying genetic algorithms to the U-shaped assembly line balancing problem. In *Evolutionary Computation Proceedings, 1998. IEEE World Congress on Computational Intelligence.* pp.96-101.

Andradóttir, S., Ayhan, H., and Down, D. G. (2001). Server assignment policies for maximizing the steady-state throughput of finite queueing systems, *Management Science*, **47**(10), 1421–1439.

Andradóttir, S. and Ayhan, H. (2005). Throughput maximization for tandem lines with two stations and flexible servers, *Operations Research*, **53**(3), 516–531.

Andradóttir, S., Ayhan, H., and Down, D. G. (2011). Queueing systems with synergistic servers, *Operations Research*, **59**(3), 772–780.

Armbruster, D., and Gel, E. S. (2006). Bucket brigades revisited: Are they always effective? *European Journal of Operational Research*, **172**(1), 213–229.

Askin, R. G. and Chen, J. (2006). Dynamic task assignment for throughput maximization with worksharing, *European Journal of Operational Research*, **168**(3), 853–869.

Baudin, M. (2002). Lean assembly: the nuts and bolts of making assembly operations flow. *CRC Press.*

Bartholdi III, J. J. and Eisenstein, D. D. (1996a). A production line that balances itself, *Operations Research*, **44**(1), 21–34.

Bartholdi III, J. J. and Eisenstein, D. D. (1996b). Bucket brigades: A self-organizing order picking system for a warehouse, *Working paper*, School of Industrial and Systems Engineering, Georgia Institute of Technology.

Bartholdi III, J. J., Bunimovich, L. A., and Eisenstein, D. D. (1999). Dynamics of two-and three-worker "bucket brigade" production lines, *Operations Research*, **47**(3), 488–491.

Bartholdi III, J. J., Eisenstein, D. D., and Foley, R. D. (2001). Performance of bucket brigades when work is stochastic, *Operations Research*, **49**(5), 710–719.

Bartholdi III, J. J. and Eisenstein, D. D. (2005). Using bucket brigades to migrate from craft manufacturing to assembly lines, *Manufacturing and Service Operations Management*, **7**(2), 121–129.

Bartholdi, J. J., Eisenstein, D. D., and Lim, Y. F. (2006). Bucket brigades on in-tree assembly networks, *European Journal of Operational Research*, **168**(3), 870–879.

Baskak, M. (2008) Assembly line balancing in a clothing company. *Fibres and Textiles in Eastern Europe*, **16**(1), 66.

Baybars, I. (1986). A survey of exact algorithms for the simple assembly line balancing problem. *Management Science*, **32**(8), 909-932.

Becker, C. and Scholl, A. (2006). A survey on problems and methods in generalized assembly line balancing, *European Journal of Operational Research*, **168**(3), 694–715.

Bratcu, A. I. and Dolgui, A. (2005). A survey of the self-balancing production lines ("bucket brigades"), *Journal of Intelligent Manufacturing*, **16**(2), 139–158.

Boysen, N., Fliedner, M., & Scholl, A. (2007). A classification of assembly line balancing problems. *European Journal of Operational Research*, **183**(2), 674-693.

Boysen, N., Fliedner, M., and Scholl, A. (2008). Assembly line balancing: Which model to use when?. *International Journal of Production Economics*, **111**(2), 509-528.

Bukchin, J., Dar-El, E. M., & Rubinovitz, J. (2002). Mixed model assembly line design in a make-to-order environment. *Computers and Industrial Engineering*, **41**(4), 405-421.

Buzacott, J. A. (1996) Commonalities in reengineered business processes: models and issues, *Management Science*, **42**(5), 768–782.

Ellegärd, K., Jonsson, D., Engström, T., Johansson, M. I., Medbo, L., and Johansson, B. (1992). Reflective production in the final assembly of motor vehicles–an emerging Swedish challenge, *International Journal of Operations and Production Management*, **12**(7/8), 117–133.

Engström, T. and Medbo, L. (1994). Intra-group work patterns in final assembly of motor vehicles, *International Journal of Operations and Production Management*, **14**(3), 101–113.

Erel, E., Sabuncuoglu, I., & Aksu, B. A. (2001). Balancing of U-type assembly systems using simulated annealing. *International Journal of Production Research*, **39**(13), 3003-3015.

Falkenauer, E. (2005). Line balancing in the real world. In *Proceedings of the international conference on product lifecycle management PLM,* **5**, 360-370.

Gershwin, S. B., and Schor, J. E. (2000). Efficient algorithms for buffer space allocation, *Annals of Operations Research*, **93**(1), 117–144.

Ghosh, S., and Gagnon, R. J. (1989). A comprehensive literature review and analysis of the design, balancing and scheduling of assembly systems. *International Journal of Production Research*, **27**(4), 637-670.

Goldratt, E. M., and Cox, J. (1986). The goal: A process of ongoing improvement (rev. ed.). North River Press, Croton on Hudson, NY.

Hirotani, D., Morikawa, K., and Takahashi, K. (2006). Analysis and design of self-balancing production line *Computers and Industrial Engineering*, **50**(4), 488–502.

Hopp, W. J. and Van Oyen, M. P. (2004). Agile workforce evaluation: a framework for cross-training and coordination, *IIE Transactions*, **36**(10), 919–940.

Hopp, W. J., Tekin, E., and Van Oyen, M. P. (2004). Benefits of skill chaining in serial production lines with cross-trained workers. *Management Science*, **50**(1), 83-98.

Kucukkoc, I., and Zhang, D. Z. (2017). Balancing of mixed-model parallel U-shaped assembly lines considering model sequences. *International Journal of Production Research*, **55**(20), 5958-5975

Kriengkorakot, N., and Pianthong, N. (2007). The assembly line balancing problem: review articles. *Engineering and Applied Science Research*, **34**(2), 133-140.

Lapierre, S. D., Ruiz, A., & Soriano, P. (2006). Balancing assembly lines with tabu search. *European Journal of Operational Research*, **168**(3), 826-837.

Lim, Y. F. (2011). Cellular bucket brigades, *Operations Research*, **59**(6), 1539–1545.

Lim, Y. F. (2012). Order-picking by cellular bucket brigades: a case study. In R. Manzini (ed), *Warehousing in The Global Supply Chain* (London: Springer), chapter 4, 71–85.

Lim, Y. F. and Yang, K. K. (2009). Maximizing throughput of bucket brigades on discrete work stations, *Production and Operations Management*, **18**(1), 48–59.

Lim, Y. F. and Wu, Y. (2014). Cellular bucket brigades on U-lines with discrete work stations, *Production and Operations Management*, **23**(7), 1113–1128.

Mandelbaum, A., and Reiman, M. I. (1998). On pooling in queueing networks. *Management Science*, **44**(7), 971-981.

McClain, J. O., Thomas, L. J., and Sox, C. (1992). "On-the-fly" line balancing with very little WIP, *International Journal of Production Economics*, **27**(3), 283–289.

McClain, J. O., Schultz, K. L., and Thomas, L. J. (2000). Management of worksharing systems, *Manufacturing and Service Operations Management*, **2**(1), 49–67.

McGraw, D. (1996). Staying loose in a tense tech market, *US News and World Report*, 46.

Miltenburg, G. J., and Wijngaard, J. (1994). The U-line line balancing problem. *Management Science*, **40**(10), 1378-1388.

Miltenburg, J. (1998). Balancing U-lines in a multiple U-line facility. *European Journal of Operational Research*, **109**(1), 1-23.

Miltenburg, J. (2001). U-shaped production lines: A review of theory and practice. *International Journal of Production Economics*, **70**(3), 201-214.

Miltenburg, J. and Sparling, D., (1995). Optimal solution algorithms for the U-line balancing problem. *Working Paper*, McMaster University, Hamilton

Peltokorpi, J., Tokola, H., and Niemi, E. (2015). Worker coordination policies in parallel station systems: performance models for a set of jobs and for continuous arrival of jobs, *International Journal of Production Research*, **53**(6), 1625–1641.

Salas, E., Dickinson, T. L., Converse, S. A., and Tannenbaum, S. I. (1992). *Toward an understanding of team performance and training*. Ablex Publishing.

Sengupta, K. and Jacobs, F. R. (2004). Impact of work teams: a comparison study of assembly cells and assembly line for a variety of operating environments, *International Journal of Production Research*, **42**(19), 4173–4193.

Sennott, L. I., Van Oyen, M. P., and Iravani, S. M. (2006). Optimal dynamic assignment of a flexible worker on an open production line with specialists, *European Journal of Operational Research*, **170**(2), 541–566.

Sivasankaran, P., & Shahabudeen, P. (2014). Literature review of assembly line balancing problems. *The International Journal of Advanced Manufacturing Technology*, **73**(9-12), 1665-1694.

Scholl, A., & Klein, R. (1999). ULINO: Optimally balancing U-shaped JIT assembly lines. *International Journal of Production Research*, **37**(4), 721-736.

Sparling, D., & Miltenburg, J. (1998). The mixed-model U-line balancing problem. *International Journal of Production Research*, **36**(2), 485-501.

Sparling, D. (1998). Balancing just-in-time production units: the N U-line balancing problem. *INFOR: Information Systems and Operational Research*, **36**(4), 215-237.

Van Oyen, M. P., Gel, E. G., and Hopp, W. J. (2001). Performance opportunity for workforce agility in collaborative and noncollaborative work systems, *IIE Transactions*, **33**(9), 761–777.

Villalobos, J. R., Munoz, L. F., and Mar, L. (1999). Assembly line designs that reduce the impact of personnel turnover. In *Proceedings of IIE Solutions Conference, Phoenix, AZ*.

Villalobos, J. R., Estrada, F., Munoz, L. F., and Mar, L. (1999). Bucket brigade: A new way to boost production. *Twin Plant News*, **14**(12), 57-61.

Wang, X., Andradóttir, S., and Ayhan, H. (2015). Dynamic server assignment with task-dependent server synergy. *IEEE Transactions on Automatic Control*, **60**(2), 570-575.

List of Publications

A. Published international journal papers

1. **<u>Pratama, A. T.</u>**, Takahashi, K., Morikawa, K., Nagasawa, K., and Hirotani, D., "Integration of bucket brigades and worker collaboration on a production line with discrete workstations", *Industrial Engineering and Management Systems*, Vol.17(3), pp.514-530, 2018.

2. **<u>Pratama, A. T.</u>**, Takahashi, K., Morikawa, K., Nagasawa, K., and Hirotani, D., "Cellular bucket brigades with worker collaboration on U-lines with discrete workstations", *Industrial Engineering and Management Systems,* Vol,.17(3), pp.531-549, 2018**.**

B. Published international conference papers

1. **<u>Pratama, A. T.</u>**, Takahashi, K., Morikawa, K., Nagasawa, K., and Hirotani, D., "Integration of bucket brigades and worker collaboration on discrete work stations", in *Proceedings of the 17th Asia Pacific Industrial Engineering and Management Systems Conference (APIEMS 2016)*, December 7-December 10, 2016, Taipei, Taiwan.

2. **<u>Pratama, A. T.</u>**, Takahashi, K., Morikawa, K., Nagasawa, K., and Hirotani, D., "Cellular bucket brigades with worker collaboration on U-lines with discrete workstations", in *Proceedings of the 18th Asia Pacific Industrial Engineering and Management System Conference (APIEMS 2017)*, December 3-December 6, 2017, Yogyakarta, Indonesia.

3. **<u>Pratama, A. T.</u>**, Takahashi, K., Morikawa, K., Nagasawa, K., and Hirotani, D., "Migrate from craft manufacturing to assembly lines by integrating bucket brigades and worker collaboration", in *Proceedings of the 14th International Conference on Industrial Management (ICIM 2018)*, September 12-September 14, 2018, Hangzhou, China.