T.C.
BAHÇEŞEHİR UNIVERSITY

ORDER RELEASE PLANNING UNDER UNCERTAINTY

M.S. Thesis

Emre TÜRKBEN

Istanbul, 2011

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Bahçeşehir Unıversıty
Institute Of Science
Industrial Engineering

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Acting Director

This is to certify that we have read this thesis and that we find it fully adequate in scope, quality and content, as a thesis for the degree of Master of Science

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Emre TÜRKBEN

ABSTRACT

ORDER RELEASE PLANNING UNDER UNCERTAINTY

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There are a lot of different production control principles and concepts in manufacturing environment. The main idea of all these concepts is minimize the total cost of production systems and planning them easy. As a handicap of these concepts, these concepts are not close to real-life cases because there exist alot of surprising conditions in real-life manufacturing environments.

The uncertainties and variations in production systems are the main reasons which make production controlling and planning hard. Uncertainty represents the usual and random changes in production lines, but variations represent unusual and rapid changes in the production system. In manufacturing environments, these two factors have the most important roles in increasing total costs of production systems. In literature, there exist the idea of changing the main production control parameters adaptively according to unstable changes of production and demand conditions. In this master thesis, a comparision of a traditional Kanban system with a flexible kanban system which can adapt to unstable changes have maken. The flexible kanban system has modeled by adaptively changing the number of kanban cards in production centre according to inventory levels. Manufacturing process has designed as a multistage CONWIP system and performance analysis of this adaptive kanban controlled production system have been made according to the different characteristics of this system via simulation.

Keywords: Kanban, CONWIP, Adaptive kanban controlled production systems, JIT, Pull production systems

ÖZET

BELİRSİZLİK ALTINDA ÜRETİM PLANLAMA

TÜRKBEN, Emre

Endüstri Mühendisliği

Danışman: Yrd. Doç. Barış SELÇUK

(Haziran, 2011) XVI + 116

Üretim çevrelerinde kullanılmakta olan birçok üretim kontrol uygulaması mevcuttur. Bütün bu uygulamaların temel hedefi üretimin planlanmasını kolaylaştırmak ve toplam maliyetleri minimize etmektir. Ancak gerçek hayatta birçok sürpriz koşul bulunması nedeniyle, kullanılmakta olan üretim politikaları gerçek üretim koşullarına yakın değildir bu da mevcut üretim planlama tekniklerinin bir handikapı olarak değerlendirilebilir.

Üretim sistemlerindeki belirsizlikler ve değişkenlikler üretimin planlanması ve kontrolunü zorlaştıran temel etkenlerdir. Belirsizlik; üretim hattındaki ve talepteki olağan ve rassal değişimleri, değişkenlik ise bu sistemdeki olağan olmayan ve ani değişiklikleri temsil eder. Günümüz karmaşık iş yapış şekillerinde her iki faktör de maliyetlerin artmasında önemli rol oynamaktadır. Değişen üretim ve talep koşullarına göre temel üretim kontrol parametrelerinin adaptif bir şekilde değiştirilmesi fikri literatürde mecvuttur. Bu çalışmada belirsizliklere ve stabil olmayan değişikliklere karşı esnek davranış gösterebilen bir Kanban sisteminin, geleneksel Kanban sistemine göre ne gibi farkları olduğu araştırılmıştır. Esnek kanban sistemi üretim merkezindeki kanban sayısı stok seviyesine bağlı adaptif bir şekilde değiştirilerek modellenmiştir. Üretim merkezi çok seviyeli bir CONWIP sistemi olarak düşünülmüştür ve adaptif kanban kontrol modelinin bu sistemin farklı özelliklerine göre performans değerlendirmesi, bilgisayarda benzetim yazılımı kullanılarak gerçekleştirilmiştir.

Anahtar Kelimeler: Kanban, CONWIP, Adaptif Kanban Kontrol Sistemleri, Tam Zamanlı Üretim, Çekme Üretim Sistemleri

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LIST OF SYMBOLS

Production Rates at each stage : λ_{P1}, λ_{P2}, $\lambda_{P3,}$ λ_{P4}
Demand arrival rate : λ_D
Production rate of bottleneck workstation : r_b
Random variate : U
Quantile function : F^{-1}
Number of kanban cards : K
Starting value of kanban cards : K^*
Number of extra kanban cards : E
Release threshold value : R
Capture threshold value : C
Number of kanbans in process at time t : N(t)
Number of extra kanbans in process at time t : X(t)
Demand arrival time for i^{th} demand : D_i
Production process time at j^{th} station for k^{th} order : P_{jk}
Inventory Levels : I
Penalty cost of average backordered demands : p
Average cost of work-in-process levels : WIPC
Average cost of inventory levels : IC
Total cost of system : TC
Total time of simulation : T
Utilization Rate : u
Filled i^{th} workstation : FilledWSi
Work In Process levels at each station : WIP1, WIP2, WIP3, WIP4
Number of backorders : BO

LIST OF ABBREVIATIONS

Just-In-Time : JIT

Constan work in process : CONWIP

Workstations : WS1, WS2, WS3, WS4

Backorder Queue : BO

Demand Queue : D

1. INTRODUCTION

1.1 INTRODUCTION

In manufacturing environment, there are different types of production control mechanisms. One of them is Just In Time (JIT) production systems which use demands as a signal for the production system. The main concept of JIT is to produce the product when it is needed and according to the requested amount. JIT systems help us to reduce setup times, improve the flow of products from warehouse to shelves and take advantage of employees more effectively. Since the production process is related to demand in JIT systems, if there is no demand there will be no production. Furthermore, JIT helps us to improve the importance of the relationship with the supplier. The expectation from JIT system is avoiding waste products and inventory, but especially decreasing the amount of inventory to zero, which is physically and practically impossible for production systems.

Even though the JIT systems have benefits, there are some missing links between theory and practice of JIT settings. JIT systems are designed for perfect conditions with stable demands, constant and balanced processing times, very low uncertainties and no breakdowns, but in real life cases there happen too much problems in the production process such as processing times variations, unexpected breakdowns, demand uncertainties. Many manufacturing companies which use JIT systems, are trying to avoid these uncertainties and increase efficiency of their production systems.

Considering the definition of JIT systems, we call the system “pull production systems” since the systems use the demands as signal. Pull system is a kind of manufacturing method which controls the flow of resources by only using what has been demanded from system. In the pull systems, consumers request product and “pull” it through the delivery channels. In these systems, the production process starts from the last stage, any demand starts the production process. The main characteristic of the pull systems is that production and distributions are demand-driven, and this enables producers to decrease lead times; however, pull systems are difficult to implement. Implementing manufacturing systems is based on production control policies. “In a manufacturing system at the shop-floor level, these control policies help to identify when to start and stop producing a product and when to switch from one product to another”(Altıok 1996, pg.274).

“The single technique most closely associated with the JIT practices of the Japanese is the “pull system” known as kanban developed at Toyota”(Hopp, J. W. and Spearman, M. L.,2008, pg.168). Kanban system is a kind of production control system and Kanban means “card” in Japanese. Kanban system is also known as Toyota’s production control system. This system is not an inventory control system, it is a system which tells manufacturers what to produce, when to produce and how much to produce by using the information on the cards. Using Kanban, manufacturers handle with the product and information flow together. There is no need for extra stock management. A Kanban card used in a factory is shown in Figure 1.1. As we see from the picture there is much information and data on the card. The information on a typical kanban card is as follows;

- the stage where card is used
- the number of component
- the name of component
- the definition of component
- the kanban number
- the name or the code number of the box which kanban card is regularly put in
- the workstation adress where Kanban card will be released. (the code number or the name).

STORE ADDRESS
1 57-B-NB
KANBAN NO.
N762
LINE-SIDE ADDRESS
2W-10-3
PART NO.
22020-03011-00
PART DESCRIPTION
METER ASSY AIR
FLOW/V-AIR CLEA
ROUTE
F-1
GROUP CODE
IA520
DOCK CODE
N2
SUPPLIER
NIPPONDENSO
PURODENSO 1950-5
Q'TY / CONT
4
SERIAL NO
345

Figure 1.1: A picture of Kanban card

There are different types of Kanban systems in a manufacturing environment. Main Kanban concept is the classical Kanban system. In classical concept, when a demand enters the system, a part is removed from the system's inventory point, then the workstation which feeds the inventory point sends an authorization signal to replace the part which was removed from inventory point. Then, each workstation does the same thing. Authorization signals are represented by Kanban cards. In the Kanban system, an operator requires both parts and an authorization signal (kanban) to work. A schematic working method of classical kanban system is shown in Figure 1.2.

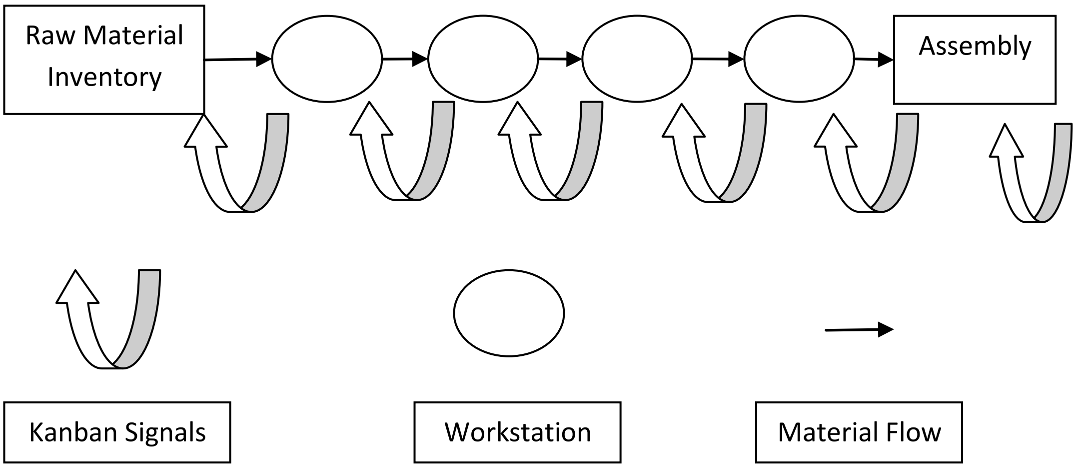

Figure 1.2: Schematic working method of a classical Kanban system

According to figure 1.2, we can tell that there is one authorization signal only for the product but in Toyota's kanban system, they make use of two types of cards to authorize production and movement of product. Toyota's two-card Kanban system's schematic model is shown in Figure 1.3. As we mentioned before, classical kanban is designed for favorite conditions in a manufacturing environment. However, there exist systems which have uncertainties in systems' performance measures such as demand or production process times. To avoid these uncertainties, many researchers, muanufacturing companies, academicians have tried to adapt the kanban systems to these uncertainties. In adaptive kanban systems, setting up the required kanban levels to avoid fill rates and related costs is complicated. That's why, the aim of most of researches about JIT systems is to define the optimal solutions and measures for uncertainties in JIT systems and to specify how to design, monitor, and control kanban levels according to changes in demand, production capacity, and uncertainty levels to improve fill rate performance.

In genereal, the traditional kanban system is the most famous implementation of pull systems in which WIP levels are controlled at each station via cards but it's not the simplest way for implementing the pull systems. To implement it easier, there is a variant which is named of kanban system which named Constant Work-in-process (CONWIP). CONWIP is a kind of single-stage kanban system which is easier to implement and adjust because in a traditional kanban system the production line uses cards for each product but in CONWIP the production line uses a set of cards for managing all the system. For sample, in a traditional kanban system to produce a finished item in the system there is a card for each part of the item, but in CONWIP system there is only one card which authorizes all parts of product. In figure 1.4, a scheme which shows a sample CONWIP system.

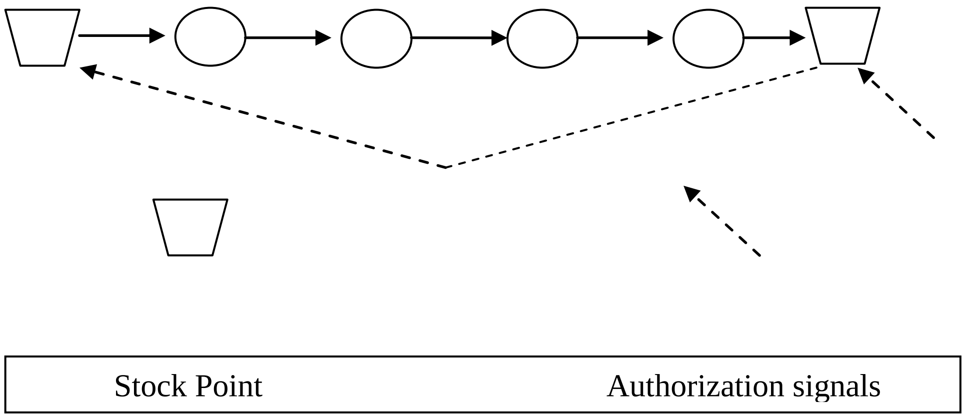

Figure 1.3: Schematic model of a sample CONWIP system

In manufacturing environment all companies which are using Kanban systems as

production controlling policy try to adjust their system to real-life conditions. In that way academicians, researchers and companies do researches on production controling systems.

1.2 OBJECTIVE

The objective of this research is to develop a methodology to be used during the design of Kanban systems under uncertain conditions such as demand, lead time uncertainties. In this research a multi-stage, single-product CONWIP system is modeled and analyzed via simulation. The expectation is to decide how we can adjust a CONWIP kanban system to the uncertain conditions. Using extra kanban cards can help us to adjust the system at the right time or we can stabilize the production process against uncertainties, which helps us to save the cost of the system.

1.3 ORGANIZATION OF THE DISSERTATION

This research focuses on the effects of uncertainties on a single-card, single-product CONWIP based Kanban controlled production system. Chapter 2 represents a detailed literature review with the previous works which are focused on production control systems and policies. Chapter 3 describes the algorithms and formulas which are used for developing an sample model for analyzing the system. Chapter 4 represents the simulation model, experimental cases and results which are analyzed via simulation. Chapter 5 represents the conclusion of all the results.

2. LITERATURE REVIEW

As we mentioned in Chapter 1, there are a lot of alternative production systems and control policies which are used in manufacturing environment. General alternatives are pull and push systems. Pull systems can be implemented in several ways. Kanban system is the most popular pull system in manufacturing environment, but kanban systems show their best performance under the ideal conditions such as stable demand, stable lead times, stable inter-arrival times between demands that create a missing link between theoritical and practical implementations of kanban systems. Due to this reason many researchers, academics or companies made a lot of research about how to implement kanban systems under the real-life conditions or how to reduce missing links between theoritical and practical implementations of a kanban system. Also there are different control policies such as base stock policy which is very easy to implement C. Duri et al. (2000).

From the point that there exist a lot of studies about Kanban systems with different algorithms and formulas Akturk & Erhun,(1999) made a literature review and classified different ways of determining design parameters and kanban sequences techniques for just in time systems. The important point is to state the relationships between design parameters which are number of kanbans, kanban sizes and scheduling decisions. The authors stated the relationships between parameters in a multi-item, multi-stage and multi-horizon kanban system. A model has been developed by authors to make some experiments for evaluating the impact of operational issues, like sequencing rules and actual lead times on design parameters. Methods which are used to determine design parameters have some steps such as model development, solution approaches, defining decision variables, defining performance measures, objectives of system, system's configuration, type of kanban and the assumptions of model. The sample models are presented for sequencing production kanbans at each stage. Under different experimental conditions, sample models are analyzed. Analysis shows that none of the existing models of JIT considers the impact of operational issues on design parameters. There is a lack of different experimental kanban models for elaboration on scheduling kanban systems, these models have to work under different experimental conditions. Also, analysis which is done under different experimental conditions show that most commonly used combination of First Come First Serve (FCFS) rule with instantaneous kanban withdrawal mechanism may not be a good policy all the time. FCFS rule performs better when the withdrawal cycle lengths are long enough for justifying setup times. By using four commonly used sequencing rules in literature Akturk & Erhun (1999) analyzed the impact of operational issues on design parameters.

As Akturk & Erhun (1999) mentioned in their detailed literature review, there are lots of different implementations of production control mechanisms. C. Duri et al. (2000) handled three different implementation types of production control systems and compared them with each other. They worked on make to stock pull control mechanisms such as kanban policy, base stock policy and generalized kanban policy which includes special cases of classical kanban and base stock policy. Authors noticed that the best known pull system is the kanban policy. This policy contains one design parameter per stage and for each type of product: the number of kanbans in stage. This parameter limits the maximum level of work-in-process (WIP) and finished parts inventory. The second policy is the base stock policy which includes one design parameter at each stage of system and for each type of product. Also base stock policy is very reactive. To show the characteristics of these policies with samples, authors made a quantitative comparison of these three control policies. These samples are analyzed with analytical methods for estimating the systems' performance measures which depend on manufacturing processes, arrival process of external demands and parameters of different stages. For comparing three policies they designed three systems for each one of the policies. The authors noticed that optimization methods are not enough to analyze the generalized kanban system which is defined with design criteria of their work. These design criteria can be used by base stock and classical kanban because these systems are a kind of special case of generalized kanban system. They aimed at making a quantitative and qualititative comparison of three different pull mechanism production control systems, to choose the best policy to implement for controlling a production system and give practical rules to be used for choosing the system. Generally, their selection criteria is systems' cost performances for the same production qualities under the same conditions. They show that if there is no delay in filling orders, all three policies have similar costs. However, if there is a delay in filling orders, generalized kanban systems and base stock systems yield close to optimal costs that are lower than the costs of kanban system for the same production quality.

However, Duri et al. (2000) compared and analyzed different control policies such as kanban, generalized kanban and base stock systems. They did not consider the fact that there are different applications of production control policies. Schonberger Richard J. (1983) handled with different applications of kanban systems such as single-card and dual-card kanban systems. As we mentioned before, there are different implementations of kanban systems, one is single-card kanban system and the other one is dual-card kanban system which is known as Toyota production system. Schonberger defines kanban, push, and pull systems, and gives information about general characteristics of these systems such as where they are used, the ease of associating these systems, and any weak or powerful sides of theirs. Also, he showed a schematic comparison of different production control systems' characteristics. In Figure 2.1, we can see the schematic model of these characteristics.

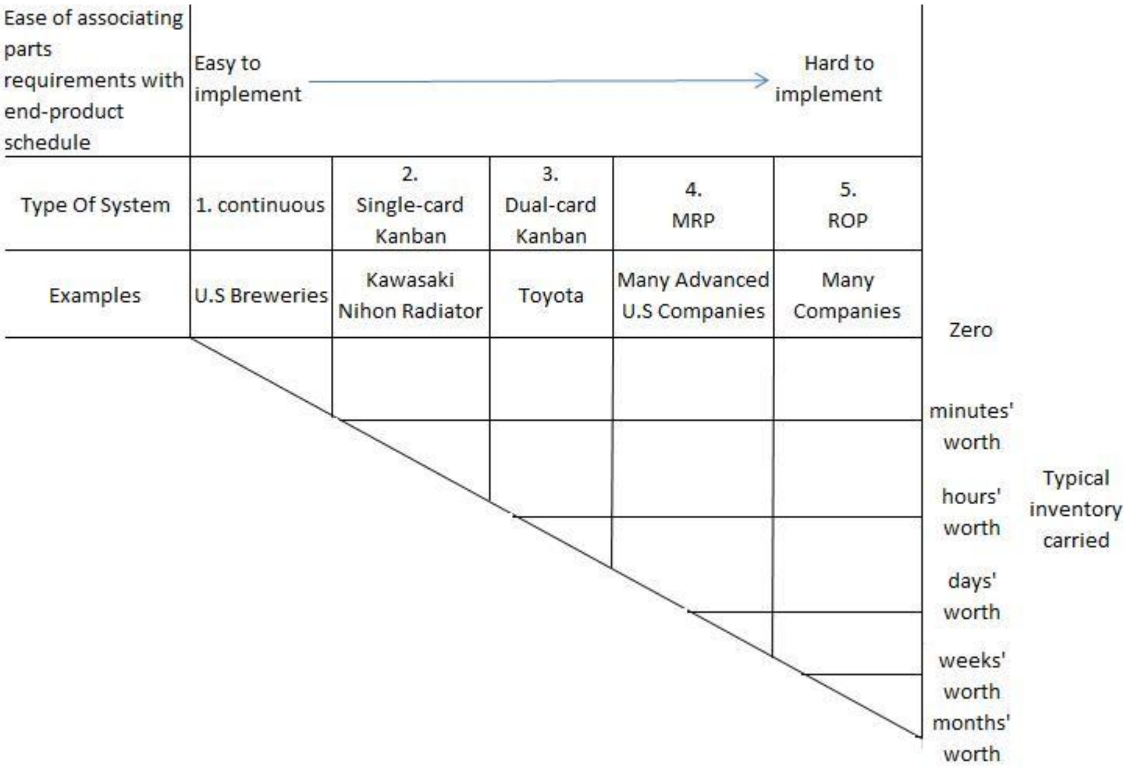

Figure 2.1: Single-card kanban, MRP, ROP, and the continuous system, in a continuoum. As it becomes harder to associate parts and end product demands, inventories likely increase-from theoritical zero on the extreme left to months' worth on the extreme right.

Source: *Rıchard J. Schonberger, (1983), "Applications Of Single-Card And Dual-Card Kanban", Production Scheduling, Materials Handling, 65.*

He shows and makes criticism of different production control mechanisms and defines their characteristics in his work. Although there are different types of kanban in manufacturing environment, generally firms use classical kanban system, which can be single-product or multi-product kanban systems. This can create a difference between systems.

As we can see there are different pull production systems which are controlled by kanban cards in manufacturing environment. Woodruff et al. (1990) described a new pull based kanban system called CONWIP which means Constant Work-in-process. They compared the new system with classic kanban and push based production control of a single production line. They tell that CONWIP differs from Kanban in three main ways. These ways are as follows;

- The use of backlog helps dictate the part number sequence,
- cards are associated with all parts produced on a line rather than individual part numbers,
- and jobs are pushed between workstations in series once they have authorized by a card to start at the beginning of the line.

They analyzed the new system by developing a simulated system. They have conducted numerous simulaitons to make comparisons between CONWIP and push based systems. They discuss the results of simulation study that illustrates some of advantages of CONWIP over a push based system. The system does offer some distinct advantages over kanban. For example, CONWIP can be used in some production environments where using classical kanban is not effective and practical because of too many part numbers or because of significant setups.

CONWIP concept has been used in different studies for solving different problems in pull production systems. Sarah M. Ryan et al. (1998) conducted a research on controlling a job shop setting within the concept of CONWIP. They tried to solve the problem of determining fixed overall WIP level to meet a uniformly high customer service requirement for all types of product and optimizing a queuing network model in which orders pull completed product from the system. Under assumptions of heavy demand there is a throughput target for each product type. A simple heuristic has been provided for finding minimum total WIP and WIP (mix) which will achieve throughput through operating close to the throughput target. WIP (mix) is mixed WIP for all types of product. They focused on the proportion of orders which wait to be fulfilled by the production system. They worked on the problem to make a card count for each type of product so that the probability of waiting for an order to be fulfilled can be lower according to the production capacity. As a result, a higher total throughput could have been achieved without product mix constraint, but resulting system design would greatly favor orders for some products at the expense of others.

We know that a production system can produce single or multiple product also kanban systems can be single or multi product kanban systems. Schonberger Richard J. (1983) handled this subject but he didn’t analyze a sample model, he only defined the characteristics of the system and made criticism about the systems. C. Duri et al. (1995) concerned a kanban system analysis which produces several types of products. Also, they present an analytical method for analyzing the performance of a multi-product kanban system with using a closed multi-class queuing network model which each class represents one type of kanban. The system produces two types of products on the same machine so this creates ordering problem, which product would be the first. The setup times can be distinguishing characteristic for defining processing orders. There are two cases: the first one is; if setup times are not zero, we have to try to limit the number of setup, but if setup times are zero, we can choose and define processing orders. Therefore, there is no need to worry about setups number limitation. They focused on the second case for analyzing the system performance. They aimed at approximating an analytical method for analyzing the speed and accuracy for designing of a multi-product kanban system where they need to test numerous configurations of systems for selecting the best one to use in real-life production systems.

In a kanban system, one of the most important performance measure is Kanban sizes. Setting up kanban sizes in a production system is very important but we have to know the factors which influence the number of kanbans in a kanban controlled production system. Philpoom et al. (1987) made an investigation to identify these factors. The factors which they tried to identify include throughput velocity, coefficient of variations in procesing times, the machine utilization and autocorrelation of processing times. All these factors are analyzed by using a simulation model. In a pull system, the system's efficiency is measured with number of containers which include finished goods produced and stored, it means that more inventory is equal lower efficiency. When the authors analyzed the factors that influence the number of kanbans, they assume that one workcentre encompasses only one machine, and the system produces only one product in each processing time. Conveyance time and kanban collecting time are all zero or relative to processing time, also setup times are all zero and all processing times are equal. Analysis of sample simulation models show that if variability in processing times increase, the number of kanbans increase too. If the machine utilization increases, the number of kanbans increase and correlation of processing times have the same effect as other parameters.

While we design a production system, we have to choose system options carefully. To take the best performance results from the designed system, the system options have to be close to the real life production system options. In this respect, Deleersnyder (1989) noticed that there are three problems in designing and implementing a kanban controlled JIT system such as followings;

1. the identification of flow lines which is important for achieving the flow lines operating around the production families with a good level of utilization but with a minimal extra investment,
2. loading flow lines, which is important for avoiding bottlenecks developing in work stations,
3. controlling the operations, which is important for controlling the interaction between production and inventory levels and for determining the expected number of kanbans in systems under stochastic conditions.

They developed a 3 stage serial production model based on N-stage serial production systems. Also, the system is developed as a discrete time Markov model. They described their models with 4 levels which are variability in number of kanbans, the impact of machine reliability, the impact of demand variability and the impact of safety stock in the system. The system performance analyses are based on three sources which are; uncertainties of machine reliabilities, capaciy constraints and uncertainty of demand. They aimed at analyzing a sample kanban based production system under these sources. They tested the effect of the number of kanbans variations on the system's performance parameters such as average total inventory, average backlog, variance backlog, % lost demand, average job flow time. As a result, until the number of kanbans become 15, there is a small increase in all the performance parameters except average total inventory, but when the number of kanbans become more than 15, the effect on performance parameters will be dramatically bigger. When the production system becomes more reliable the average backlog decreases, this is the result of changing production reliability and the overall system performance. Also, the impact of demand variability makes the system more sensitive. Another result of the system is that while number of kanbans and safety stock increases, the average backlog decreases and average total inventory increases.

For analyzing the kanban production systems' performance, there are a lot of models developed, but the analysis methods are different from each other. For sample as we noticed before, Deleersnyder et al. (1989) analyzed his model in a whole perspective. Also, Di Mascolo et al. (1996) used a different method to analyze the performance of a kanban system. They developed a general purpose of analytical method for analyzing the performance of multi-stage kanban controlled production system by using decomposition method. They considered single type production system and decomposed this system into stages in series. The basic principle of decomposing a system is to decompose main system into subsytems. They used a product form approximation technique for each subsystem's analysis in isolation, after that an iterative procedure is used for determining the unknown parameters such as the percentage of demands that are backordered (not immediately satisfied), average waiting time of backordered demands and average work-in-process. The authors modeled the system as a queuing network. They analyzed the system for presenting the problems of single-stage and multi-stage systems. After the analysis of models, they first focused on the production capacity of the system because it's the system's maximum throughput. In the system developed in this work demand always comes to system for finished parts. As a result of the analysis, they noticed that production capacity increases with the number of kanbans at each stage.

On the contrary to Di Mascolo et al. (1996), Krieg Georg N.&K. Heinrich(2004) developed a decomposition based method that analyzes and generates accurate estimates for steady-state performance measures of a kanban production system. A sample model of kanban system which can produce multi-product is developed. In the sample system, the setup and processing times are assumed to be exponentially distributed. According to mutually independent Poisson process, customers arrive to system. There is a target inventory level given by the number of kanbans. When the number of productions reach the target inventory level, the facility stops and setup for the next product according to a fixed setup sequence if the next product inventory is below target. Otherwise, this product is shipped. Also, when all products are at their target level, the facility idles. Another point in the system when a customer arrives to system, if there is no product in the inventory of the product which customer orders, customer satisfies his demand elsewhere, it is named as “Lost Sales”. According to Continuous Time Markov Chain algorithms; for a system which has five different products and five kanbans, systtem has 64805 states. For another system with 10 different products and 10 kanbans for each of them, the number of state is greater than 471 billion, as a result of this state space explosion, exact analysis of a model is mathematically not possible even for smaller systems. In this work as an alternative method the authors used decompositon method. Krieg &Kuhn (2004) decomposing figure can be seen in Figure 2.2.

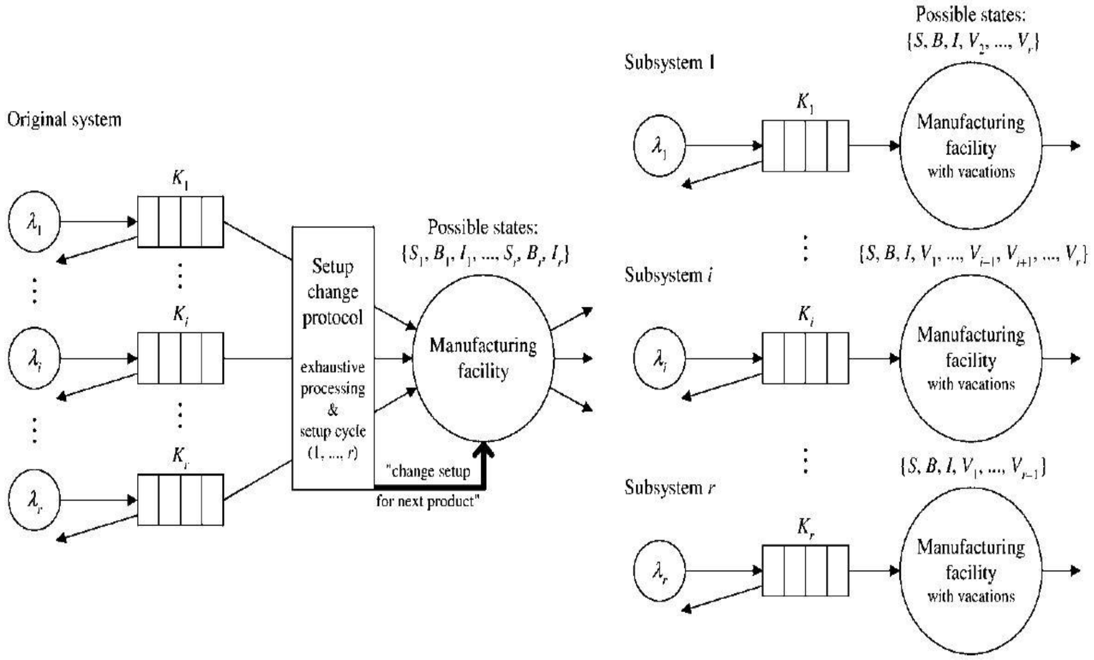

Figure 2.2: Decomposition of the original system into r single-product subsystems.
Soruce: Georg N. Krıeg, Heınrıch Kuhn, (2004), "Analysis Of Multi-Product Kanban Systems With State-Dependent Setups And Lost Sales", Annals Of Operations Research 125, 145.

The number of kanbans play a major role in the performance of kanban controlled production systems. Bard & Golany (1991) has developed a single-card production system which the empty containers function as kanbans and are used to trigger orders. They developed the system which is designed for a given demand and planning horizon. This sample model is very general, it is committing the problem in a wide range. The first and most important interest of the authors is the number of kanbans in the system. They made some assumptions that there is precisely one kanban of each product type for each container, the number of kanbans are equal to the number of containers and for each part it should be minimized, the containers which are used in the system have to be standard and must always be filled with the prescribed quantity. They also assumed that the production and withdrawal can be started only by appropriate kanbans. They aimed at minimizing holding and shortage costs without ignoring the basic kanban principles and balancing these costs over the planning horizon. They think that this system and algorithm may help assist line managers in determining optimal kanban numbers at each workstation. As a result, they noticed that this system is the most appropriate when demand is steady and lead times are short. Making careful analysis can yield immediate benefits by reducing inventories and provide managers with a more detailed picture of current activites.

Determining the number of kanbans and analyzing its effects can be done by different methodologies for different systems. Markham et al. (1998) made a rule induction for using the number of kanbans in a JIT system by using a classification and regression tree (CART) technique which is developed by Briemen et al. (1984). If the production system is under ideal conditions such as stable demand, low process times, welltrained workers, there is no need for an adjustment on the number of kanbans in the system. However, in real life conditions it is impossible to make every condition ideal. From this point, they presented a methodology which allows the shop floor manager to identify the relationships between shop factors which need to be monitored if the firm's aim is to operate its shop at least cost production kanban level in the near future. The methodology has been used on a sample in three steps which are data collecting, formation of desicion tree and interpretation of decision tree. There is a simple heuristic they noticed as a result, if there exist a high demand variability in the current period and if the lead time in the previous period is short and vendor supply variability is high in the previous period, then only a few kanbans are required for the system. Also using CART in a rule induction provides us with a viable solution to the knowledge acquisition bottleneck.

As a case study about Kanban controlled production systems Orbak & Bilgin (2005) conducted a research about Kanban systems. They tried to apply Kanban system in a small automotive raw part manufacturing company. Before starting to implement Kanban system, in a firm there are important things to do. These things are processing times' standardization, reducing setup times, setting up the utilities according to JIT philosophy, total quality management applications for JIT systems such as the targets which are zero inventory and zero waste product. According to the firm's production procedure they get data to analyze the system. The data includes average mean of demand interval, setup times, lead times, the number of lots produced, having inventory cost and not having an inventory cost. Considering the data collected by using Monden's formula which has been described by Monden (1993), the authors tried to determine the optimal number of kanbans which get the system to minimize the costs. As a result of these calculations, they noticed that implementing kanban system in this firm causes a decrease in counts of inventory with a rate of 50%, a decrease in counts of lots and this causes to an increase of lead times. Kanban system implementation gives company a lot of advantages to firm such as controlling defects quickly, decrease in waste products. Also, the production process becomes easier to understand and implement, and over-production is prevented. In a phrase, this study showed us implementing kanban system to a production system make production system easier and provide production managers with an easier control of system.

Generally researchers make assumptions about analyzing and designing a production sytem on the given kanban sizes. Chan (2001) tried to investigate the effect of kanban size variations on the performance of JIT manufacturing systems. There exist two types of JIT production systems; one is pull-type, the other one is hybrid type. These are analyzed by using computer simulation models. Author considered some performance measures such as fill rate, inprocess inventory and manufacturing lead time. Also, some other parameters such as demand rate, processing times are taken into consideration. He developed two simulation models for testing the effect of kanban sizes on different JIT systems. He aimed at determining optimal kanban size for optimizing the performance of system in terms of lead time and fill rate. As a result of single product system performance analysis while kanban size increases, fill rate decreases but inprocess inventory and manufacturing lead time increase. For multi product system analysis, he noticed while kanban size increases fill rate increases, too. However, manufacturing lead time decreases in the system when kanban size of system increases.

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As we mentioned before, changing the number of kanbans in a kanban system is a big problem. Considering this problem Toyota Motor Corporation developed a new kanban system called "e-Kanban" which utilizes computers and a communication network established between Toyota and its suppliers. Kotani (2007) makes a description of e-Kanban system which we can see in Figure 2.3.

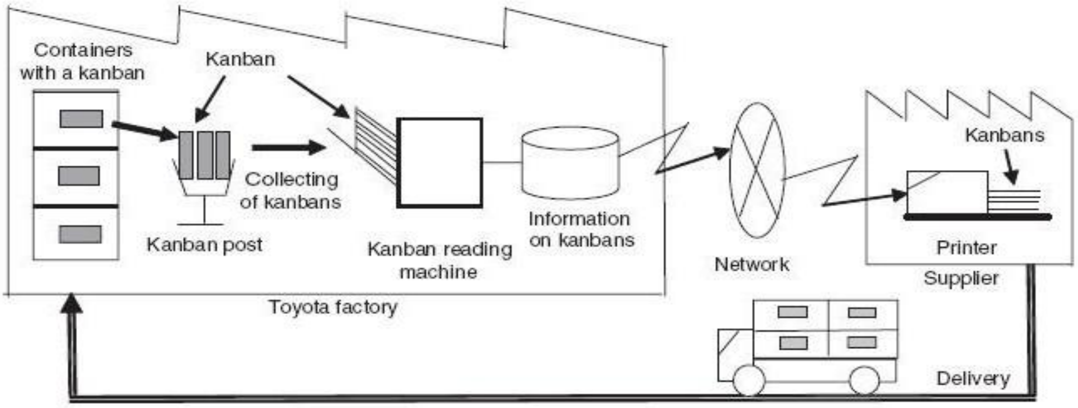


Figure 2.3: Description Scheme of an e-kanban system

Source: Kotani, S.(2007) 'Optimal Method For Changing The Number Of Kanbans İn The <i>e</i>-Kanban System And İts Applications', International Journal Of Production Research, 45: 24, 5792

From the point that one goal of e-kanban system is improving the method which is used to change the number of kanbans, the author investigated a means of achieving this and proposed an optimal method for changing the number of kanbans. There are some improvements which are the result of implementing e-Kanban system. These are greater efficiency in the control of kanbans, reduced fluctuation in order quantity and appropriate changes in the number of kanbans, reduced parts inventories and quick response to changes in demand. Also, applying this method to e-kanban system showed us e-Kanban system can manage parts ordering and delivery activities more efficiently and effectively than kanban system.

We know that there is a missing link between theory and practical applications of JIT systems. Theoretically implementing JIT system can be the best choice for a manufacturer but practically it’s hard to implement because in real life cases the manufacturing environment is very dynamic. Also, adapting the JIT systems to dynamic manufacturing environment is very important for the implementation of JIT systems. According to the idea of adapting JIT systems to dynamic environment Gupta & Al Turki (1997) developed a new system which uses an algorithm for manipulating the number of kanbans. They called the new system as “Flexible Kanban System (FKS)”. Gupta et al. (1995) noticed that FKS is a system which is quite robust and its performance is superior to TKS even for high processing times. In FKS, the idea is to increase the flow of production by reducing the blocking and starvation caused by the variability in processing times. This is achieved by increasing the number of kanbans in the system. FKS can increase or decrease the number of kanbans according to a base level number of kanbans, the system can’t reduce the number of kanbans below the base level. They developed a simulation model and analyzed it under the conditions that manufacturing system is composed by 8 stages, there is a demand for finished goods between 140 and 260 units for a planning horizon which is formed from 10 days, at every station processing times are independent and normally distributed, base level of number of production kanbans and withdrawal kanbans are set at two for each station, and transition times are 30 seconds for all kanbans. Also, to work on the sample model simulation they assumed that at station 1 there are always raw material available, each container includes one part, for producing one unit of demand raw material have to be processed at each station and first come first serve queuing discipline is used for processing the parts. For four performance measures which are time in system (TIS), work-in-process (WIP), average order completion time (OCT), and total number of units backlog 20 replications are made. They made this analysis for TKS and FKS to make a comparison between them. As the results of analysis, they noticed that average time in the system for FKS is longer than TKS, the average work-in-process in FKS is higher than TKS, the average order completion time in TKS is longer than FKS and the total number of units which are backlogged during 50 days are zero for FKS. They aimed at developing a flexible kanban system which reduces the backlogs in the system by manipulating the number of kanbans in the system under these assumptions. We can see that they succeeded that aim.

Another work about adapting kanban systems to dynamic manufacturing environment was done by Takahashi & Nakamura (1999). They propose a system that can detect unstable changes in demand by using Exponentially Weighted Moving Average (EWMA) charts, and determine the revision of buffer size for the detected unstable changes based on tradeoff between performance measures under stable conditions. They used simulation experiments for analyzing and comparing performance of proposed JIT ordering systems. JIT systems being used in this work are kanban system and the concurrent ordering system which has been modified by Takahashi et al. (1996). In the modified concurrent ordering system when a demand arrives from succeeding stage an order is released immediately at the production system. Concurrent ordering system includes only one kind of information which is about the demand arrival at the production system. Besides that information, minimum releasing orders are considered. Also base stock system which is investigated by Buzacott & Shantikumar (1993) is the same system as concurrent ordering system. They developed two multi-stage JIT production systems. One is Kanban based, the other one is concurrent ordering system based. They simulated the systems and they compared the results of simulations. The production systems have same assumptions that a standard product is produced, the demand has stable and unstable changes, interarrival time of demand is distributed stochastically with unstable changes in the mean but variance is constant, production time at each stage is distributed stochastically, transportation process between *(n-1)*st and *n*th stages is called *n*th transportation stage, each stage has two inventory points named before and after inventory points, backorder is allowed and buffer sizes and the number of kanbans are controlled dynamically for reacting unstable changes in demand. As a result of simulation analysis both system can react to the unstable changes. Under tight requirement for waiting time of demand, kanban system is more efficient. Also, total mean of WIP inventories in kanban system is less than the concurrent ordering system.

In another study about adaptive kanban systems, Tardif & Maaseidvaag (2001) developed a new adaptive kanban system. This system is able to determine when to release or reorder raw parts based on customer demands, inventory and backorders. In this work authors developed the system for a single-stage and single product system. The proposed system helps us evaluate the performance of the system where the demands arrive according to a Poisson process. There is an extra card inventory in the system but these cards are free and ready to enter to production units. There are capturing and releasing thresholds which help us to decide when we have to release an extra kanban card to production unit or when we have to capture an extra card from the system. They simulated a sample system and results show that this system is able to completely dominate the traditional kanban system under certain conditions.

For adapting kanban systems to unstable changes and dynamic manufacturing system, again Takahashi & Nakamura (2002) proposed a decentralized reactive kanban system. The system is a multi-stage production and transportation system which is controlled by kanban system with reactive buffer size controllers for each stage. Controllers can detect the unstable changes in demand from succeeding stage and adjust buffer size in response to unstable changes. Unstable changes in demand are detected by utilizing control charts. To develop the decentralized system, they decomposed a multi-stage production system and the performance of decomposed system is analyzed by simulation experiments under various stable demand conditions. Based on the results of decomposed system’s performance, they developed the decentralized reactive kanban system. The assumptions of the system are all the same with Takahashi & Nakamura (1996) work except one assumption. In the previous system they assumed that there is a constant variance of demand but in this work they assume the variance is unstable. They decomposed the systems which are developed in Takahashi & Nakamura (1996) such as the kanban and concurrent system. Again, they used EWMA charts to detect the unstable changes in demand from the succeeding stage. They simulated the sample system, analyzed it and compared with previous centralized systems. The results of analysis showed that the proposed system’s performance is similar to the previous systems. Kanban systems need small work-in-process inventories for satisfying the required level of mean waiting time of product demand than the centralized reactive systems.

There are different types of reactive kanban systems in literature. In one of reactive systems, unstable changes in demand are detected by using control charts, and in these systems kanban numbers and buffer sizes are adjusted according to detected unstable changes. Another reactive system is based on inventory levels but this system's performance has not yet been analyzed. Therefore, Takahashi (2003) proposed two reactive systems for analyzing and comparing performances. One of the system is control chart based and the other one is inventory based. He designed a new inventory based reactive kanban system and analysed its performance. In the inventory based system, instead of monitoring time series data, he monitored the inventory level to detect unstable changes in demand and adjust number of kanbans according to detected changes. He compared three systems which are control chart based system which is developed by Takahashi & Nakamura (1999) and previous inventory based system which is developed by Tardiff & Maaseidvaag (2001) and new inventory based system developed by Takahashi (2003). All systems' performances are analyzed for unstable changes in demand. Systems are developed under the same assumptions as we mentioned in Takahashi & Nakamura (1999). Performance measures for analysis are the mean waiting time of product demand and the total mean WIP inventories. Analyzing these three systems' performance results showed that both the proposed inventory based and control chart based systems are designed to minimize total WIP while maintaining waiting time less then the required level. Also, he noticed that control chart based and inventory based systems are robust for unexpected unstable changes in demand. We can expect good performances from these systems by setting the parameters for severe conditions and considering three reactive systems. The control chart based system is the most effective system since it responds to unstable changes in demand. Performance analysis showed that in the proposed system which is inventory based, exponentially smoothed inventory levels are used to detect unstable changes in demand and that causes a delay in detecting unstable changes in demand, also this causes an increase in total WIP. In all of these three reactive systems, unstable changes occurs in demand but in real life unstable changes can occur in production time or capacity and in these systems the variance of demand is assumed to be constant but there can be unstable changes in the variance of the mean.

According to the probability of having unstable changes in the variance of the mean, Takahashi et al. (2004) proposed a reactive kanban system for multi-stage production systems with unstable changes in demand, not only in the mean but also in the variance. Their reactive system is very similar to previous reactive systems which are developed by Takahashi & Nakamura (2002) and the assumptions are the same as the previous system. We mentioned that in the previous system the authors analyzed the system by decomposing multi-stage system into the single stage systems. Systems' performance measures are the mean waiting time of demand and total mean WIP inventories. For analyzing the systems' performance, the time series data on demand are grouped into batches and the batch mean. And, variance are utilized to detect unstable changes in the mean and variance of demand. Grouping causes a delay on detecting unstable changes. The batch size in grouping and multiplier of EWMA charts have an important effect on the system's performance. They noticed that because of delay in detecting unstable changes and controlling buffer size causes not to satisfy the required level of mean waiting time but this problem can be solved with holding a little safety stock at the final inventory point. The system which they developed is effective in reacting kanban system to unstable changes.

As we mentioned in the previous works about adaptive kanban systems, researchers used different analyzing methods and developed algorithms. Sivakumar & Shahabudeen (2009) developed a multi-stage kanban system which is adapted from a traditional and adaptive kanban system. They used genetic and simulated annealing algorithms used for setting the parameters of systems. They created different cases for analyzing the systems and as a difference from other adaptive systems in some cases their systems have parallel servers. The objective of the models is minimizing the costs of systems. The cost of the system is also a performance measure, and the other performance measure is the number of kanbans. The main characteristic and difference of this system is the algorithms being used such as genetic algorithm and simulated annealing algorithm. The numerical results of analysis showed that multi-stage adaptive kanban system gives a better performance than multi-stage traditional kanban system. Also using simulated annealing algorithm has a better performance on analyzing kanban systems than genetic algorithm.

As we see in literature, different algorithms, methods and systems have been developed and analyzed about kanban controlled production systems by different researchers. Our system shows similar characteristics with the work of Tardiff & Maaseidvaag (2001). Our system is a sample of adaptive kanban system and it is based on CONWIP concept. In literature some researchers analysed their system with mathematical algorithms, whereas some of them analysed with a simulation model of system. The performance of system was analysed with simulation model of system. The systems developed in the previous works were designed without blocking. Difference of our system from these previous works is in our system there can be blocking and our queues of the system are limited. Because of blocking and limited queue, we need a complex mathematical model, also to make our analysis easier we have conducted our analysis with simulation. All the methodologies used and the model can be seen in Chapter 3.

3. PROBLEM DESCRIPTION AND MODEL

3.1 PROBLEM AND SYSTEM DESCRIPTION

In the kanban controlled production systems the most important problem is adapting system to uncertain conditions. As we mentioned before, JIT systems show their best performance under favorable conditions such as certain demand, certain lead times, certain process times but in real-life cases most of these conditions are uncertain. According to these uncertain conditions we tried to develop an adaptive kanban controlled JIT production system.

We considered a multi-stage, single-product and single-card kanban system which works under CONWIP methodology. The system is formed by 4 serial workstations, and each Workstation acts as a single server, also all workstations include a queue of products which are waiting to be produced. Queue has a limited capacity. In our study, we consider each workstation has a queue that can hold at most 3 items. The number of kanban cards in the system can change according to current inventory and backorders. The Manufacturing process is represented by “MP”, the inventory is represented by “I” in the system in which the containers of finished parts are holded, the queue of demand is represented by “D”, the queue BO contains backordered demands and the queue Total Waiting Work contains the jobs which are waiting to enter to Workstation 1 with its’ kanban card. The adaptive system uses K number of kanban cards and E number of extra cards. Initially, before a demand arrives to the system, the number of containers in the queue of I is equal to K. Before system starts producing, D and MP are empty. N(t) is the number of cards in use at time t. Also, let X(t) be the number of extra cards in use at time t. R represents the release threshold for adding an extra card and C represents capture threshold when one retrieves an extra card from circulation.

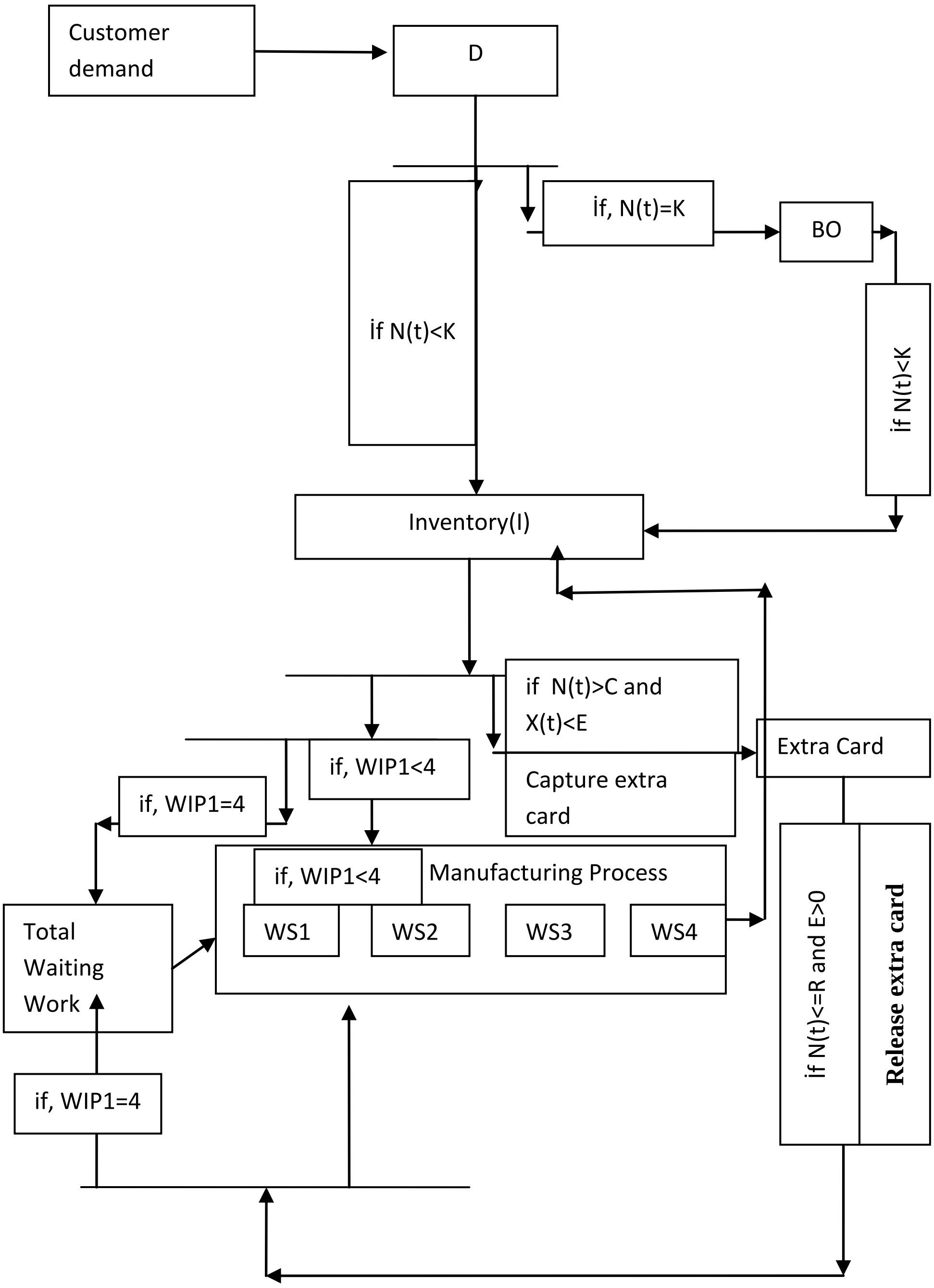


Figure 3.1: Algorithm of adaptive kanban system's processing principles

When a customer demand arrives to the system, if N(t) > 0, demand is satisfied from inventory (I) with a filled container and the card of this container is released to workstation 1. Every production has to be processed at each workstation in the system. When a production authorization finishes in the Workstation 4, it becomes a finished good and also it is holded in inventory (I) with its card. The system allows blocking because there is a limited capacity of workstations. Because of this, in the sytem there is a waiting queue for the demands which can not arrive to workstation 1 for production.

Also, if a workstation is filled with four production authorization, no other production authorization can arrive from previous workstation. Releasing an extra card to system is upon to arrival of demand to the system at time *t*, if N(*t*) $\leq$ R and E > 0, the system satisfies the customer demand with a container in the inventory and releases its card to MP. Also, at the same time an extra card is released from EC to MP. However, if N(*t*) > C and E(*t*)< E, when a customer demand arrives, the system satisfies the demand from inventory, release its card to EC, and this demand is not released to the MP. When a demand arrives to the system at time *t*, if N(t) = 0, the demand is holded in BO and the demand which is holded in BO is released when N(*t*) becomes higher than zero. In the adaptive system, R must be less than C. The algorithm of the system's processing principles are shown in Figure 3.1. In the model, the queuing system is a kind of closed queuing network as CONWIP production systems are. The model's queuing system combines the components that have been considered so far; an arrival process, a production process and a queue of jobs. Jobs are identical, and interarrival times between two jobs are random. Workstations have a single machine and a queue which has a limited capacity with three jobs. In our system, if a workstation is fully filled with jobs, previous workstation can not release the finished job to this workstation and waits in the queue of previous workstation. If there is a product in inventory and the first stage is fully filled, production order waits in the total waiting work queue. We thought that this model will help us to adapt a system to unstable changes in demand and processing times. We focused on the changes of some performance measures such as average WIP level at each station and utilization rate.

Some adaptive systems can be modeled in terms of (*i*, *x*) whose evolution describes the continuous time Markov chain. State (*i*, *x*) denotes the total number of parts in queue I minus the total number of backorders in queue BO with *i*, and the number of extra card circulation with *x*. Fig 3.2 shows this makrov process when R>0 also C must be less than or equal to K+1 to ensure that the system is able to return the initial state (K,0). Our system can not be modeled by using the continuous time Markov chain, because our system is complex to solve by using this method. This method is useful when there is no queuing system in the production line. There can be blocking but in our system there exist blocking between each Workstation. Also the queue of the system has to be unlimited, but in our system our queues are limited.

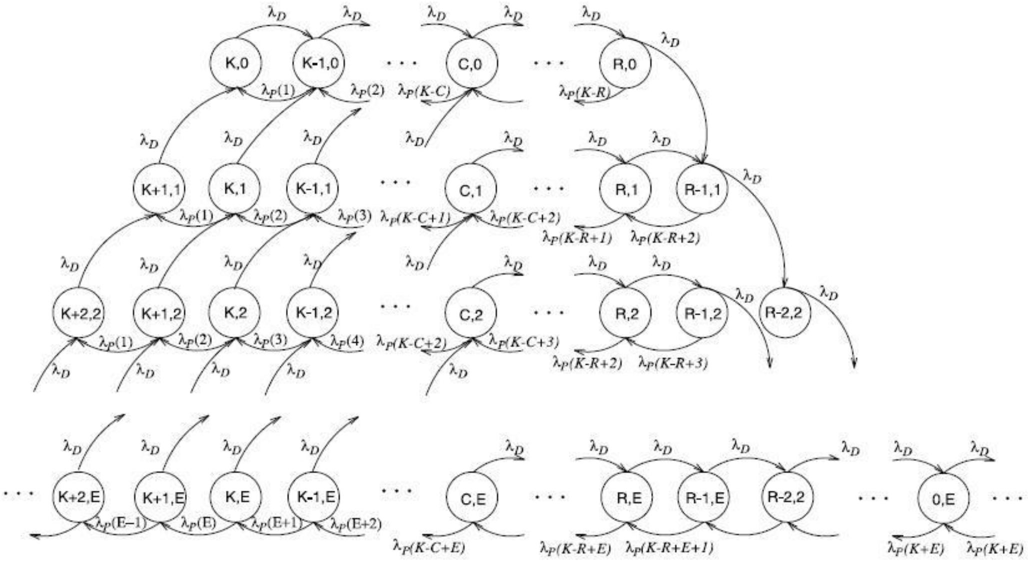


Figure 3.2: Schematic model of a continuous time Markov Chain

Source: *Tardif Valerie, Maaseidvaag Lars (2001), "An Adaptive Approach To Controlling Kanban Systems", European Journal Of Operational Research", 132, 418*

3.2 ASSUMPTIONS

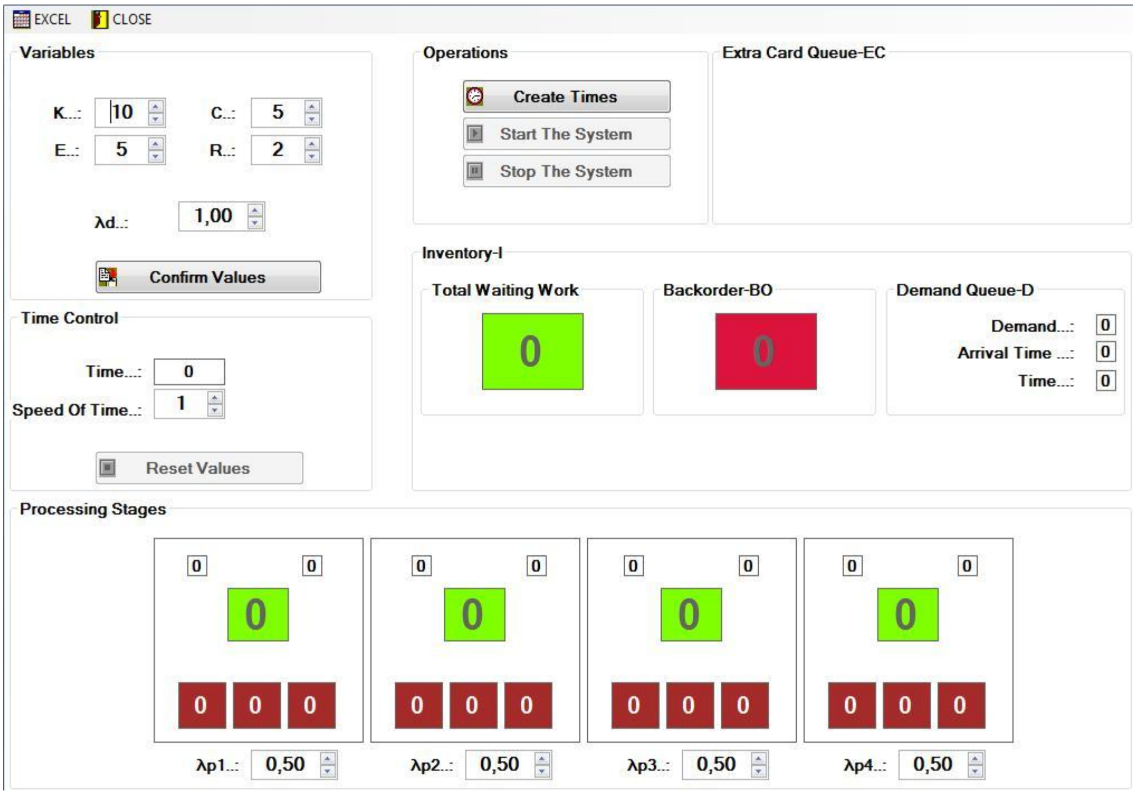
We developed the model according to assumptions following;

- Arrival time of demands are random with an exponential ditribution. Arrival rate of demand is represented with λ_d.
- Production rates are random with an exponential ditribution. Production rates are represented with $\lambda_{P1.}$ $\lambda_{P2,}$ $\lambda_{P3,}$ λ_{P4}.
- Each workstation can produce one container at a time and 3 containers can wait in the queue of Workstation.
- The number of demand arriving to the system with the rate of λ_d is equal to one at each demand arrival.
- Min{ $\lambda_{P1.}$ $\lambda_{P2,}$ $\lambda_{P3,}$ λ_{P4}}= r_b. r_b is the notation of production rate of bottleneck workstation.

According to these assumptions, we developed a production system and simulated it to analyze systems performance measures such as number of kanban cards, number of extra kanban cards, average number of WIP for each Workstation in the system, utilization rate, and average number of backorders.

3.3 METHODOLOGY AND MATHEMATICAL MODEL

There are a lot of methodologies and algorithms exist in the literature about JIT systems but in our thesis we can not analyze the system with existing mathematical models. Therefore, we have developed a simulation of the production system to analyse our system by using C# software. Figure 3.3 shows an interface picture of simulation. In the interface of simulation we can see all processes which are existing in the system such as instantaneous capacities of workstations, WIP levels, inventory levels and extra card queue. Also, in the simulation interface we can see K, E, R, C values.



K..: 10
C..: 5
E..: 5
R..: 2
λd..: 1,00
Time...: 0
Speed Of Time..: 1
Total Waiting Work: 0
Backorder-BO: 0
Demand...: 0
Arrival Time ...: 0
Time...: 0
λp1..: 0,50
λp2..: 0,50
λp3..: 0,50
λp4..: 0,50

Figure 3.3: A screenshot of the simulation model interface

In the system we need to check stability condition which is mentioned in (Tardiff 2001). Stability condition is if, $\lambda_D / \lambda_P(K)$ is less than 1 or not where λ_D is rate of demand arrival to the system and $\lambda_P(K)$ is the throughput rate of the CONWIP system with K cards. In our system, we assume λ_D and λ_P values are defined before and conidering this we will try to find the optimal number of kanban which can satisfy the stability condition. In fact, our system is not suitable to apply this formula for stability condition because of blockings in the system. However, we defined some of our parameters by using this formula of stability condition and we took reasonable values. In the system, the main production rate is the bottleneck rate of system if a bottleneck station exists in the system. For K cards, system's production rate is; $\lambda_{P(K)} = \frac{\min(\lambda p1, \lambda p2, \lambda p3, \lambda p4) \times K}{K + M - 1}$ where M is equal to the number of workstations in the system. In our system M is equal to 4. The bottleneck production rate is represented by r_b which is equal to, $\min(\lambda p1, \lambda p2, \lambda p3, \lambda p4) = r_b$. Also, the rates of demand arrival and production process times are being used for defining time variables of system. As we said in assumptions part, the times of system which are being used for production and demand arrivals are exponentially distributed. In the system, generating these exponential varieties are based on inverse transform sampling. Given a random variate U drawn from the uniform distribution on the unit interval (0,1), the variate;

$$T = F^{-1}(U) \tag{3.1}$$

has an exponential distribution , where F^{-1} is the quantile function, defined by

$$F^{-1}(P) = \frac{-\ln(1-p)}{\lambda} \tag{3.2}$$

Moreover if U is uniform on (0,1), then so is 1-U. this means one can generates exponential variaties as follows;

$$T = \frac{-\ln(U)}{\lambda} \tag{3.3}$$

Also, the model system generates a random number between 0 and 1. This variable is equal to U as in the inverse transform sampling and after this system uses U variable in the formula of (3.3), with that way the system generates a time variable according to the exponential distribution with its' rate of λ. In the model, we defined a 5×10000 matrix which is named “T” and includes time variables which are randomly generated in the system according to the rates of demand arrival and production processing with the formulates of (3.1), (3.2) and (3.3). Demand arrival times are represented as D_i and I represents the number of demand arrival to the system; for the first demand arrival i=1. Production processing times are represented by P_{jk} in which j shows the number of station and k shows the order number, for sample for the first production process in the first stage j=1 and k=1.

$$T = \begin{bmatrix} D_1 & P_{11} & P_{21} & P_{31} & P_{41} \\ D_2 & P_{12} & P_{22} & P_{32} & P_{42} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ D_{10000} & P_{110000} & P_{210000} & P_{310000} & P_{410000} \end{bmatrix}$$

In the matrix, D_1 represents the first demand arrival time to the system and P_{11} represents the first production processing time for the first stage in the system. Also, in the simulation of system, each time transition represents one hour. In the system finding optimal kanban number is an important issue to analyze the production system correctly. To find the optimal trial time of the system we made some trials for different time values. Warm-up figures are shown in Figure 3.4.

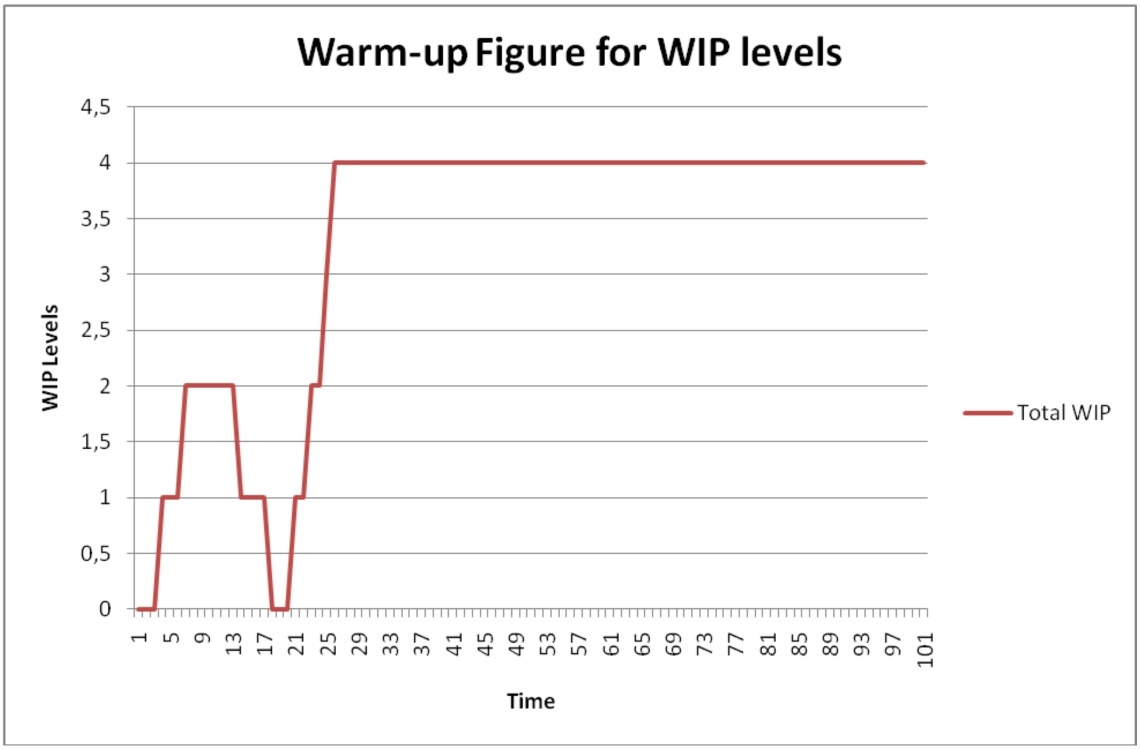


Figure 3.4: Warm-Up Figure For WIP Levels

To find the optimal number of kanbans, after controlling the stability condition we would have a feasible value of K+E and we will try it until we minimize the total cost of system. Starting value of K is represented by K^*. Tardif, V. & Maaseidvaag, L.(2001) noticed that the optimal number of kanban which satisfies the stability condition and minimizes the total cost is for traditional kanban systems and it may not be equal to optimal number of kanbans in an adaptive system. In this thesis, we assume that the number of kanban which satisfies the stability condition and minimizes the total cost is the optimal number of kanbans in our adaptive system we will add extra kanban cards to the system by using this optimal K value and see the effects of adding an extra card to the traditional system. And, this also helps us to develop our adaptive kanban system. We used different cost parameters when we found the total costs of system for different cases. At each trial of the simulation of system, we have used the cost parameters as follows;

- For backordered demands there is a penalty cost which is represented by *p* and the first trial value of the average cost of a backorder demand is equal to \$3000 second one is \$1500
- There is a cost for the total average of WIP level at each station which is represented by *WIPC* and the first trial value of it is equal to \$50, second value is \$25.
- Also there is a cost of average inventory which is represented by *IC* and the first trial value of it is equal to \$1000, second is \$500.

We will find total cost of systems for different cases and for different cost parameters. We want to analyse which cost parameter is more effective for the system. At each trial we will assume two cost parameter constant one is variable.

The total cost (TC) of system is the sum of these costs. According to this formulas we can analyze a system step by step. For an sample problem in which λ_D=0.3 and $\min(\lambda p1, \lambda p2, \lambda p3, \lambda p4)$ = min (0.6 , 0.8 , 0.8 , 0.8) = r_b= 0.6, we can define these steps as following;

1. Control stability condition;

If,

$$\lambda_P(K^*+E)=\frac{\min(\lambda p1,\lambda p2,\lambda p3,\lambda p4)\times(K^*+E)}{K^*+E+M-1}=\frac{r_b\times(K^*+E)}{K^*+E+4-1}=\frac{r_b\times(K+E)}{K+E+3}=$$

$$\frac{0,6(K^*+E)}{K^*+E+3}$$

$$\frac{0.3}{\dfrac{0.6(K^*+E)}{K^*+E+3}}=\frac{0.3(K^*+E)+1.5}{0.6(K\quad+E)}<1\Rightarrow 1.5<0.3(K^*+E)\Rightarrow K^*+E>5$$

2. According to step 1, firstly take the value of E=0 and check different values of K^* for finding the optimal number of kanbans.

   For sample; for $K^*=6$, E=0, R=0, C=0 start trying the system. Then we will increase K^* value one a piece, at each increasing total cost of system will decrease. When the total cost of system starts to increase again, we will stop the system and take the value of K on the point where the total cost is minimum.

   We find the average number of backorders and inventories in the system from the equations;

$$\text{Average number of backorders}=\frac{\sum_{t=0}^{t}BO}{T}=\frac{1476392}{10000}=147,624 \tag{3.4}$$

$$\text{Average Inventory}=\frac{\sum_{t=0}^{t}I}{T}=\frac{70}{10000}=0,0069 \tag{3.5}$$

$$\text{TC(K)}=\left(WIPC(K)\times\sum_{t=0}^{t}\overline{WIP}(K)\right)+(\overline{BO}(K)\times P)+(\bar{I}(K)*IC) \tag{3.6}$$

$$\text{TC(K+1)}=\left(WIPC(K+1)\times\sum_{t=0}^{t}\overline{WIP}(K+1)\right)+(\overline{BO}(K+1)\times P)+(\bar{I}(K+1)*IC)$$

There will be 4 total cost value for each case. Because we have four different average cost value. If, TC(K+1)>TC(K) stop the system and take the result as the optimal value of kanban K. Also Figure 3.1 shows us the relationship between total cost and optimal kanban number in our adaptive kanban system.

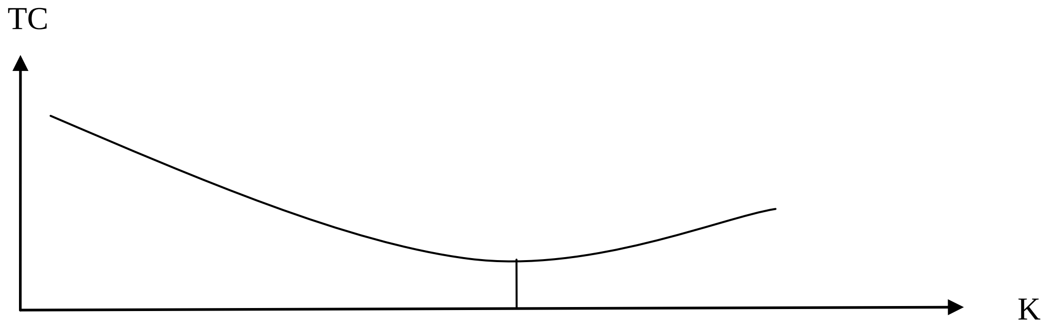


Figure 3.5: Relation Curve between optimal kanban number and total cost in a kanban controlled production system

3. While we are trying to find the optimal value of K, we find the performance measures which are WIP levels and utilization rates. The average WIP level at the stations can be calculated by dividing the total WIP in the station to the time that we use the system.

   Average WIP Level at i^{th} station = $\mathrm{WIP}_{wsi} = \dfrac{\sum_{t=0}^{t} WIPi}{T}$ (3.7)

   Filled WSi is the number of product produced in machine of station *i*. So we can calculate the utilization rate by dividing the filledWSi to time that we use the system.

   Utilization Rate at i^{th} station $= u = \dfrac{\sum_{t=0}^{t} FilledWSi}{T} \times 100$ (3.8)

4. Compare the results of those cases. Analyze the differences such as total costs, wip levels, utilization rates, between systems which are working with different number of kanban cards.

4. EXPERİMENTAL CASES AND RESULTS

4.1 EXPERİMENTAL CASES

According to all assumptions and conditions, we define some different cases and analyze them via simulation.

4.1.1 Case 1

4.1.1.1 Case 1-a

We assumed that;

λ_D= 0,4

λ_{P1}=0,8

λ_{P2}=0,8

λ_{P3}=0,8

λ_{P4}=0,8

Stability condition: $\lambda_D / \lambda_P(K+E) < 1$, so;

$$\lambda_P(K^*+E)=\frac{\min(\lambda p1,\lambda p2,\lambda p3,\lambda p4)\times(K^*+E)}{K^*+E+M-1}=\frac{r_b\times(K^*+E)}{K^*+E+4-1}=\frac{r_b\times(K+E)}{K+E+3}=$$

$$\frac{0{,}8(K^*+E)}{K^*+E+3}\Rightarrow\frac{0{,}4}{\frac{0{,}8(K^*+E)}{K^*+E+3}}<1\Rightarrow K^*+E>3\Rightarrow$$

starting value of $K=K^*=4$, E=0, R=0, C=0. With these variables we analyzed the model via simulation and found these results;

For K=4,E=0, R=0, C=0;

Average Total WIP

$$=\frac{WIP1+WIP2+WIP3+WIP4}{4}=\frac{10181+10112+9716+9925}{4}=9983{,}5$$

Average WIP Level at 1st station = $WIP_{ws1}=\frac{\sum_{t=0}^{t}WIP1}{T}=\frac{10181}{10000}=1{,}018$

Average WIP Level at 2nd station = $WIP_{ws2}=\frac{\sum_{t=0}^{t}WIP2}{T}=\frac{10112}{10000}=1{,}0112$

Average WIP Level at 3rd station = $\text{WIP}_{\text{ws3}} = \frac{\sum_{t=0}^{t} WIP3}{T} = \frac{9716}{10000} = 0{,}9716$

Average WIP Level at 4th station = $\text{WIP}_{\text{ws4}} = \frac{\sum_{t=0}^{t} WIP4}{T} = \frac{9925}{10000} = 0{,}9925$

Average number of backorders= $\frac{\sum_{t=0}^{t} BO}{T} = \frac{1476392}{10000} = 147{,}624$

Average Inventory= $\frac{\sum_{t=0}^{t} I}{T} = \frac{70}{10000} = 0{,}0069$

Average total WIP level= $\sum_{t=0}^{t} \overline{WIP}(K) = 1{,}018 + 1{,}0111 + 0{,}9715 + 0{,}9924 = 3{,}993$

Total cost of model;

For WIPC(K)=\$50, BO(K)=\$3000, and I(K)=\$1000;

TC(K)= $\left(WIPC(K) \times \sum_{t=0}^{t} \overline{WIP}(K)\right) + (\overline{BO}(K) \times P) + (\bar{I}(K) \times IC)$

TC(K)= $(50 \times 3{,}993) + (3000 \times 147{,}877) + (0{,}0069 \times 1000) = \$443.080$

For WIPC(K)=\$50, BO(K)=\$1500, and I(K)=\$1000;

TC(K)= $\left(WIPC(K) \times \sum_{t=0}^{t} \overline{WIP}(K)\right) + (\overline{BO}(K) \times P) + (\bar{I}(K) \times IC)$

TC(K)= $(50 \times 3{,}993) + (1500 \times 147{,}877) + (0{,}0069 \times 1000) = \$221.627$

For WIPC(K)=\$50, BO(K)=\$3000, and I(K)=\$500;

TC(K)= $\left(WIPC(K) \times \sum_{t=0}^{t} \overline{WIP}(K)\right) + (\overline{BO}(K) \times P) + (\bar{I}(K) \times IC)$

TC(K)= $(50 \times 3{,}993) + (3000 \times 147{,}877) + (0{,}0069 \times 500) = \$443.045$

For WIPC(K)=\$25, BO(K)=\$3000, and I(K)=\$1000;

TC(K)= $\left(WIPC(K) \times \sum_{t=0}^{t} \overline{WIP}(K)\right) + (\overline{BO}(K) \times P) + (\bar{I}(K) \times IC)$

TC(K)= $(25 \times 3{,}993) + (3000 \times 147{,}877) + (0{,}0069 \times 1000) = \$442.954$

Utilization Rate at 1st station = $u = \frac{\sum_{t=0}^{t} FilledWS1}{T} \times 100 = 0{,}7014 = \%70{,}14$

Utilization Rate at 2nd station = $u = \frac{\sum_{t=0}^{t} FilledWS2}{T} \times 100 = 0{,}7025 = \%70{,}25$

Utilization Rate at 3rd station = $u = \frac{\sum_{t=0}^{t} FilledWS3}{T} \times 100 = 0{,}6919 = \%69{,}19$

Utilization Rate at 4th station = $u = \frac{\sum_{t=0}^{t} FilledWS4}{T} \times 100 = 0{,}6950 = \%69{,}50$

According to the results of the first trial of the system we can not say this is the optimal value of kanban cards in the system. So we have to try the system for the value of K^*+1 to see the difference between performance measures, especially the total cost.

The second trial for finding the optimal number of kanban is done by increasing K^* one. So we tried simulation for; K=5, E=0, R=0, C=0.

Average Total WIP

$$= \frac{WIP1 + WIP2 + WIP3 + WIP4}{4} = \frac{11723 + 11314 + 11462 + 11521}{4} = 11505$$

Average WIP Level at 1st station = $WIP_{ws1} = \frac{\sum_{t=0}^{t} WIP1}{T} = \frac{11723}{10000} = 1{,}1723$

Average WIP Level at 2nd station = $WIP_{ws2} = \frac{\sum_{t=0}^{t} WIP2}{T} = \frac{11314}{10000} = 1{,}1314$

Average WIP Level at 3rd station = $WIP_{ws3} = \frac{\sum_{t=0}^{t} WIP3}{T} = \frac{11462}{10000} = 1{,}1462$

Average WIP Level at 4th station = $WIP_{ws4} = \frac{\sum_{t=0}^{t} WIP4}{T} = \frac{11521}{10000} = 1{,}1521$

Average number of backorders= $\frac{\sum_{t=0}^{t} BO}{T} = \frac{49684}{10000} = 4{,}97$

Average Inventory= $\frac{\sum_{t=0}^{t} I}{T} = \frac{3976}{10000} = 0,398$

Average total WIP level = $\sum_{t=0}^{t} \overline{WIP}(K) = \frac{1,1723 + 1,1314 + 1,1462 + 1,1521}{4} = 4,601$

Total cost of model;

For WIPC(K)=\$50, BO(K)=\$3000, and I(K)=\$1000;

TC(K+1)= $\left(WIPC(K+1) \times \sum_{t=0}^{t} \overline{WIP}(K+1) \right) + (\overline{BO}(K+1) \times P) + (\bar{I}(K+1) * IC)$

TC(K)= $(50 \times 4,601) + (3000 \times 4,97) + (0,398 \times 1000) = \$15.531$

For WIPC(K)=\$50, BO(K)=\$1500, and I(K)=\$1000;

TC(K+1)= $\left(WIPC(K+1) \times \sum_{t=0}^{t} \overline{WIP}(K+1) \right) + (\overline{BO}(K+1) \times P) + (\bar{I}(K+1) * IC)$

TC(K)= $(50 \times 4,601) + (1500 \times 4,97) + (0,398 \times 1000) = \$8.058$

For WIPC(K)=\$50, BO(K)=\$3000, and I(K)=\$500;

TC(K+1)= $\left(WIPC(K+1) \times \sum_{t=0}^{t} \overline{WIP}(K+1) \right) + (\overline{BO}(K+1) \times P) + (\bar{I}(K+1) * IC)$

TC(K)= $(50 \times 4,601) + (3000 \times 4,97) + (0,398 \times 500) = \$15.291$

For WIPC(K)=\$25, BO(K)=\$3000, and I(K)=\$1000;

TC(K+1)= $\left(WIPC(K+1) \times \sum_{t=0}^{t} \overline{WIP}(K+1) \right) + (\overline{BO}(K+1) \times P) + (\bar{I}(K+1) * IC)$

TC(K)= $(25 \times 4,601) + (3000 \times 4,97) + (0,398 \times 1000) = \$15.186$

Utilization Rate at 1st station = $u = \frac{\sum_{t=0}^{t} FilledWS1}{T} \times 100 = 0,7396 = \%73,96$

Utilization Rate at 2nd station = $u = \frac{\sum_{t=0}^{t} FilledWS2}{T} \times 100 = 0,7328 = \%73,28$

Utilization Rate at 3rd station = $u = \frac{\sum_{t=0}^{t} FilledWS3}{T} \times 100 = 0,7335 = \%73,35$

Utilization Rate at 4th station = $u = \dfrac{\sum_{t=0}^{t} FilledWS4}{T} \times 100 = 0{,}7309 = \%73{,}09$

According to the results of simulation which is tried for K=5, E=0, R=0, C=0, we noticed that the total cost has rapidly decreased, the average number of backorders has decreased, and also, the average inventory has increased. But these results are not enough to find the optimal value of kanban cards. As we said before we have to try it until the total cost increase again.

The third trial of system is for; K=6, E=0, R=0, C=0 and the results are as follows;

Average Total WIP

$$= \frac{WIP1 + WIP2 + WIP3 + WIP4}{4} = \frac{12066 + 11783 + 12074 + 11938}{4} = 11965{,}25$$

Average WIP Level at 1st station = WIP$_{\text{ws1}}$= $\dfrac{\sum_{t=0}^{t} WIP1}{T} = \dfrac{12066}{10000} = 1{,}206$

Average WIP Level at 2nd station = WIP$_{\text{ws2}}$= $\dfrac{\sum_{t=0}^{t} WIP2}{T} = \dfrac{11783}{10000} = 1{,}193$

Average WIP Level at 3rd station = WIP$_{\text{ws3}}$= $\dfrac{\sum_{t=0}^{t} WIP3}{T} = \dfrac{12074}{10000} = 1{,}207$

Average WIP Level at 4th station = WIP$_{\text{ws4}}$= $\dfrac{\sum_{t=0}^{t} WIP4}{T} = \dfrac{11938}{10000} = 1{,}193$

Average number of backorders= $\dfrac{\sum_{t=0}^{t} BO}{T} = \dfrac{13588}{10000} = 1{,}3586$

Average Inventory= $\dfrac{\sum_{t=0}^{t} I}{T} = \dfrac{12104}{10000} = 1{,}2102$

Average total WIP level = $\sum_{t=0}^{t} \overline{WIP}(K) = \dfrac{1{,}206 + 1{,}178 + 1{,}207 + 1{,}193}{4} = 4{,}785$

Total cost of model;

For WIPC(K)=\$50, BO(K)=\$3000, and I(K)=\$1000;

$$\text{TC(K)= } \left(WIPC(K) \times \sum_{t=0}^{t} \overline{WIP}(K) \right) + (\overline{BO}(K) \times P) + (\bar{I}(K) * IC)$$

$$\text{TC(K)= } \left(50 \times 4{,}785\right) + (3000 \times 1{,}3586) + (1{,}2102 \times 1000) = \$5.526$$

For WIPC(K)=$50, BO(K)=$1500, and I(K)=$1000;

$$\text{TC(K)= } \left(WIPC(K) \times \sum_{t=0}^{t} \overline{WIP}(K) \right) + (\overline{BO}(K) \times P) + (\bar{I}(K) * IC)$$

$$\text{TC(K)= } \left(50 \times 4{,}785\right) + (1500 \times 1{,}3586) + (1{,}2102 \times 1000) = \$3.464$$

For WIPC(K)=$50, BO(K)=$3000, and I(K)=$500;

$$\text{TC(K)= } \left(WIPC(K) \times \sum_{t=0}^{t} \overline{WIP}(K) \right) + (\overline{BO}(K) \times P) + (\bar{I}(K) * IC)$$

$$\text{TC(K)= } \left(50 \times 4{,}785\right) + (3000 \times 1{,}3586) + (1{,}2102 \times 500) = \$4.875$$

For WIPC(K)=$25, BO(K)=$3000, and I(K)=$1000;

$$\text{TC(K)= } \left(WIPC(K) \times \sum_{t=0}^{t} \overline{WIP}(K) \right) + (\overline{BO}(K) \times P) + (\bar{I}(K) * IC)$$

$$\text{TC(K)= } \left(25 \times 4{,}785\right) + (3000 \times 1{,}3586) + (1{,}2102 \times 1000) = \$4.766$$

Utilization Rate at 1st station = $u = \dfrac{\sum_{t=0}^{t} FilledWS1}{T} \times 100 = 0{,}7391 = \%73{,}91$

Utilization Rate at 2nd station = $u = \dfrac{\sum_{t=0}^{t} FilledWS2}{T} \times 100 = 0{,}7301 = \%73{,}01$

Utilization Rate at 3rd station = $u = \dfrac{\sum_{t=0}^{t} FilledWS3}{T} \times 100 = 0{,}7310 = \%73{,}10$

Utilization Rate at 4th station = $u = \dfrac{\sum_{t=0}^{t} FilledWS4}{T} \times 100 = 0{,}7234 = \%72{,}34$

The results of third trial shows that the total cost is still decreasing. So we have to try the system for the fourth time. The fourth trial of system is for K=7, E=0, R=0, C=0. The results fort his trial are as follows;

Average Total WIP

$$=\frac{WIP1+WIP2+WIP3+WIP4}{4}=\frac{12329+12106+12517+12288}{4}=12310$$

Average WIP Level at 1st station = WIP_{ws1}= $\frac{\sum_{t=0}^{t} WIP1}{T}=\frac{12329}{10000}=1{,}233$

Average WIP Level at 2nd station = WIP_{ws2}= $\frac{\sum_{t=0}^{t} WIP2}{T}=\frac{12106}{10000}=1{,}211$

Average WIP Level at 3rd station = WIP_{ws3}= $\frac{\sum_{t=0}^{t} WIP3}{T}=\frac{12517}{10000}=1{,}252$

Average WIP Level at 4th station = WIP_{ws4}= $\frac{\sum_{t=0}^{t} WIP4}{T}=\frac{12288}{10000}=1{,}229$

Average number of backorders= $\frac{\sum_{t=0}^{t} BO}{T}=\frac{5250}{10000}=0{,}525$

Average Inventory= $\frac{\sum_{t=0}^{t} I}{T}=\frac{20708}{10000}=2{,}071$

Average total WIP level = $\sum_{t=0}^{t}\overline{WIP}(K)=\frac{1{,}1723+1{,}1314+1{,}1462+1{,}1521}{4}=4{,}601$

Total cost of model;

For WIPC(K)=\$50, BO(K)=\$3000, and I(K)=\$1000;

TC(K)= $\left(WIPC(K)\times\sum_{t=0}^{t}\overline{WIP}(K)\right)+(\overline{BO}(K)\times P)+(\bar{I}(K)*IC)$

TC(K)= $(50\times 4{,}923)+(3000\times 0{,}525)+(2{,}071\times 1000)=\$3.892$

For WIPC(K)=\$50, BO(K)=\$1500, and I(K)=\$1000;

TC(K)= $\left(WIPC(K)\times\sum_{t=0}^{t}\overline{WIP}(K)\right)+(\overline{BO}(K)\times P)+(\bar{I}(K)*IC)$

TC(K)= $(50\times 4{,}923)+(1500\times 0{,}525)+(2{,}071\times 1000)=\$3.079$

For WIPC(K)=\$50, BO(K)=\$3000, and I(K)=\$500;

TC(K)= $\left(WIPC(K)\times\sum_{t=0}^{t}\overline{WIP}(K)\right)+(\overline{BO}(K)\times P)+(\bar{I}(K)*IC)$

TC(K)= $\left(60\times 4{,}923\right)+(3000\times 0{,}525)+(2{,}071\times 500)=\$2.807$

For WIPC(K)=\$25, BO(K)=\$3000, and I(K)=\$1000;

TC(K)= $\left(WIPC(K)\times\sum_{t=0}^{t}\overline{WIP}(K)\right)+(\overline{BO}(K)\times P)+(\bar{I}(K)*IC)$

TC(K)= $\left(25\times 4{,}923\right)+(3000\times 0{,}525)+(2{,}071\times 1000)=\$2.696$

Utilization Rate at 1st station = $u=\frac{\sum_{t=0}^{t}FilledWS1}{T}\times 100=0{,}7359=\%73{,}59$

Utilization Rate at 2nd station = $u=\frac{\sum_{t=0}^{t}FilledWS2}{T}\times 100=0{,}7280=\%72{,}80$

Utilization Rate at 3rd station = $u=\frac{\sum_{t=0}^{t}FilledWS3}{T}\times 100=0{,}7288=\%72{,}88$

Utilization Rate at 4th station = $u=\frac{\sum_{t=0}^{t}FilledWS4}{T}\times 100=0{,}7201=\%72{,}01$

As we can see from the results of the fourth trial, the total cost is still decreasing. We had to try the system one more time, for the values of K=8, E=0, R=0, C=0. As a result of this trial, we noticed these results;

Average Total WIP

$$=\frac{WIP1+WIP2+WIP3+WIP4}{4}=\frac{12704+12466+12794+12389}{4}=12588{,}25$$

Average WIP Level at 1st station = $WIP_{ws1}=\frac{\sum_{t=0}^{t}WIP1}{T}=\frac{12704}{10000}=1{,}270$

Average WIP Level at 2nd station = $WIP_{ws2}=\frac{\sum_{t=0}^{t}WIP2}{T}=\frac{12466}{10000}=1{,}247$

Average WIP Level at 3rd station = $WIP_{ws3}=\frac{\sum_{t=0}^{t}WIP3}{T}=\frac{12794}{10000}=1{,}279$

Average WIP Level at 4th station = WIP$_{ws4}$= $\frac{\sum_{t=0}^{t} WIP4}{T} = \frac{12389}{10000} = 1{,}239$

Average number of backorders= $\frac{\sum_{t=0}^{t} BO}{T} = \frac{2631}{10000} = 0{,}2631$

Average Inventory= $\frac{\sum_{t=0}^{t} I}{T} = \frac{29544}{10000} = 2{,}954$

Average total WIP level= $\sum_{t=0}^{t} \overline{WIP}(K) = 1{,}270 + 1{,}246 + 1{,}279 + 1{,}239 = 5{,}0355$

Total cost of model;

For WIPC(K)=$50, BO(K)=$3000, and I(K)=$1000;

TC(K)= $\left(WIPC(K) \times \sum_{t=0}^{t} \overline{WIP}(K) \right) + (\overline{BO}(K) \times P) + (\bar{I}(K) * IC)$

TC(K)= $(50 \times 5{,}0355) + (3000 \times 0{,}2631) + (2{,}954 \times 1000) = \$3.995$

For WIPC(K)=$50, BO(K)=$1500, and I(K)=$1000;

TC(K)= $\left(WIPC(K) \times \sum_{t=0}^{t} \overline{WIP}(K) \right) + (\overline{BO}(K) \times P) + (\bar{I}(K) * IC)$

TC(K)= $(50 \times 5{,}0355) + (1500 \times 0{,}2631) + (2{,}954 \times 1000) = \$3.574$

For WIPC(K)=$50, BO(K)=$3000, and I(K)=$500;

TC(K)= $\left(WIPC(K) \times \sum_{t=0}^{t} \overline{WIP}(K) \right) + (\overline{BO}(K) \times P) + (\bar{I}(K) * IC)$

TC(K)= $(50 \times 5{,}0355) + (3000 \times 0{,}2631) + (2{,}954 \times 500) = \$2.465$

For WIPC(K)=$25, BO(K)=$3000, and I(K)=$1000;

TC(K)= $\left(WIPC(K) \times \sum_{t=0}^{t} \overline{WIP}(K) \right) + (\overline{BO}(K) \times P) + (\bar{I}(K) * IC)$

TC(K)= $(25 \times 5{,}0355) + (3000 \times 0{,}2631) + (2{,}954 \times 1000) = \$2.352$

Utilization Rate at 1st station = $u = \frac{\sum_{t=0}^{t} FilledWS1}{T} \times 100 = 0{,}7346 = \%73{,}46$

$$\text{Utilization Rate at } 2^{nd} \text{ station} = u = \frac{\sum_{t=0}^{t} FilledWS2}{T} \times 100 = 0{,}7290 = \%72{,}9$$

$$\text{Utilization Rate at } 3^{rd} \text{ station} = u = \frac{\sum_{t=0}^{t} FilledWS3}{T} \times 100 = 0{,}7293 = \%72{,}93$$

$$\text{Utilization Rate at } 4^{th} \text{ station} = u = \frac{\sum_{t=0}^{t} FilledWS4}{T} \times 100 = 0{,}7180 = \%71{,}80$$

These results show us that the total cost of the system in the fifth trial has increased so we have to stop trying the system. The optimal number of kanban is K=7 for the first case. Also, we can see the variations of performance measures such as WIP levels, total costs, average backorder and inventory levels and utilization rates between the different trials of Case 1-a. The variations of WIP levels for each trial of the system are shown in Figure 4.1 and the variations of backorders and inventory levels of the system for different numbers of kanbans are shown in Figure 4.2. Also, the total costs of each trial for Case 1-a are shown in Figure 4.3. Also, variables which have been tried with simulation to find the optimal kanban number for Case 1-a are shown in Table 4.1.

Table 4.1: Trial values of Case 1-a

Trial No	K	E	R	C
1	4	0	0	0
2	5	0	0	0
3	6	0	0	0
4	7	0	0	0
5	8	0	0	0

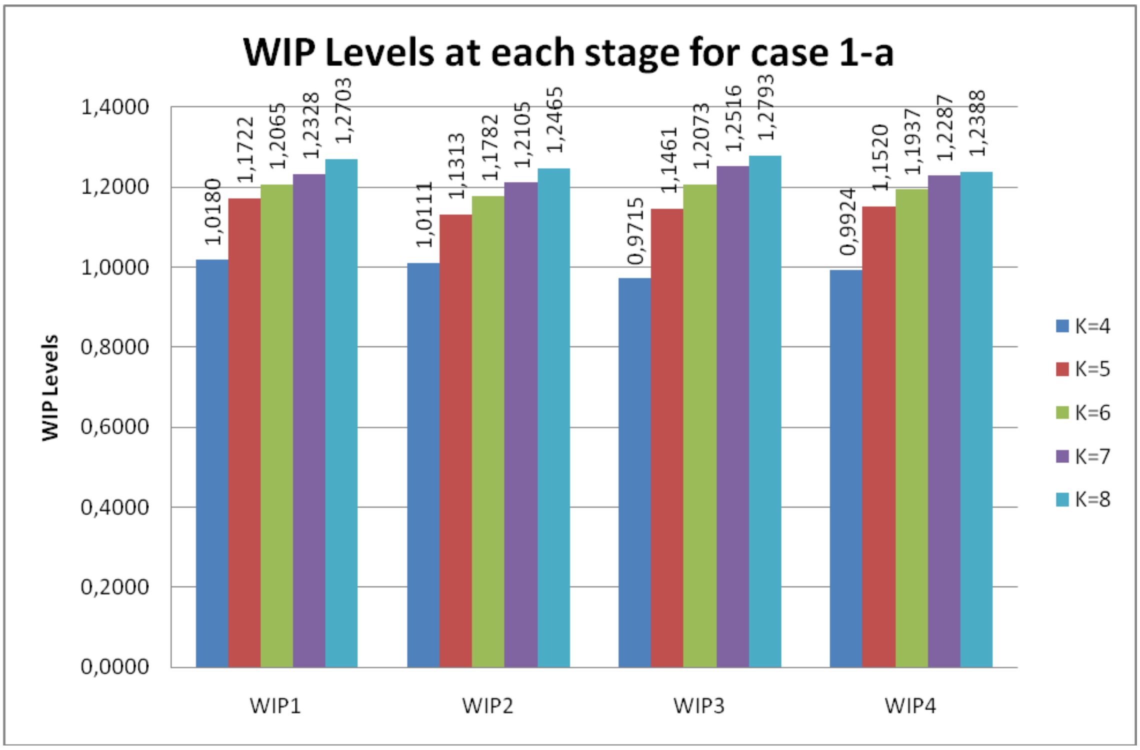


Figure 4.1: WIP Levels variations at each stage for Case 1-a

Considering the calculation results of Case 1-a, we can say that our system is infeasible for K=4 because the system can not satisfy customer demands. Since the system can not produce enough for K=4, the system's WIP levels get lower. We can see from the Figure 4.1 that increasing the number of kanbans to 5 causes a rapid increase in WIP levels at each station. We can notice that when the number of kanbans increase in a kanban controlled production system, the average WIP levels at each stage increases, too. For a production system, the total cost is one of the most important measure to choose the optimal system. As we mentioned in the equation (3.6), to calculate the total cost of the system we have to know the number of backorders and inventory levels of the system. These parameters are important to optimize the system. The variations of backordered demands and inventory levels for different numbers of kanbans in the system are shown in Figure 4.2.

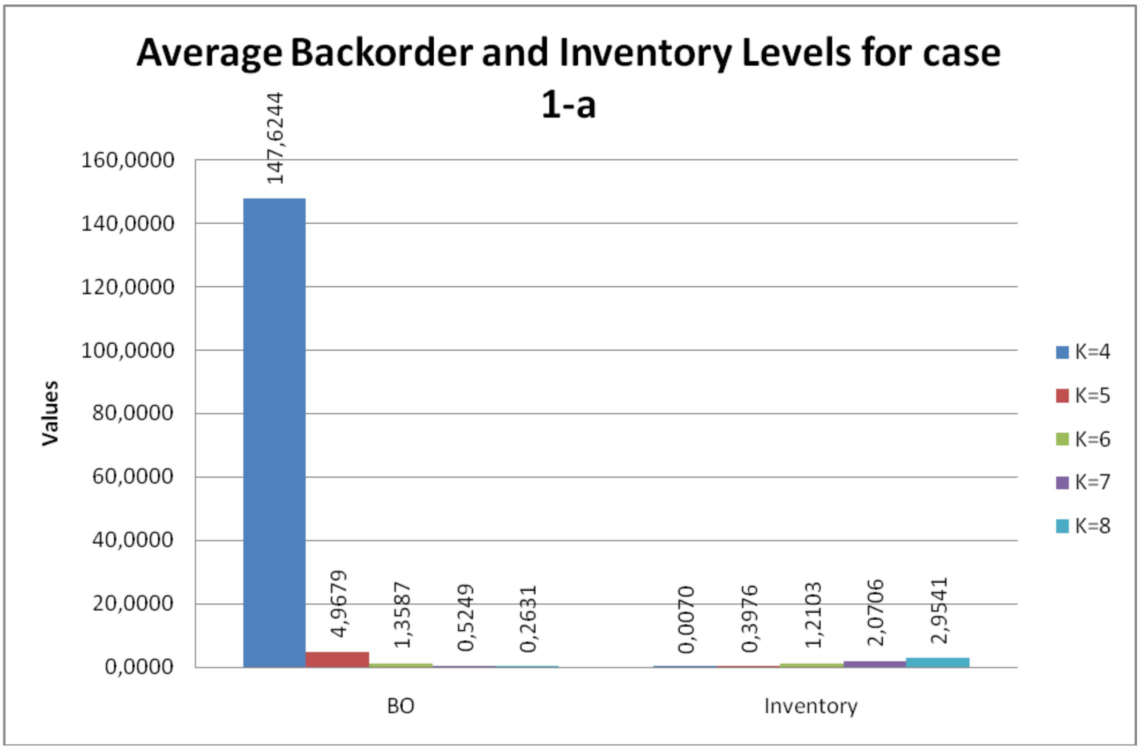


Figure 4.2: Average backorder and inventory variation for Case 1-a

As we can see from the figure in the first trial which is for K= 4, the system can not satisfy the demand on time and too much backordered demand exists in the system. This would cause an increase in the total cost of the system. As we noticed before, for K=4 our system is infeasible to implement, because the backorder level is too high. Increasing kanban number decreases the number of average backorder in the system, but it increases the inventory level of system. These variations on backorders and inventory levels affect the system's total cost. Total cost values of the system for different numbers of kanbans in Case 1-a are shown in Figure 4.4.

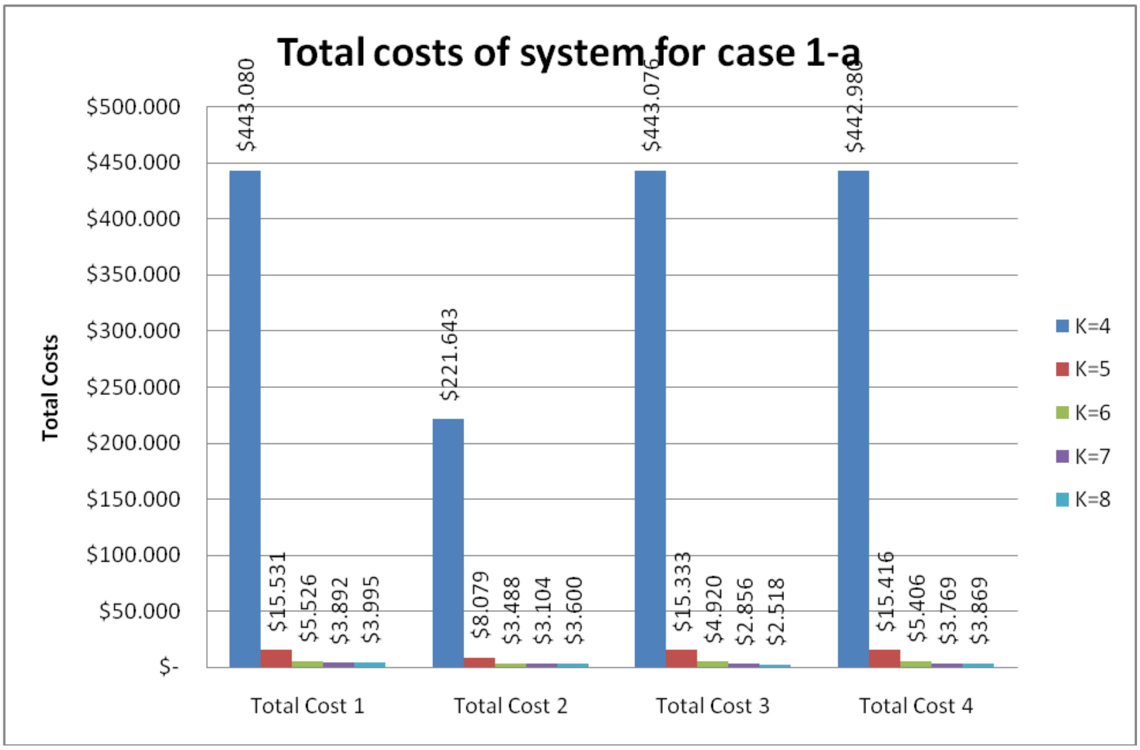


Figure 4.3: Total costs variations of system for Case 1-a

The figure 4.4 helps us to see the variations of the total cost for different numbers of kanbans and different cost parameters in the system. For the first cost parameters, the minimum total cost of the system is obtained when kanban number is 7. We assume that the optimal K is equal to 7 for traditional system and we will take this value as optimal for our adaptive kanban system, too. As we noticed in Chapter 3, at each trial, we changed only one cost parameter to see which cost parameter is the most effective on the system. These results belong to a traditional kanban system, to make our system adaptive we have to add extra cards and analyze it via simulation.

4.1.1.2 Case 1-b

In the Case 1-b, we will try the system for the same production and demand arrival rates as in Case 1-a and we will use K number which we found as optimal value in Case 1-a. In this case, we will add extra cards to the system and assume constant numbers for release and capture thresholds. We will only change the number of extra cards which we add to the system. We created 2 different variable sets for Case 1-b and tried them via simulation. The variable sets of Case 1-b which we will try via simulation are shown in Table 4.2. After taking the results of Case 1-b we will compare it with the first case's optimal results. In this case, we will focus on the effect of adding an extra card to the system on the performance measures of system such as total cost, utilization rates, backorders and inventory levels, and WIP levels.

Table 4.2: Trial values of Case 1-b

Trial No	K	E	R	C
1	7	2	1	2
2	7	10	1	2

We used the same equations such as (3.1), (3.2), (3.3), (3.4), (3.5) and (3.6) to find the results. According to the results of Case 1-b, WIP levels at each stage for Case 1-b are shown in table 4.3, the values of utilization rates of system for Case 1-b are shown in Table 4.4, number of backordered demands and inventory levels of system for Case 1-b are shown in Table 4.5 and at the end of Case 1-b, total cost values are shown in Table 4.6.

Table 4.3: WIP levels at each stage for Case 1-b

Trial No	WIP1	WIP2	WIP3	WIP4
1	1,5370463	1,42515748	1,39366063	1,330366963
2	2,12878712	1,52824718	1,54554545	1,363563644

Table 4.4: Utilization rates of Case 1-b at each stage for each trial

Trial No	U1	U2	U3	U4
1	73,09%	74,04%	74,02%	73,14%
2	73,51%	68,99%	73,65%	72,12%

Table 4.5: Number of backordered demands and inventory levels for Case 1-b

Trial No	Backorder	Inventory
1	0,335766	2,246475
2	0,285571	2,957604

Table 4.6: Total cost values of Case 1-b at each stage for each trial

Trial No	Total Cost 1	Total Cost 2	Total Cost 3	Total Cost 4
1	$3.538	$3.034	$2.415	$3.396
2	$ 4.143	$3.714	$2.664	$3.978

The effect of extra cards on the system's performance measures is the most important result for our thesis. WIP levels at each station for the trials of Case 1-b are shown in Figure 4.4.

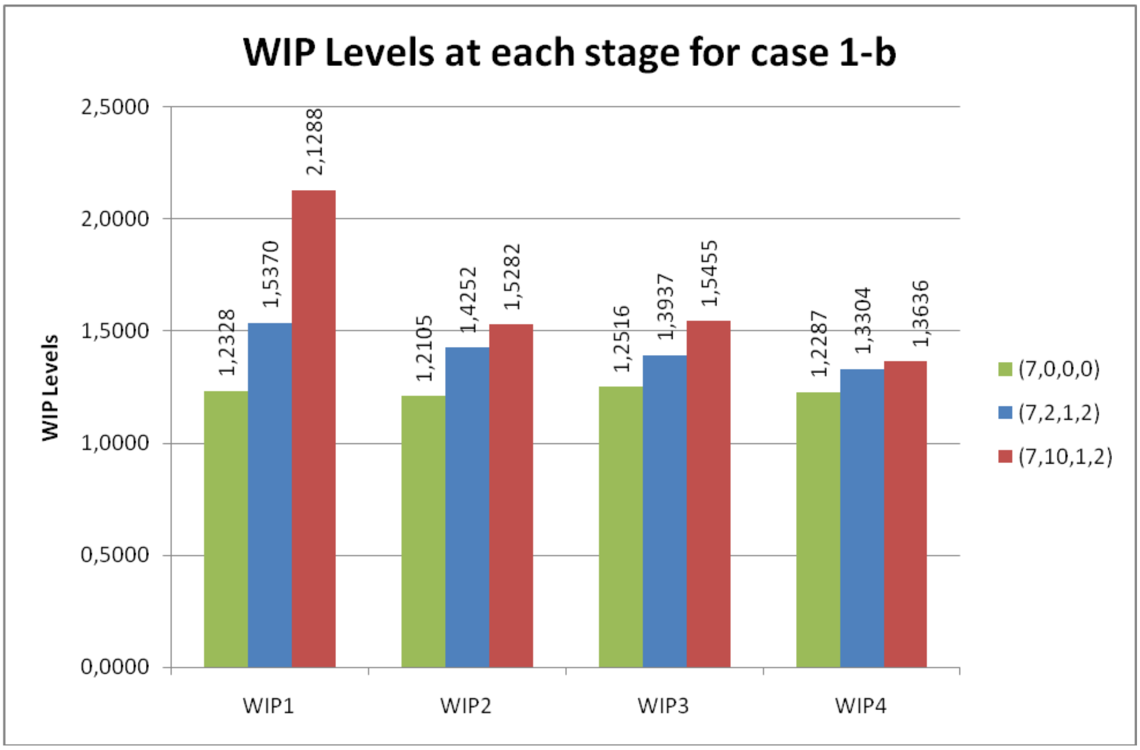


Figure 4.4: WIP levels variation for Case 1-b

As we can see from the Figure 4.5, adding extra cards to a traditional kanban system enables the system to produce more and therefore, WIP levels at each station increase. Another important performance measure for our system is the total cost of the sytem. To find the total cost of the system, we have to know the number of backorders and inventory levels. The variations of backorders and inventory levels are shown in Figure 4.5.

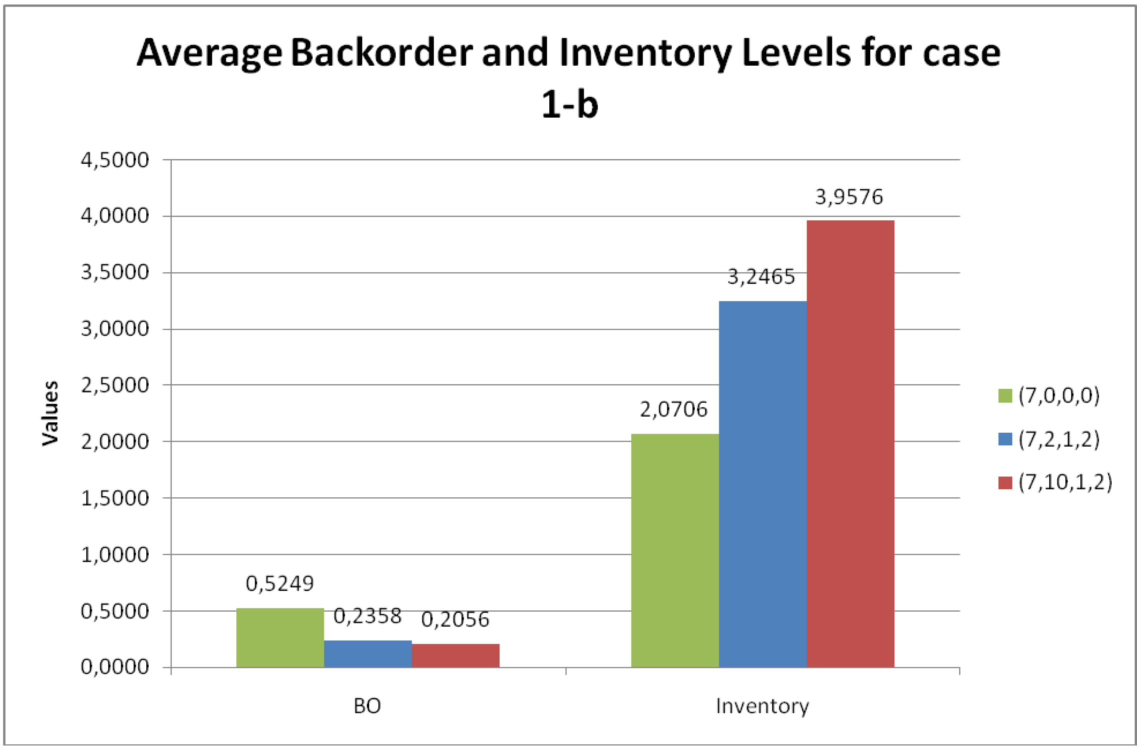


Figure 4.5: Average backorder and inventory variation for Case 1-b

According to this figure, we can say that adding extra card to the system helps the system to decrease backorders. This means our system is more adapted to unstable changes rather than a traditional kanban system. When we add extra cards to the system, the system produces more product and inventory levels of the system increase. Another point in this case, when we increase the number of extra kanban cards in the system, the system holds to decrease backorders and increase inventory levels. These variations cause change in the total cost of the system. Differences between the total costs of the system and optimal cost of traditional system are shown in Figure 4.6.

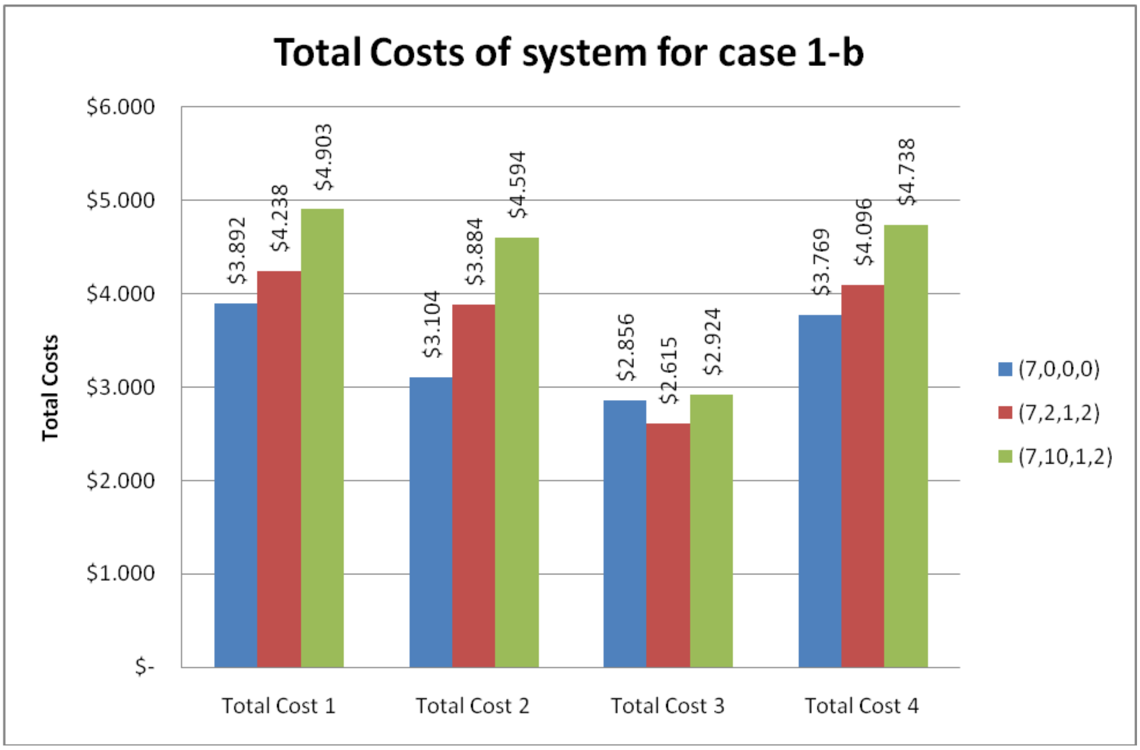


Figure 4.6: Total Costs variations of system for Case 1-b

As we can see from Figure 4.7, adding extra cards to the traditional system enables the system to change the total costs. When we add extra cards, generally total costs of the system increase because the decrease rate of backorders and the increase rate of inventory levels are not equal. The increase rate of the inventory is higher than the decrease rate of backorders in the system so inventory costs increase in the system. When we decrease the cost parameter of inventory, the total cost of traditional kanban system decreases when 2 extra kanban cards are added. As a result of all these comments, we can say that for case 1-b the most effective cost parameter is the cost of the inventory levels. When we decrease the cost of the inventory levels, the system becomes more optimal.

We can not say these conditions are optimal for our adaptive system. We have to try our system for different conditions and see the variations in the performance measures. According to this, we tried the system for different conditions in Case 1-c.

4.1.1.3 Case 1-c

In Case 1-a and Case 1-b, we have changed different parameters to see the effect of these parameters on our adaptive kanban system’s performance measures. In Case 1-c, we expect the same production and demand rates as in Case 1-a and Case 1-b. In this case, we will only change the release threshold value which is represented by R. The number of kanban cards is equal to 7 and the number of extra cards is equal to 10. The capture threshold value will be constant and it is equal to 6. Two different values of R have been tried via simulation. The values which have been tried in Case 1-c are shown in Table 4.7.

Table 4.7: Trial values of Case 1-c

Trial No	K	E	R	C
1	7	10	1	6
2	7	10	5	6

After simulating the system, we calculated the new values of performance measures from the equations (3.1), (3.2),(3.3), (3.4), (3.5) and (3.6) as in Case 1-a and Case 1-b. The values of WIP levels, utilization rates, backorders and inventory levels, and the total costs which are the performance measures we have focused on, for Case 1-c are shown in Table 4.9, table 4.9, table 4.10 and 4.11.

Table 4.8: WIP levels at each stage for Case 1-c

Trial No	WIP1	WIP2	WIP3	WIP4
1	2,08609139	1,76712329	1,6210379	1,430856914
2	2,42925707	1,90990901	1,71472853	1,498950105

Table 4.9: Utilization rates at each stage for Case 1-c

Trial No	U1	U2	U3	U4
1	72,46%	73,03%	72,67%	71,71%
2	71,48%	71,13%	71,33%	70,29%

Table 4.10: Backorders and inventory levels for Case 1-c

Trial No	Backorder	Inventory
1	0,16588341	3,93810619
2	0,12578742	4,81461854

Table 4.11: Total cost of system for Case 1-c

Trial No	Total Cost 1	Total Cost 2	Total Cost 3	Total Cost 4
1	$4.781	$4.532	$2.812	$ 4.608
2	$5.570	$5.381	$3.162	$5.381

These results are also shown with figures to see the variations more easily. WIP levels at each station for this case are shown in Figure 4.7, the variation of backorders and inventory levels are shown in Figure 4.8 and the total costs for each trial of Case 1-c are shown in Figure 4.9.

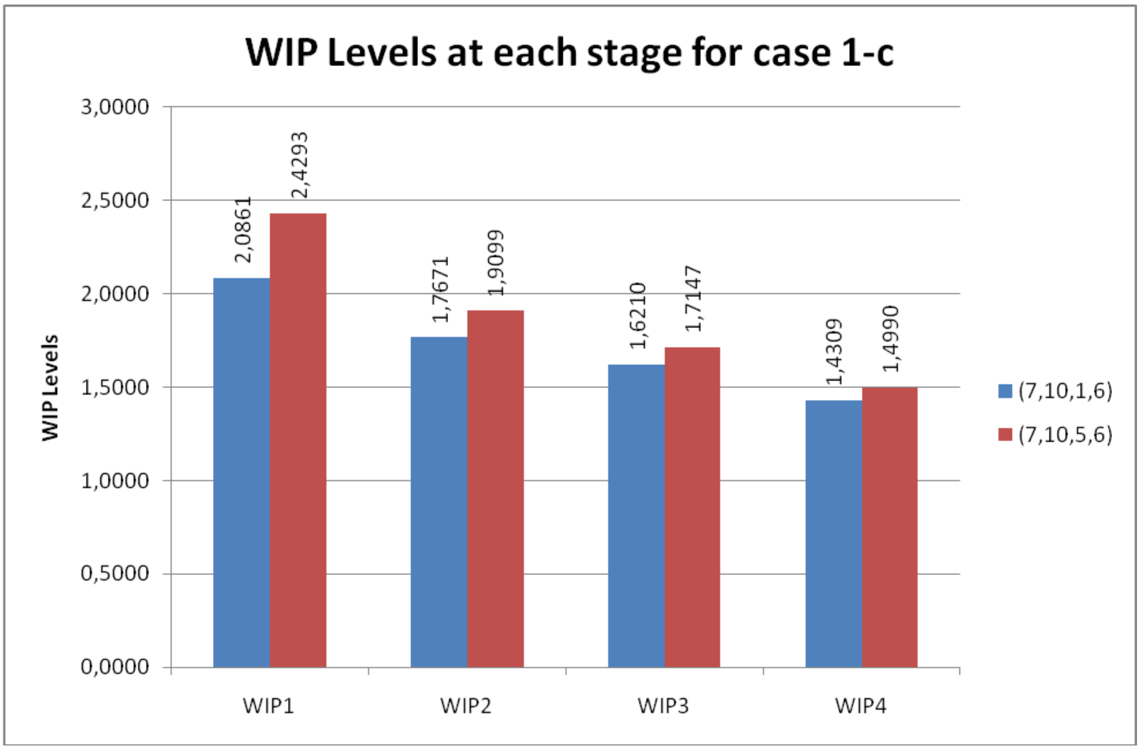


Figure 4.7: WIP levels variations at each station for Case 1-c

As we can see from the Figure 4.7, increasing release threshold value in the system causes to release extra cards to the manufacturing process earlier and because of that, WIP levels at each station increase.

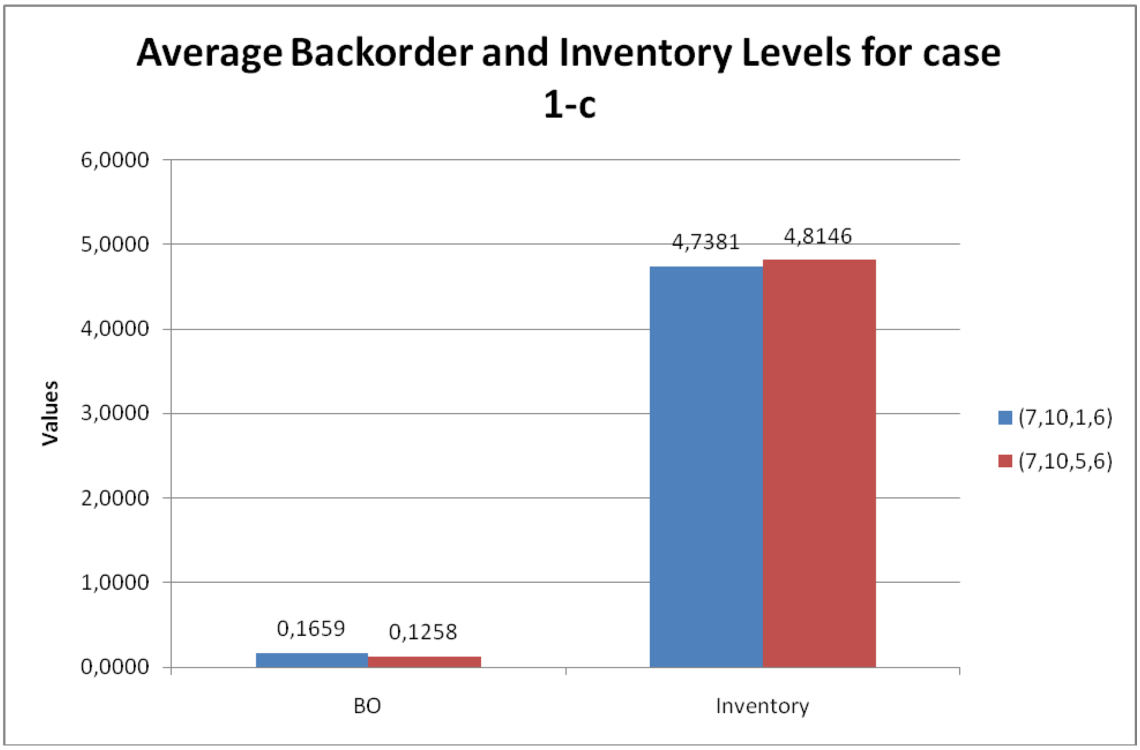


Figure 4.8: Average backorder and inventory levels variations for Case 1-c

As we can see in the Figure below, when we increase the value of release threshold in the system, backorders of the system and inventory levels of the system decrease.

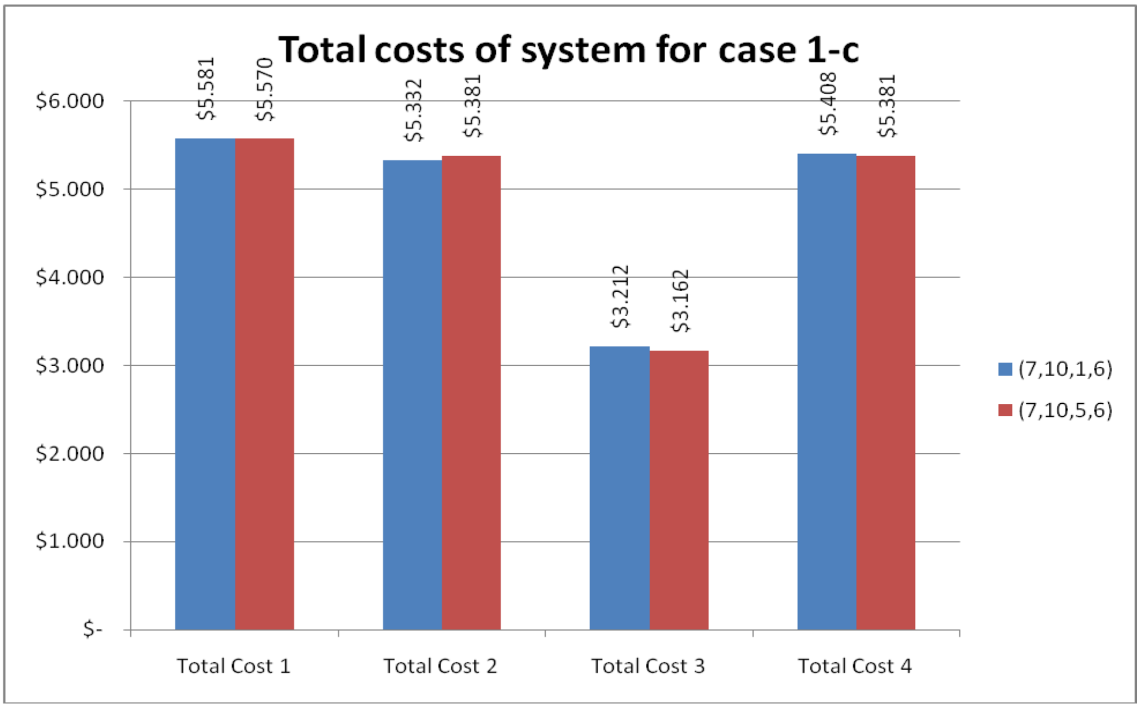


Figure 4.9: Total costs variations of system for Case 1-c

Increasing the value of R in our adaptive system increases WIP levels and inventory levels, as we have seen before in Figure 4.7 and 4.8. Figure 4.10 helps us to see the changes in the total costs of the system. Increasing the release threshold value of the system does not directly affect the total costs of the system. As we can see from the figure below, the total costs of the system are similar. Again in this case the most effective cost parameter is the cost of inventory levels, because at the level of minimum inventory level cost the total cost of system is minimized. In all these cases, we tried to see the variations in performance measures by changing one parameter with the same production and demand rates. We only did not change capture threshold value in the system.

4.1.1.4 Case 1-d

In this case, we changed only capture threshold value of the system to see its' effect on the system's performance measures. K is equal to 7, E is equal to 10 and R is equal to 1 and these values are constant for this case. Again the production and demand rates are the same as in Case 1-a, b and c. The values which are tried via simulation of system are shown in table 4.12.

Table 4.12: The values of Case 1-d

Trial No	K	E	R	C
1	7	10	1	2
2	7	10	1	6

After simulating our adaptive system with our simulation, we calculated the new values for the trial values of Case 1-d. We have calculated the values of the system's performance measures by using the same equations as in other cases. As a result of Case 1-d, WIP levels at each station are shown in Table 4.13. Utilization rates at each station are shown in table 4.14, backorders, inventory levels are shown in Table 4.15, and total costs of system are shown in table 4.16.

Table 4.13: WIP levels at each stage for Case 1-d

Trial No	WIP1	WIP2	WIP3	WIP4
1	2,12878712	1,52824718	1,54554545	1,363563644
2	2,08609139	1,76712329	1,6210379	1,430856914

Table 4.14: Utilization rates at each stage for Case 1-d

Trial No	U1	U2	U3	U4
1	72,46%	73,03%	72,67%	71,71%
2	71,48%	71,13%	71,33%	70,29%

Table 4.15: Backorders and inventory levels for Case 1-d

Trial No	Backorder	Inventory
1	0,28557144	2,95760424
2	0,16588341	3,93810619

Table 4.16: Total costs of systems for Case 1-d

Trial No	Total Cost 1	Total Cost 2	Total Cost 3	Total Cost 4
1	\$4.143	\$3.714	\$2.664	\$3.978
2	\$4.781	\$4.532	\$2.812	\$4.608

To see the variations of performance measures more easily, we have to show them with figures. Variations of WIP levels at each station for Case 1-d are shown in Figure 4.10.

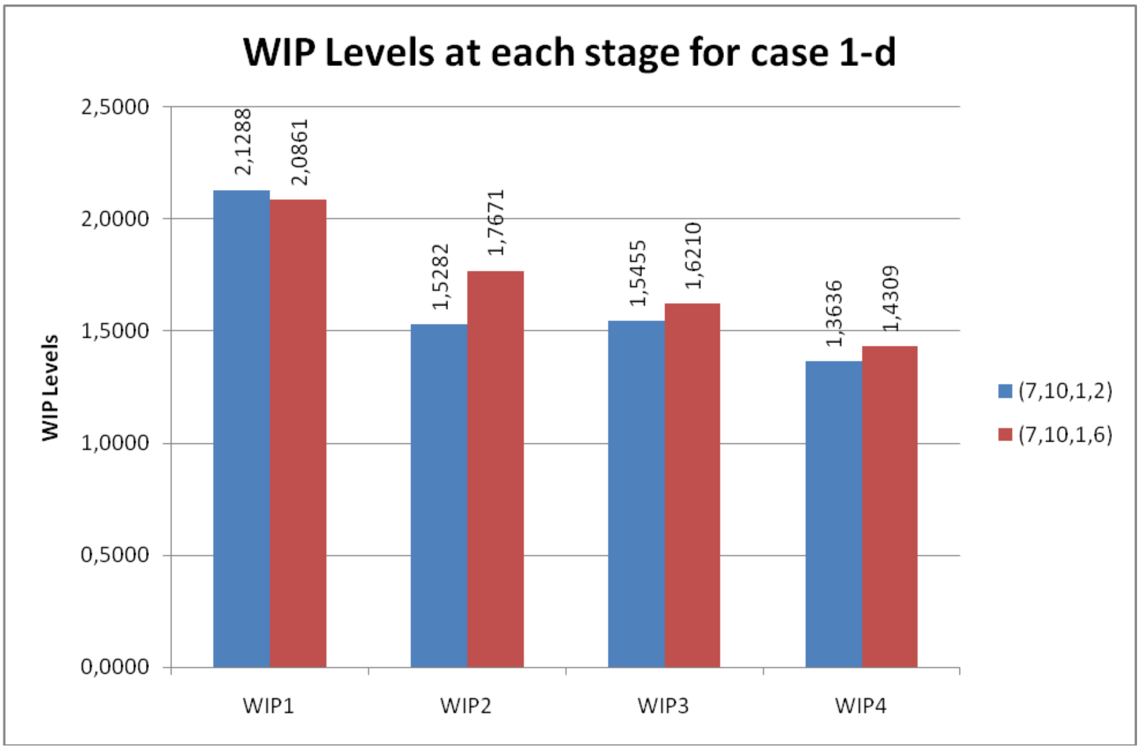


Figure 4.10: WIP levels variations at each station for Case 1-d

As we can see from the figure 4.10, increasing capture threshold does not directly affect the WIP levels of the system but generally WIP levels increase when we increase the capture threshold value of the system. Backorders and inventory levels variations are important points in Case 1-d. These variations are shown in Figure 4.11.

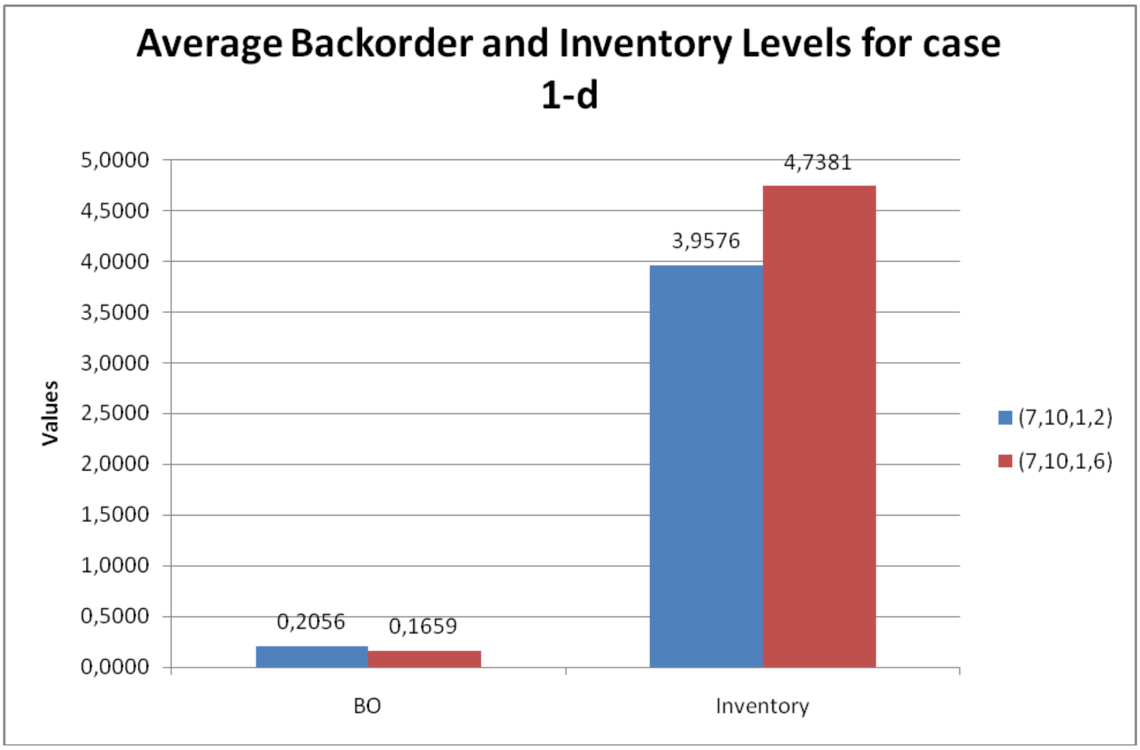


Figure 4.11: Average backorder and inventory variation for Case 1-d

The main effect of increasing capture threshold value is on inventory levels. Average inventory level of system increases when we increase the capture threshold because increasing capture threshold means holding finished containers in inventory for more time. The variations of total costs of the system for Case 1-d are shown in Figure 4.16.

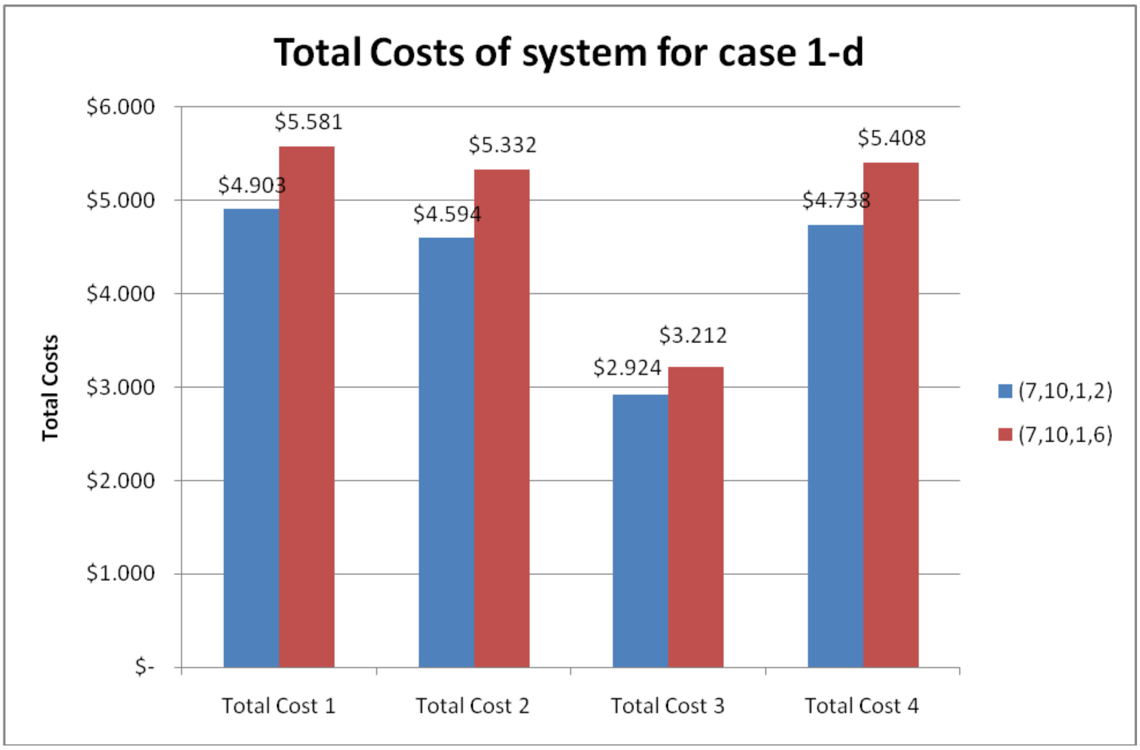


Figure 4.12: Total costs variations of system for Case 1-d

Increasing the value of C in our adaptive system causes increase because increasing C value means holding finished products in inventory for longer and this causes increase in inventory costs. Increase in inventory costs cause increase in total costs. Again in this case, the most effective cost parameter is the cost of inventory levels, because at the level of minimum inventory level cost, the total cost of system is minimized.

In all these cases, we assumed the same production and demand rates. We have to analyze our system for bottleneck cases because in real-life cases there may be a bottleneck workstation in the production system. To see the effects of bottleneck workstation in a kanban controlled adaptive production system we created new cases.

4.1.2 Case 2-Bottleneck Case for station 1

4.1.2.1 Case 2-a

In Case 2-a we made some new assumptions. These assumptions are as follows;

- Demand rate= λ_D=0,4
- Production rates;

- λ_{P1}=0,6=r_b
- λ_{P2}=0,8
- λ_{P3}=0,8
- λ_{P4}=0,8

Also these assumptions are used for Case 2-b, 7 and 8.

Stability condition for Case 2-a;

$\lambda_D / \lambda_P(K+E) < 1$, so;

$$\lambda_P(K^*+E)=\frac{\min(\lambda p1,\lambda p2,\lambda p3,\lambda p4)\times(K^*+E)}{K^*+E+M-1}=\frac{r_b\times(K^*+E)}{K^*+E+4-1}=\frac{r_b\times(K+E)}{K+E+3}=$$

$$\frac{0{,}6(K^*+E)}{K^*+E+3}\Rightarrow\frac{0{,}4}{\dfrac{0{,}6(K^*+E)}{K^*+E+3}}<1\Rightarrow K^*+E>6\Rightarrow$$

As we did in other cases again we will start our trials with finding the optimal kanban number for our system with assuming our system is a traditional system. then we will try different cases with adding extra cards and making system adaptive.

The first trial values for Case 2-a are shown in table 4.17.

Table 4.17: The trial values of Case 2-a

Trial No	**K**	**E**	**R**	**C**
1	7	0	0	0
2	8	0	0	0
3	9	0	0	0
4	10	0	0	0

These values are tried via simulation. In this case simulation get new process times and deman arrival times by using equations (3.1), (3.2), (3.3). according to new times and assumptions we analyzed system for the values in Table 4.17 and get new results for systems’ performance measures. WIP levels at each station for Case 2-a are shown in table 4.18, also utilization rates of each station for Case 2-a are shown in table 4.19, backorders and inventory level values are shown in Table 4.20 and total costs of system for each trial of Case 2-a are shown in table 4.21.

Table 4.18: WIP levels at each station for Case 1-d

Trial No	WIP1	WIP2	WIP3	WIP4
1	1,8335	1,3057	0,9965	1,3099
2	1,8778	1,3194	1,3357	1,3211
3	1,9333	1,3328	1,3609	1,3267
4	1,9644	1,3505	1,3704	1,3263

Table 4.19: Utilization rates at each station for Case 1-d

Trial No	U1	U2	U3	U4
1	83,83%	75,40%	63,05%	74,66%
2	83,84%	75,45%	75,34%	74,62%
3	83,69%	75,53%	75,29%	74,47%
4	83,63%	75,64%	75,31%	74,47%

Table 4.20: Backorders and inventory levels of system for Case 2-a

Trial No	Backorder	Inventory
1	1,5522	1,4841
2	1,0052	2,0400
3	0,5576	2,8802
4	0,3170	3,7648

Table 4.21: Total costs of system for Case 2-a

Trial No	Total Cost 1	Total Cost 2	Total Cost 3	Total Cost 4
1	$ 6.413	$4.085	$ 5.671	$ 6.277
2	$5.348	$3.840	$ 4.328	$ 5.202
3	$4.851	$4.014	$ 3.411	$ 4.702
4	$5.016	$ 4.541	$ 3.134	$ 4.866

To see the effects of different kanban number variations and defining optimal kanban number for system, the values of performance measures are shown with figures. WIP levels at each station are shown in Figure 4.17, variation of backorders and inventory levels are shown in Figure 4.19 and total cost values are shown in Figure 4.20.

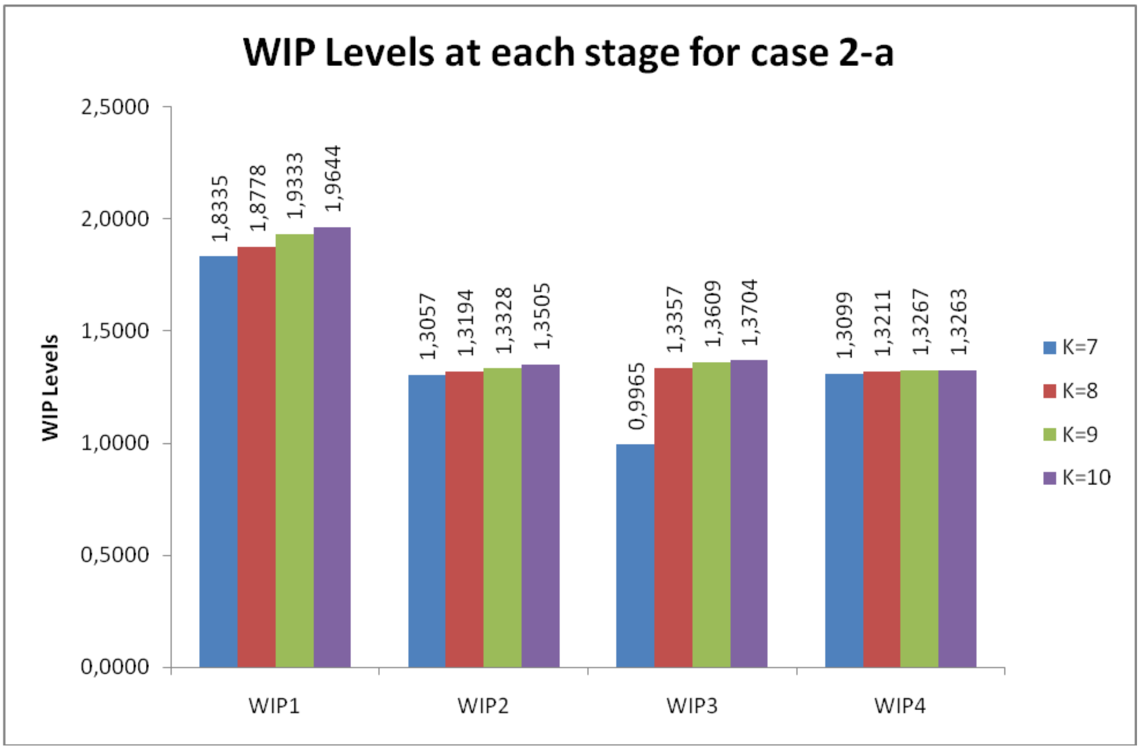


Figure 4.13: WIP levels variations at each station for Case 2-a

As we can see from figure 4.17 the WIP levels at the stations are similar in the trials of Case 2-a. The process times of station 1 are higher than the other stations, because station1 is the bottleneck station. Because of this, the highest WIP levels exist at the staton 1. When we increase the number of kanbans in the system, WIP levels does not have a rapid change.

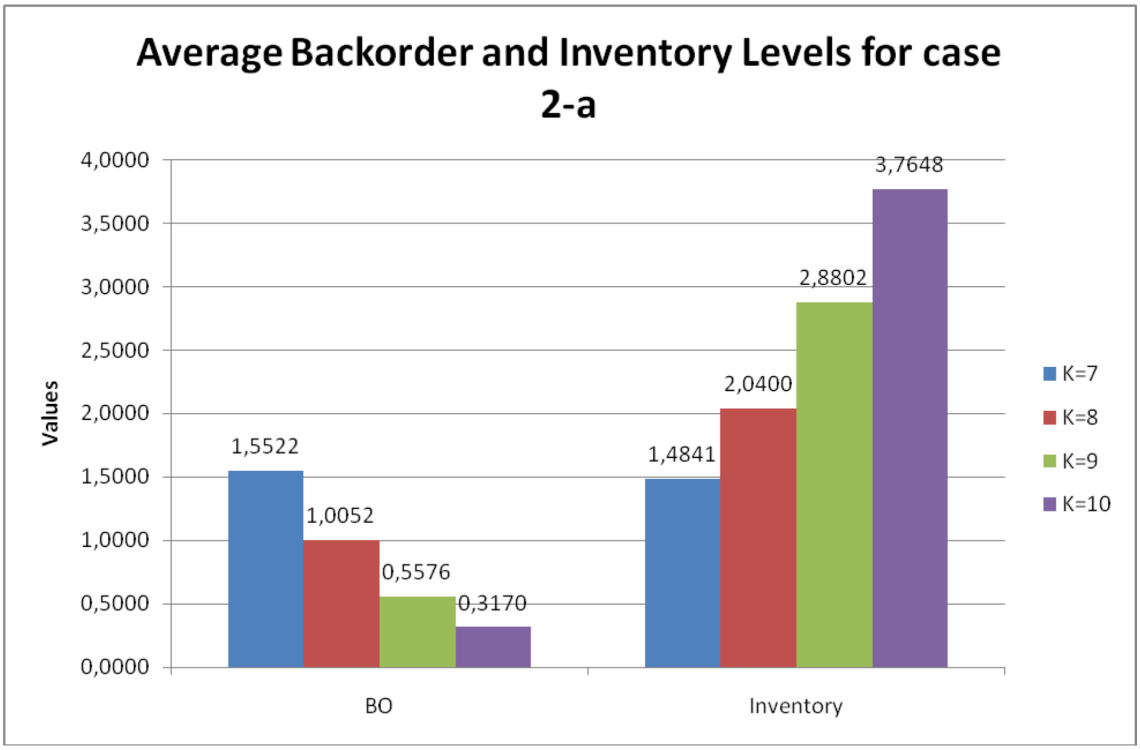


Figure 4.14: Average backorder and inventory variation for Case 2-a

As we can see from the figure, increasing the number of kanbans decrease the number of average backorders in the system, but it increases the inventory levels of the system. These variations on backorders and inventory levels effect the system's total cost. Total cost values of system for different number of kanbans in Case 1-a are shown in Figure 4.15.

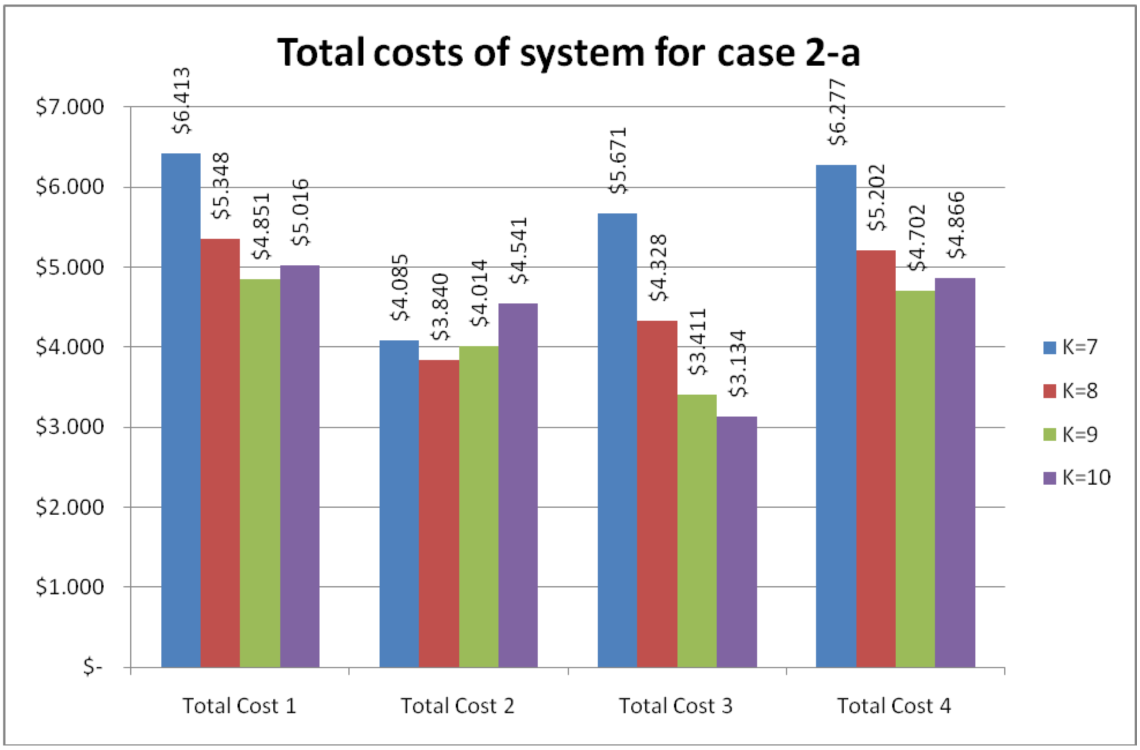


Figure 4.15: Total costs variation of system for Case 2-a

The number of kanbans which minimize the total cost of system is the optimal value for kanban controlled system. When we change the cost parameter of the system, the optimal value of kanban cards changed, but we assume this value is our adaptive kanban system's optimal value. In this case the minimum total cost has been satisfied with 9 kanban cards with the first values of cost parameters.. So we can say that the optimal values for traditional kanban system in our case are; K=9, E=0, R=0 and C=0 with a bottleneck workstation in the start point of manufacturing process. In this case changing cost parameters effect the total cost of the system more than Case 1-a.

4.1.2.2 Case 2-b

In Case 2-a we tried to find optimal kanban number for our system with assumption of our system is a traditional kanban system. Again in Case 2-b workstation 1 is the bottleneck station and we will add extra cards to system to adapt our system uncertain changes and see the effects of extra cards to system's performance measures.

The release and capture threshold values are constant and they are, R=1 and C=2. Also number of kanbans in the system equals to optimal kanban number which we found in Case 2-a for the traditional system. We have formed 2 different trial versions for Case

2-b to analyze the effects of adding extra cards to system with assumption of workstation 1 is bottleneck station. Trial values are shown in Table 4.22.

Table 4.22: Trial values of Case 2-b

Trial No	K	E	R	C
1	9	1	1	2
2	9	10	1	2

We analyzed these values via our simulation, and values of system’s performance measures which are WIP levels, utilization rates, backorders and inventory levels and total costs are founded by equations (3.1),(3.2), (3.3), (3.4),(3.5) and (3.6). the values of WIP levels are shown in table 4.23, utilization rates are shown in Table 4.24, backorders and inventory levels are shown in Table 4.25 and total costs are shown in Table 4.26.

Table 4.23: WIP levels at each stage for Case 2-b

Trial No	WIP1	WIP2	WIP3	WIP4
1	2,1056	1,3919	1,3966	1,3416
2	2,3271	1,8632	1,3990	1,3572

Table 4.24: Utilization rates at each stage for Case 2-b

Trial No	U1	U2	U3	U4
1	82,87%	75,49%	75,08%	74,40%
2	80,76%	76,60%	74,37%	74,31%

Table 4.25: Backorders and inventory levels of Case 2-b

Trial No	Backorder	Inventory
1	0,2694	3,8479
2	0,2305	4,1093

Table 4.26: Total costs of systems for Case 2-b

Trial No	Total Cost 1	Total Cost 2	Total Cost 3	Total Cost 4
1	$ 4.968	$ 4.564	$3.044	$4.812
2	$ 5.148	$ 4.802	$3.093	$4.974

All these result which we found for Case 2-b are important to see their effects to our system. The variation of WIP levels at each station are shown in Figure 4.16.

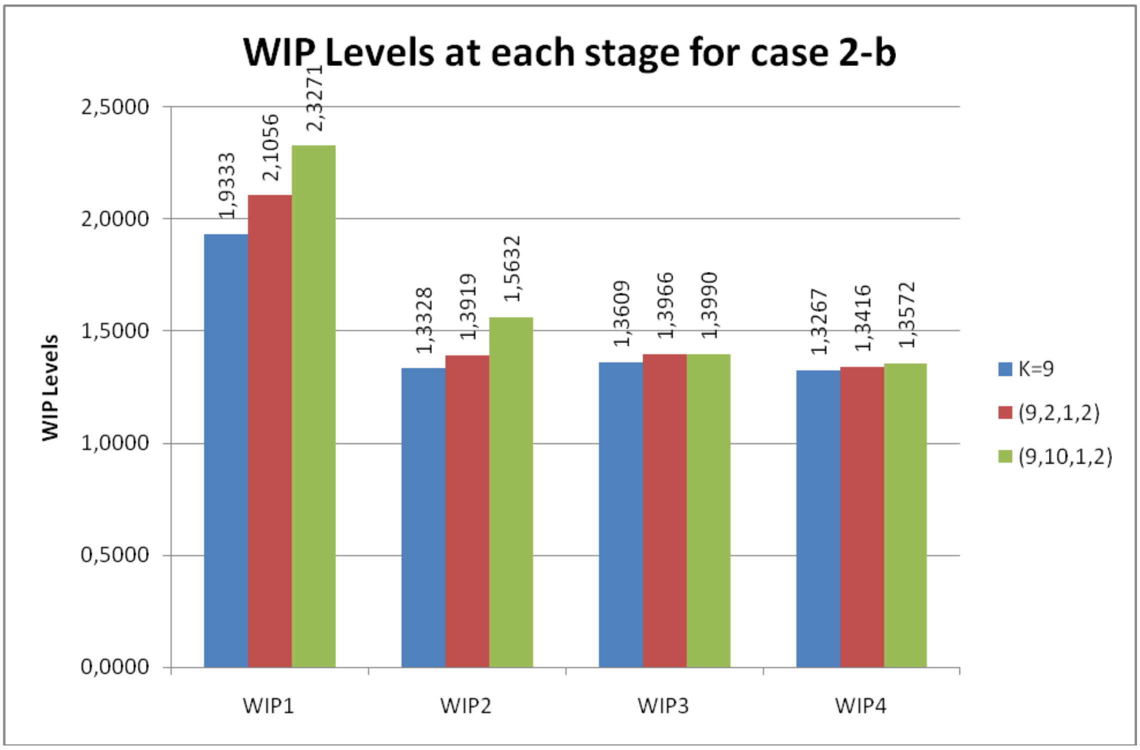


Figure 4.16: WIP levels variations at each station for Case 2-b

According to the figure 4.16 we can notice that adding extra kanban cards to a traditional kanban system to adapt system unstable changes, increases WIP levels at each workstation of system. the largest WIP level is in the bottleneck station, because in this station process times are longer than the others and the products which are waiting to be processed wait longer than other workstations in the system

We have analyzed WIP levels which effect total cost of system directly in Figure 4.16. The other measures which are effecting total cost directly are backorders and inventory levels. Backorders and inventory levels and their variations are shown in Figure 4.17.

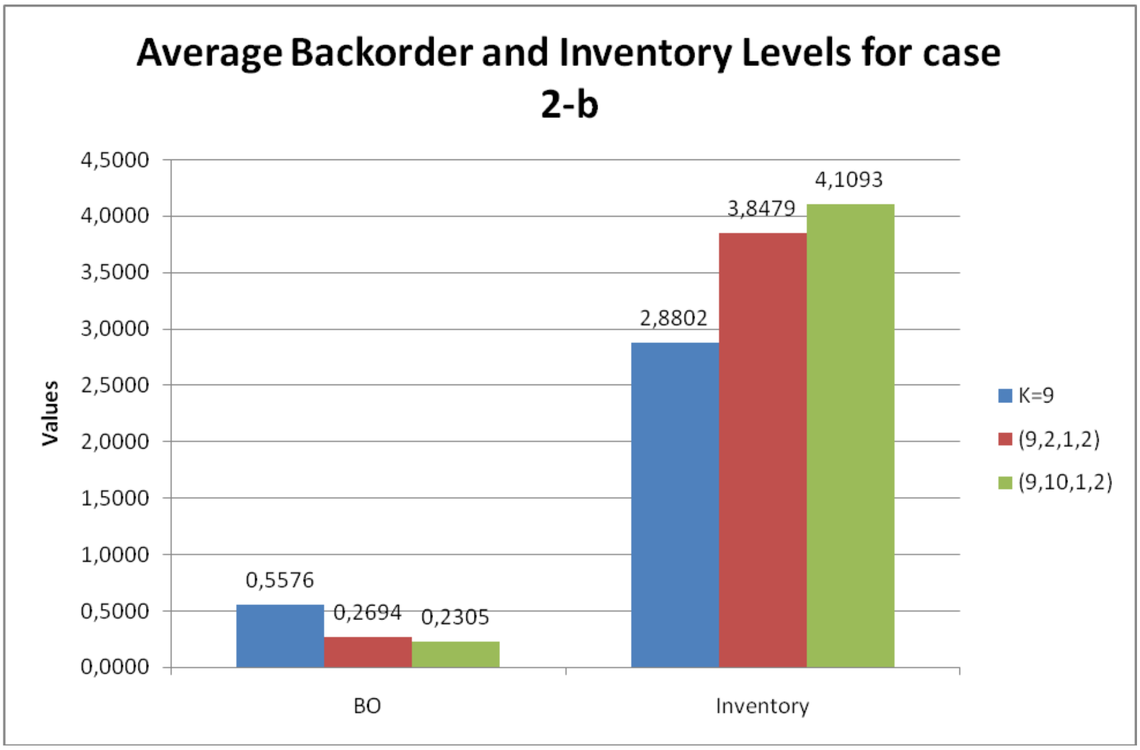


Figure 4.17: Average backorder and inventory variation for Case 2-b

Adding extra kanban cards to system increases the inventory level and decreases backorders. Because, adding extra cards to a kanban controlled production system causes to produce more product and it makes satisfying demand easier, so backorders decrease. But producing more product means holding more product in inventory and that cause to increase of inventory levels. After analyzing these results we have to analyze variation of total costs in the system to optimize our system and choose the best values to use for. Variations in total costs of system are shown in Figure 4.18.

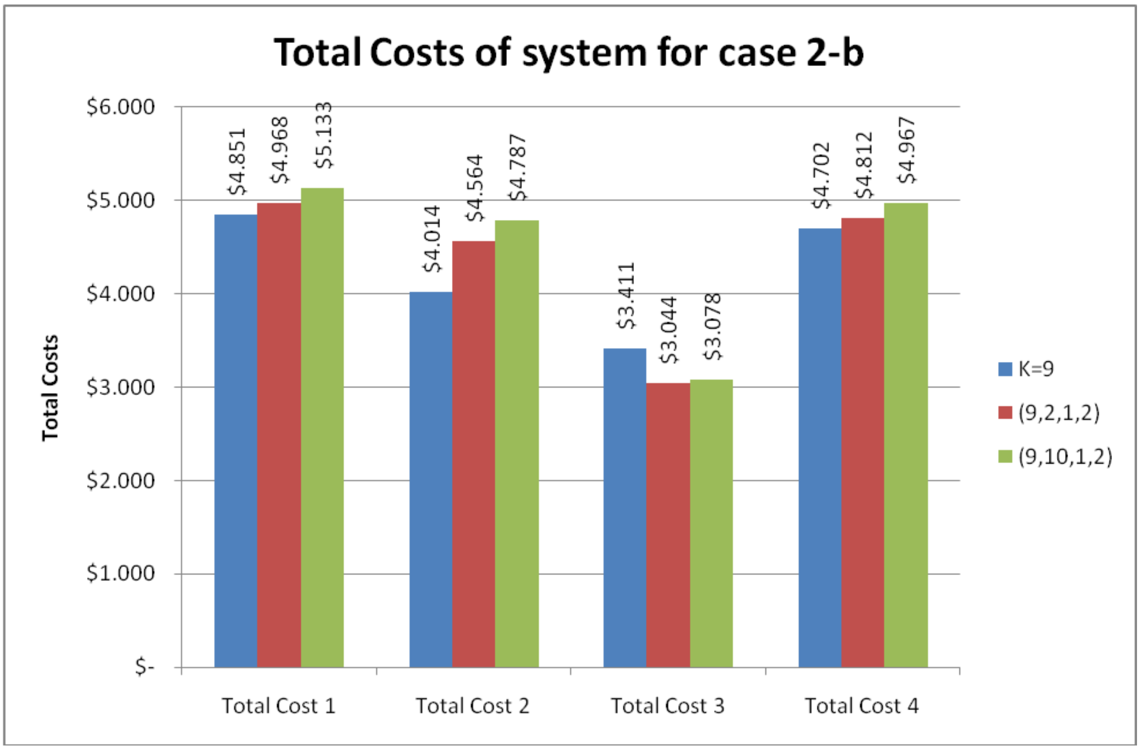


Figure 4.18: Total costs variations of system for different trial values of Case 2-b

As we can see from Figure 4.24 adding extra cards to the traditional system enable the system to change the total costs. When we add extra cards, generally total costs of the system increase because the decrease rate of backorders and the increase rate of inventory levels are not equal. Increase rate of inventory is higher than the decrease rate of backorders in the system so inventory costs increase in the system. When we decrease the cost parameter of inventory, the total cost of traditional kanban system decrease. As a result of all this comments, we can say that for case 2-b the most effective cost parameter is the cost of the inventory levels. When we decrease the cost of the inventory levels, the system becomes more optimal.

For analyzing the effects of variations in release and capture threshold values we have to form another cases. In Case 2-c we will try to see the effect of changing release threshold value in our adaptive system.

4.1.2.3 Case 2-c

In this case, again with same assumptions and equations as in Case 2-a and 6 we tried to analyze and see the effects of changing release threshold value in an adaptive kanban controlled production system to the performance measures. The values of K, E and C are constant and we take K and E values from the optimal choice of Case 2-b. These are; K=9, E=1. Capture threshold is equal to 6. We formed two different set of values to analyze via simulation. Sets of values to be analyzed in this case are shown in Table 4.27.

Table 4.27: The trial values for Case2-c

Trial No	K	E	R	C
1	9	2	1	8
2	9	10	7	8

With these values we analyzed our adaptive system via simulation and take some values of performance measures as result of Case 2-c. WIP levels at each stage for Case 2-c are shown in Table 4.28, utilization rates at each stage are shown in Table 4.29, backorders and inventory levels are shown in Table 4.30 and total costs are shown in Table 4.31.

Table 4.28: WIP levels at each stage for Case 2-c

Trial No	WIP1	WIP2	WIP3	WIP4
1	2,5012	1,7677	1,4239	1,3990
2	2,6719	1,9446	1,4349	1,2689

Table 4.29: Utilization rates of Case 2-c at each stage for each trial

Trial No	U1	U2	U3	U4
1	80,54%	75,63%	73,40%	73,45%
2	80,04%	74,41%	70,46%	66,29%

Table 4.30: Backorders and inventory levels of Case 2-c

Trial No	Backorder	Inventory
1	0,2010	4,4235
2	0,1003	6,3249

Table 4.31: Total costs of systems in Case 2-c

Trial No	Total Cost 1	Total Cost 2	Total Cost 3	Total Cost 4
1	$5.381	$5.079	$3.169	$5.204
2	$6.992	$6.841	$3.829	$6.809

These values are the results of Case 2-c after analysis of trial sets via simulation. To see the effect of increasing release threshold value in adaptive system on the performance measures of system. The results are shown with figures. WIP levels at each stage and variation of them are shown in Figure 4.25.

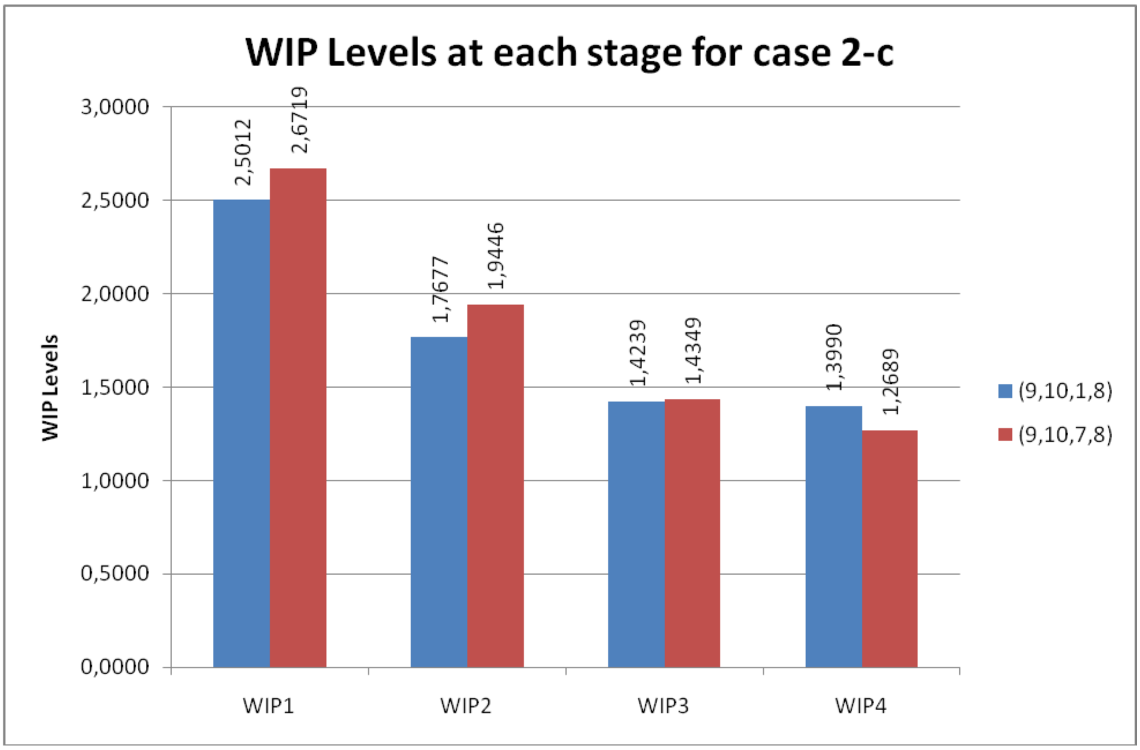


Figure 4.19: WIP levels variations at each station for Case 2-c

As we can see from the Figure 4.19, increasing release threshold value in the system did not enable the system to change WIP levels rapid. The WIP levels of the stations are similar. But the total WIP levels in the system increased.

Another important performance measures are backorders and inventory levels in the system and how they changed according to the increase in release threshold value. Variation in backorders and inventory levels are shown in Figure 4.20.

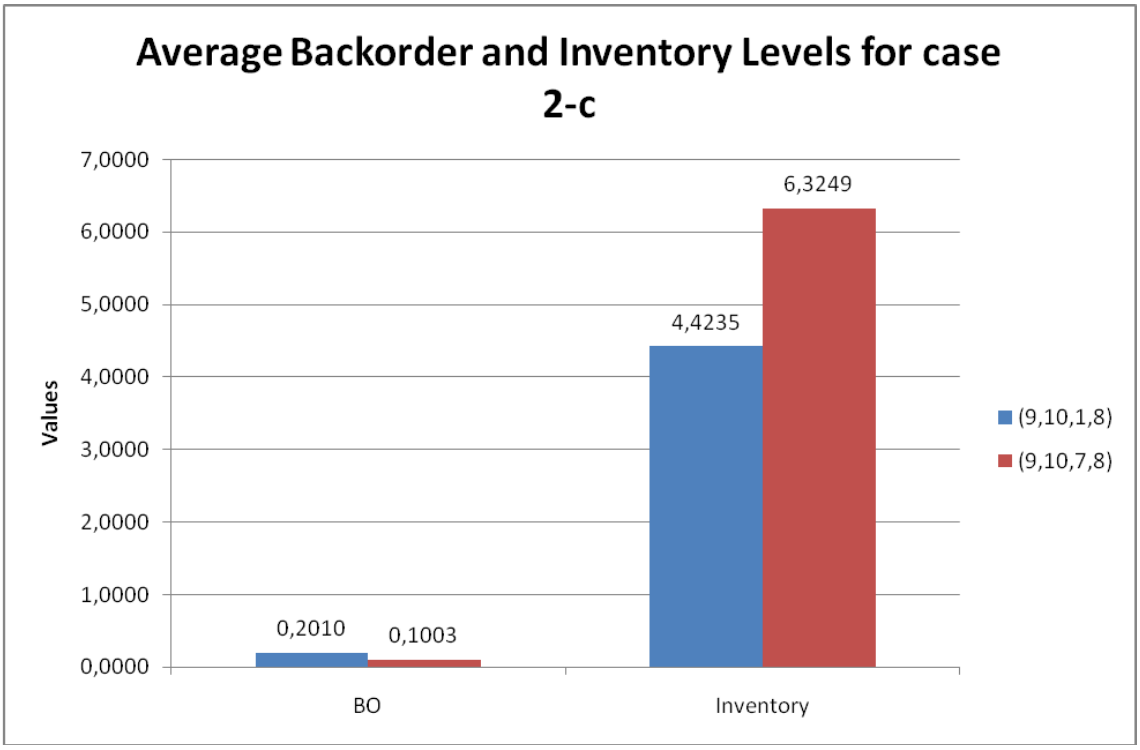


Figure 4.20: Average backorder and inventory variation for Case 2-c

In this case, when we increase relaese threshold value, again backorders decrease and inventory levels increase in the system. To choose the optimal result for Case 2-c and to see the variation of total cost according to increase of R value. Total costs of system for Case 2-c are shown in Figure 4.21.

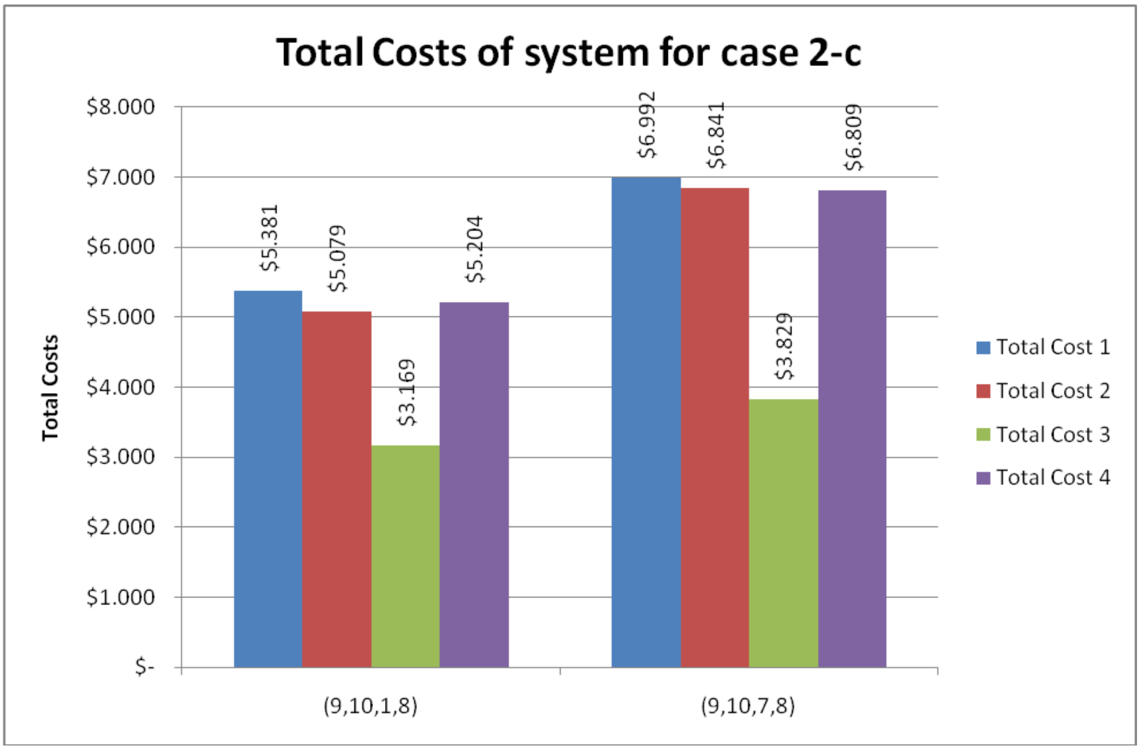


Figure 4.21: Total costs variations of system for Case 2-c

Through the figure 4.21 below, again the total cost increase according to increase of release threshold value in our adaptive system. Increase of WIP levels and inventory levels cause increasing in total cost of system, number of backorders decrease but this decreasing does not effect to decrease of the total cost in system. Until this case we have changed kanban numbers, extra card numbers and release threshold value and analyzed the effects of these changes to system's performance measure. We have to analyze the system for changing capture threshold value under same assumptions of station 1 is bottleneck station and production and demand rates are same as Case 2-a, b and c.

4.1.2.4 Case 2-d

In this case we changed only the number of capture threshold, the other parameters will be constant. Again we formed 2 set of values for analyzing via simulation. these sets of values are shown in Table 4.32.

Table 4.32: The trial values for Case2-d

Trial No	K	E	R	C
1	9	10	1	2
2	9	10	1	8

Again these values tried via simulation and according to results the values of performance measures calculated from equations which we used in other cases. WIP levels at each station are shown in Table 4.33, utilization rates at each station are shown in Table 4.34, backorders and inventory levels are shown in table 4.35 and total costs of system are shown in Table 4.36

Table 4.33: WIP levels at each stage for Case 2-d

Trial No	WIP1	WIP2	WIP3	WIP4
1	2,3271	1,5632	1,3990	1,3572
2	2,5012	1,7677	1,4239	1,3990

Table 4.34: Utilization rates at each stage for Case 2-d

Trial No	U1	U2	U3	U4
1	80,76%	76,60%	74,37%	74,31%
2	80,54%	75,63%	73,40%	73,45%

Table 4.35: Backorders and inventory levels of Case 2-d

Trial No	Backorder	Inventory
1	0,2305	4,1093
2	0,2010	4,4235

Table 4.36: Total costs of systems for Case 2-d

Trial No	Total Cost 1	Total Cost 2	Total Cost 3	Total Cost 4
1	$5.133	$4.787	$3.078	$4.967
2	$5.381	$5.079	$3.169	$5.204

From tables we can see the values of performance measures that we found as a result of simulation. We analyzed the variations in performance measures again with figures. Variations of WIP levels at each station for Case 2-d are shown in Figure 4.22.

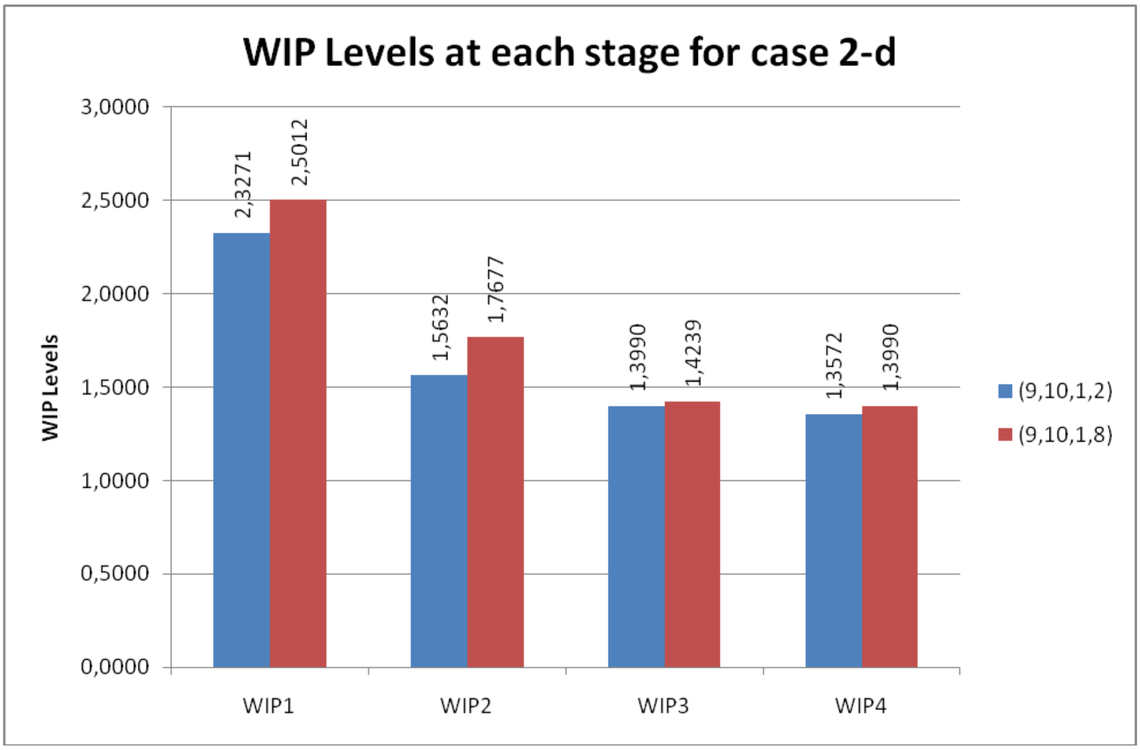


Figure 4.22: WIP levels variations at each station for Case 2-d

According to figure below, when we increase of capture threshold values, WIP levels decrease. As we know to minimize the total cost and choose the best values to use in our adaptive kanban system, we have to know the backorders and inventory levels of system which are shown in Figure 4.23.

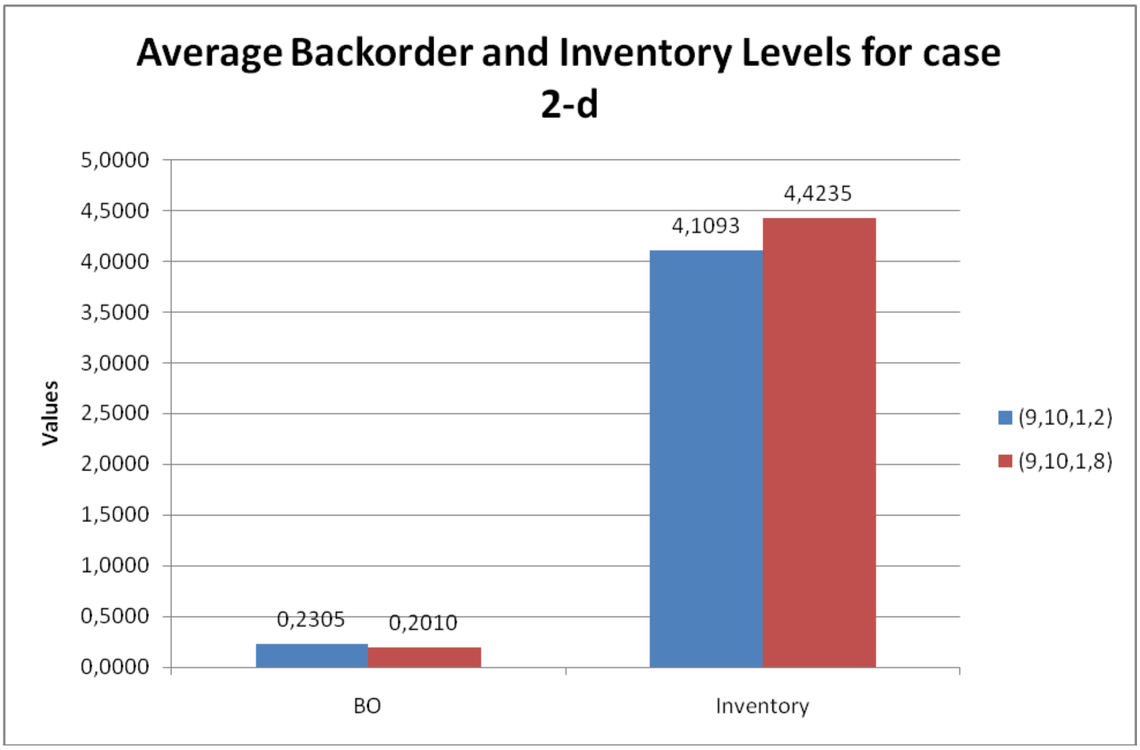


Figure 4.23: Average backorder and inventory variation for Case 2-d

As being other cases which are analyzed before, again in this case backorders and inventory levels show same variations. When capture threshold increases in an adaptive kanban system with a bottleneck station at start point of manufacturing process, backordered demands decrease and inventory levels increase. But it may not cause to decrease of total cost. Because increase of inventory levels can enable the system to increase the total costs. Variation in total costs of system are shown in Figure 4.24.

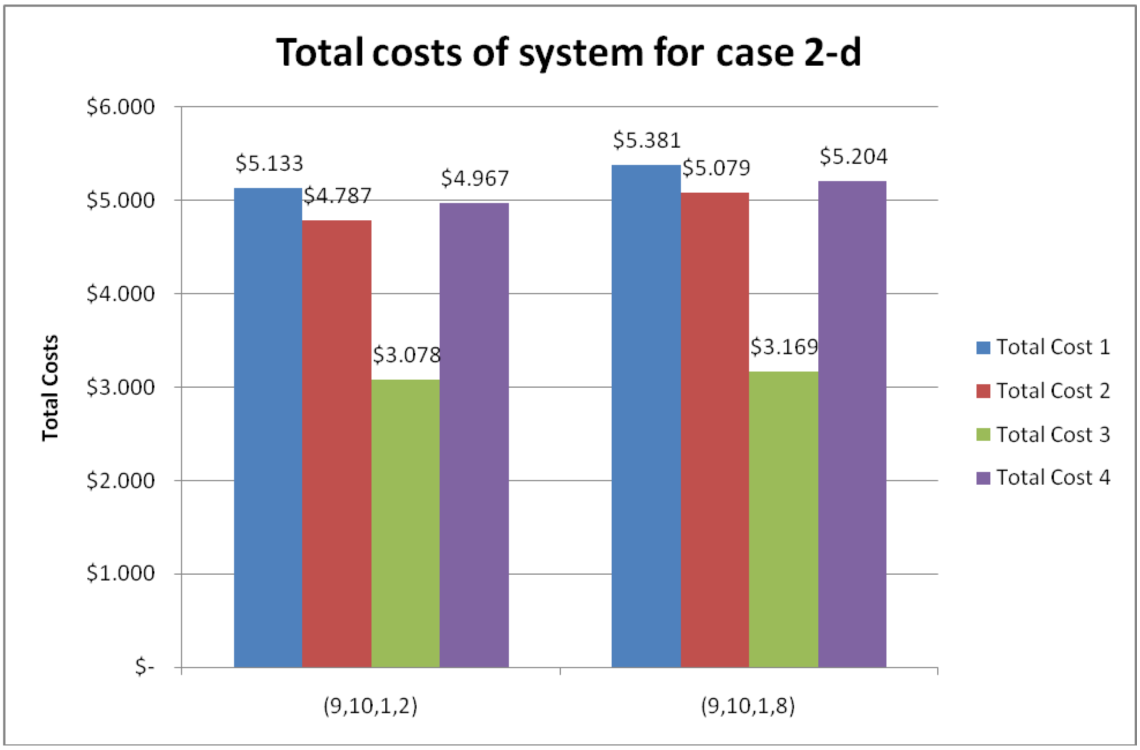


Figure 4.24: Total costs variations of system for Case 2-d

As we can see from the figure 4.23 total cost of system again increase according to increase of capture threshold value. This can be a result of increase in inventory and WIP levels. Altough backorders decrease, there exist a higher increasing in inventory levels of system so total cost increase.

In our adaptive system if the second workstation is the bottleneck station, how it effects to system's performance measures, we have to analyze the system according to this question.

4.1.3 Case 3

4.1.3.1 Case 3-a

In this case we changed the place of bottleneck station in the system and tried to analyze the effect on system's performance measures. The bottleneck station is the second station in the manufacturing process of system. The demand arrival rate and production rates assumptions of the case are as follows;

- λ_D=0,4
- λ_{P1}=0,8

- λ_{P2}=0,6
- λ_{P3}=0,8
- λ_{P4}=0,8

Also these assumptions are used for Case 3-b, 3-c, and 3-d.

Stability condition for Case 3-a;

$\lambda_D / \lambda_P(K+E) < 1$, so;

$$\lambda_P(K^*+E)=\frac{\min(\lambda p1,\lambda p2,\lambda p3,\lambda p4)\times(K^*+E)}{K^*+E+M-1}=\frac{r_b\times(K^*+E)}{K^*+E+4-1}=\frac{r_b\times(K+E)}{K+E+3}=$$

$$\frac{0{,}6(K^*+E)}{K^*+E+3}\Rightarrow\frac{0{,}4}{\frac{0{,}6(K^*+E)}{K^*+E+3}}<1\Rightarrow K^*+E>6\Rightarrow$$ so our starting value for kanban cards is equal to 7.

A set of values are formed to be tried and analyzed via simulation to see the effects of them to performance measures. These values are shown in table 4.37.

Table 4.37: The trial values for Case3-a

Trial No	K	E	R	C
1	7	0	0	0
2	8	0	0	0
3	9	0	0	0

After analyzing system for these values of kanban cards with simulation, we take some resulted values of performance measures. WIP levels at each stage are shown in Table 4.38, utilization rates are shown in Table 4.39, backorders and inventory levels are shown in Table 4.40 and total costs of system are shown in Table 4.41.

Table 4.38: WIP levels at each stage for Case 3-a

Trial No	WIP1	WIP2	WIP3	WIP4
1	1,2994	1,7087	1,2204	1,2863
2	1,4406	1,9394	1,2721	1,3309
3	1,5066	1,9397	1,2742	1,2904

Table 4.39: Utilization rates at each stage for Case 3-a

Trial No	U1	U2	U3	U4
1	76,58%	83,14%	73,70%	73,75%
2	78,29%	86,08%	73,81%	75,19%
3	77,31%	84,16%	73,52%	73,49%

Table 4.40: Backorders and inventory levels of Case 3-a

Trial No	Backorder	Inventory
1	1,1242	1,4799
2	0,5149	1,9971
3	0,2839	2,9578

Table 4.41: Total costs of systems in Case 3-a

Trial No	Total Cost 1	Total Cost 2	Total Cost 3	Total Cost 4
1	\$5.128	\$3.442	\$4.388	\$4.990
2	\$3.841	\$3.069	\$2.843	\$3.692
3	\$4.110	\$3.684	\$2.631	\$3.960

According to these values, we figured them to see the variations of performance measures. Variations of WIP levels at each stage are shown in Figure 4.25.

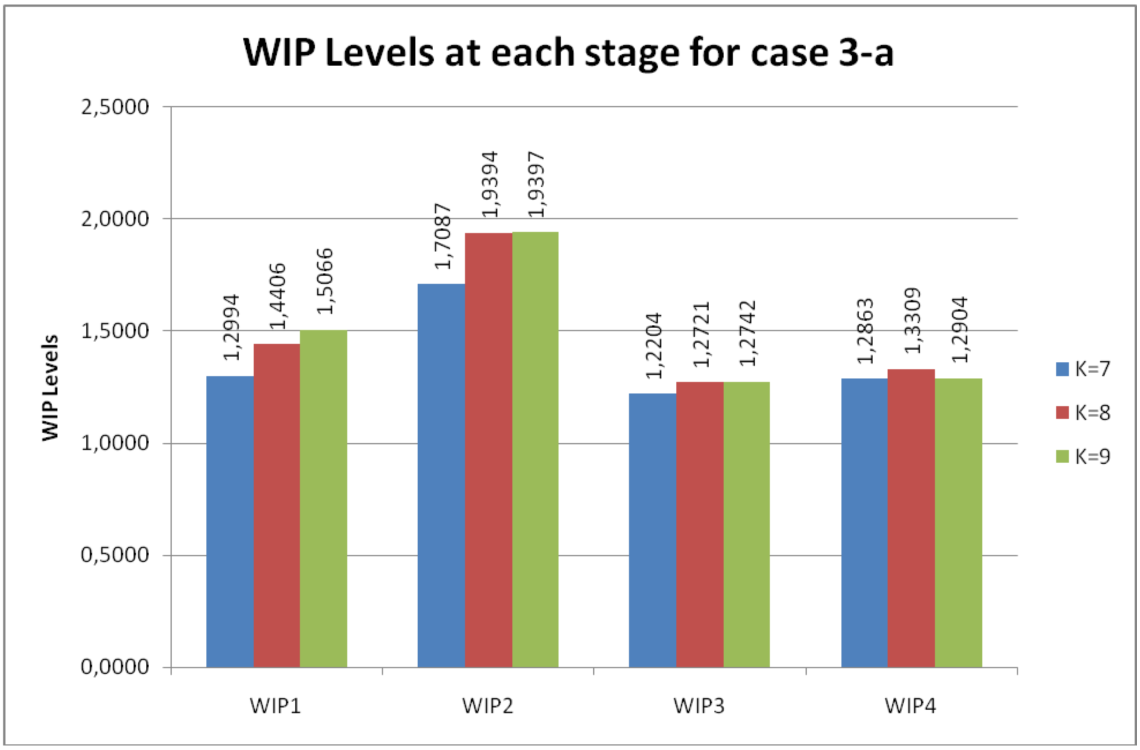


Figure 4.25: WIP levels variations at each station for Case 3-a

As we can see from figure 4.25 the WIP levels at the stations are similar in the trials of Case 3-a. The process times of station 2 are higher than the other stations, because station 2 is the bottleneck station. Because of this, the highest WIP levels exist at the staton 2. When we increase the number of kanbans in the system, WIP levels does not have a rapid change. But total of WIP levels in the system increase. Another performance measures, backorders and inventory levels which effects the total costs directly. Variations of backorders and inventory levels of system for Case 3-a are shown in Figure 4.26.

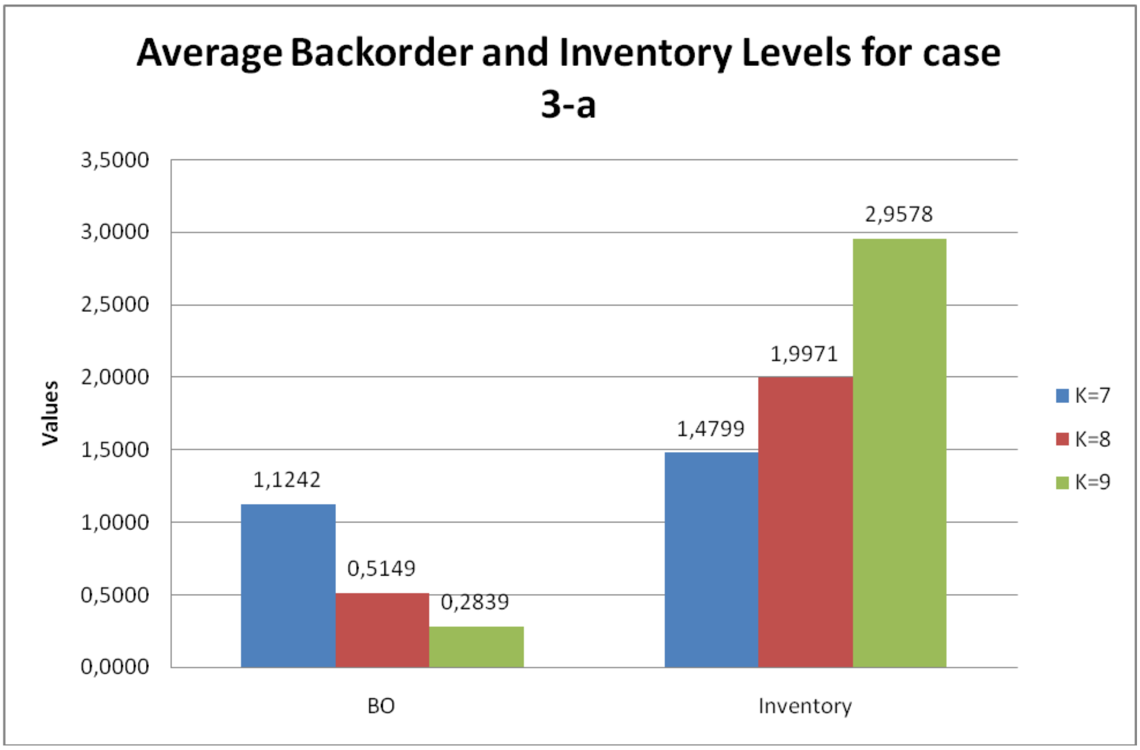


Figure 4.26: Average backorder and inventory variation for Case 3-a

When we increase the number of kanban cards in the system the number of backordered demands decrease. At the same time, the inventory levels of system increase. This causes to decrease of total cost until optimal number of kanban. The total cost variations of this case are shown in Figure 4.27.

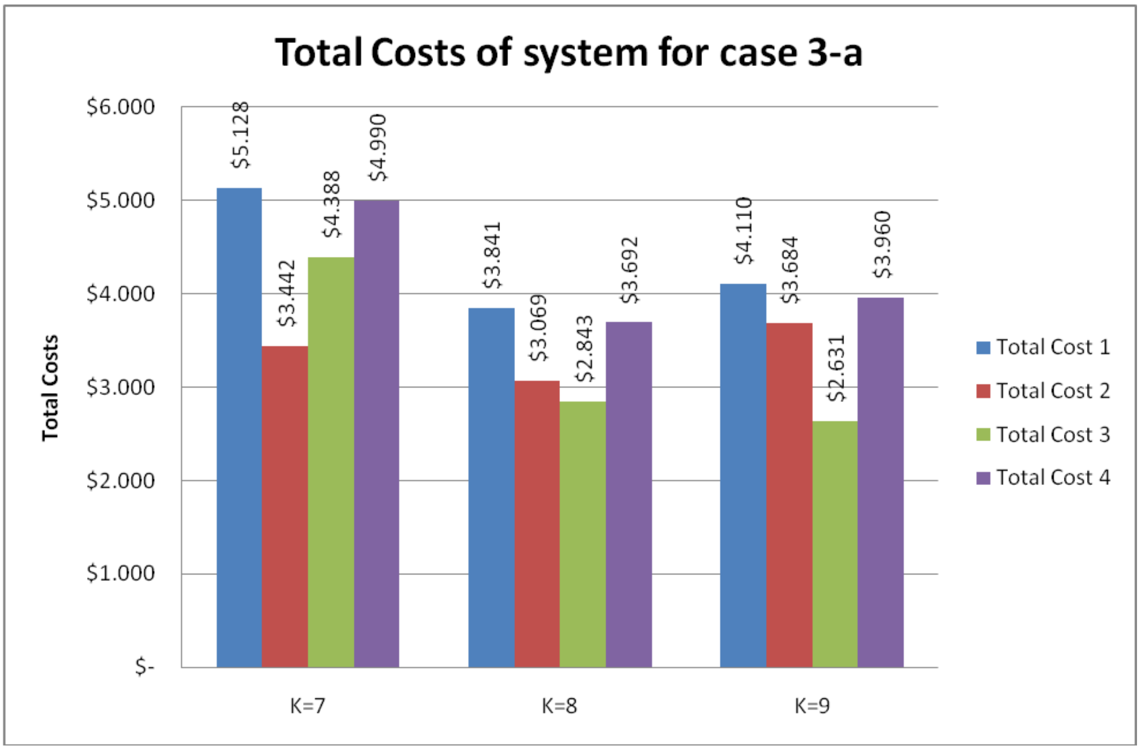


Figure 4.27: Total costs variations of system for Case 3-a

As we mentioned, the number of kanbans which minimize the total cost of the system is the optimal value of kanban cards for kanban controlled system. When we change the cost parameter of the system, the optimal value of kanban cards changed, but we assume the first values of cost parameters are our adaptive kanban system's optimal value. In this case the minimum total cost has been satisfied with 9 kanban cards with the first values of cost parameters.. So we can say that the optimal values for traditional kanban system in our case are; K=8, E=0, R=0 and C=0. In this case the most effective cost parameter is the inventory level costs for the system.

4.1.3.2 Case 3-b

In the Case 3-a we tried to find the optimal number of kanbans for traditional kanban system. In this case we will add extra cards to system, and try to see the effects of adding extra card on performance measures. We assumed the number of kanbans are equal to the number which we found as optimal in Case 3-a, release and threshold values are constant. Release threshold value is 1, capture threshold value is 2. We formed different sets of trial values for this case. These trial values are shown in Table 4.42.

Table 4.42: The trial values of Case 3-b

Trial No	K	E	R	C
1	8	1	1	2
2	8	10	1	2

After analyzing system for these values with simulation, we take some resulted values of performance measures. WIP levels at each stage are shown in Table 4.43, utilization rates are shown in Table 4.44, backorders and inventory levels are shown in Table 4.45 and total costs of system are shown in Table 4.46.

Table 4.43: WIP levels at each station for Case 3-b

Trial No	WIP1	WIP2	WIP3	WIP4
1	1,8479	2,0705	1,3131	1,3166
2	2,0375	2,1081	1,4078	1,3105

Table 4.44: Utilization rates at each station for Case 3-b

Trial No	U1	U2	U3	U4
1	76,92%	83,21%	72,89%	72,85%
2	70,50%	82,49%	73,71%	71,72%

Table 4.45: Backorders and inventory levels of Case 3-b

Trial No	Backorder	Inventory
1	0,2394	3,0961
2	0,2071	3,4695

Table 4.46: Total costs of systems in Case 3-b

Trial No	Total Cost 1	Total Cost 2	Total Cost 3	Total Cost 4
1	$4.142	$3.782	$2.594	$3.978
2	$4.434	$4.123	$2.699	$4.262

According to these values, we figured them to see the variations of performance measures. Variations of WIP levels at each stage are shown in Figure 4.28.

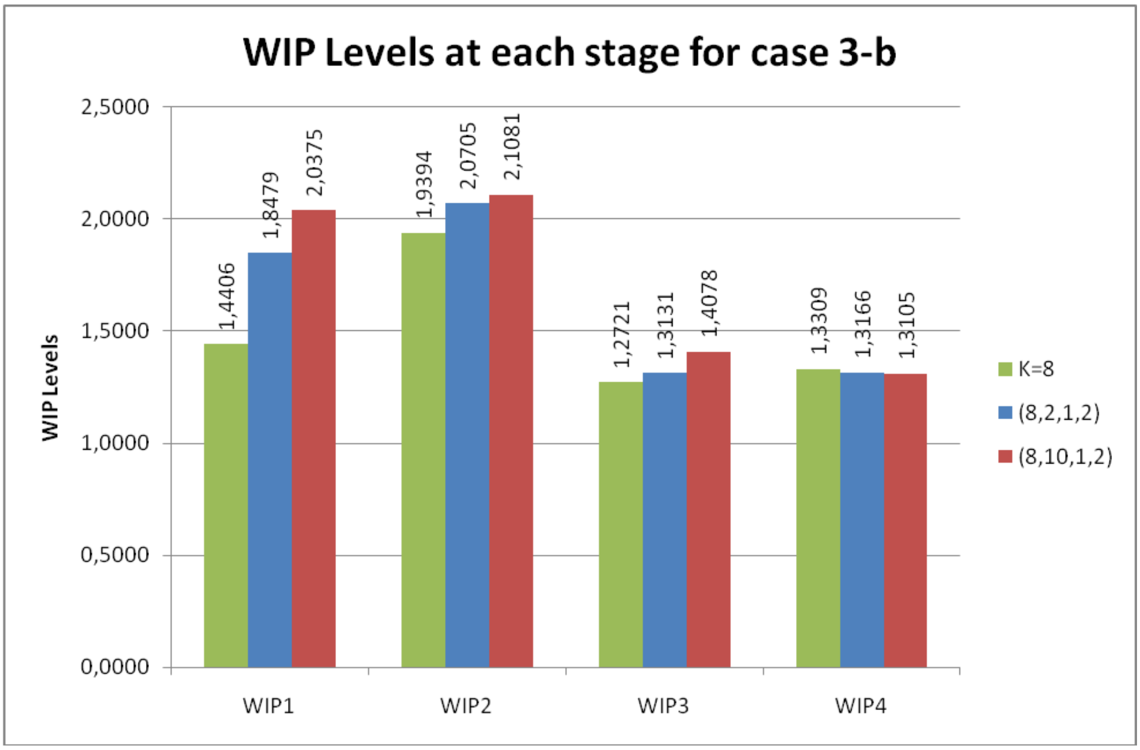


Figure 4.28: WIP levels variations at each station for Case 3-b

As we know the second station is bottleneck station and production orders wait longer in station 2 more than the others. The finished orders of station 1 wait until station 2 idles. So, as we can see from the figure below, when we add extra cards to the system WIP levels of station 1 and 2 increase. Highest WIP level is in the second station which is the bottleneck station for this case. Total WIP levels of system increase. Backorders and inventory levels of system are shown in Figure 4.29.

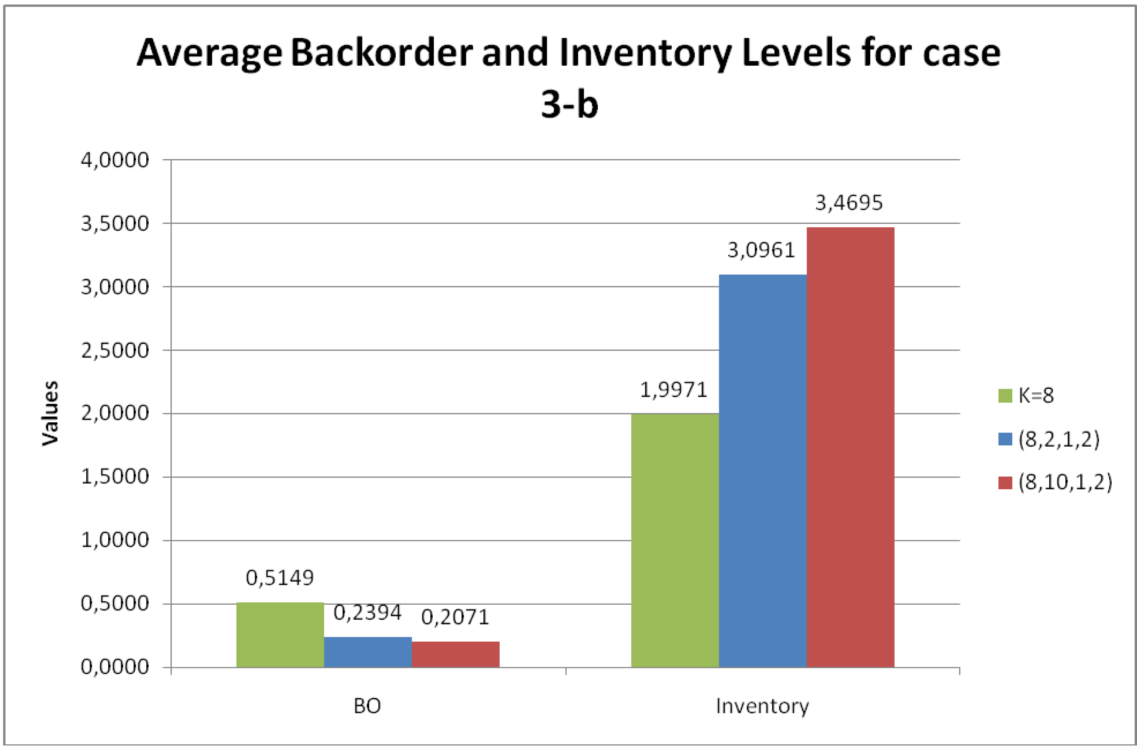


Figure 4.29: Average backorder and inventory variation for Case 3-b

As in other cases we tried before, again in this case, when we add extra cards to the system backorders decrease and inventory levels increase. These variations of backorders and inventory levels effect total cost directly. Total costs of the system are shown in Figure 4.30.

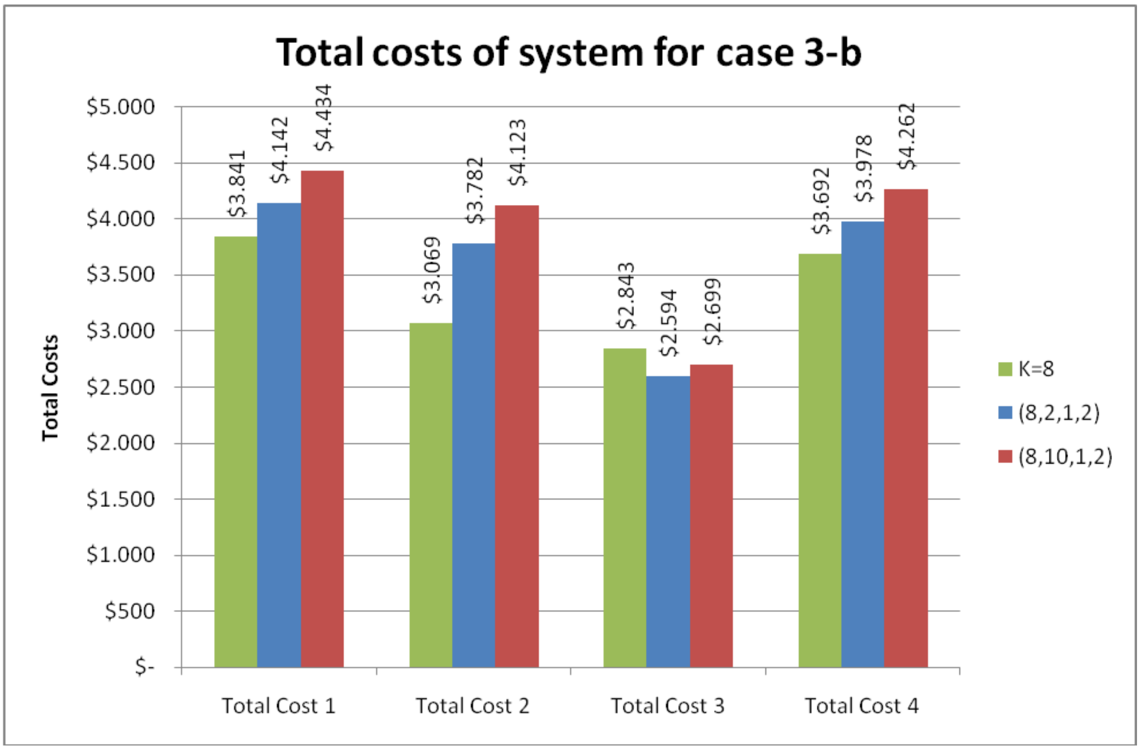


Figure 4.30: Total costs variations of system for Case 3-b

As we can see from Figure 4.30, adding extra cards to the traditional system enable the system to change the total costs. When we add extra cards, generally total costs of the system increase because the decrease rate of backorders and the increase rate of inventory levels are not equal. Increase rate of inventory is higher than the decrease rate of backorders in the system so inventory costs increase in the system. When we decrease the cost parameter of inventory, the total cost of traditional kanban system decrease. As a result of all this comments, we can say that for case 3-b the most effective cost parameter is the cost of the inventory levels. When we decrease the cost of the inventory levels, the system becomes more optimal.

4.1.3.3 Case 3-c

In this case we tried to see the effects of inreasing release threshold values to performance measures. We assumed the number of kanbans are equal to the number which we found as optimal in Case 3-a, number of extra kanban card is equal to 10 and capture threshold values are constant and C=7. We formed different sets of trial values for this case. These trial values are shown in Table 4.47.

Table 4.47: The trial values for Case 3-c

Trial No	K	E	R	C
1	8	10	1	7
2	8	10	6	7

After analyzing system for these values with simulation, we take some resulted values of performance measures. WIP levels at each stage are shown in Table 4.48. The utilization rates are shown in Table 4.49. Backorders and inventory levels are shown in Table 4.50. The total costs of system are shown in Table 4.51.

Table 4.48: WIP levels at each station for Case 3-c

Trial No	WIP1	WIP2	WIP3	WIP4
1	2,1999	2,2166	1,4150	1,3366
2	2,7476	2,3721	1,4951	1,3776

Table 4.49: Utilization rates at each station for Case 3-c

Trial No	U1	U2	U3	U4
1	72,67%	81,77%	72,81%	70,90%
2	76,87%	79,95%	72,23%	69,59%

Table 4.50: Backorders and inventory levels of Case 3-c

Trial No	Backorder	Inventory
1	0,1748	4,0874
2	0,1178	5,3594

Table 4.51: Total costs of systems in Case 3-c

Trial No	Total Cost 1	Total Cost 2	Total Cost 3	Total Cost 4
1	$4.970	$4.708	$2.926	$4.791
2	$6.112	$5.936	$3.433	$5.913

According to these values, we figured them to see the variations of performance measures. Variations of WIP levels at each stage are shown in Figure 4.41.

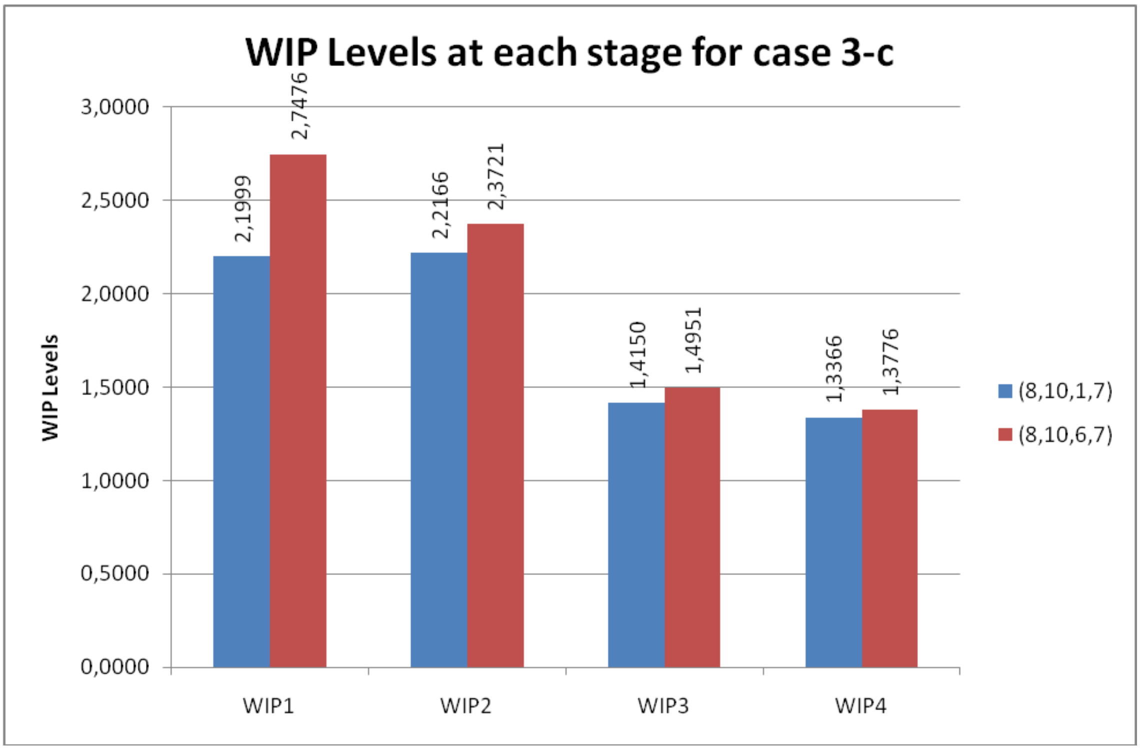


Figure 4.31: WIP levels variations at each station for Case 3-c

For this case, when we increase the release threshold values of the system, WIP levels at each station increase. Increasing release threshold value enable the system to release extra cards to manufacturing process earlier, after that WIP levels in the system increase.

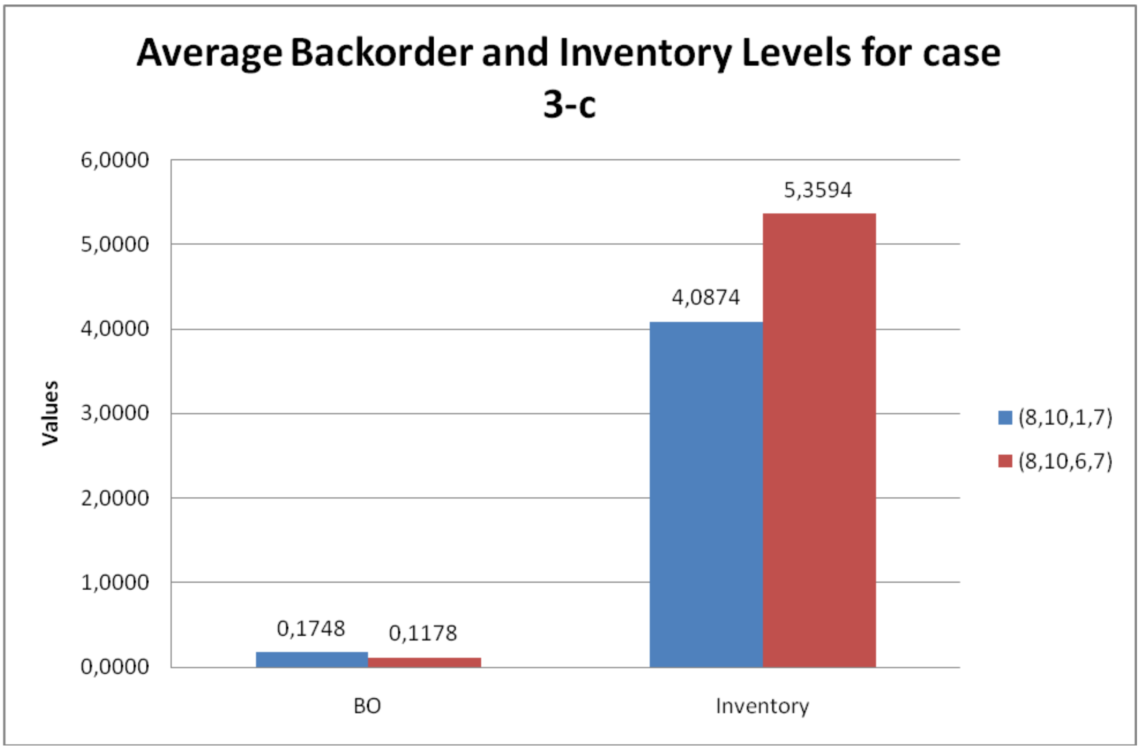


Figure 4.32: Average backorder and inventory variation for Case 3-c

As in other cases we tried before, again in this case when we incerase the value of release threshold backorders decrease and inventory levels increase. These variations of backorders and inventory levels effect total cost directly. Total costs of system are shown in Figure 4.33.

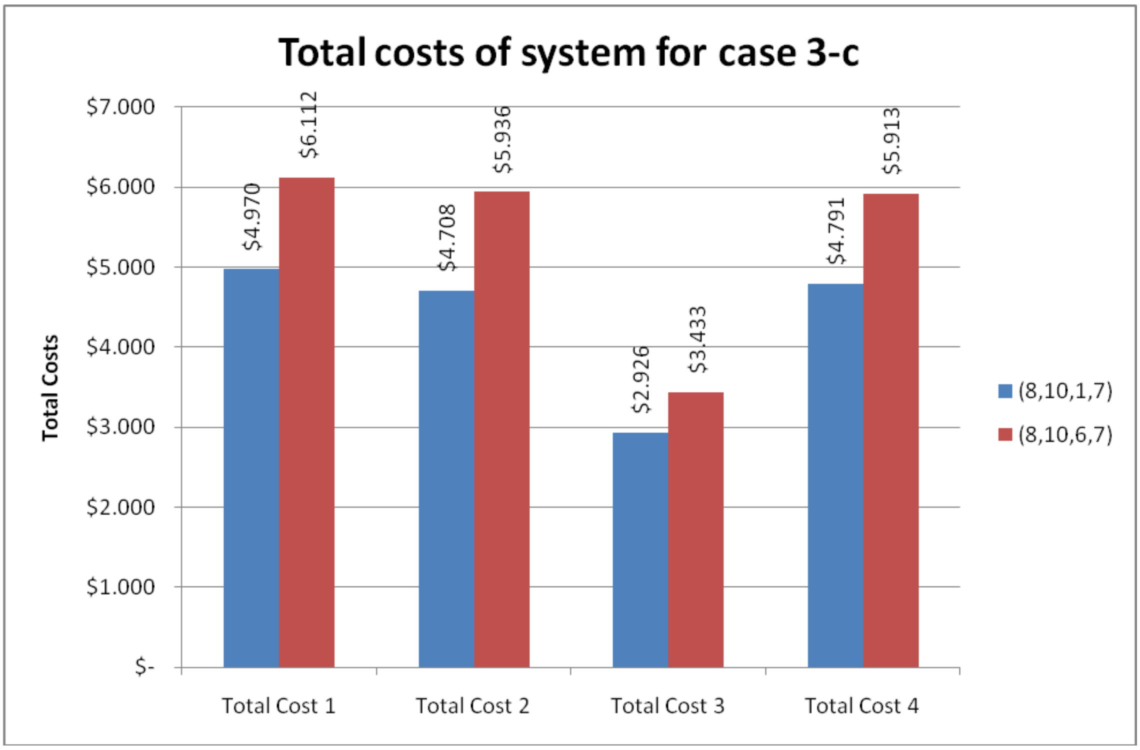


Figure 4.33: Total costs variations of system for Case 3-c

In this case, increasing release threshold value, cause increase of the total cost in the system. As a result, we can say that holding release threshold value low is more suitable and optimal for adaptiva kanban system in Case 3-c. Again in this case, the most effective cost parameter is the cost of inventory.

4.1.3.4 Case 3-d

In this case we tried to see the effects of inreasing capture threshold values to performance measures. We assumed the number of kanbans are equal to the number which we found as optimal in Case 3-a, extra kanban card is equal to 10 and release threshold values are constant and R=1 which give us minimum total cost in Case 3-c.. We formed different sets of trial values for this case. These trial values are shown in Table 4.52.

Table 4.52: The trial values for Case 3-d

Trial No	K	E	R	C
1	8	10	1	2
2	8	10	1	7

After analyzing system for these values with simulation, we take some resulted values of performance measures. WIP levels at each stage are shown in Table 4.53, utilization rates are shown in Table 4.54, backorders and inventory levels are shown in Table 4.55 and total costs of system are shown in Table 4.56.

Table 4.53: levels at each station for Case 3-d

Trial No	WIP1	WIP2	WIP3	WIP4
1	2,0375	2,1081	1,4078	1,3105
2	2,1999	2,2166	1,4150	1,3366

Table 4.54: Utilization rates at each station for Case 3-d

Trial No	U1	U2	U3	U4
1	70,50%	82,49%	73,71%	71,72%
2	72,67%	81,77%	72,81%	70,90%

Table 4.55: Backorders and inventory levels of Case 3-d

Trial No	Backorder	Inventory
1	0,473952605	2,30007
2	0,318768123	2,883112

Table 4.56: Total costs of systems in Case 3-d

Trial No	Total Cost 1	Total Cost 2	Total Cost 3	Total Cost 4
1	$4.434	$4.123	$2.699	$4.262
2	$4.970	$4.708	$2.926	$4.791

According to these values, we figured them to see the variations of performance measures. Variations of WIP levels at each stage are shown in Figure 4.34.

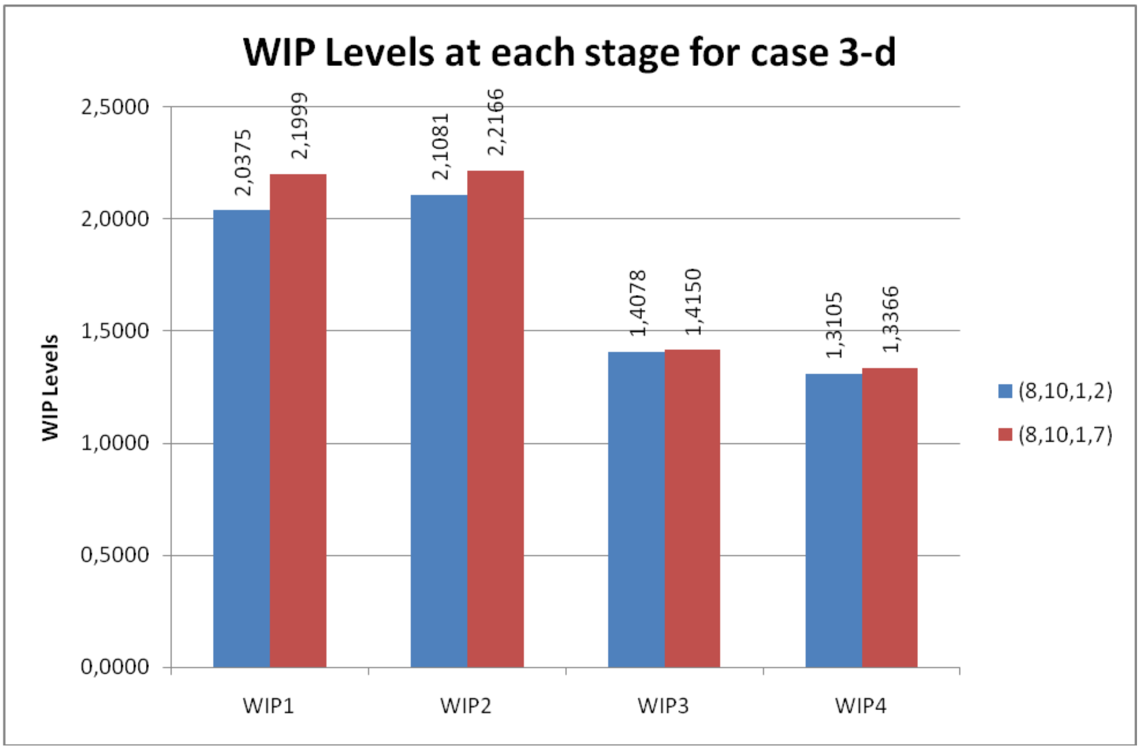


Figure 4.34: WIP levels variations at each station for Case 3-d

As we can see from the figure below, when we increase the capture threshold value of the system, WIP levels increase. But there does not exist a rapid change on this parameter, WIP levels at each station are similar. Backorders and inventory levels of system are shown in Figure 4.35.

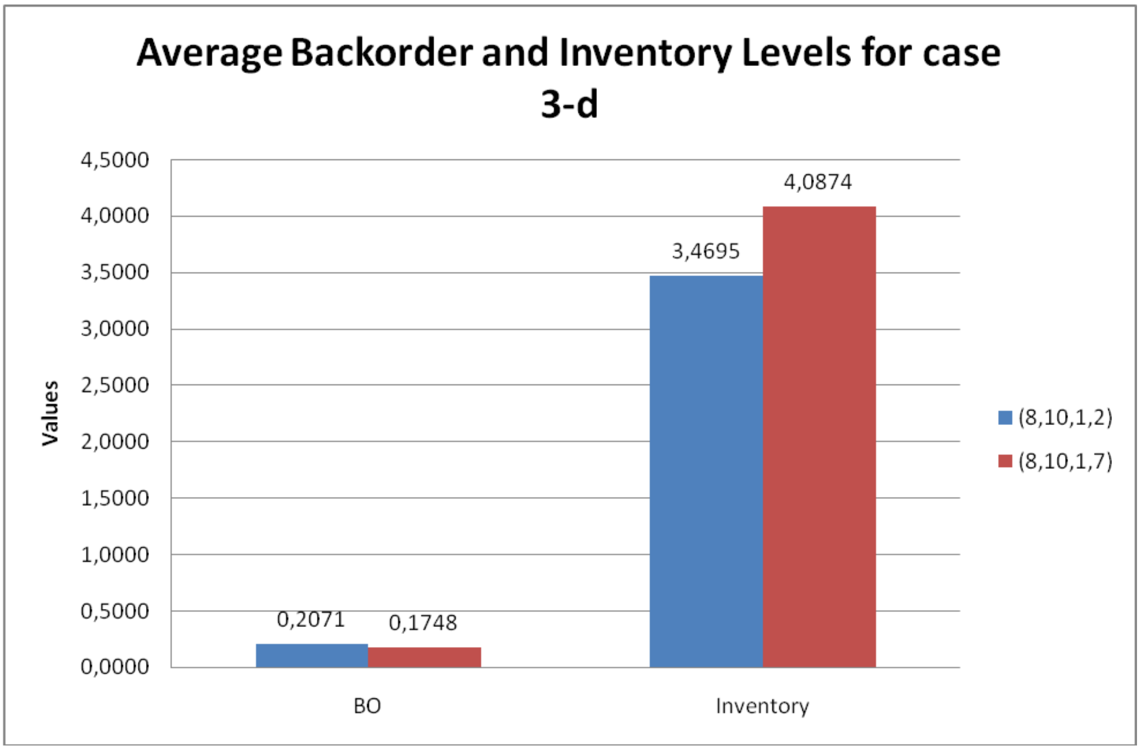


Figure 4.35: Average backorder and inventory variations for Case 3-d

As in other cases we tried before, again in this case, when we incerase the value of release threshold backorders decrease and inventory levels increase. These variations of backorders and inventory levels effect total cost directly. Total costs of system are shown in Figure 4.36.

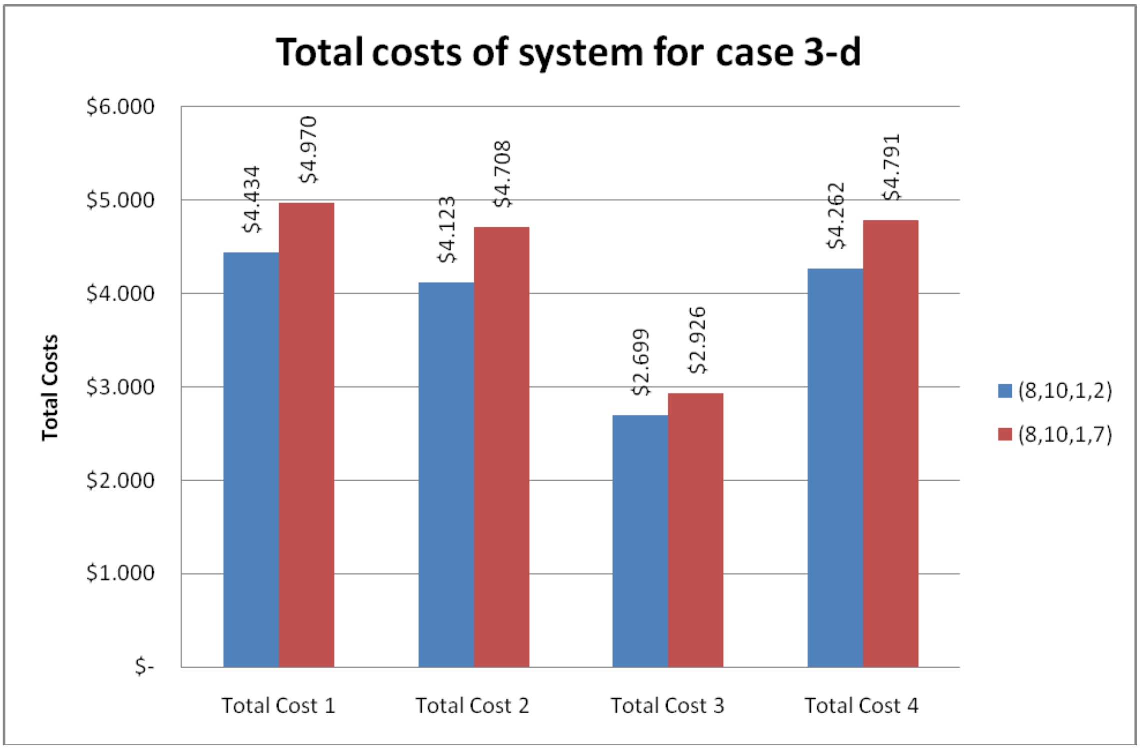


Figure 4.36: Total costs variations of system for Case 3-d

In this case, increasing release threshold value, cause increase of total cost in the system. As a result, we can say that holding capture threshold value high, is more suitable and optimal for our adaptive kanban system in Case 3-d. Again in this case the most effective cost parameter is the cost of inventory.

4.1.4 Case 4

4.1.4.1 Case 4-a

In this case again and for last time, we changed the place of bottleneck station in the system and tried to analyze the affect on system's performance measures. The bottleneck station is the last station, station 4 in the manufacturing process of system. The demand arrival rate and production rates assumptions of the case are as follows;

- λ_D=0,4
- λ_{P1}=0,8
- λ_{P2}=0,8
- λ_{P3}=0,8
- λ_{P4}=0,8=r_b

Stability condition for Case 4-a;

$\lambda_D / \lambda_P(K+E) < 1$, so;

$$\lambda_P(K^*+E)=\frac{\min(\lambda p1,\lambda p2,\lambda p3,\lambda p4)\times(K^*+E)}{K^*+E+M-1}=\frac{r_b\times(K^*+E)}{K^*+E+4-1}=\frac{r_b\times(K+E)}{K+E+3}=$$

$\dfrac{0,6(K^*+E)}{K^*+E+3} \Rightarrow \dfrac{0,4}{\dfrac{0,6(K^*+E)}{K^*+E+3}} < 1 \Rightarrow K^*+E > 6 \Rightarrow$ so our starting value for kanban cards is equal to 7.

A set of values are formed to be tried and analyzed via simulation to see the effects of them to performance measures. These values are shown in table 4.57.

Table 4.57: The trial values for Case 4-a

Trial No	**K**	**E**	**R**	**C**
1	7	0	0	0
2	8	0	0	0
3	9	0	0	0

After analyzing system for these values with simulation, we take some resulted values of performance measures. WIP levels at each stage are shown in Table 4.58, utilization rates are shown in Table 4.59, backorders and inventory levels are shown in Table 4.60 and total costs of system are shown in Table 4.61.

Table 4.58: WIP levels at each station for Case 4-a

Trial No	**WIP1**	**WIP2**	**WIP3**	**WIP4**
1	1,1953	1,2476	1,3729	1,7039
2	1,2528	1,3148	1,4401	1,7414
3	1,3026	1,3464	1,4888	1,7502

Table 4.59: Utilization rates at each station for Case 4-a

Trial No	U1	U2	U3	U4
1	71,84%	72,89%	77,19%	82,31%
2	73,96%	75,10%	77,57%	81,97%
3	74,32%	75,40%	77,61%	81,88%

Table 4.60: Backorders and inventory levels of system for Case 4-a

Trial No	Backorder	Inventory
1	1,2623	1,4714
2	0,5479	2,2372
3	0,3698	3,0910

Table 4.61: Total costs of systems for Case 4-a

Trial No	Total Cost 1	Total Cost 2	Total Cost 3	Total Cost 4
1	$5.534	$3.641	$4.798	$5.396
2	$4.168	$3.347	$3.050	$4.025
3	$4.495	$3.940	$2.949	$4.348

According to these values, we figured them to see the variations of performance measures. Variations of WIP levels at each stage are shown in Figure 4.37.

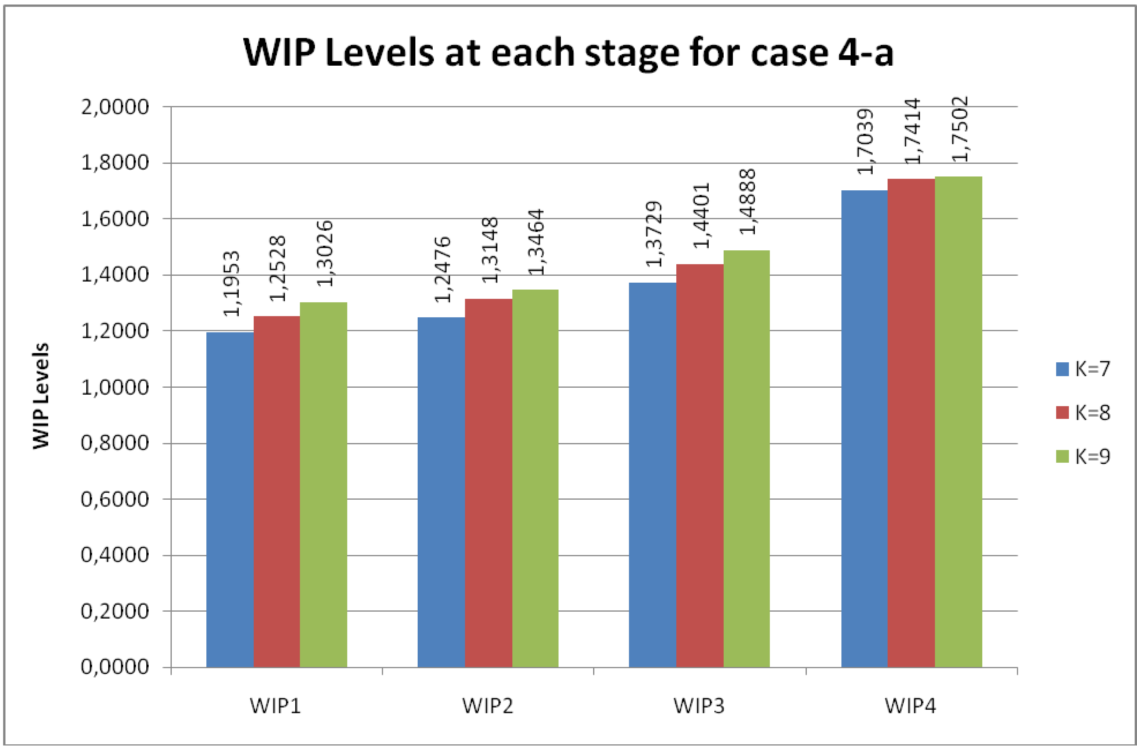


Figure 4.37: WIP levels variations at each station for Case 4-a

According to the WIP levels variation figure below, we can notice that increasing kanban level in a traditional kanban controlled production system cause to increase of WIP levels at each station. Because increasing kanban means, increasing production processing at the same time. Highest WIP levels can be seen in the last station which is the bottleneck for this case. Another performance measures which are backorders and inventory levels of system are shown in Figure 4.38.

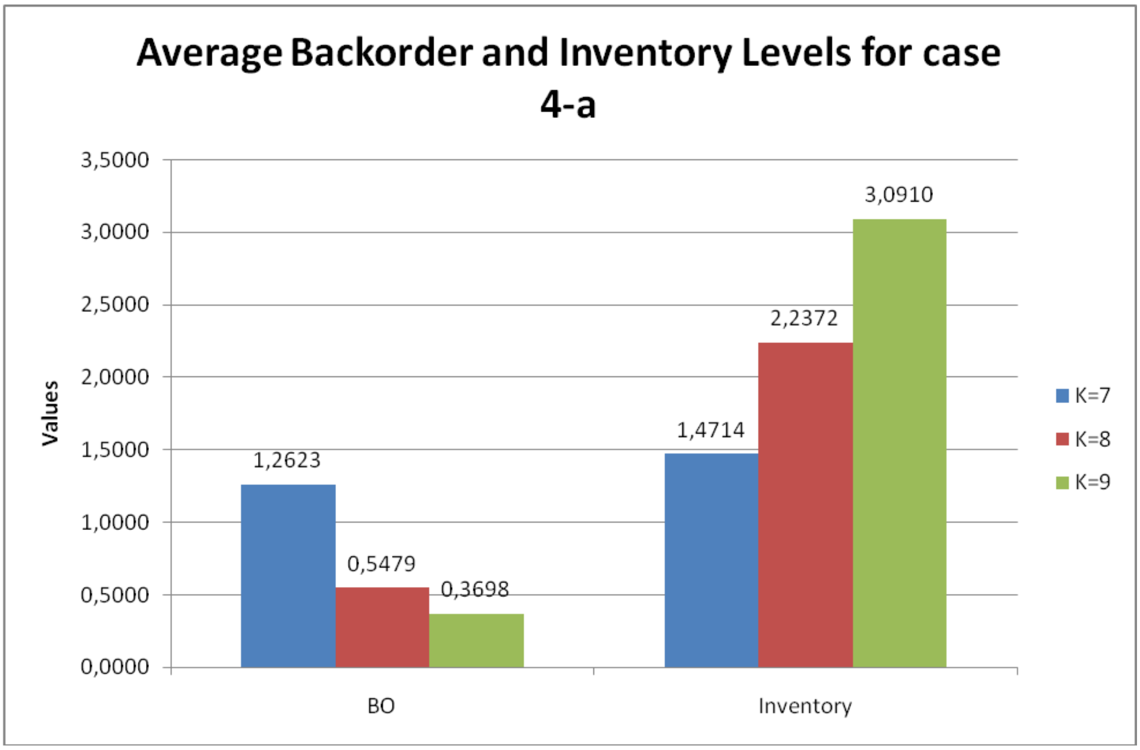


Figure 4.38: Average backorder and inventory variations for Case 4-a

As in other cases we tried before, again in this case backorders decrease and inventory levels increase when we increase the kanban level in the system. These variations of backorders and inventory levels effect total cost directly. Total costs of system are shown in Figure 4.39.

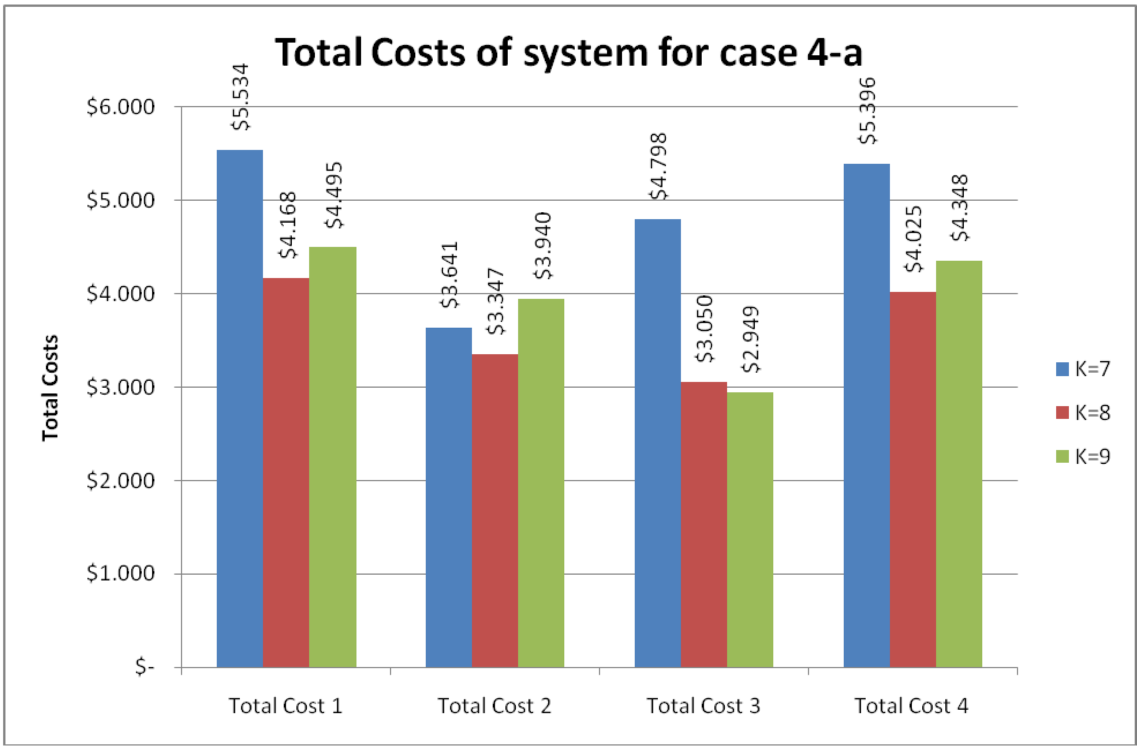


Figure 4.39: Total costs variations of system for Case 4-a

In this case, again the same variation can be seen in total cost figure. As we mentioned at starting of this case, we tried to find the optimal number of kanban cards to use for our adaptive system, assuming like a traditional system. We can see from figure 4.39, 8 is the optimal number of kanban cards for our system. For this case the most effective cost parameter is again cost of inventory. To see some other parameters' effects to our system, again we formed some other cases.

4.1.4.2 Case 4-b

In the case 4-a, we tried to find the optimal number of kanbans for traditional kanban system. In this case we will add extra cards to system, and try to see the effects of adding extra card on performance measures. We assumed the number of kanbans are equal to the number which we found as optimal in case 4-a, release and threshold values are constant. Release threshold value is 1, capture threshold value is 2. We formed different sets of trial values for this case. These trial values are shown in Table 4.62.

Table 4.62: The trial values for Case 4-b

Trial No	K	E	R	C
1	8	2	1	2
2	8	10	1	2

After analyzing system for these values with simulation, we take some resulted values of performance measures. WIP levels at each stage are shown in Table 4.63, utilization rates are shown in Table 4.64, backorders and inventory levels are shown in Table 4.65 and total costs of system are shown in Table 4.66.

Table 4.63: WIP levels at each station for Case 4-b

Trial No	WIP1	WIP2	WIP3	WIP4
1	1,51014899	1,310769	1,594741	1,784722
2	1,70160984	1,664734	1,718928	1,884512

Table 4.64: Utilization rates at each station for Case 4-b

Trial No	U1	U2	U3	U4
1	72,62%	69,66%	77,48%	81,66%
2	69,28%	72,01%	74,49%	79,10%

Table 4.65: Backorders and inventory levels of system for Case 4-b

Trial No	Backorder	Inventory
1	0,2442	3,2192
2	0,2008	3,2783

Table 4.66: Total costs of system for Case 4-b

Trial No	Total Cost 1	Total Cost 2	Total Cost 3	Total Cost 4
1	$4.262	$3.896	$2.652	$4.107
2	$4.239	$3.938	$2.600	$4.060

According to these values, we figured them to see the variations of performance measures. Variations of WIP levels at each stage are shown in Figure 4.40.

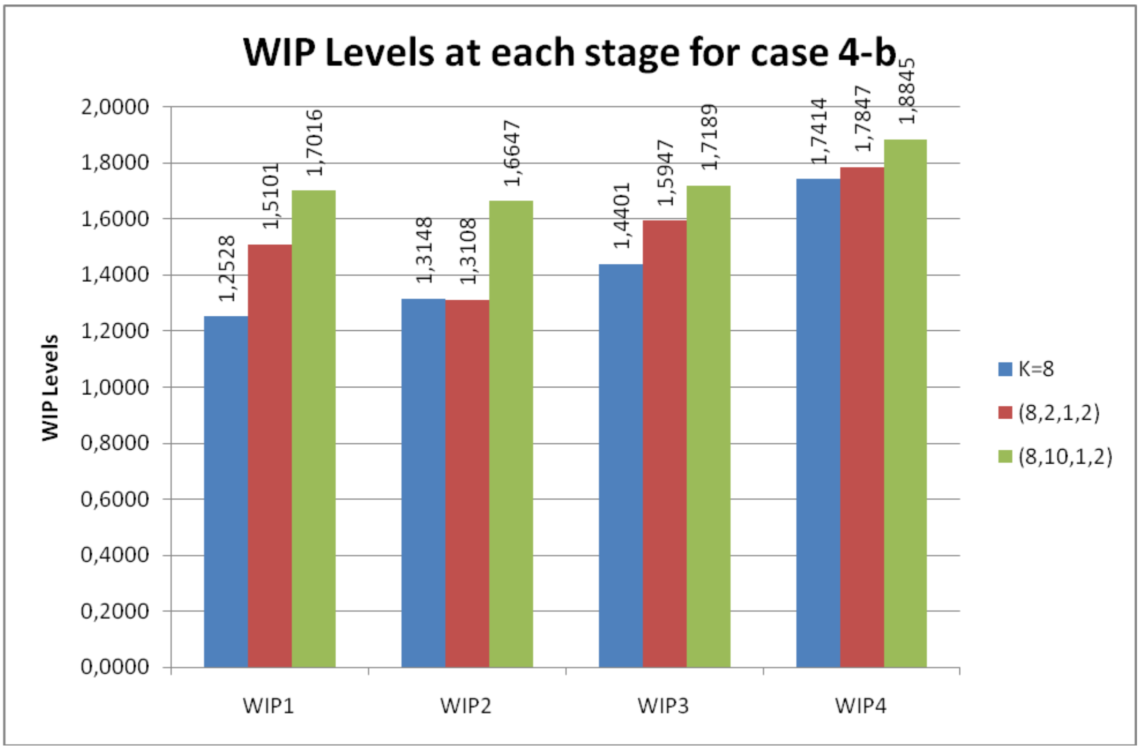


Figure 4.40: WIP levels variations at each station for Case 4-b

As we know the fourth station is the bottleneck station and production orders wait longer in station 4 more than the others. When we add extra cards to the system WIP levels at each stage increase for this case. Highest WIP level is in the fourth station which is the bottleneck station for this case. Total WIP levels of system increase. Backorders and inventory levels of system are shown in Figure 4.41.

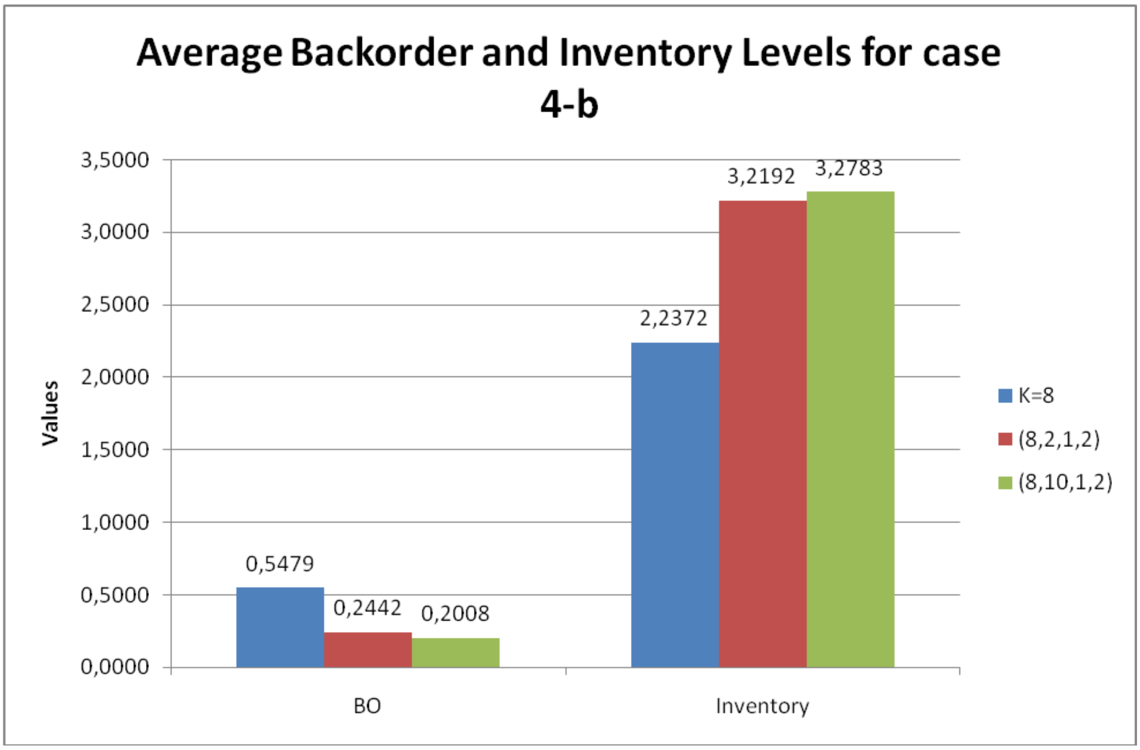


Figure 4.41: Average backorder and inventory variation for Case 4-b

As in other cases we tried before, when we add extra cards to the system backorders increase and inventory levels decrease according to adding extra cards to system. These variations of backorders and inventory levels effect total cost directly. Total costs of system are shown in Figure 4.42.

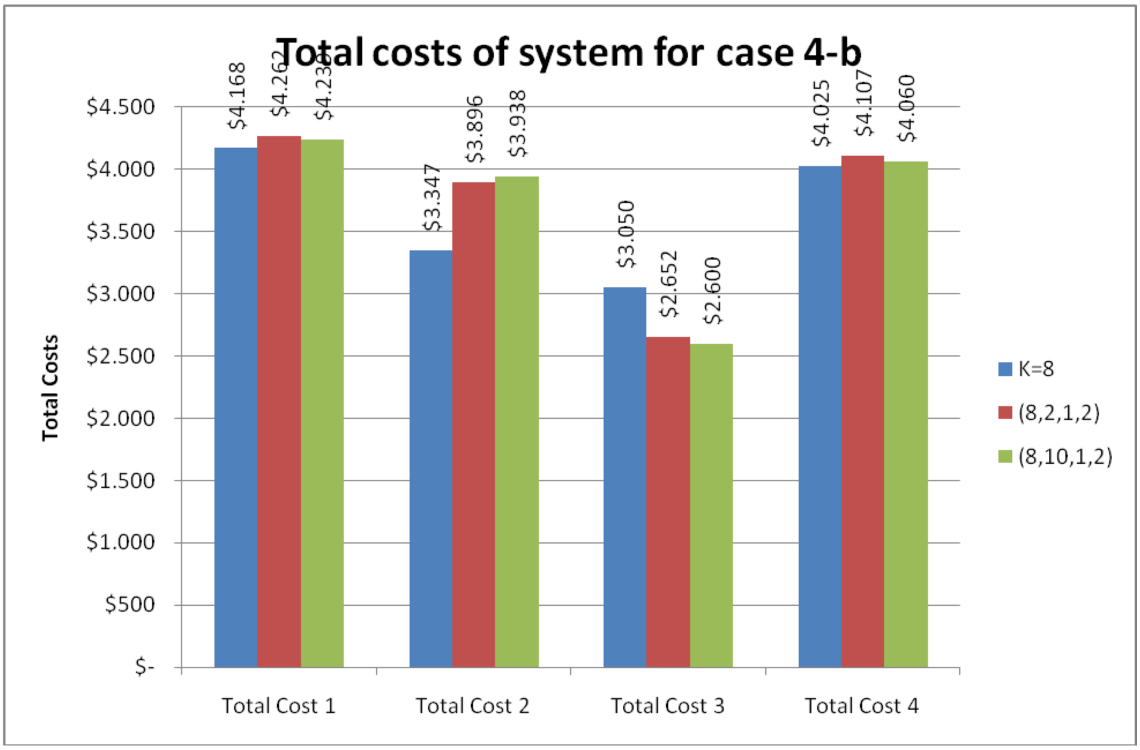


Figure 4.42: Total costs variations of system for Case 4-b

In this case, when we add extra cards to the system, total costs of system generally increase. We analyzed the system for different cost parameters and see that again the most effective cost parameter is the cost of inventory for this case.

4.1.4.3 Case 4-c

In this case we tried to see the effects of inreasing release threshold values to performance measures. We assumed the number of kanbans are equal to the number which we found as optimal in Case 3-a, extra kanban card is equal to 10 and capture threshold values are constant and C=7. We formed different sets of trial values for this case. These trial values are shown in Table 4.67.

Table 4.67: The trial values for Case 4-c

Trial No	**K**	**E**	**R**	**C**
1	8	10	1	7
2	8	10	6	7

After analyzing the system for these values with simulation, we take some resulted values of performance measures. WIP levels at each stage are shown in Table 4.68. The utilization rates are shown in Table 4.69. Backorders and inventory levels are shown in Table 4.70. The total costs of system are shown in Table 4.71.

Table 4.68: WIP levels at each station for Case 4-c

Trial No	**WIP1**	**WIP2**	**WIP3**	**WIP4**
1	1,9792	1,8405	1,8316	1,9499
2	2,3558	1,9797	1,9672	2,1355

Table 4.69: Utilization rates at each station for Case 4-c

Trial No	**U1**	**U2**	**U3**	**U4**
1	69,28%	72,01%	74,49%	79,10%
2	69,11%	74,76%	75,97%	79,18%

Table 4.70: Backorders and inventory levels of Case 4-c

Trial No	**Backorder**	**Inventory**
1	0,1508	4,2542
2	0,0968	5,4026

Table 4.71: Total costs of systems in Case 4-c

Trial No	**Total Cost 1**	**Total Cost 2**	**Total Cost 3**	**Total Cost 4**
1	$5.087	$4.860	$2.959	$4.897
2	$6.115	$5.970	$3.414	$5.904

According to these values, we figured them to see the variations of performance measures. Variations of WIP levels at each stage are shown in Figure 4.43.

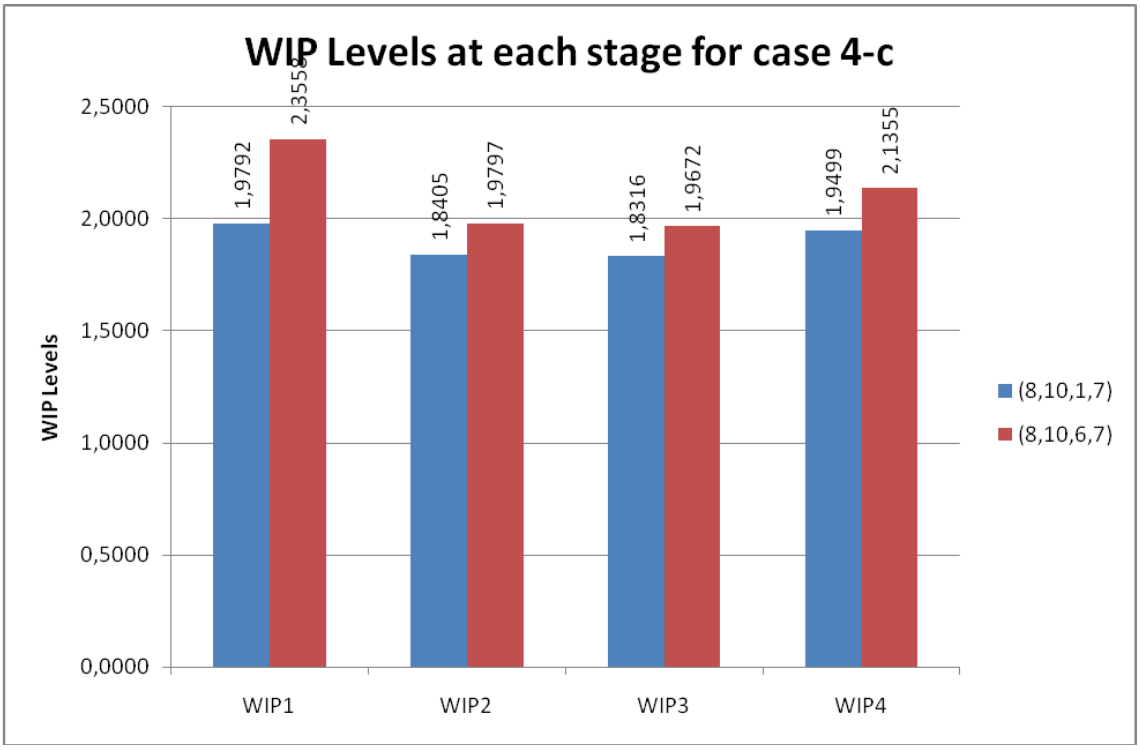


Figure 4.43: WIP levels variations at each station for Case 4-c

When we increase the release threshol value of the system, WIP levels increase for this case. Another performance measure backorders and inventory levels of system are shown in Figure 4.44.

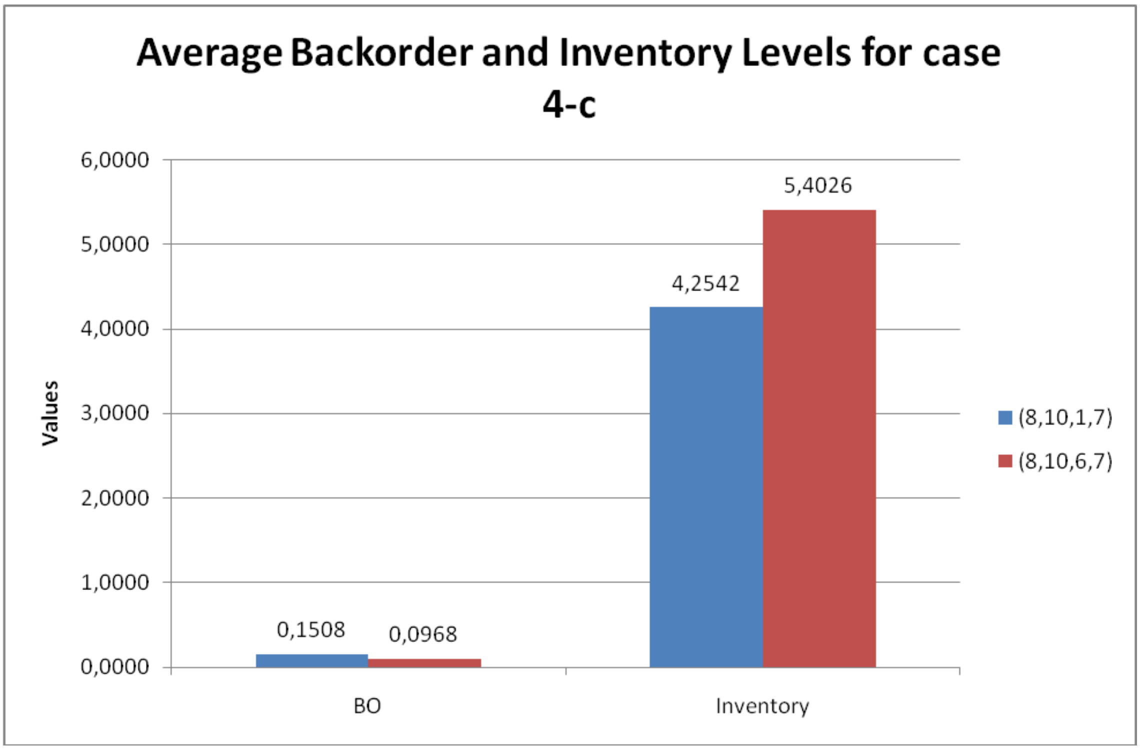


Figure 4.44: Average backorder and inventory variation for Case 4-c

As in other cases we tried before, again in this case backorders decrease and inventory levels increase when we incerase the value of release threshold. These variations of backorders and inventory levels affect total cost directly. The total costs of system are shown in Figure 4.45.

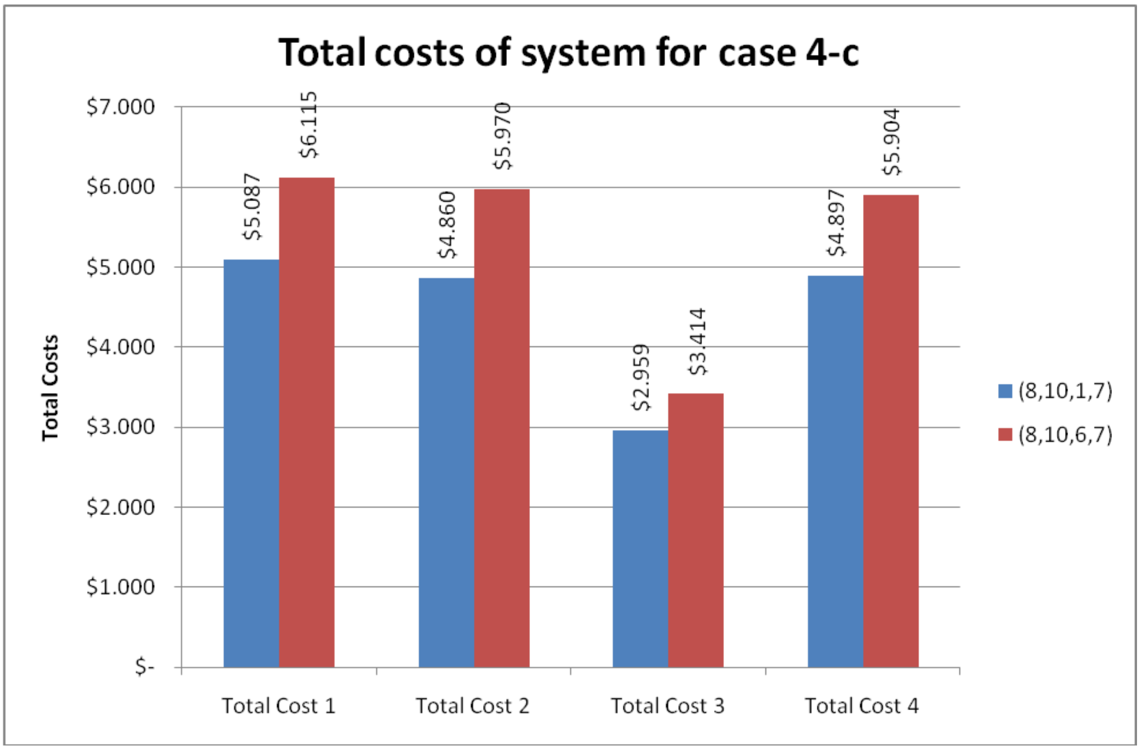


Figure 4.45: Total costs variations of system for Case 4-c

In this case, increasing release threshold value, cause increase of total cost in the system. As a result, we can say that holding release threshold value low is more suitable and optimal for adaptive kanban system in Case 4-c. In this case again the most effective cost parameter is the cost of inventory.

4.1.4.4 Case 4-d

In this case we tried to see the effects of inreasing capture threshold values to performance measures. We assumed the number of kanbans are equal to the number which we found as optimal in case 4-a, extra kanban card is equal to 1 which gives the minimum total cost for the case 4-b and release threshold values are constant and R=1 which give us minimum total cost in case 4-c. We formed different sets of trial values for this case. These trial values are shown in Table 4.72.

Table 4.72: The trial values for Case 4-d

Trial No	**K**	**E**	**R**	**C**
1	8	10	1	2
2	8	10	1	7

After analyzing system for these values with simulation, we take some resulted values of performance measures. WIP levels at each stage are shown in Table 4.73. The utilization rates are shown in Table 4.74. Backorders and inventory levels are shown in Table 4.75. The total costs of system are shown in Table 4.76.

Table 4.73: WIP levels at each station for Case 4-d

Trial No	WIP1	WIP2	WIP3	WIP4
1	1,70160984	1,664734	1,718928	1,884512
2	1,87920208	1,840516	1,831617	1,949905

Table 4.74: Utilization rates at each station for Case 4-d

Trial No	U1	U2	U3	U4
1	69,28%	72,01%	74,49%	79,10%
2	69,11%	74,76%	75,97%	79,18%

Table 4.75: Backorders and inventory levels of Case 4-d

Trial No	Backorder	Inventory
1	0,2008	3,2783
2	0,1508	4,2542

Table 4.76: Total costs of systems in Case 4-d

Trial No	Total Cost 1	Total Cost 2	Total Cost 3	Total Cost 4
1	$4.229	$3.928	$2.590	$4.055
2	$5.082	$4.855	$2.954	$4.894

According to these values, we figured them to see the variations of performance measures. Variations of WIP levels at each stage are shown in Figure 4.46.

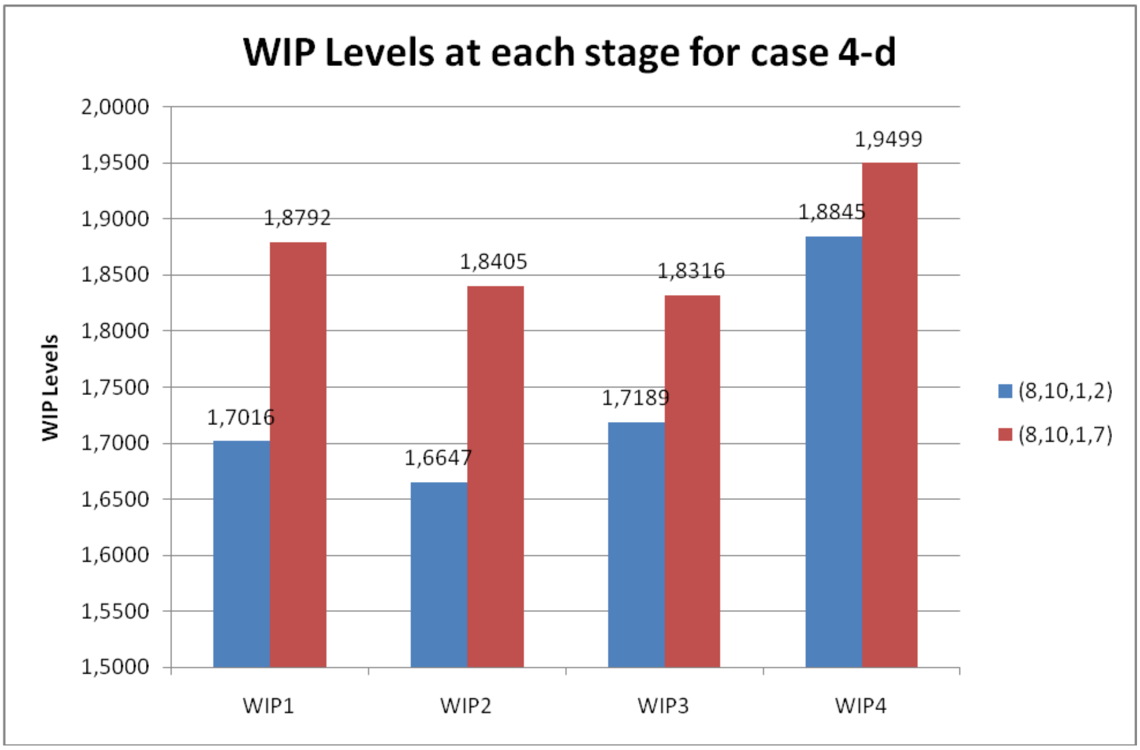


Figure 4.46: WIP levels variations at each station for Case 4-d

When we increase the capture threshold values in the system WIP levels increase. The highest WIP level is at the station 4 because the station 4 is the bottleneck station. Another performance measure average backorders and inventory levels are shown in Figure 4.47.

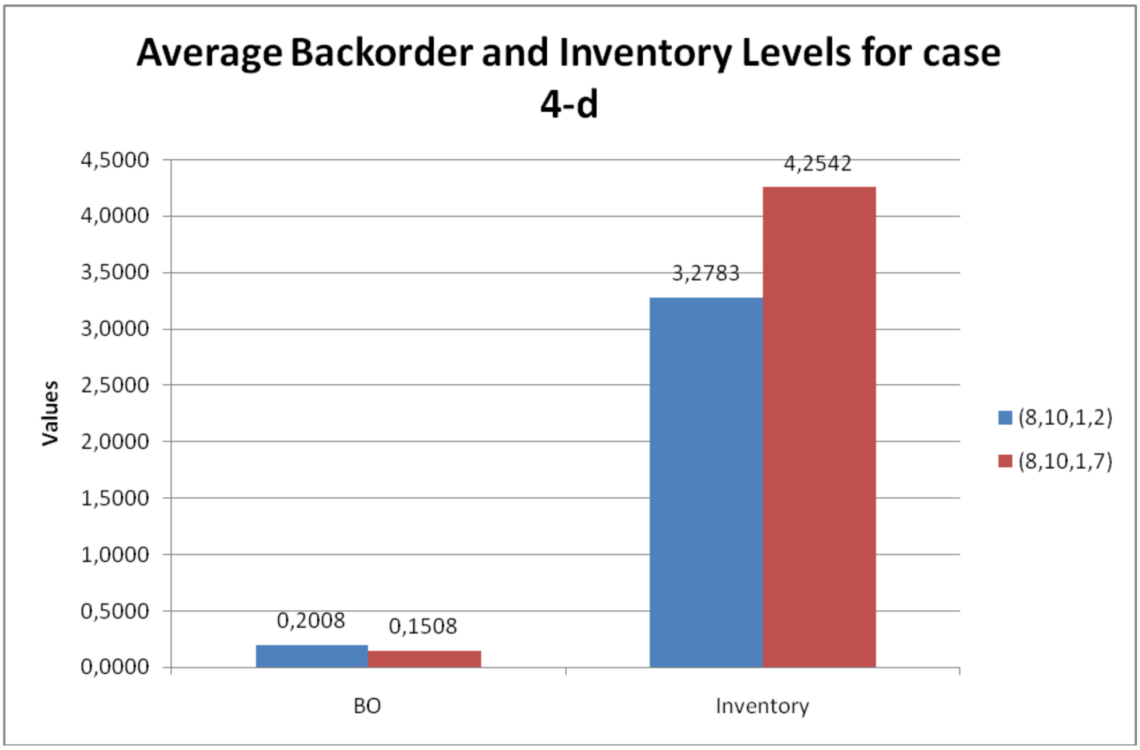


Figure 4.47: Average backorder and inventory variations for Case 4-d

As in other cases we tried before, when we incerase the value of release threshold again in this case backorders decrease and inventory levels increase. These variations of backorders and inventory levels affect total cost directly. Total costs of system are shown in Figure 4.48.

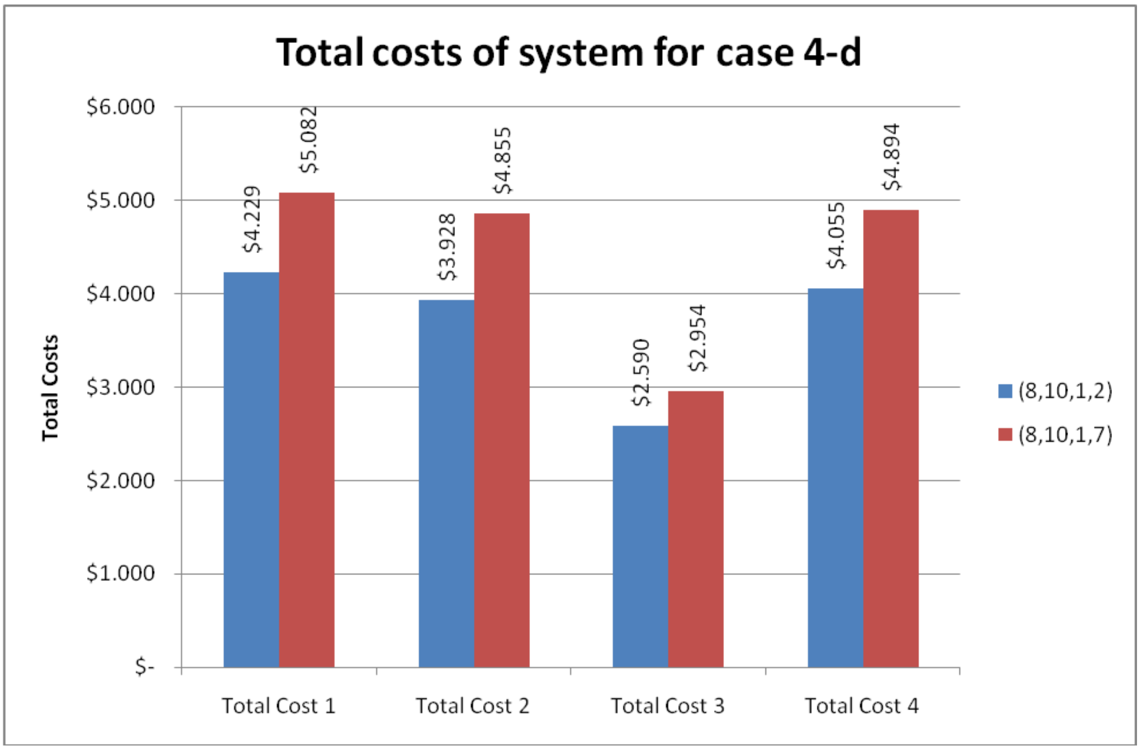


Figure 4.48: Total costs variations of system for Case 4-d

In this case, increasing release threshold value, cause increase of the total cost in the system. As a result, we can say that holding capture threshold value low, is more suitable and optimal for our adaptive kanban system in Case 4-d. Again in this case, the most effective cost parameter is the cost of inventory.

5. CONCLUSION

The adaptive kanban controlled production system developed with CONWIP concept is analyzed for different conditions and variables in this master thesis. After analyzing the system for these different conditions, generally adaptive system satisfied our objective, which is adapting a kanban system to unstable changes with minimum total costs. As we mentioned in introduction part, in CONWIP systems WIP levels are limited with the capacity of workstations in the system. In our system when we analyzed it with simulation, we noticed that WIP levels never get higher than 4, which is the capacity of each workstations in the manufacturing process. At each trial, WIP levels at each station did not change rapidly and the WIP levels were similar for different trial values of the system. Limiting the WIP levels helps us to lessen the effect of the cost parameter of WIP on the system's total cost. In the system, bottleneck workstation has the highest WIP level at each case.

Random process times and demand arrival times are so close conditions to real-life. When we look at the results of cases in Chapter 4, we can say that our system can adapt to unstable changes for time conditions. As we said before, bottleneck workstations make the system slow and cause an increase in the total cost of the system. In addition, the highest WIP levels have been seen in the systems which have bottleneck workstation. Also, in our adaptive system, we have seen that the average number of backordered demands is at very low levels, this means system can satisfy customer demands on time and it is one of the main ideas of Just-In-Time production planning concept. Only inventory levels in the system did not decrease to low levels, which can be a handicap for our adaptive kanban system. After the analysis, we noticed that our adaptive kanban system is more suitable than traditional kanban system. Since in each case, we found the best option of traditional kanban system then we got the system to be adaptive by adding extra cards to that option of the traditional system. We saw that when we made the system adaptive, the system's ability to satisfy customer demands improved.

The total cost of the system did not decrease in each case. We have analyzed the system for different cost parameters to see the most effective cost parameter in the system. As a result, the most effective cost parameter in the system is the cost of inventory. If we can decrease the inventory levels in the adaptive kanban system, we can improve our system and totally optimize the system.

We believe that we have defined some approximate solutions for the sample adaptive system we developed. In addition, the system can be analyzed for different demand and production rates, with different K, E, R and C values to deal with the handicaps we have stated before.

REFERENCES

Books

Altıok Tayfur, (1996), “Performance Analysis Of Manufacturing Systems”

Hopp J. Wallace, Spearman L. Mark (2008), “Factory Physics”, International Edition

Periodical Journals

Akturk, M. S. And Erhun, F.(1999) “An Overview Of Design And Operational Issues Of Kanban Systems”, International Journal Of Production Research, **37: 17**, 3859-3881

Bard, J. F. & Golany, B. (1991), “Determining The Number Of Kanbans In A Multiproduct, Multistage Production System”, International Journal Of Production Research, Vol.**29**, No.5, 881-895

Chan, F.T.S (2001), “ Effect Of Kanban Size On Just-İn-Time Manufacturing Systems”, Journal Of Materials Processing Technology Vol.**116**, 146-160.

Deleersnyder, J. L., Hodgson, T. J., Muller, H. and O’grady, P. J. (1989) ”Kanban Controlled Pull Systems: An Analytic Approach”, Management Science, Vol.**35**, No.9, 1079-1091

Di Mascolo, M., Frein, Y. & Dallery, Y. (1996)” An Analytical Method For Performance Evaluation Of Kanban Controlled Production Systems”, Operations Research, Vol. **44**, No. 1, Special Issue On New Directions In Operations, 50-64

Duri, C., Frein, Y. and Di Mascolo, M. (1995) “Performance Evaluatıon Of Kanban Multıple Product Productıon Systems”, IEEE, Vol. **95** 557-566

Duri, C., Frein, Y. and Di Mascolo, M. (2000), “Comparison Among Three Pull Control Policies”, Annals Of Operations Research, Vol.**93**, 41-69

Georg, N. K. & Heinrich, K. (2004), “Analysis Of Multi-Product Kanban Systems With State-Dependent Setups And Lost Sales”, Annals Of Operations Research **125**, 141–166

Gupta, S. M. & Al-Turkı, Y. A. Y. (1997) “An Algorithm To Dynamically Adjust The Number Of Kanbans In Stochastic Processing Times And Variable Demand Environment”, Production Planning & Control, **8: 2**, 133-141

Kotani, S. (2007) “Optimal Method For Changing The Number Of Kanbans in The <i>e</i>-Kanban System And its Applications”, International Journal Of Production Research, **45: 24**, 5789 — 5809, First Published On: 01 March 2007

Markham, I. S., Mathiey, R. G. and Wray, B. A. (1998),” A Rule Inductıon Approach For Determining The Number Of Kanbans In A Just-In-Time Production System”, Computers Ind. Engineering, Vol.**34**, No. 4, 717-727

Mark, L. S., David, L. W. & Wallace, J. H. (1990), “CONWIP:A Pull Alternative To Kanban”,International Journal Of Production Research, Vol.**88**, No.5, 879-894

Philipoom, R. P., Rees, P. L., Taylor, W. B. and Huang, Y. P., (1987), “An Invenstigation Of The Factors İnfluencing The Number Of Kanbans Required İn The İmplementation Of The Jıt Technique With Kanbans”, International Journal Of Production Research, Vol.**25**, No. 3, 457-472

Sarah, M. R., Bruno, B. and Fred, F. C. (1998), “Determining Inventory Levels in A CONWIP Controlled Job Shop”, IEEE Transactions Special Issue On Manufacturing Logistics.

Sivakumar, G. D. & Shahabudeen, P.(2009) 'Algorithms For The Design Of A Multi-Stage Adaptivekanban System', International Journal Of Production Research, **47: 23**, 6707 — 6738

Schonberger, R. J. (1983), “Applications Of Single-Card And Dual-Card Kanban”, Production Scheduling, Materials Handling, INFORMS, **13,** 56-67.

Takahashi, K. & Nakamura, N. (2001), “ Decentralized Reactive Kanban System”, European Journal of Operational Research, **139**, 262-276

Takahashi, K. & Nakamura, N.(1999) 'Reacting Jıt Ordering Systems To The Unstable Changes In Demand', International Journal Of Production Research, **37: 10**, 2293-2313

Takahashi, K. (2003), “Comparing Reactive Kanban Systems”, International Journal Of Production Research, **41: 18**, 4317-4337

Takahashi, K., Katsumi, M. and Nakamura, N. (2003), “ Reactive JIT Ordering System for Changes In The Mean and Variance of Demand”, International Journal Of Production Economics, Vol. **92**, 181-196

Tardif, V. & Maaseidvaag, L. (2001), “An Adaptive Approach To Controlling Kanban Systems”, European Journal Of Operational Research”, **132**, 411-424.

Other Publications

Orbak, A. Y. & Bilgin, S. (2005), “Kanban Sisteminin Bir Uygulama Örneği”V. Ulusal Üretim Araştırmaları Sempozyumu, İstanbul Ticaret Üniversitesi

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