Robust Production & Inventory Control Systems for Multi-product Manufacturing Flow Lines

By

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DECLARATION

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Doctor of Philosophy is entirely my own work, that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

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ABSTRACT

The production line of modern multi-product manufacturing with erratic demand profiles shows that the selection and implementation of appropriate production control strategy are an important challenge. Organisations that adopt pull-type production control strategies, such as Kanban control strategy, for multi-product production lines find that is necessary to plan high Kanban card allocations in order to maintain volume flexibility to manage demand variability. This can result in line congestion, long lead times and low throughput rate. A recently proposed shared Kanban allocation policy has the benefit of minimising inventories in the line by allocating Kanbans accordingly and therefore maintains volume flexibility. However, many pull production control strategies that have been shown to be successful in single product manufacturing environments, for instance Kanban, CONWIP and Basestock cannot operate the shared Kanban allocation policy naturally.

This Thesis presents a practically applicable modification approach to enable pull production control strategies that are naturally unable to operate in a shared Kanban allocation policy mode to operate it. Furthermore, the approach enables the development of a new pull production control strategy referred to as Basestock Kanban CONWIP control strategy that has the capability to operate the shared Kanban allocation policy, minimising inventory and backlog while maintaining volume flexibility.

To investigate the performance of the pull production control strategies and policies, discrete event simulation and evolutionary multi-objective optimisation approach were adopted to develop sets of non-dominated optimal solutions for the experiments. Nelson’s screening and selection procedure were used to select the best pull control strategy and Kanban allocation policy when robustness are not considered. Additionally, Latin hypercube sampling technique and stochastic dominance test were employed for selection of a superior policy and strategy under environmental and system variability. Under non-robust conditions (anticipated environmental and system variability), pull control strategies combined with the shared Kanban allocation policy outperforms pull control strategies combined with

dedicated Kanban allocation policy. Conversely, pull control strategies combined with the dedicated Kanban allocation policy outperforms pull control strategies combined with shared Kanban allocation policy when the system is prone to environmental and system variabilities. Furthermore Basestock Kanban CONWIP control strategy outperforms the alternatives in both robust and non-robust conditions.

DEDICATION

To my beloved parents whose rare qualities are second to none

To my adored wife full of grace and goodwill

To my sons (Samuel, Israel & Michael) in whom I am well pleased

Thank you for all your love and support.

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List of Abbreviations

Abbreviation	Description
BK-CONWIP	Basestock Kanban CONWIP control strategy
BL	Backlog
BOM	Bill of Materials
BSCS	Basestock Control Strategy
CONWIP	Constant Work-In-Process control strategy
DBR	Drum-Buffer-Rope
DES	Discrete Event Simulation
D-KAP	Dedicated Kanban Allocation Policy
EA	Evolutionary Algorithm
ECKCS	Extended CONWIP Kanban control strategy
EKCS	Extended Kanban Control Strategy
EP	Evolutionary Programming
ERP	Enterprise Resource Planning
ES	Evolution Strategies
FDKS	Forecast Driven Kanban Systems
FIFO	First In First Out
GA	Genetic Algorithms
GKCS	Generalised Kanban Control Strategy
GPOLCA	Generic Paired-Cell Overlapping Loops of Cards with Authorisation
HIHPCS	Horizontally Integrated Hybrid Production Control Strategies

HK-CONWIP	Hybrid Kanban CONWIP control strategy
HPCS	Hybrid Production Control Strategy
KAP	Kanban Allocation Policy
PCS-KAP	A specified PCS and specified KAP combination
KCS	Kanban Control Strategy
LHS	Latin Hypercube Sampling
MDP	Markov Decision Process
MPME	Multi-Product Manufacturing Environment
MRP	Material Requirement Planning
MRP II	Manufacturing Resource Planning
MTBF	Mean Time Before Failure
MTTR	Mean Time To Repair
PAC	Production Authorisation Card
PCS	Production Control Strategy
POCSLWIP	Pareto Optimisation Curves of Service Level against Work-In-Process inventory
POLCA	Paired-Cell Overlapping Loops of Cards with Authorisation
PSE	Production Systems Engineering
RDKS	Requirements Driven Kanban Systems
ROP	Reorder-point
ROQ	Reorder-Quantity
SA	Starvation Avoidance
S-KAP	Shared Kanban Allocation Policy

SL	Service Level
TBL	Total Backlog
TSL	Total service level
TWIP	Total Work-In-Process inventory
VIHPCS	Vertically Integrated Hybrid Production Control Strategies
WIP	Work-In-Process inventory
WIP-Cap	Limiting the Proportion of WIP in a System via PAC
	Manufacturing Process unit of stage *j*
	Inventory buffer of product *i* and stage *j*

CHAPTER 1: INTRODUCTION

1.1 Background

Production control of a manufacturing flow line regulates the throughput times, the flow of parts and the work-in-process inventory in a system. It includes the process of authorisation of parts for production, the release of raw material/semi-finished or finished products in a stage/system, the setting of priorities for production of raw material or semi-finished parts, the control of the transportation of parts and/or other activities such as quality control in the system [1]. Over the years, various production control strategies (PCS) have evolved. Push and pull production control strategies are the two main philosophical approaches found in the literature. Pull production control strategies have been widely used in manufacturing systems owing to their documented performance and effectiveness with stochastic demand [2-5]. A pull production control strategy uses actual customer demands in planning, scheduling and control of production in a system. In academic research works, demands are often represented using a single demand profile or a linear time series model; however, in the manufacturing industry, practitioners report, that actual customer demands are irregular and non-linear in nature [6]. Managing such non-linear demands is challenging and requires the proper selection and implementation of a pull production control strategy with volume flexibility. Volume flexibility is used in this study to mean the ability of a pull production control strategy to adequately respond to demand variations without reconfiguration of the production control parameters at any given production period. However, pull production control strategies such as Kanban and CONWIP have demonstrated poor responses to large product volume and mix variations [7-9]. The poor response is largely attributed to the requirement of steady demand flow in pull production control strategy. This issue of product mixes and volume variations often results in flow line congestion, long lead times and low throughput rate in a Multi-Product Manufacturing Environment (MPME), such that the performance goals and the principles of lean manufacturing are greatly undermined.

A majority of the studies on pull production control strategies have considered single-product production lines [10-15]. However, any assumption that the results of such studies would be automatically scalable to multi-product lean manufacturing environments is not reliable because a pure implementation of a pull production control strategy in a multi-product environment requires maintaining semi-finished parts of each of the products distributed throughout the system resulting in a proliferation of work-in-process inventory. To minimise the large work-in-process inventory in multi-product systems, Baynat et al. [16] proposed a flexible Kanban allocation policy that allows Production Authorisation Cards (PAC) to be shared among part-types. Two Kanban allocation policies found in the literature are hereinafter referred to as the Dedicated Kanban Allocation Policy (D-KAP), which is the traditional rigid PAC (note: in this thesis, Kanbans and CONWIP cards are interchangeable and they are PAC), and Shared Kanban Allocation Policy (S-KAP), which is the flexible PAC. The findings of Baynat et al. [16] showed that S-KAP maintained lower work-in-process inventory in a multi-product manufacturing environment than D-KAP when implemented with the same pull production control strategies. In this thesis, PAC refers to all Kanbans and CONWIP cards, use to authorise the release of a part-type in a system.

1.2 Motivation and Objectives

Managing environmental and system variability is a challenging task in manufacturing environments. Organisations that implement pull production control strategies in a multi-product manufacturing environment plan a large volume of production authorisation cards to respond to environmental variability [17, 18]. The difficulties accompanying a high volume of production authorisation cards for each part-type in a multi-product manufacturing environment are proliferating Work-In-Process (WIP), line congestion and low throughput. To achieve low WIP, high production flexibility, less line congestion, high quality and delivery performance in a multi-product manufacturing environment, an appropriate production control strategy and Kanban allocation policy are required.

The choice and implementation of a production control strategy have significant influence on the performance of multi-product manufacturing flow line. Demand variability has a negative effect on the performance of both push and pull production control strategies in multi-product manufacturing flow lines. However, pull production control strategies, as opposed to alternatives such as push control strategies, are examined in this study owing to their documented performance and effectiveness in WIP control [2-5].

The effects of the high-level of WIP in multi-product systems are induced long quality feedback loops, high cycle time, high machine utilisation and low throughput. Recent decades have seen significant research regarding production control strategy and Kanban allocation policy in multi-product manufacturing environments. According to Rossi [19], a practical production control strategy based on the needs of a company and its customers is required. A practically applicable production control strategy should be able to address issues such as level of performance regarding WIP control, service level in complex and non-repetitive multi-product manufacturing environments, and flexibility in terms of response to changes in product mix and demand volume.

The objectives of this study are (1) to develop a modification approach that enables pull production control strategies that currently fail to operate in shared Kanban allocation mode to operate in that mode in order to increase the strategies' performance in complex and non-repetitive multi-product systems; (2) to develop a practically applicable pull production control strategy that has the capability to operate in complex and non-repetitive multi-product manufacturing environments, maximising service levels, minimising inventory and backlog, while maintaining volume flexibility among product types. The new pull production control strategy is intended to integrate the benefits of the three traditional pull control strategies (Kanban, Basestock and CONWIP) and it is suggested that it will have improved WIP control over its alternatives.

1.3 Scope and Delimitation

The work contained in this thesis is related to an emerging branch of engineering referred to as Production Systems Engineering (PSE) with the objective of providing the basic principles governing production systems for analysis, continuous improvement and design [20]. One of the areas of interest for PSE is the investigation of the flow of parts in a manufacturing system, making production control strategy an important area of PSE. This is because production control strategy refers to the process of regulating resources in a manufacturing system for the production of goods. The strategy controls the release and flow of parts in a system, and is composed of the information flow that controls material flow, part release authorisation, setting of production priority (sequence of tasks), control of flow of parts, transportation of parts, quality control and throughput monitoring [21-23]. In this thesis, a manufacturing system relates to a production facility, which is commonly classified owing to its production process. The three types of manufacturing processes are the job-shop, the batch and the flow line. The job-shop manufacturing system produces custom parts in a small quantity. The batch manufacturing system produces parts via stage by stage over a series of workstations and a variety of products are manufactured. The flow line manufacturing system is a process in which several operations are carried out on parts in a definite direction. This thesis focuses on the flow line systems.

This research focuses on the information flow that controls the flow of parts and part release authorisation in a manufacturing system. Furthermore, depending on the flow of parts/material in a system, production can be classified as continuous or discrete. Continuous production refers to production in which products are invariably transferred along a specified route such as in food or chemical industries, while discrete production refers to the production of parts that are transferred between processes at a given time and in most cases in batch-sizes [24]. The work in this thesis considers only the discrete production system with defined levels of feasible operational complexity.The level of operational complexity of a manufacturing system targeted in this study includes (1) low number of products-types in a multi-stage serial and/or parallel/serial production or assembly lines with simple or complex material flow. (2) Similar or different process times for product types, and infinite or finite buffer sizes. (3) Significant or insignificant environmental and system variability.

This work is designed based on the waste reduction and continuous improvement principles of lean manufacturing and applicable to both simple and complex manufacturing systems. Relevant theoretical and industrial cases were used for examination and analysis of the performance of various pull production control strategies in multi-product manufacturing environments. The conceptual models were translated into simulation models and the quantitative techniques used relating to the queuing theory, production systems engineering, decision support analysis and simulation.

1.4 Structure of Thesis

This thesis is organised into eight chapters. The first chapter presents a brief and brisk introduction of the areas of interest, followed by a literature review in the second chapter, which provides a review of the state-of-the-art knowledge of production control strategies. The objectives of the review of relevant literature are to present a clear understanding of related works, the contributions and the current problems/challenges that require attention. Chapter 3 describes the approach for modifying pull control strategies and the development of a new pull production control strategy. The factors influencing pull production control strategies to operate in dedicated and shared Kanban allocation policy modes were examined and followed by the process of alteration of pull production control strategies to operate in shared Kanban allocation policy mode. The approach was used to develop a new pull production control strategy referred to as Basestock Kanban CONWIP (BK-CONWIP) control strategy.

The details of the research methodology are presented in chapter 4. The optimisation, simulation and comparison tools and techniques used to examine the performance of pull control strategies in this work are defined. The theoretical and industrial multi-product multi-stage manufacturing systems and assembly lines used in this study are described. The theoretical manufacturing system is a two-product three-stage serial manufacturing line with negligible setup times, having linear demand, while the industrial system used is an automotive electronics component production facility that produces four products-types of two product families in a five stage assembly line with significant set-up times and non-linear demand (erratic demand). Furthermore, a description of the simulation models of the system for each production control strategy and Kanban allocation policy is presented. Chapter 5 describes the experimental conditions and the simulation results obtained. Discrete event simulation and an evolutionary multi-objective optimisation approach were adopted to develop Pareto-frontiers for the appropriate settings of the control parameters of the S-KAP and D-KAP models. Nelson’s screening and selection procedure were utilised to establish a superior policy under anticipated environmental variability, while Latin hypercube sampling technique and stochastic dominance test were employed for selection of a superior policy when significant environmental variability was considered. It was shown that PCS combined with S-KAP outperformed PCS combined with D-KAP when robustness were not considered. Robustness analysis of the control strategies and policies is provided in chapter 6. The Latin hypercube sampling technique and stochastic dominance test were employed for selection of a superior policy under environmental and system variability. The outcome shows that under ±5% environmental variabilities, PCS combined with D-KAP outperformed PCS combined with S-KAP when service level has a higher priority for selection of PCS. S-KAP is selected as superior KAP when WIP control is considered for selection of PCS in both simple and complex multi-product manufacturing flow lines. Chapter 7 discusses and concludes the findings of the study and the implications of these findings to real system. Chapter 8 presents the main contributions of the study and future research areas. The findings of this research, the limitations and directions for further works are summarised. Figure 1.1 presents a graphical representation of the structure of this thesis.

Figure 1.1: Structure of the thesis

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter provides a review of relevant publications on production control strategies and production authorisation cards. It examines various production control strategies and Kanban allocation policies apply to single and multi-product production systems with a view to understanding the work done in this area and the challenges that multi-product manufacturing flow lines such as health care and automotive manufacturing businesses are faced with, in order to present a clear view of the need for this study.

Today, many production firms are configured as multi-product production lines to enable them to satisfy varieties of custom made and highly engineered products. The products may be similar, with several variations, which could include size, colour, shape, etc. depending on the market demand. The changes and improvements from single product production system to multi-product production systems not only advanced the technologies in production systems, but also enhanced various production control strategies used in production systems. The production control strategy is concerned with the control of the flow of material and parts in a system. The determination of an effective mechanism to control the flow of materials through a manufacturing system is an important decision in a manufacturing business [14]. The production control strategy addresses issues of the proportion of the parts to be authorised into a system and the time to release them into the system in order to achieve a specified service level while minimising work-in-process inventory. Capacity, and lead time issues arise in production systems with poor control strategies. For instance, a push controlled system with high product mix and volume variance would result in a high WIP level, long lead time and poor delivery performance. Therefore, regulating the flow of material into a system would improve the system productivity and delivery performance. The difficulties in the control arise due to production and demand variability. These variations are the major factors in the advancement of production control strategies in order to adapt to the global market changes.

2.2 Production Control Strategy

The primary roles of a production control strategy are to authorise the release of parts into a system and to control the flow of parts in the system. According to Fernandes and Carmo-Silva [25] the manner of authorisation of part of a system, regulates the time and production schedule for parts. The authorisation for release of parts into a system depends largely on the control strategy and very often the release is based on the demand priority and the minimisation of the negative effect of demand on the shop floor at a given time [26]. The control mechanism of some production control strategies authorises the release of a part into a system based on the availability of raw material as in the case of a push production control strategy, while in pull production control strategy, the release of a part into a system is regulated by the availability of a signal card and/or demand information and raw material. Additionally, another vital element of the control strategy is the dispatching rule; this defines the order for processing part-types in a system [25]. However, production controlled using dispatching rules in isolation tends to perform poorly [27-29].

The variations found in production control strategies have led to the classification of production control strategy in order to gain insight of their control mechanisms. Fernandes and Carmo-Silva [25] suggested two classifications based on the authorisation for the release of parts (order release) into a system and the material flow in a system. The classification of production control strategy based on the authorisation of parts into a system and based on material flows is illustrated in Figure 2.1.

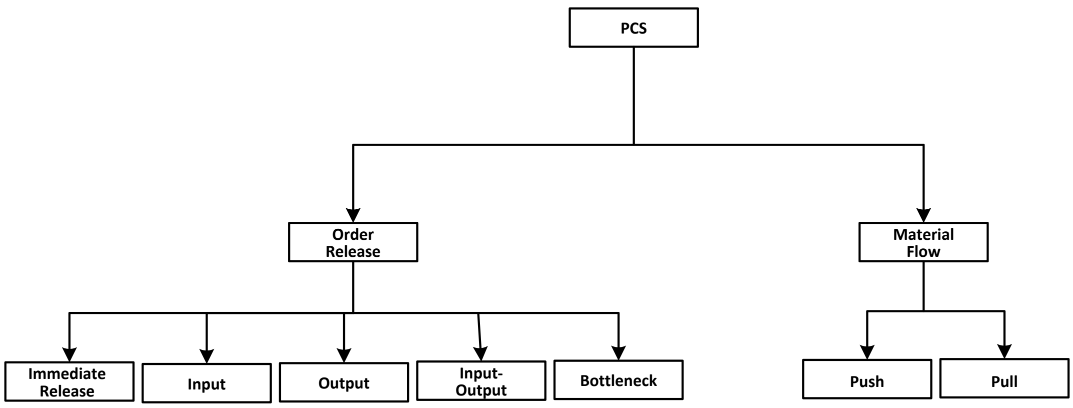


Figure 2.1: Classification of production control strategy

An Immediate Release control mechanism releases parts into a system immediately a demand occurs. In this group, the state of the system is not considered before parts are released, one example is the Base Stock Control Strategy (BSCS) [30]. On the other hand, the Input control mechanism schedules the release of part into a system based on order due date. This group follows a schedule from a master production schedule in releasing a part-type into a system without considering the status of a manufacturing system. Material Requirement Planning (MRP) is a typical example of this group [31]. The release time for a variety of product-types is determined by backward scheduling due dates based on estimated lead times for material supply and production [25]. Similarly the Output control mechanism authorises the release of part-types into a system based on the present utilisation or depletion of the final goods inventory of the output buffer. This group considers the system status in setting the base-stock level or workload planned levels for the release of parts into a system, while the product due date is insignificant in the release of the parts. Additionally, it controls the work-in-process inventory while observing the throughput of the system. Some examples of production control strategies in this group are Kanban Control Strategy (KCS) [32], Constant Work-In-Process control strategy (CONWIP) [14], and Basestock Kanban-CONWIP control strategy [15]. They are based on minimum work-in-process inventory level planned for a manufacturing system often referred to as an inventory replenishment control mechanism. The Generic Paired-Cell Overlapping Loops of Cards with Authorisation (GPOLCA) strategy is also a member of this group and is based on workload planned levels often referred to as load-limited control mechanism.

In some cases, especially in make-to-order systems, the inventory replenishment control mechanism is planned with production authorisation cards unattached to parts at initial state of the system (free or unattached production authorisation cards) and zero initial work-in-process inventories, for example when a demand occurs, an available unattached production authorisation card synchronises with the demand information to authorise a release of part-type into a system to satisfy the demand on time [17, 18]. The Input-output control mechanism group integrates the characteristics of Input and Output control mechanisms, with the authorisation of a part-type release into a system based-on the synchronisation of the release date (based on the due date) and the availability of production authorisation cards. Some of the production control strategies in this group include Synchro-MRP [33] and

Paired-Cell Overlapping Loops of Cards with Authorisation (POLCA) strategy [8]. The Bottleneck control mechanism group authorises the release of a part-type depending on the completion of a task on a bottleneck station, for instance, when a part-type completes its processing in a bottleneck station a similar part-type is released into the system, also a minimum work-in-process inventory is maintained in an input buffer of the bottleneck station in order to maintain the maximum throughput feasible in such a system. The production rate at the bottleneck station determines the rate of product-types release into a system. Examples of this group include Drum-Buffer-Rope (DBR) developed by Goldratt and Fox [34], as well as Starvation Avoidance (SA) proposed by Glassey and Resende [35].

In the classification of production control strategies based on how parts or materials flow in a system, production control strategies are grouped into push and pull control strategies [25]. The push and pull type of classification is frequently used in the literature in classifying production control strategies [36]. A Push production control strategy requires demand forecast in order to develop a production schedule and release parts into a system to ensure that production meets the anticipated demand. Conversely, a pull production control strategy uses actual demand to authorise material release into a production system and it has a feedback loop to communicate and regulate the work-in-process inventory of a system while monitoring the throughput.

2.2.1 Push Production Control Strategies

A push control strategy aims at providing order processing, data handling and inventory management. It regulates the throughput of a system from the view of the first workstation. The accuracy of the forecasted demand and production scheduling determines the effectiveness and efficiency of the production flow. Noticeable and major implementations of the concept of push production control strategy are found in the Material Requirement Planning (MRP), Manufacturing Resource Planning (MRP II) and Enterprise Resource Planning (ERP).

MRP was developed in the 1960s. It offered users an advanced method of controlling inventory in a manufacturing system when compared with the Reorder-point/Reorder-Quantity (ROP/ROQ) strategies (inventory management and control strategies used before the development of MRP). MRP gained popularity up to the early 1980s, when Manufacturing Resources Planning (MRP II) evolved [37, 38]. MRP II was an advancement of MRP. It uses a combination of MRP with master scheduling, rough-cut capacity planning, input/output control and other modules for production and inventory control. These two production control strategies were found to give a new life to production industries in America. They sold in great numbers and were very popular [38]. ERP was an advancement of MRP II. The development of ERP provided businesses the ability to integrate all of a corporation's business applications with a mutual database via ERP's client/server information technology architecture [39]. This strategy was the first production control strategy that offered users the integration of business applications with a mutual database. ERP gained great popularity due to its advantages, yet its implementation is costly [37]. It was observed that environmental and system variability cause changes in production scheduling resulting in long lead times and capacity infeasibility [40-42]. Additionally, demand varied influences the accuracy of a forecasted demand leading to an increase in the cost of production and reduction in the service level.

2.2.2 Pull Production Control Strategies

The concept of pull production control strategy is based on the principles of automation and just-in-time production [37, 43]. Automation aims at establishing the optimal approach to carry-out a task and brand the approach as the standard method to perform such a task. It stops production to correct any problem in the production line. The standard approach eliminates the requirement for rework lines and scraps. Just-in-time production establishes the use of signal cards (often referred to as Kanbans) to authorise the release of parts into a system, as well as the application of production levelling in a system. The goals of these two principles are to eliminate several wastes in a manufacturing system and drastically reduce changeover times. Pull production control strategies regulate the work-in-process inventory of a system while observing the throughput [14]. The concept of pull production control strategy is implemented in several strategies, including Kanban control strategy [32], Basestock control strategy [30], Constant Work-In-Process control strategy [14], Generalised Kanban Control Strategy (GKCS) [44, 45], Extended Kanban Control Strategy (EKCS) [46], Hybrid Kanban CONWIP (HK-CONWIP) control strategy [47], Extended CONWIP Kanban control strategy

(ECKCS) [48], et cetera. The symbols used in the figures in chapter 2 are described in Table 2.1.

Table 2.1: Description of symbols

Symbol	Description	Symbol	Description
$D_{1,2,\ldots}$	Demand card for stage 1,2, ...	DCC	CONWIP card attached to demand card for a system
$D^{1,2,\ldots}_{1,2,\ldots}$	Demand card for product 1,2,... at stage 1,2, ...	CC	CONWIP card in a system
$K^{1,2,\ldots}$	Kanban card for product 1,2,...	$I^{1,2,\ldots}_{1,2,\ldots}$	Inventory output buffer for product 1,2, ... at stage 1,2, ...
$K^{1,2,\ldots}_{1,2,\ldots}$	Kanban card for product 1,2, ... at stage 1,2, ...	I_j^i	Output buffer for product 1,2, ... at stage 1,2, ...
$DK_{1,2,\ldots}$	Kanban card attached to demand card for stage 1,2,...	$MP_{1,2,\ldots}$	Manufacturing Process at stage 1,2,...
$RM^{1,2,\ldots}$	Raw material for product 1,2, ...	MP_j	Manufacturing Process unit at stage 1,2,...

The Basestock control strategy was reported as the first pull production control strategy developed [49]. In BSCS system, each inventory stage is initialised to a pre-set level of inventory [46]. When an actual demand occurs, an authorisation or demand information is globally sent to all the stages of the production line. Depending on the availability of raw material or part to be processed, the demand information is attached to the available raw material/semi-finished part to commence production operations on that part. The demand information is rescinded immediately the production starts on the tagged part [50]. One of the merits of BSCS is its ability to rapidly respond to demand occurrence. The demand information is transmitted to all production stages instantaneously. The rapid response in production is achieved because each production stage is directly informed of the demand occurrence. However, there are some criticisms on the control mechanisms of BSCS system based on its inability to secure and control the number of parts that enter the system and its loose coordination between the stages [46]. Figure 2.2 is an illustration of the BSCS control mechanism.

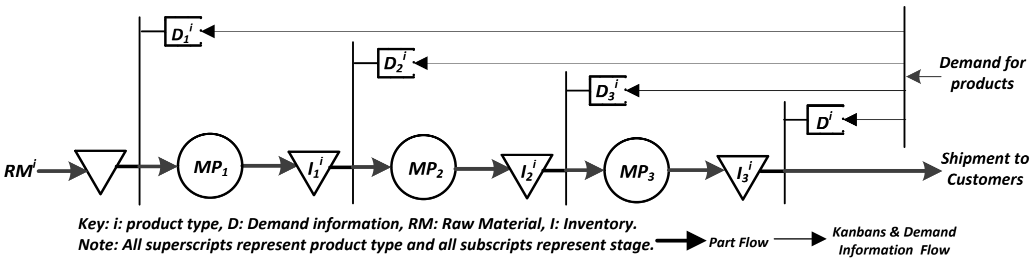


Figure 2.2: Queuing network model of Basestock control strategy

The Kanban control strategy was the first pull production control strategy that used the signal cards (Kanbans) to authorise the production of a part on a stage. It uses a local information flow sequence in transmitting demand information and Kanbans. It has one parameter (Kanban) that controls both the work-in-process inventory and the release of parts onto a stage [51]. In KCS systems, a Kanban card is tagged onto a part to authorise the release and the processing of a part in a stage. The part batched with Kanban stays in the output buffer of that stage, waiting for the next stage to request a new part. When the next stage places an order for a new part, the previous stage releases the part, simultaneously detaching the previous stage Kanban and attaching the next stage Kanban to the part. One of the merits of KCS is that it controls WIP. The Kanban control strategy works well in production systems with small lot sizes and product variation [14, 47]. However, it performs poorly in production systems with large lot sizes, bottlenecks, long lead times and changeovers. The basic control mechanism of Kanban control strategy is represented in Figure 2.3.

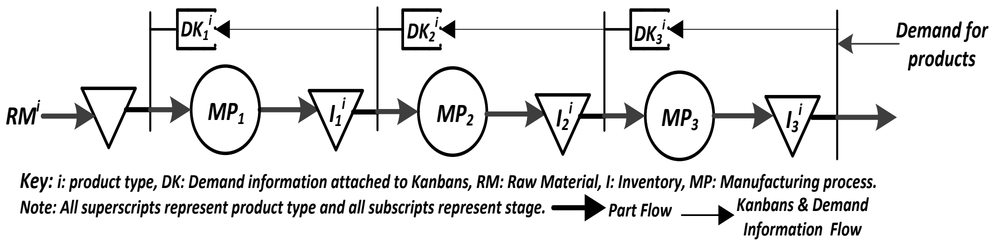


Figure 2.3: Queuing network model of Kanban control strategy

The development of Constant Work-in-Process control strategy was primarily to proffer a solution to non-repetitive manufacturing environments where KCS was undependable, unfavourable and unreliable [14]. CONWIP combines the merits of KCS (that is: low-level of inventory) and the merits of MRP (that is: high throughput) in its control strategy. The ability of CONWIP to use actual market demand in the authorisation of a new product makes it a pull-type PCS [47, 52-54]. The CONWIP control mechanism uses a “WIP Cap” to control the amount of inventory in a system at a given period of time. The ability of CONWIP to authorise the release of parts and control inventory in a system through a global set of signal cards makes it easy for implementation and maintenance. This set of cards is attached to the raw material at the entry/initial input buffer of a system. The set of cards remains attached onto the part until the part leaves the final stage output buffer when it satisfies a demand. The set of cards is then detached and used for authorisation of another part [7]. A major drawback in the CONWIP control mechanism is the loose coordination between stages [47]. Figure 2.4 shows the CONWIP control mechanism.

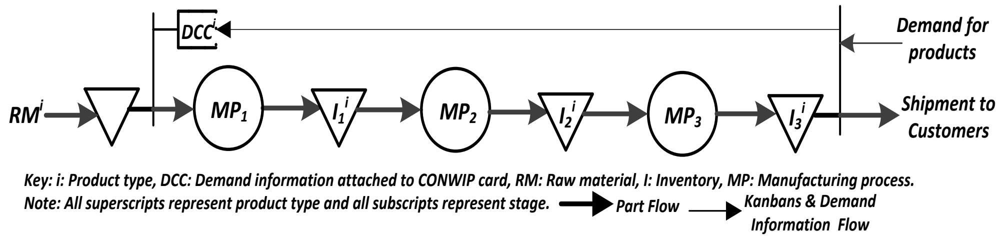


Figure 2.4: Queuing network model of CONWIP control strategy

The concept of Generalised Kanban control strategy is centred on the combination of KCS and BSCS to harness their merits into one control strategy [45, 55]. GKCS uses two parameters (basestock and Kanban) in each stage in the production line to control inventory and authorise production. The basestock of the finished parts controls the total stage inventory while the number of Kanban controls the quantity of products to be stored in a stage's output buffer [44, 46]. The inventory level of each stage is initialised to a pre-set level and the demand information is transmitted to each stage. The flow of product in the system is controlled by Kanban just as in the case of KCS system. The actual market demand information is transmitted as demand cards to the last stage of the production line and if a Kanban matches the demand card, then a demand card is sent to the next stage upstream. If there is no Kanban at any stage to match the demand card at that stage, then the demand card remains at that stage and no demand card will be sent to the next stage upstream until a Kanban becomes available in that stage. Demand and processing time variations negatively affect the performance of GKCS [16, 45, 46, 55, 56]. The control mechanism of GKCS is shown in Figure 2.5.

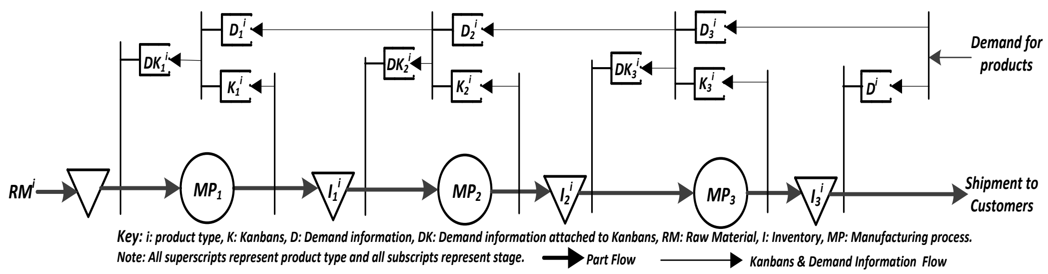


Figure 2.5: Queuing network model of Generalised Kanban control strategy

The Extended Kanban control strategy uses the same control parameters as GKCS in a simpler way. It was developed to control process time variables [46]. In the initial state of an EKCS controlled system, the base-stock level is initialised to a pre-defined value. The Kanban cards are attached to the base stocks. The demand information is globally transmitted to all stages in a system, resulting in quick response to demand. Therefore, the roles of Kanban and the basestock of the finished parts are wholly decoupled from each other, unlike in GKCS with the partial decoupling of the roles of basestock and Kanban [16, 44, 46, 50]. Figure 2.6 shows the control mechanism of EKCS.

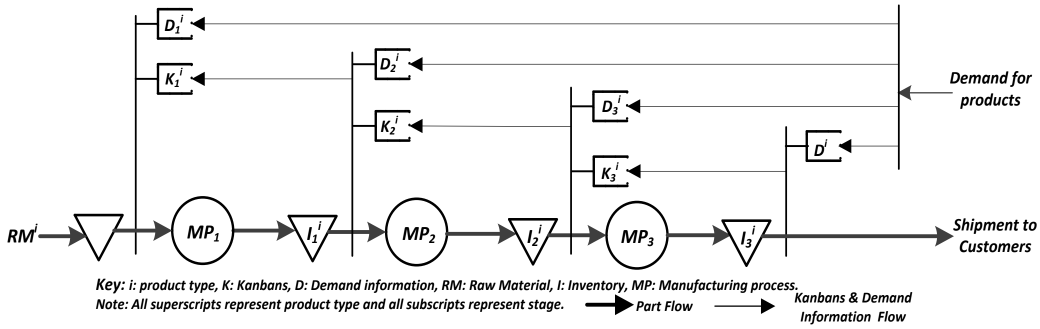


Figure 2.6: Queuing network model of Extended Kanban control strategy

The Hybrid Kanban-CONWIP control strategy is based on the concept of CONWIP. However, it uses Kanban cards to control the inventory level at every stage in the production line except for the final stage that uses push control mechanism, while the CONWIP cards control the inventory of the entire system [47]. The coordination between the stages of HK-CONWIP via Kanbans proffers a solution to the issues of a large quantity of stage inventories and bottleneck issues in a manufacturing system [57]. Figure 2.7 shows the control mechanism of Hybrid Kanban CONWIP control strategy.

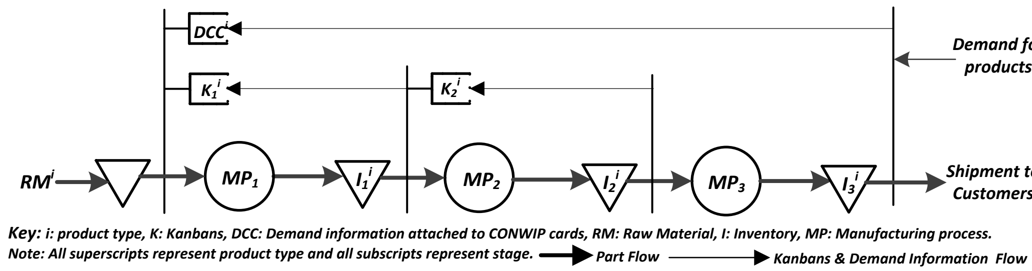


Figure 2.7: Queuing network model of Hybrid Kanban CONWIP control strategy

The Extended CONWIP Kanban control strategy (ECKCS) uses three parameters in its control mechanism. It was proposed by Boonlertvanich [48] and was suggested to have superior performance in terms of WIP control, managing demand

and processing time variations over EKCS, GKCS, HK-CONWIP and the traditional pull PCS in a single product multi-stage manufacturing environment. However, this has not been investigated in a multi-product multi-stage manufacturing environment. The control mechanism operates with a set of stage production authorisation cards (Kanbans) and a set of entire system production authorisation cards (CONWIP cards). The stage production authorisation cards function like GKCS system such that the Kanban used in the stage inventory control are detached from the finished parts immediately the finished parts leave the manufacturing process unit (the stage Kanban is detached simultaneously from a part when the part leaves the stage machines). In addition, the CONWIP cards attached onto parts in an ECKCS controlled system are detached on the finished product immediately they leave the final stage manufacturing process unit. The basestock in the output buffer of the final stage is used to satisfy customer actual demand. The demand is globally transmitted to all stages. Figure 2.8 shows the control mechanism of ECKCS.

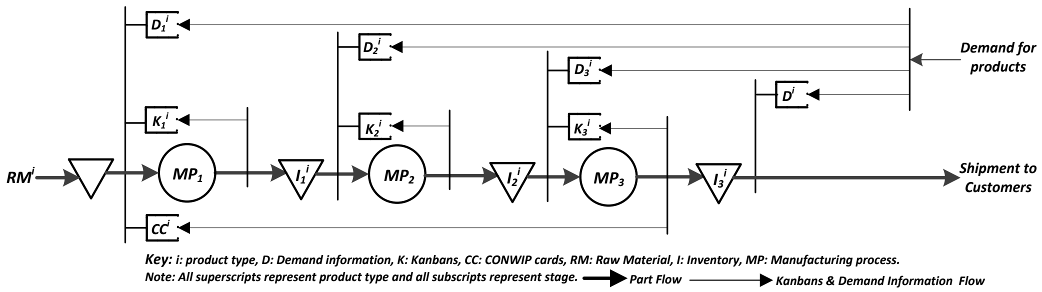


Figure 2.8: Queuing network model of Extended CONWIP Kanban control strategy

Today, several modified pull production control strategies have been developed for quick response to variations, especially in multi-product manufacturing environments, for instance, Paired-Cell Overlapping Loops of Cards with Authorisation [8]. The benefits of these pull production control strategies over push production control strategies include reduced production cost, minimise material waste, improved quality control and just-in-time delivery of products [42, 58-60]. In spite of these benefits, pull production control strategies have drawbacks for instance; it exhibits a poor response to large product mix and volume variations [7].

2.2.3 Combination of Production Control Strategies

The three traditional pull production control strategies are KCS, BSCS and CONWIP, while the primary traditional push production control strategies are

MRP and MRP II. The modification of the traditional pull or push PCS and/or the combinations of multiple pull or push PCS in a control strategy is regarded as a Hybrid Production Control Strategy (HPCS). It brings together elements of the push and/or pull production control strategies in various ways in order to manage and control the production variables. Depending on the modification of these traditional push and pull PCS, such modifications are grouped into three categories.

The first group of HPCS refers to pull production control strategies that are embedded into push production control strategies. The second group is known as the Vertically Integrated Hybrid Production Control Strategies (VIHPCS), while the third group is called the Horizontally Integrated Hybrid Production Control Strategies (HIHPCS) [61].

The first group is subdivided as the Forecast Driven Kanban Systems (FDKS) and Requirements Driven Kanban Systems (RDKS). FDKS are non-repetitive, such that the item batch size and item card counts are adjustable to accommodate predicted demand and variation in demand [62]. In RDKS systems, the item card counts are regulated by determining the gross requirements at the part level via a single level of the Bill of Materials (BOM) and changing the BOM into card releases [50]. The approximated processing times for production are used to offset the releases.

In VIHPCS, a push-type production control strategy is used to create the production schedule, while the pull-type production control strategy is used to control the production at each stage, such that production at each stage is only authorised by Kanban availability and the demand. This means that in each production stage the push and pull production control strategies are used in the control of the system [63, 64]. Although this concept is interesting, the fact that MRP is tied to each production stage makes the implementation complex. VIHPCS is applicable to production systems with a high product mix and custom-made orders [50].

In HIHPCS, the entire production stages are not controlled by one control strategy. Some stages are controlled by pull-type PCS and other stages are controlled by push-type PCS. Most research on this area is concerned either with the determination of the best strategy for the horizontal integration (example, optimal location of the junction point between push and pull control and optimal distribution of Kanban cards in the pull-controlled section) or the comparison of the hybrid push-pull type strategies to push-type strategies and pull-type strategies. HIHPCS is applicable to production systems with a bottleneck and product volume variations [50].

2.3 Effect of a Production Control Strategy on a System's Operational Performance

Operational performance refers to the performance of a manufacturing system calculated based on a set of significant parameters of the effectiveness and efficiency of the system. It is often calculated in three proportions (quality, cost and delivery of product) [65].

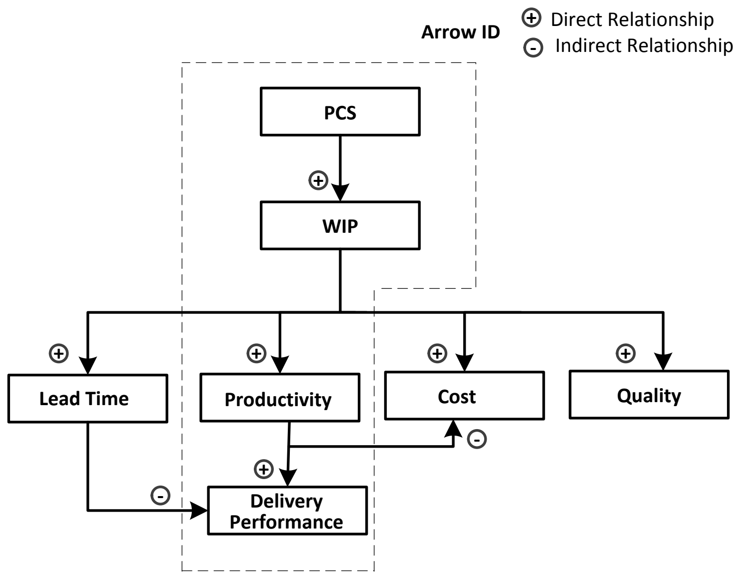


Figure 2.9: Effect of PCS on the operational performance of a system

Figure 2.9 describes the most significant fundamental chains from production control strategy over system characteristics to operational performance. The arrow identification (Arrow ID) in the figure identifies the manner of relationship existing between two subjects such as a direct (+) or indirect (-) relationship. In a direct relationship, a change in one of any two subjects causes a corresponding change in the other subject, while in an indirect relationship, an increase in one of any two subjects will cause a decrease in the other subject. The dash line in the figure shows the area within the scope and the relevance of this thesis.

The effects of the control strategy on the operational performance of a system, as shown in Figure 2.9, are summarised as follows:

- The production control strategy controls the authorisation and flow of material in a system. It influences the location, type and amount of the work-in-process inventory in a system [36]. Therefore PCS is directly proportional to WIP.
- WIP is the proportion of material released into a system that has not left the system [24]. It directly influences the productivity of a system. For instance, when sufficient resources (such as WIP) required for production of a given quantity of products are available in a given manufacturing system, it is expected that the required quantity will be produced (high productivity). However, if WIP is insufficient, the productivity is expected to decrease.
- Similarly, WIP directly influences the cost of production. In this study, the cost of production is referred to as the cost incurred on a product during the process of transforming raw materials into a finished product [66, 67]. At each stage of the production, value is added to the WIP. If WIP stays long in a queue, some values (such as temperature, paints, etc.) fall below the required standard, resulting in the need for additional values via reneging, rework or scrap. For instance, in a hot rolling mill (metal forming), if the temperature of a metal stock decreases below its recrystallization temperature while waiting in a queue, the metal stock is reneged to previous stage to raise its temperature to its recrystallization temperature. This additional value increases the cost of production. A high proportion of WIP in a system increases the probability of WIP staying long in a queue.
- WIP directly relates to production lead time because WIP affects the time parts wait in a buffer in front of a stage or a process point in a system [68]. If WIP stays a long time in a queue, it results in a long production lead time.
- Change in WIP feature influences the product quality. The product quality is the product's ability to have a pre-defined standard or features. The availability of suitable material (WIP of appropriate standard) and the process reliability influence product quality (changes in manufacturing processes, process control, product specification will give to product quality issues) [65]. For instance, in manufacturing systems with quality feedback loops

such that the quality of parts is assessed after several processes or near completion. When the WIP specification changes, it changes the quality of the product. Therefore, WIP has direct relationship with lead time, productivity, cost and quality.

- The productivity of a system is the measure of finished products to the resources (WIP) used in the production process. It influences the delivery performance of a system. The delivery performance refers to as the level to which the demands are satisfied with the finished products. An increase in the productivity of a system will increase the delivery performance of the system. Therefore, productivity directly affects the delivery performance and indirectly influences the product cost [36]. Similarly, lead time has an indirect relationship with product delivery performance.

Finally, the PCS effect diagram shows that the production control strategy influences the WIP inventory of a system which affects the production lead time, product cost, product quality and productivity in a system. Productivity influences the delivery performance of a system. This analysis shows that the production control strategy directly or indirectly plays an important role in determining the cost, quality and delivery performance of a system. They are the three significant factors for measuring the operational performance of a system. This study examines the behaviour of PCS by measuring its WIP level, productivity and delivery performance.

2.4 Single and Multi-product Production Control Strategies

A single-product manufacturing system is often used in representing a simple framework of a manufacturing process for the production of discrete items. Single-product refers to the production of one type of product in a manufacturing system and a manufacturing system in some cases is divided into multi-stages, where each stage is considered a workstation. A workstation consists of a manufacturing process and an output buffer (inventory queue) [48].

Issues associated with global market changes and advancements in manufacturing industries, have influenced the development of complex frameworks for flow lines of complex manufacturing systems such as in multi-product multi-stage flow lines. One of the important issues facing multi-product multi-stage manufacturing systems is how to design and operate production control strategy in such a manufacturing environment without proliferation of WIP, while maintaining low operating parameter settings and high customer service levels.

A review of the literature on production control strategies shows that a majority of these studies were conducted on single product manufacturing environments [10-15, 53, 69-76]. The findings of these studies show that push controlled systems have high WIP and throughput with negligible line congestion. While pull controlled systems have low WIP levels and high delivery performance in a system. A review of studies on multi-product manufacturing environments shows that the findings from single product systems are not scalable to multi-product systems [10-15, 53, 69-76]. In multi-product systems, push production control strategies build-up a large inventory of product-types in response to schedule or forecast demand. However, any change in demand information results in line congestion, long lead time and low throughput [40-42]. Similarly, the application of a pull production control strategy (example, KCS) in a multi-product manufacturing system involves keeping semi-finished parts of every product-type in all the stages of the system resulting in a proliferation of work-in-process inventory. The large WIP in pull controlled multi-product systems undermine the objectives of pull principles and cause long lead times, production waste, poor just-in-time delivery and increased production cost [58-60]. Pull PCS in a multi-product system also performs poorly in the presence of variations in product volume and mix [7-9]. Variation in product volume refers to as the difference between the current quantity of demand to the demand used in the planning or the configuration of the system's control parameter, while variation in product mix is the difference between the current quantity of product A and the quantity of the planned product A or the difference between the current quantity of product B to the quantity of the planned product B.

The low throughput, line congestion and high WIP level associated with PCS in multi-product systems adversely affect the operational performance of a multi-product system. Owing to these drawbacks and unsuccessful implementation of pull and push production control strategies in complex manufacturing environments such as Kanban controlled multi-product systems created the bases for research to proffer solutions, especially to minimise the WIP level and improve delivery performance of pull controlled multi-product systems.

2.4.1 Pull Production Control Strategies in Multi-product systems

In pull controlled systems, there are three components in a system that are transferred from one place to another; (i) the product-type is transferred downstream as the raw material is transformed into finished parts, (ii) the demand information flows upstream in the system and (iii) the production authorisation card is either batched with demand information or product-type in a system. The way in which the demand information and the production authorisation cards are transferred into a system is the main distinguishing factor among various pull production control strategies. The term stage or system is interchangeable throughout this section.

In multi-product pull manufacturing environments, prior to the S-KAP proposal by Baynat et al. [16], D-KAP was assumed sufficient. However, they caused increased WIP inventory, making them undesirable. Multi-product systems operating D-KAP function as a series of single product systems with shared manufacturing process units [15, 16, 77]. The findings of [15] showed that the tight-coupling between demand information and authorisation cards has a high influence on pull production control strategies that only operates D-KAP causing them to behave as extended single product systems.

For successful implementation of pull production control strategies in multi-product manufacturing environments, issues such as how the production authorisation cards are distributed between product types require attention as this regulates the WIP in a system. The production authorisation card could be designed as rigid or flexible in terms of its distributions to product-types. Rigid and flexible techniques for distribution of production authorisation cards are the two most documented Kanban allocation policies in the literature for multi-product pull systems and are known as D-KAP and S-KAP.

The concept of D-KAP is such that it allocates a prearranged number of production authorisation cards to a specific product type in a system. For instance, a product type can be released into a system only when a corresponding production authorisation card is available to match it. S-KAP, on the other hand, allocates production authorisation cards for any available product type in a system, depending on the demand of a product-type and the availability of the production authorisation cards. It responds to any available demand regardless of the product-type. In cases where there are orders for product-types, but no available production authorisation cards, there will be no release of product-types into the system. S-KAP responds to a corresponding shift in product volume within product-types in a multi-product system by allocating production authorisation cards appropriately to product-types without reconfiguration of optimised or initial production authorisation card setting defined for the system. D-KAP would require reconfiguration and/or re-optimisation of the number of production authorisation cards for any corresponding shift in product volume within product-types in a multi-product system. The control mechanisms of D-KAP and S-KAP are illustrated in Figure 2.10.

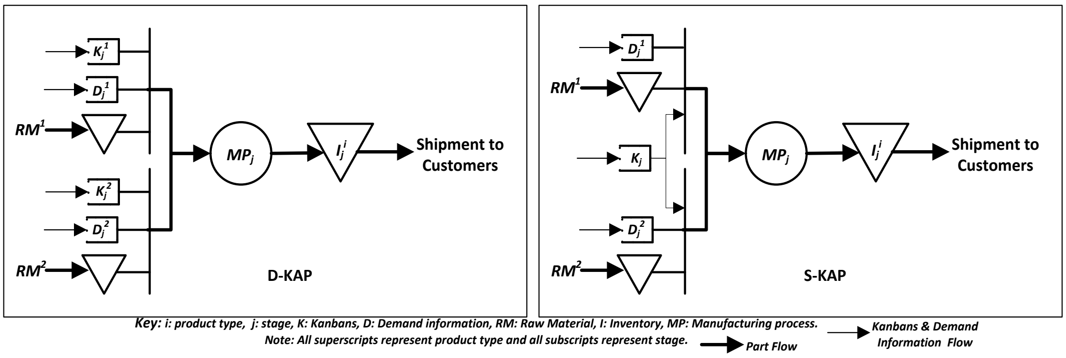


Figure 2.10: Control mechanisms of Kanban allocation policies

2.5 Comparison of Production Control Strategies

Comparison studies of production control strategies often place two or more production control strategies for evaluation of their performance based on one or more performance metrics. The effect of environmental and system variability on the production control strategies is analysed in some cases to demonstrate the superiority of one strategy over the alternatives. The majority of these studies applied a quantitative method for modelling using Markov Decision Process (MDP), Petri nets, and Discrete Event Simulation (DES). The focus of this work is on the quantitative method and a summary of recent comparisons of production control strategies are presented in Tables 2.1 and 2.2 for single product systems and multi-product systems respectively. The key elements of the comparison are the performance of the push and pull PCS and methodology used in these studies. The performance metrics often considered in PCS studies are WIP, delivery performance, throughput, machine utilisation and raw material consumption rate, while simulation and analytical methods are used to examine PCS [36, 69, 77].

Table 2.2: Comparison of production control strategies in single product systems

Study Reference	**Strategies Compared**	**Environ-mental / System Variability**	**Performance Metrics**	**Method-ology Applied**	**Manufact-uring System**	**Findings**
Sarker and Fitzsimmons [71]	Push, Pull (Kanban)	Cycle time Variations	WIP, throughput	Simulation	3 stage, serial flow line	As the coefficient of variation of the processing time increases, push systems perform better than pull
Grosfeld-Nir et al.[72]	Push, Pull	Uncertainty in processing times, number of stages	WIP, throughput	Simulation	Serial line with 1 to 20 stages	Pull outperformed push when stages are less than 7. When stages are more than 7 push outperformed pull
Weitzman and Rabinowitz [74]	Push, Pull (CONWIP)	Rate of data update, failure features of machines	WIP, delivery performance	Simulation	Single serial flow line with 8 machines	Pull outperformed push. The worse the information update, the worse the push become
Hoshino [78]	Pull, Push	Demand variation, variation of forecast error	WIP	Analytical Method	single process step	Push outperformed pull
Wang and Xu [79]	Push, Pull (Kanban), Hybrid (each stage can either push or pull)	Not Applicable	WIP, delivery performance	Simulation	Several single product systems examined	Hybrid outperformed the alternatives
Huang et al. [80]	MRP, Kanban, CONWIP	Not Applicable	WIP, throughput, raw material consumption rate, machine utilization	Simulation	6 stage, serial cold rolling plant.	CONWIP outperformed the alternatives
Ozbayrak et al. [75]	Push, Kanban, CONWIP	Not Applicable	WIP, delivery performance, responsiveness, mean flow time	Simulation	assembly line, routing	Depending of the performance metrics, either Push, Kanban or CONWIP outperformed the alternatives
Kleijnen and Gaury [70]	Kanban, CONWIP, Kanban/CONWIP, Generic Kanban	Not Applicable	WIP, short term delivery performance	Simulation	4 stage, serial flow line	Hybrid outperformed the alternatives
Koh and Bulfin [73]	CONWIP, Drum-buffer-rope, horizontally integrated hybrid system with junction point at bottleneck (DBR)	Not Applicable	WIP, throughput	Markov process model	3 stage, serial flow line	DBR outperformed the alternative
Geraghty and Heavey [69]	Kanban/CONWIP, Kanban Hybrid (horizontal), Basestock, GKCS, EKCS	Not Applicable	WIP, delivery performance	Simulation	5 stage, parallel/ serial line	Kanban/Hybrid outperformed the alternatives. Kanban was consistently the worst performer
Gstettner and Kuhn [81]	Kanban, CONWIP	Not Applicable	WIP, throughput	Simulation	Multi- stage serial line	Kanban outperformed CONWIP
Sharma & Agrawal [76]	Kanban, CONWIP, Hybrid	Demand distribution	Utility function	Analytical method	multi-stage serial line	Kanban outperformed the alternatives
Bonvik and Gershwin [53]	Kanban, Minimal Blocking, Basestock, Kanban/CONWIP	Not Applicable	WIP, delivery performance	Simulation	4 stage, serial flow line	Hybrid dominated, then CONWIP and Basestock

Table 2.3: Comparison of production control strategies in multi-product systems

Study Reference	Strategies Compared	Environmental / System Variability	Performance Metrics	Methodology Applied	Manufacturing System	Findings
Tsubone et al. [82]	Push, Pull (Kanban)	Machine breakdowns, processing time, flow sequence	Lead time	Simulation	Multi-product serial flow, with different process sequences	Small differences was found between Push and Pull, but Push is more sensitive to variations
Persentili and Alptekin [83]	Push, Pull	Product flexibility	WIP, throughput, average flow time, backorder levels	Not stated	Two-product, 5 stage, convergent and divergent material flows	No significant difference between push and pull
Kilsun et al. [84]	Push, Pull (Kanban)	Demand variation, emergency orders	Cost (WIP holding and set-up cost)	Simulation	Ten-product, 2 stage, serial line with demand variations	When demand variations is low and no emergency orders, push outperformed pull, else pull outperformed push
Lee and Lee [85]	Push, Pull	Not Applicable	WIP, throughput	Simulation	Multi-product, production facility	Pull outperformed push in terms of low WIP but lower (negligible) throughput
Ozbayrak et al. [86]	Push, Pull (Kanban)	Not Applicable	Activity based costing	Simulation	Ten-product, make-to-order system with scrap, rework, breakdowns	Pull outperformed push
Papadopoulou and Mousavit [87]	Push, CONWIP	Dispatching rule (buffer dispatching policy)	Average WIP, mean flow time, deviation from due date (earliness, tardiness), total time in queue	Simulation	Job shop, 8 stage, 10 job types revisiting of processes possible, batch size of 10-50 units	CONWIP outperformed the alternatives
Olaitan and Geraghty [77]	Kanban, CONWIP, Basestock, GKCS, EKCS	Machine failure, demand variability	WIP, delivery performance	Simulation	Two-product, 3 stage, serial flow line	GKCS (S-KAP) outperformed the alternatives under negligible variability, EKCS (D-KAP) outperformed the alternatives under significant variability

The aim of the comparison summary is to outline the current state of the art and to identify the type of manufacturing systems where such production control strategy is applied. In Tables 2.2 and 2.3, studies that considered a push and pull PCS were presented first, followed by studies that considered only push or pull PCS.

Observation from Tables 2.2 and 2.3 shows that at low environmental variation (low demand variation, product mix and volume) based on the performance metrics analysed (WIP, throughput, delivery performance), push PCS outperformed pull

PCS. However, when a manufacturing system is subject to high environmental variation, pull outperformed push PCS [78, 82, 84]. Similarly, when the system is subject to system variability, pull outperformed push PCS. The performance of a production control strategy differs for different manufacturing conditions. However, it was shown that pull and/or hybrid PCS dominated the alternative (push) in the studies, especially under uncertainty in environmental or system variability. The effective performance of pull PCS over push PCS has been widely documented [9] and has led some researchers to question whether the superior performance of pull over push in WIP control is due to smaller batch sizes or differences in how each control the flow of material [88]. According to Spearman and Zazanis [52], the effective performance of pull over push is a result of the effective limitation and control of work-in-process inventory into a system. In practice, it is claimed that, a pull production control strategy is easier to implement and regulate as it emphasises WIP control while push places the emphasis on throughput rate control. However, the throughput rate is not easily and visually perceived like WIP.

Furthermore, an observation from Tables 2.2 and 2.3 indicates that a majority of the comparison studies were conducted using single product manufacturing systems with simple configurations. A review of additional research studies shows that single product systems have been widely studied, with the postulation that their findings are scalable to multi-product systems [15-18, 77]. Geraghty and Heavey [89] showed that the HIHPCS controlled system developed by Hodgson and Wang [90, 91] is the same as the HK-CONWIP in the single product manufacturing environment. In another study, Geraghty and Heavey [69] conducted an in-depth study of KCS, BSCS, GKCS, EKCS and HK-CONWIP. Their findings show that HK-CONWIP outperformed the alternatives and that KCS maintained the worst performance in all the scenarios. In addition, their performance evaluation indicates a significant difference between the performance of Kanban and the rest of the strategies and that the efficient and effective performance of HK-CONWIP is based on the CONWIP’s capability to communicate demand information directly to the first stage in a system. The question is; are these findings scalable to multi-product and complex systems with complex configurations? The findings of [16] showed that the outcomes of single product systems are not scalable to multi-product systems. The study showed a large build-up of WIP in pull controlled multi-product system and showed that S-KAP reduced the proportion of WIP in the system. Olaitan and Geraghty [77] examined the performance of five production control strategies (KCS, BSCS, CONWIP, GKCS and EKCS) in a multi-product manufacturing environment under environmental variability and negligible setup. The study considered the two Kanban allocation policies (D-KAP and S-KAP) and they showed that GKCS in S-KAP mode outperformed the alternatives under steady or negligible variability. However, when the system was subjected to significant variability, EKCS in D-KAP mode outperformed the rest. Hence, the behaviour of the control strategies in complex and multi-product systems with respect to different levels of variability require further examination. Their findings agreed with Baynat et al. [16], that KCS could not perform favourably in multi-product manufacturing environment and, hence, could not operate in S-KAP mode. A further question, therefore, is; can these production control strategies be modified to harness their benefits in multi-product manufacturing environments?

2.5.1 Comparison of Kanban Allocation Policies in Multi-product systems

The study of the dedicated and shared policies of the multi-product pull PCS suggested that PCS combined with the dedicated policy in multi-product systems are an extension of the single product pull PCS [16]. The only difference noted was the sharing of the capacity of the manufacturing process. Their paper proposed that GKCS, EKCS and KCS operating D-KAP produced an equivalent performance in WIP control when the quantity of the basestock is equal to the number of Kanbans. S-KAP produces distinctive performance in the WIP control of multi-product systems. This is a result of the type of coupling existing between the parameters that influence the performance of the policy. The transmission of the demand information is conducted in a manner that it is wholly or partially decoupled from the Kanbans. If the Kanbans are unattached to demand information or parts, they are free for allocating for authorisation of any available part-type demand. However, when the Kanbans are coupled to demand information, it implies that the Kanbans are not free and when the finished product satisfies a demand, the Kanban card is detached from the finished product and attached to the demand information for authorisation of that product-type replenishment. This means some of the pull PCS with close-knit coupling between the flow of the demand information, production authorisation cards and the part types would not operate S-KAP naturally because the Kanbans are attached to parts and immediately they are detached from parts they are coupled with demand information for replenishment of a corresponding part. For instance, KCS in S-KAP mode is equivalent to KCS in D-KAP mode, owing to the rigid coupling of the Kanbans and demand information [16], while GKCS and EKCS provided distinctive performances in WIP control depending on which KAP was applied. This is because in EKCS, the Kanbans are wholly decouple from the demand information, while in GKCS, the Kanbans are partially decouple from the demand information.

According to Deokar [92], GKCS and EKCS operating S-KAP in multi-product systems control the WIP in the system better than GKCS and EKCS operating D-KAP. It was noted that PCS with the S-KAP controls WIP, demand and processing time variations better than PCS with the D-KAP regardless of the number of stages, arrangement of stages (serial or parallel) and service levels of the systems. The paper found that GKCS in S-KAP mode performed better than EKCS S-KAP under low demand and processing time variations. However, in a large processing time and demand variations, EKCS outperformed GKCS. It reports that the delivery performance of PCS with the S-KAP is more efficient than PCS with the D-KAP. PCS with the S-KAP achieve lower backlogs (30 to 40% lower) than PCS with the D-KAP. The study inferred that PCS with the S-KAP in pull controlled multi-product systems produce a lower number of backlogs, lower average waiting time for backlogs and lower WIP inventory.

Another investigation of these two policies in a multi-product pull PCS (KCS, BSCS, CONWIP, GKCS and EKCS) was conducted by Olaitan and Geraghty [77]. Their study showed that PCS with the S-KAP provides a reduction in the number of Kanbans and that it is superior to PCS with the D-KAP because it reduced the average WIP of the system. It was suggested that GKCS controls WIP better than EKCS at 95% service level. However, under ±5% environmental variability, EKCS outperformed the alternatives. According to the study, KCS, BSCS and CONWIP were found not to operate S-KAP based on the close-knit coupling between the flow of the demand information and production authorisation cards. The findings of these studies [16, 77, 92] suggest that S-KAP is a promising policy for multi-product manufacturing environments with the steady material flow.

There are other strategies which have not been examined under the shared policy of a multi-product system such as HK-CONWIP. Additionally, some of these pull PCS that failed to operate in S-KAP mode, would operate in S-KAP mode if they are modified such that the coupling existing between the control parameters becomes flexible and not closely knit. This thesis develops a technique that would enable modification of some of the strategies (example, HK-CONWIP) and use them to further investigate the shared Kanban allocation policy of pull PCS in a multi-product manufacturing environment.

2.5.2 Performance Metrics

The determination of appropriate performance measures of the pull PCS is important for evaluation and comparison of the pull PCS investigated. In Table 2.2 and Table 2.3, the widely used performance metrics are the work-in-process inventory and the delivery performance (service level and/or backlogs). The work-in-process inventory is the instantaneous number of parts in the system. It is a vital performance measure because it has significant influence on the operational performance of a system. The service level is another important performance measure in pull PCS studies. It is the portion of the total demand, which is satisfied. A demand is satisfied when a corresponding finished product matches with the demand within a given period and the product is shipped to a customer that placed the order. If the customer's order for a product is not met with as specified, the demand is not satisfied and is calculated as the backlog until it is satisfied. Backlog is a performance measure which occurs when a demand arrives in a system, but because of unavailability of finished part-type, was delayed or unsatisfied. This is measured with respect to a specified time period. A Backlog(BL) for a period of time (t) is given by subtracting the satisfied demand in that period from total demand in that period and the backlog of the previous period.

$$BL_t = BL_{t-1} + D_t - S_t \qquad 2.1$$

{Where BL is Backlog, $D$is Demand, S is satisfied demand, t is period}

The Service Level (SL) versus WIP trade-off is widely used in several studies, for the comparison of the pull PCS performance as shown in Table 2.1. Other performance measures, which are not frequently used in pull PCS comparison, include the Cycle Time and Throughput Rate Stability. The throughput rate was used in place of service level, especially in studies which adopted unlimited demand for PCS. The comparison of pull PCS by Geraghty and Heavey [69] focused on the achievement of 95% and 99% target service level using the WIP level of the pull PCS. Studies like [93, 94] used the target service level approach in their comparison of the pull PCS. In this research, the performance measures for comparison considered are the delivery performance (service level and/or backlog) and WIP. The two conflicting objectives in SL versus WIP trade-off are the maximisation of the service level and the minimisation of the WIP. The total WIP is given by the summation of the WIP of the stages. The service level is determined by total demand divided by satisfied demand.

2.6 Summary and Positioning of this Research

The previous sections (2.1 to 2.5) have provided understanding of the fundamental principles of production control strategies, the effect of a production control strategy on the operational performance and the current state of the art of research on production control strategies. A summary of these sections (2.1 to 2.5) and the positioning of this research are presented here.

The analysis of production control strategies in chapter 2 shows that there are two main conventional groups of production control strategies; namely push and pull. The push control strategy uses a market forecast in the authorisation of production of part type while the pull PCS concept is based on using the actual demand in the authorising of the production of a part type. Also, various hybrids of these strategies have been developed from the combination of the pull or push PCS and/or pull/push combination. The push PCS was widely used since the 1960s, for inventory management and control of manufacturing systems. However, pull PCS has a WIP control advantage over push PCS in a manufacturing system.

Furthermore, the literature reveals that the principles of effective WIP control in a pull control strategy are undermined in complex and multi-product manufacturing environments. PCS combined with S-KAP allows the sharing of resources such as the production authorisation cards and it reduces the WIP level than PCS combined with D-KAP. It shows that PCS combined with S-KAP has a distinctive character of using a shared resource pool to respond to shifts in demand volume of product-types than PCS combined with D-KAP. Some pull PCS such as KCS, CONWIP, BSCS and HK-CONWIP cannot operate in S-KAP mode naturally. Studies on S-KAP and D-KAP showed that PCS combined with S-KAP outperformed PCS combined with D-KAP under insignificant environmental variability. S-KAP showed a reduction in the number of Kanbans (PAC) used in multi-product manufacturing systems.

KCS, CONWIP and HK-CONWIP that have been successfully implemented in single-product manufacturing systems, were unfavourable in multi-product systems. Existing studies provided a guide to understand the reasons why some pull production control strategies failed to operate in S-KAP mode naturally, but did not provide any solution to this problem. Therefore, an approach that modifies the concept of these pull control strategies to operate in the S-KAP mode without changing the concept of these pull control strategies is required. The modified pull control strategies will perform better in terms of WIP control.

Furthermore, the studies that considered D-KAP and S-KAP in multi-product systems did not examine the possibility and the significance of using three parameters in the control mechanism of pull production control strategies and none considered the performance of the HK-CONWIP, which has been shown to have superior performance in WIP control over KCS and CONWIP.

This research work answers the questions regarding pull control strategies failing to operate in S-KAP mode. It develops a methodology for modifications of pull control strategies to enable them to operate in S-KAP mode. It conducts analysis on the applicability of such modifications to pull PCS for further study of S-KAP in multi-product environments to provide a clearer understanding of pull PCS in S-KAP mode. Furthermore, this research establishes the performance of the pull PCS under varying manufacturing conditions and identifies a superior PCS-KAP for coordination of inventory and environmental variation management in a multi-product environment. The purpose is to develop and identify a PCS-KAP with effective WIP and demand variations control as well as improve delivery performance in any multi-product systems, especially systems under erratic demand profile.

CHAPTER 3: MODIFICATION APPROACH

3.1 Introduction

This chapter presents an approach for modifying pull PCS that failed to operate in S-KAP mode and the development of a new pull control strategy. PCS combined with S-KAP has better WIP control over PCS combined with D-KAP. However, KCS, CONWIP and HK-CONWIP fail to operate S-KAP naturally. An in-depth understanding of the behaviour of these pull PCS provides the idea on how to modify KCS, CONWIP and HK-CONWIP to operate in S-KAP mode. The control mechanism of KCS uses one parameter (i.e. Kanbans) to control the release of parts, WIP and base stock level in a stage. To release a part into a stage, the Kanban card detaches from the part and instantaneously attaches to the demand information and is transmitted upstream for the release of a corresponding part-type. Owing to the tight coupling between Kanbans and demand information, the stage cannot perform effectively in terms of WIP control of multi-product systems with a large number of product-type without keeping large quantity of WIP in the stage. For instance, a three-stage KCS serial flow line will require keeping basestock of each product type in the three stages resulting in large WIP in the system. A similar issue occurs in CONWIP and HK-CONWIP. In both CONWIP and HK-CONWIP, the CONWIP cards are tightly coupled with the demand information resulting in the use of the CONWIP cards for replacement of a corresponding product type in the system. This tight coupling existing in the control mechanisms of these pull PCS is the primary cause of their failure to operate in S-KAP mode.

The manner in which the Kanbans (i.e. PAC) detach from parts and simultaneously attaches to demand information does not allow these PACs to be used for authorisation of a different product type. To solve this problem, demand information and PACs are required to be transmitted upstream partly or wholly unattached. In this chapter, the CONWIP cards and Kanbans are referred to as PACs and are interchangeable.

3.2 Modification Method for Pull Production Control Strategy

To determine an approach for modifying pull PCS, the type of coupling existing between the PACs, parts and flow of demand information in pull PCS is identified as a main factor for modification. The control mechanisms of KCS, CONWIP and HK-CONWIP have a rigid coupling of the PACs, parts and flow of demand information. Additionally, these pull strategies use one parameter (PACs) to control WIP inventory and provide the targeted basestock level at the output buffer. The maximum number of PACs determines the maximum WIP level achieved in a system controlled by these pull PCS. Therefore, reducing the maximum number PACs will give to a reduction in the maximum WIP level achieved in a system. In the case of a change in product mix and volume in a system, pull PCS will perform poorly in terms of WIP and delivery performance, owing to the tight coupling PACs to parts and/or demand information. The rigid coupling will prevent PACs to be used for another part-type other than the pre-defined part-type. Therefore, it is vital to decouple the demand information from the production authorisation cards and parts for a better performance. This provides the basis for the modification technique proposed here.

To decouple the demand information flow, production authorisation cards and parts of any pull control strategy, the concept of such strategy must be taken into account to avoid a complete change of the control mechanism. In order to retain the characteristics of the underlying control strategy, the decoupling should be applied to as few production stages as possible, starting with the final stage and moving progressively forward if the desired effect has not arisen.

The demand information of a pull controlled system, should be transmitted upstream unattached to PACs, as shown in Figure 3.1.

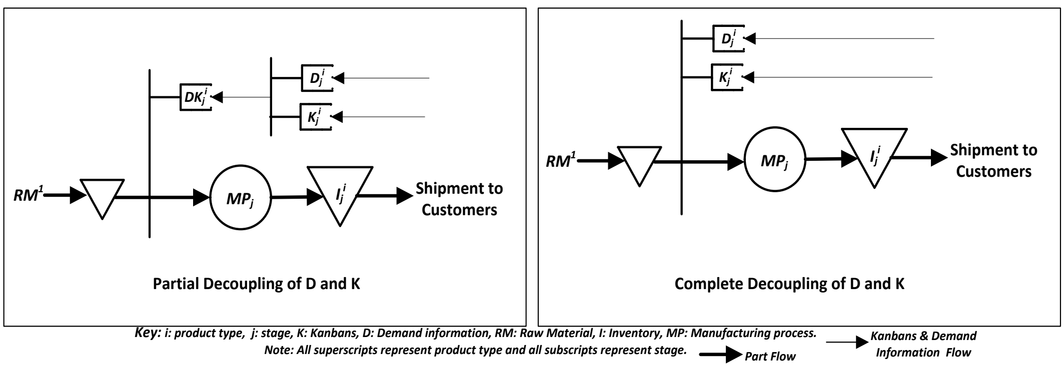


Figure 3.1: Decoupling of demand information from Kanbans

In the partially decouple diagram, PACs are unattached to demand information. If a demand occurs in a system, PAC authorises the release of part by attaching to the demand information and this generates demand information that is sent further upstream (if applicable). In the wholly decouple diagram, demand information is instantaneously transmitted to all stages, unattached to PACs. To authorise the release of a part-type into a system, the demand information and the appropriate PAC are matched and then attached to part-type. The part-type with the attached demand information and PAC is transferred to the manufacturing process unit for production. Both concepts (partial and wholly decoupling techniques) allow PACs to be shared among product types such that any available PACs will respond to demand of any product types.

The application of these concepts to pull strategies that could not operate in S-KAP naturally gives rise to them operating in S-KAP mode. For instance, applying this approach on the pull PCS which could not operate S-KAP ordinarily (KCS, CONWIP, BSCS, HK-CONWIP), the following observations were made: (i) KCS alteration developed EKCS, or when the alteration was made such that demand information was partially decoupled from Kanbans, it developed GKCS, implying that KCS could not be modified using this approach without additional parameter such as CONWIP because EKCS and GKCS already exist, (ii) CONWIP alteration is feasible because demand information flow is globally transmitted. Applying this approach to CONWIP such that CONWIP cards are released after the last stage manufacturing process unit, allowing the final goods buffer to operate push PCS, implying that the authorisation card and demand information is completely decoupled from each other. (iii) BSCS alteration is not feasible using this approach. This is because there is no parameter for the system to control the stage or system WIP and the stage or system base stock level. This means that the demand information flows without any form of coupling in the system. Therefore, for this approach to hold there needs to be a relationship between authorisation card and demand information. (iv) HK-CONWIP alteration is feasible because the demand information is globally transmitted as in CONWIP. CONWIP cards are released after the last stage manufacturing process unit.

3.3 Basestock Kanban-CONWIP Control Strategy

A description of a new pull control strategy called Basestock Kanban-CONWIP control strategy is presented here. Issues of the inefficiency of pull (example, KCS, BSCS and CONWIP) controlled multi-product systems in the presence of demand variations motivated the search for a robust pull control strategy. For instance, in KCS, Kanbans play two opposing roles (limiting total WIP and providing targeted basestock). In pull controlled systems, resources are regulated such as to achieve a targeted output with a minimum WIP. Therefore, the minimum PACs (as few as possible) that can achieve a predefined output are required. Base stocks are for cushioning interruption and variations. This means that additional PACs (higher than the minimum PACs that can achieve a defined output) are necessary in order to respond to interruptions and variations. Pull controlled systems with one parameter (example, KCS, CONWIP, HK-CONWIP) for the control of WIP and basestock level cannot (i) operate in the S-KAP form naturally (ii) effectively respond to interruptions and variations. These two problems require attention in order to develop a pull control strategy with the capability to respond to interruptions and variations in a multi-product system. To achieve a robust pull strategy, (i) one parameter should not be used to control the two roles. (ii) The demand information should be transmitted upstream to all stages and the final product buffer without the requirements to pass from a stage to another. (iii) The entire system WIP is partially or wholly controlled.

These characteristics are given consideration in developing BK-CONWIP. The control mechanism of BK-CONWIP has three parameters such that each stage is controlled by two parameters (Kanbans and basestock level) and the third parameter (CONWIP cards) controls the entire system WIP. The two roles of controlling WIP and basestock levels are wholly decoupled such that the strategy operates in S-KAP mode. Therefore, the control parameters of a multi-product system can be configured with the minimum basestock level that can achieve a targeted output such as to maintain low WIP based on the configured demand profile. The quantity of PACs can be set high to respond to interruptions and variations. Demand information is transmitted instantaneously to all stages such that negligible delay in part replenishment is achieved.

Similar to HK-CONWIP, BK-CONWIP uses CONWIP card to control the WIP level of a system. In multi-stage flow line, CONWIP provides a stronger WIP control than KCS. For instance, WIP accumulates at the input buffer of a failed machine pending repair in a CONWIP controlled system. However, in KCS, WIP will accumulate in all stages upstream of the failed machine. Two important differences between BK-CONWIP and HK-CONWIP are (i) that BK-CONWIP uses a global transmission of demand information, which is initialised immediately a demand occurs and (ii) the CONWIP cards are released after the last stage manufacturing process. The queuing network model of BK-CONWIP is presented in Figure 3.2 and Table 3.1 shows the content of the model in Figure 3.1.

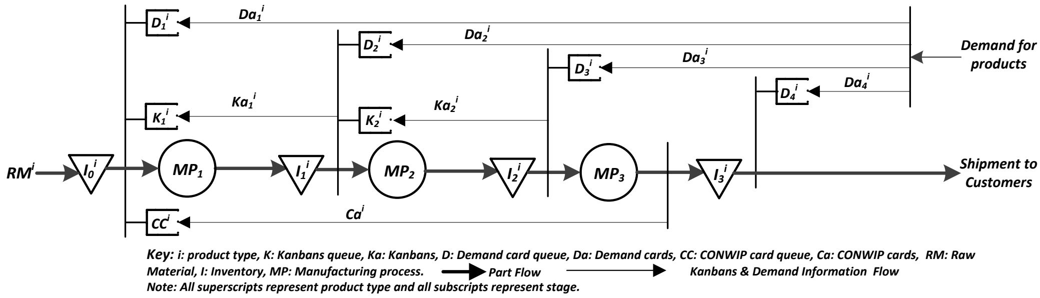


Figure 3.2: Queuing network model of multi-product multi-stage BK-CONWIP

Table 3.1: Symbols and content of the queuing network model of BK-CONWIP

Symbol	Description	Content	Initial Value
i	Product type, where $i = 1,2 \ldots, M$		
j	Stage number, where $j = 1,2 \ldots, N$		
Ca	Number of CONWIP cards		
Ka	Number of Kanbans		
Da	Demand cards (demand information)		
S	basestock		
P	Parts		
CC	Queue block containing CONWIP cards	Ca	$Ca - \sum_{j=1}^{N-1} S_j$
K	Queue block containing Kanbans	Ka	Ka
D	Queue block containing Demand cards	Da	0
I	Queue block containing WIP	(P, Ka, Ca)	S
I_N^i	Queue block containing WIP at final stage	(P)	S
I_{N-1}^i	Queue block containing WIP excluding final stage	(P, Ka, Ca)	S
MP	Manufacturing process unit	(P, Ka, Ca, Da)	0
RM	Raw material	P	P

All subscripts represent stages and all superscripts represent product type

The model depicted in Figure 3.2 has three manufacturing stages ($N = 3$) in series. Each depends on two parameters, which are the Kanbans, Ka_j^i, and the Basestock level, S_j^i, of each stage j. The third parameter, which is the WIP cap, Ca^i, controls the WIP of the entire system. In each stage j, the Kanbans, Ka_j^i, determines the maximum quantity of parts in that stage. The basestock level, S_j^i, of the stage j is the quantity of parts in the output buffer of that stage. In the initial state of the system, the parameters, S_j^i, Ka_j^i and Ca^i are initialise to predetermined levels. This process, in pull PCS is known as the production levelling. The basestock, S_j^i, level is set to a minimum value that is capable of responding to an anticipated demand volume, while the Kanbans and the CONWIP cards, Ka_j^i and Ca^i, are set at a high volume. High volumes of Ka_j^i and Ca^i are important to cushion variations. For instance, if demand volume rises above, S_j^i, the additional planned, Ka_j^i and Ca^i, are used to respond to the surge. Also, if demand volume falls back to its planned volume or below the WIP cap, the additional planned, Ka_j^i and Ca^i, return to their initial position (maintaining a low WIP level in the system). The processed part, P_j^i, of each stage j is stored in the output queue, I_j^i, on that stage. The Kanban cards, Ka_j^i, are stored in the queue, K_j^i, while the CONWIP cards Ca^i are stored in the queue, CC. The initial stage queue, I_0^i, contains the raw material, RM^i.

The authorisation of a part is driven by actual customer demand. Immediately the demand for a specific part arrives at the final stage of the BK-CONWIP controlled system, the demand is multiplied into $N+1$ demand cards, Da_j^i. These demand cards, Da_j^i, are transmitted to all the stages' demand cards queues, D_j^i, including the finish product inventory queue, D^i. The next events are the authorisation and commencement of production of a new part. For instance, in the initial stage, the production of a new part starts by matching together the raw material/part, P_j^i, the Kanbans, Ka_j^i, the demand card, Da_j^i, and the CONWIP card, Ca^i. The batched part is transmitted into the manufacturing process unit, MP_j, and the production commences. The demand information is destroyed, when production commences in the manufacturing process unit on a part synchronised with a demand card (i.e. demand information), a Kanban card and CONWIP card. However, the Kanban and CONWIP cards remain attached to the part. The Kanban is detached when the part leaves the output queue of that stage and the CONWIP card is detached after the final stage manufacturing process. After the production in the first stage, the processed part, (P_j^i, Ca^i, Ka_j^i), is sent to the output queue, I^i. If there is an available demand card, Da_{j+1}^i, and a stage Kanban card, Ka_{j+1}^i for the next stage $j+1$, the part simultaneously attaches to the next stage demand information and the next stage production authorisation card, Ka_{j+1}^i, while the current stage

Kanban card, Ka_j^i, is detached. The part $(p_{j+1}^i, Ca^i, Da_{j+1}^i, Ka_{j+1}^i)$, is sent to the next stage manufacturing process unit, MP_{j+1}, for production. The demand information, $Da_{j+1,}^i$ is destroyed as soon as the production commences in the stage, $j+1$. The processed part $(p_{j+1}^i, Ca^i, Ka_{j+1}^i)$, is sent further downstream. The final stage has no stage Kanbans. The part, $(p_{N-1}^i, Ca^i, Ka_{N-1}^i)$, at the output queue of stage, $N-1$, entering the final stage is batched with the demand card, Da_n^i, while, Ka_{N-1}^i, is detached. The demand card, Da_n^i, is destroyed as soon as the production commences. The CONWIP card Ca^i is detached from the part immediately the part leaves the final stage manufacturing process, $MP_{n,}$ while, the finished product is stored in the final product queue, where it is used to satisfy the actual demand.

In summary, the control mechanism of the BK-CONWIP controlled system integrates the control mechanisms of CONWIP, BSCS and KCS. The stages in the BK-CONWIP controlled system can be classified into two: (i) general stage, which operate with parts, Kanbans, demand cards and CONWIP cards and (ii) final stage, which operate with parts, demand cards and CONWIP cards. The CONWIP cards are detached from the parts after the manufacturing process unit of the final stage. The demand cards are globally transmitted in BK-CONWIP and it is an important factor for releasing parts into a system such that the availability of Kanbans, CONWIP cards and raw materials will not cause a release of part into the system. Therefore, a large volume of Kanbans and the CONWIP cards in the system will not increase the WIP, except for an increase in demand volumes. The total WIP in a BK-CONWIP controlled multi-product system is limited by the number of the CONWIP cards like the CONWIP controlled system. A finished part-type, (p_j^i, Ca^i, Ka_j^i) in a stage, j, output buffer is transported downstream in the next stage $j+1$ manufacturing process MP_{j+1}, only when the next stage $j+1$ Kanbans (like in the case of KCS) is available to batch with the part-type, except for the last stage where stage j = N.

CHAPTER 4: RESEARCH METHODOLOGY

4.1 Introduction

This chapter provides the approach used in assessing the suitability and performance of the pull production control strategies under investigation. The approach is used to examine the complex interactions between control parameters of pull strategies and apply the outcome of the examination to achieve balance between conflicting objectives. The tools used include simulation, design of experiments, optimisation, curvature analysis, Nelson's screening and selection techniques and stochastic dominance techniques.

The approach is a structured procedure which uses the concepts and theory of production systems engineering for conducting evidence-based analysis of the pull production control strategies. It provides the methodology for investigating the application and behaviour of the pull production control strategies in multi-product manufacturing systems and the effect of the control factors on their performance metrics such as the level of work-in-process inventory and the delivery performance (service level and/or backlogs). The three fundamental segments of this chapter is (i) Modelling (ii) Optimisation and (iii) comparison tools.

4.2 Modelling

In modelling, various significant entities, interactions between components of a system and the performance metrics are identified and theoretical designs are developed. The control mechanisms of GKCS, EKCS, HK-CONWIP and BK-CONWIP are modelled. The input variables and performance measures of the pull PCS are identified. Analysis of conceptual models should provide a good illustration of the system's features. Similarly, conceptual models can be translated into simulation models for the simulation study. The development of conceptual models of the pull PCS for production and inventory control is carried out. In order to develop a conceptual model, a good understanding of the system is required. Therefore, subsequent sections provide a description of the systems under examination, development of conceptual models and translation of conceptual into simulation models.

4.2.1 System Description

Two manufacturing systems were used as case studies in this work. The first case study (Case 1) is a three-stage serial manufacturing line with negligible setup times described by Olaitan and Geraghty [77]. The minimal blocking policy was removed because it allows WIP in the system in order to avoid blocking and congestion. This modification is important to study the control of the amount of inventory in a stage that can cause congestion and to understand the behaviour of the system with no input buffer in place to release or make available the authorisation cards before a part-type is actually processed in the manufacturing process unit. A schematic diagram of the model is shown in Figure 4.1. The symbols used in the figures in chapter 4 are described in Table 4.1.

Table 4.1: Description of symbols

Symbol	Description	Symbol	Description
$D_{1,2,\dots}$	Demand card for stage 1,2, …	DCC	CONWIP card attached to demand card for a system
$D_{1,2,\dots}^{1,2,\dots}$	Demand card for product 1,2,… at stage 1,2, …	CC	CONWIP card in a system
$K^{1,2,\dots}$	Kanban card for product 1,2,…	$I_{1,2,\dots}^{1,2,\dots}$	Inventory output buffer for product 1,2, … at stage 1,2, …
$K_{1,2,\dots}^{1,2,\dots}$	Kanban card for product 1,2, … at stage 1,2, …	I_j^i	Output buffer for product 1,2, … at stage 1,2, …
$DK_{1,2,\dots}$	Kanban card attached to demand card for stage 1,2,…	$MP_{1,2,\dots}$	Manufacturing Process at stage 1,2,…
$RM^{1,2,\dots}$	Raw material for product 1,2, …	MP_j	Manufacturing Process unit at stage 1,2,…

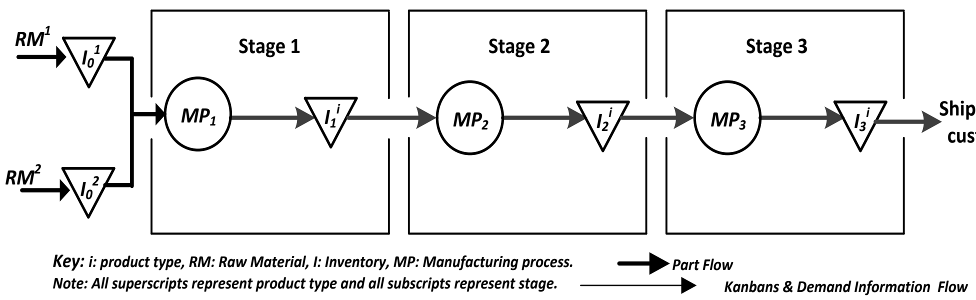


Figure 4.1: Schematic diagram of three-stage multi-product manufacturing system

This system produces two product-types, in a three-stage production line with product 1 having high demand variability (50% variation of mean of the demand) and product 2 having a low demand variability (10% variation of mean of the demand). The control parameters were optimised in order to achieve the least possible WIP required to deliver a targeted service level of 95% in the system. The flow line has constant processing times at each stage in the system. The capacity variability is as a result of breakdown maintenance, which is modelled using an exponential distribution because it adequately captures the failure rate of the system which occurs continuously and independently at a constant mean rate. Another variation modelled on the system is the low to high demand variability.

The second system (Case 2) investigated is a five-stage serial manufacturing line with an erratic demand profile and significant set-up times in three of the stages. The model was developed from observations of a real world automotive multi-product manufacturing facility. The system has two product families, with two part-types in each as shown in Figure 4.2. The first product family starts production on the first stage and flows through all the five stages. In the second stage, the part-types are transferred to the next stage via a pallet which has a capacity limit of 16 boxes and the total number of pallets available for the first product family is ten. The second product family enters the line at stage 3. The two part-types of the second product family, enter the system on pallet quantities of 16 boxes. In stage three the four part-types are processed using some priorities (for instance; day-to-be-produced or demand priority). The minimum run/batch quantity (also referred to as changeover factor) parameters, is a parameter which defines the batch quantity of a product type required to be processed before a changeover occurs. The changeover factor is important for minimising the frequency of set-up. Stages 4 and 5 are quality control inspection stages with electrical testing at stage 4 and a visual inspection unit at stage 5.

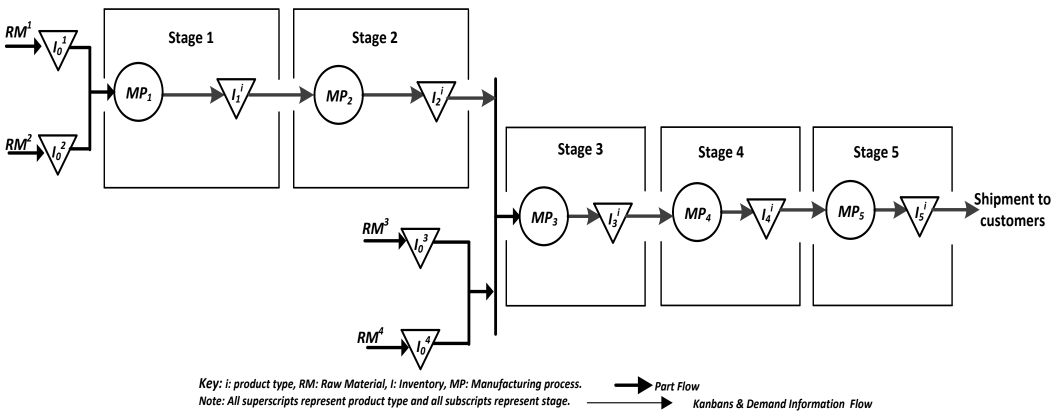


Figure 4.2: Schematic diagram of five-stage multi-product manufacturing system

The final products from stage 5 are transferred to a supermarket area where the demands for final products are satisfied every two hours based on the current week's demand. If final products are available within a two-hour interval, they are transferred to the shipping section and despatched to customers at the end of the production week. Any unsatisfied demand is processed as a backlog and added to the next week's demand, such that the new week's demand is the summation of the actual demand for that week and the backlog of the previous week (if any).

The manufacturing system operates three 8-hour shifts, five days per week and is idle for the weekend except in an emergency. Operators are provided with a 30 minute break after 3.75 hours on a shift. Products from the first family are given priority on stage 3 for the first, second and fourth day of each production week. Products from the second family are given priority on stage 3 on the third day of each production week. The product families have equal priority at stage 3 on the final day of each production week.

Processing times for any specific part-type on a machine are identical and constant across part-types, but they vary in different production stages. Setups are only significant for the stages 3, 4 and 5 in the flow line beginning at stage 3. When a set-up is conducted on stage 3, production of stage 4 and stage 5 is stopped. The set-up time includes line clearance time. The machines are unreliable. When a failure occurs on either stage 1 or 2, production on the other stage is stopped. Similarly, if one of the other three stages (3, 4 and 5) fails the other two stages cease production immediately. The demand exhibits an unpredictable pattern with a high and low volume at different intervals.

4.2.2 The Development of Conceptual Model

The control mechanism of the multi-product multi-stage pull-PCS manages the part-type flow, inventories (stage WIP and entire system WIP) and the information flow of the production system. Each of the stages is considered as a work station in a production line. A workstation consists of a set of machines and output buffers.

The D-KAP and S-KAP conceptual models are implemented in the multi-product multi-stage HK-CONWIP as shown in Figure 4.3. In the D-KAP conceptual model of the multi-product multi-stage HK-CONWIP, a defined WIP Cap is assigned to each part-type in the production line for the control and release of the that part-type of a system. The CONWIP cards are dedicated to specific part-type and can only be used for the authorisation of the specified part-type. In the S-KAP conceptual model of the multi-product multi-stage HK-CONWIP, a defined WIP-Cap is assigned to the entire system in the production line for the authorisation of various part-types. The CONWIP cards are shared by various part-types in a system. Also the Kanbans are used to control the stage production and inventory as in the case of KCS, except for the last stage which has no Kanban for its stage control.

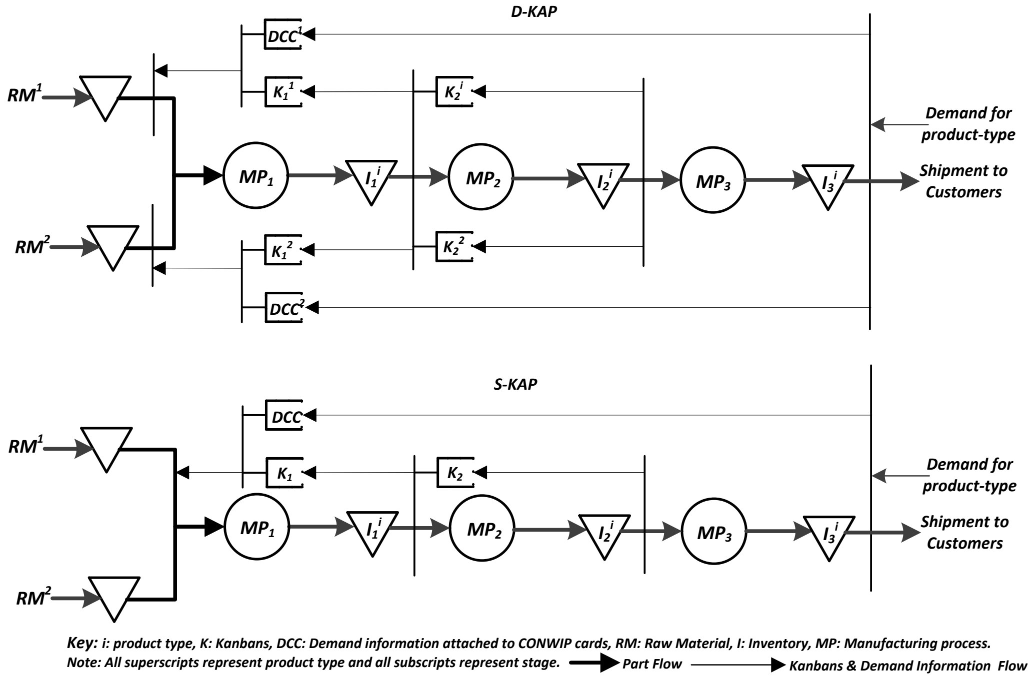


Figure 4.3: Conceptual models of multi-product HK-CONWIP (D-KAP & S-KAP)

When a demand for a part-type is placed, the part-type in the finished product buffer at the final stage, simultaneously releases the attached CONWIP card and satisfies the demand. The released CONWIP card is batched with the demand information and then transmitted upstream to the first stage for the authorisation of production of the part-type. Depending on the availability of the raw material for the part-type and stage Kanban, if available, the raw material attaches to the stage Kanban, CONWIP card and demand information which initialises the production of the part-type in the stage manufacturing process unit. If any of the four components is not available, the demand information accumulates as backlog at the final stage of the system. After the first stage manufacturing process, the batched part-type is sent to the output buffer of the stage waiting for the next stage order. Depending on the availability of a Kanban for the part-type in the next stage, the part-type accumulates as a stage inventory. If there is an available Kanban in the next stage, the processed part-type simultaneously detaches the previous stage Kanban and attaches the next stage Kanban for the production of the part-type in the next stage manufacturing process unit. The final stage has no stage Kanban and any part-type in the output buffer of the stage before the final stage is sent to the manufacturing process of the final stage on the first come first serve order (as the Push PCS), depending on the manufacturing process capacity availability. The finished parts are held with the CONWIP cards attached to them in the output of the final stage. The CONWIP card is released simultaneously as the part-type satisfies a demand.

The conceptual model of GKCS (D-KAP and S-KAP) on the multi-product multi-stage is shown in the Figure 4.4. In GKCS D-KAP, a defined number of Kanbans are dedicated to each part-type at each stage for the control and release of the part-type of a system. The Kanbans are dedicated to specific part-type and can only be used for the authorisation of the specified part-type. In the S-KAP conceptual model of the multi-product multi-stage GKCS, a fixed number of Kanban is assigned to each stage in the production line for the authorisation of various part-types. The Kanban cards are shared by various part-types in a system.

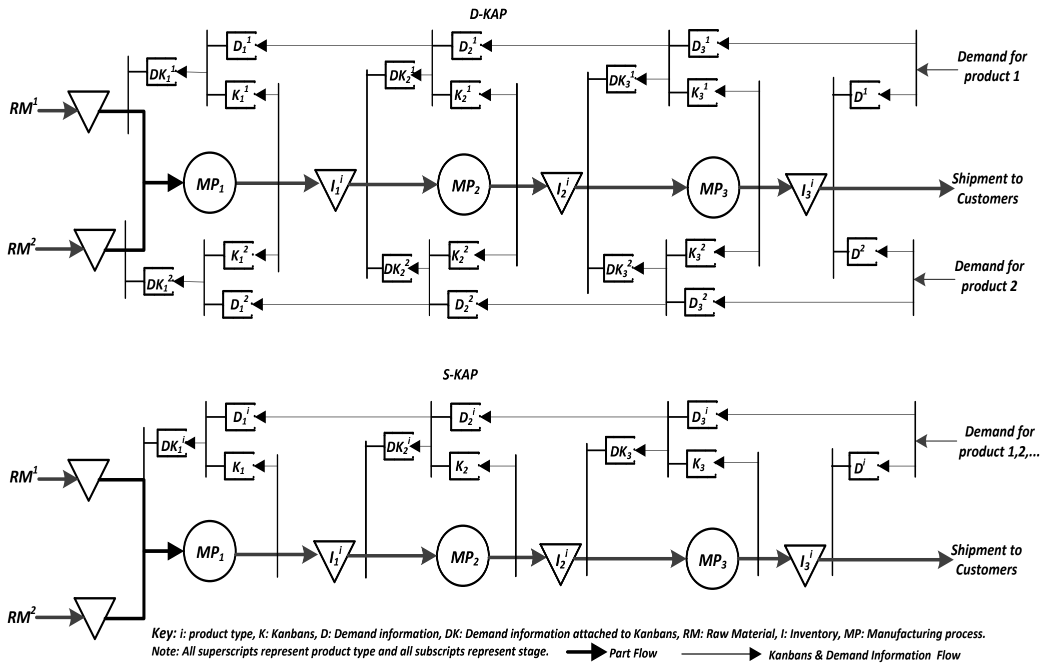


Figure 4.4: Conceptual models of multi-product GKCS (D-KAP & S-KAP)

In both the D-KAP and the S-KAP models, the demand information is transmitted to the last stage of the production line and if a Kanban matches the demand card, then a demand card is sent to the next stage upstream. If a Kanban for the part-type is not available at any stage to match the demand card at that stage, then the demand card remains at that stage, which accumulates as the backlog. The Kanbans of each stage is released from the part-type immediately the part leaves the manufacturing process unit of the stage.

The D-KAP and S-KAP conceptual models are implemented on the multi-product multi-stage EKCS as shown in the Figure 4.5. In the D-KAP conceptual model of the multi-product multi-stage EKCS, a defined number of Kanbans assign to each part-type in each stage of the production line for the control and the release of part-types. The Kanbans are dedicated to specific part-type and can only be used for the authorisation of the specified part-type. In the S-KAP conceptual model of the multi-product multi-stage EKCS, a defined number of Kanbans are assigned to each stage of the production line for the stage authorisation of various part-types. The Kanbans are shared by various part-types in each stage.

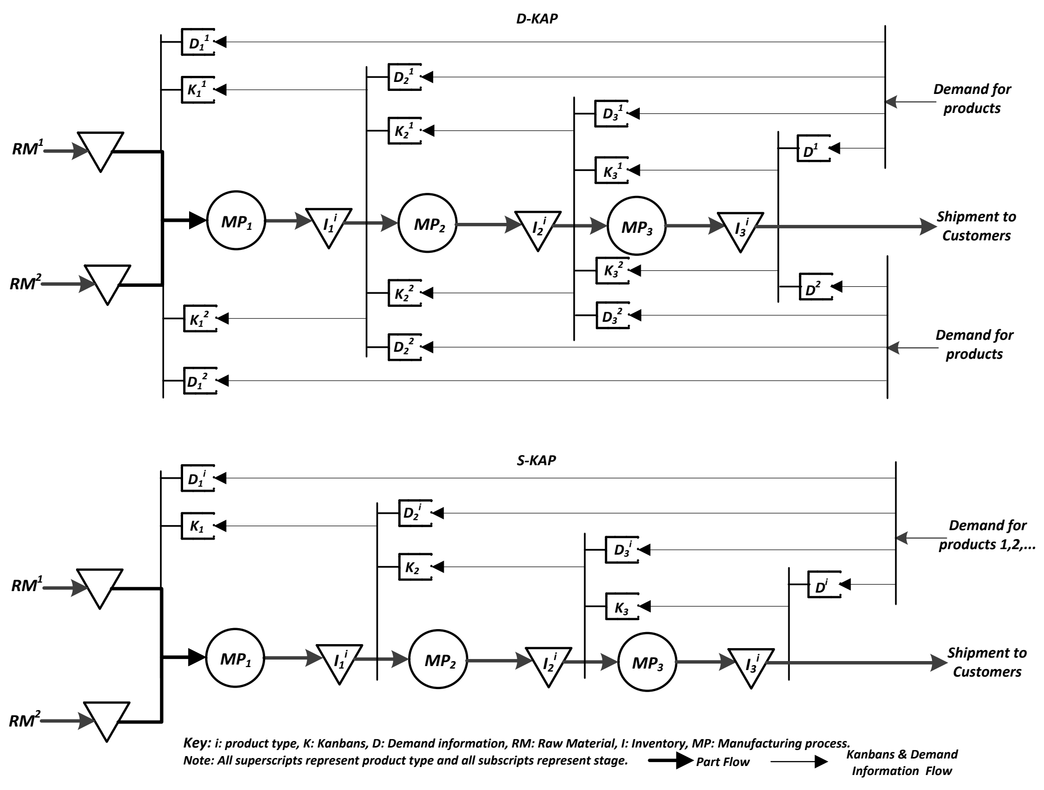


Figure 4.5: Conceptual models of multi-product EKCS (D-KAP & S-KAP)

The demand flow in EKCS is the same as in BSCS and the two roles of the Kanban were completely decoupled. When a demand for a part-type is placed, it is transmitted as demand cards using a transmission approach (global information technique) that transfers the demand cards to all the stages and to the finished product buffer. This causes a part-type to be released from the finished product buffer of the final stage to satisfy the demand. In each stage, the Kanban attaches to the demand information card and the part-type for the production of the part-type. Depending on the availability of part-type in the raw material buffer or in the output buffer of the previous stage, if part-type is available, simultaneously the stage Kanban will be attached to the demand card and part-type for the production.

The implementation of the D-KAP and S-KAP conceptual models on the multi-product multi-stage BK-CONWIP is illustrated in Figure 4.6. BK-CONWIP uses two production authorisation cards; CONWIP cards as a global card for an entire system and Kanban cards for a single stage, however, the last stage has no Kanbans.

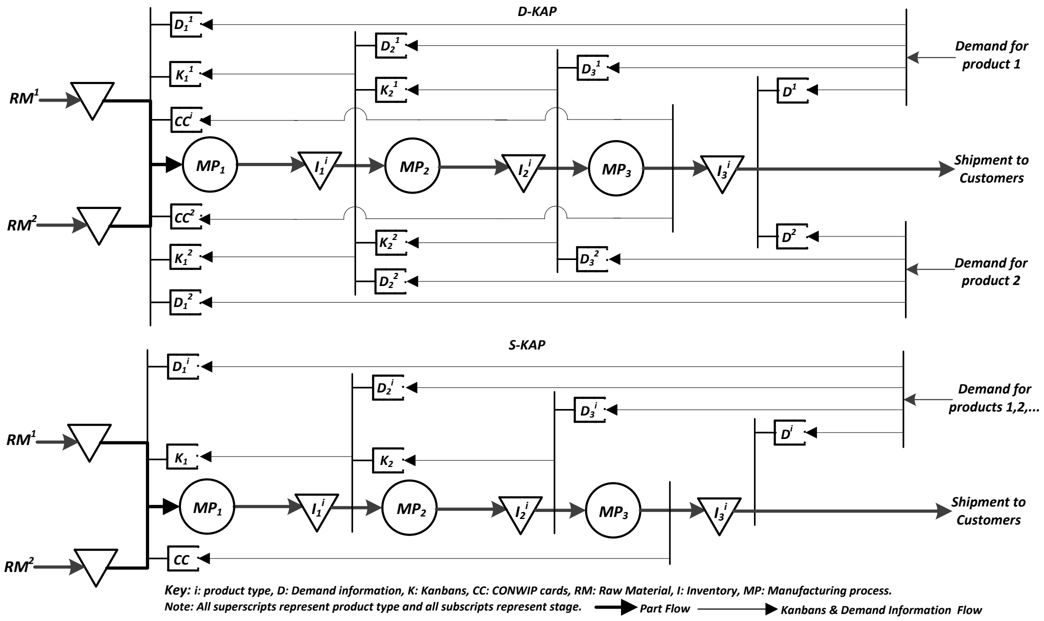


Figure 4.6: Conceptual models of multi-product BK-CONWIP (D-KAP & S-KAP)

A CONWIP card is attached to the part-type at the first stage and it is detached from the part-type immediately the part-type leaves the manufacturing process of the last stage. A stage Kanban is attached to the part-type simultaneously as the part-type leaves the raw material buffer or the output buffer of a stage. The attached Kanban is detached from the part-type immediately the part-type leaves the output buffer of that stage. In the D-KAP conceptual model of the multi-product multi-stage BK-CONWIP, a defined number of CONWIP cards are dedicated to each part-type for the entire system production authorisation. Also Kanbans are dedicated to each part-type at each stage for the production within that stage. The Kanbans are dedicated to specific part-type in a specific stage and can only be used for the authorisation of the specified part-type in that stage. In the S-KAP conceptual model of the multi-product multi-stage BK-CONWIP, a fixed number of CONWIP cards are assigned for the production authorisation of various part-types in the system. Also the stage Kanbans are assigned for production authorisation of various part-types within the stage. The CONWIP and the Kanban cards are shared by various part-types in a system and the stage respectively.

The demand information of BK-CONWIP is transmitted using a global information technique to all the stages including the finished product buffer like the BSCS. Both the CONWIP and the Kanban cards are required for the production authorisation of the part-type.

4.3 The Development of the Simulation Models

To understand the behaviour of the parameters that significantly influence and control the pull production control strategies under investigation, a discrete event simulation approach was adopted. Discrete event simulation modelling provides a virtual imitation of a real-world system for evaluation of the underlying control mechanisms that impact the behaviour of the system. It captures the dynamics of the system by means of utilising statistical distributions and unpredicted events. Simulation offers a user the benefits of a practical response when designing a real world system. It allows a problem to be examined at numerous levels of abstractions. It is cheaper than real world systems. Apart from being cheaper and faster than designing, building and testing a real system, it provides a certain level of detailed data for evaluation of a system, for instance the interaction between two control parameters in a complex system.

In the simulation modelling stage, the conceptual model is translated into the simulation model. Depending on the simulation application, in most cases, blocks representing entities that perform certain activities are used to model the identified system's vital components and the performance metrics. In this study, ExtendSim (www.extendsim.com) simulation software from Imagine That Inc. is used to develop the models for experimentation. ExtendSim is application software that allows discrete event, continuous and combined processes to be modelled. It has several libraries for various fields of application. In addition, users can build customised blocks and can modify blocks to perform personalised activities. The translation of the conceptual models into simulation models was created using the various blocks in the item, value and utility libraries of Extendsim, while the items and information flows are modelled using connectors. Some of the events, modelled in this work include: (i) the manufacturing stage (ii) the creation of part-types, (iii) the arrival of demands from customers, (iii) the movement of Kanbans (Kanban and CONWIP cards are interchangeable and are generally called PAC) in the system and (v) the local or global transmission of demand information.

The pull control system examined here is modelled using Kanbans. Kanbans are modelled as resource items stored in a resource pool block. They are linked to the demand item queue blocks such that demand item is synchronised with Kanbans, while finished part exit the system through the exit block. Resource pool release blocks detach resource items such as Kanbans attached to parts and return them to their initial position, while the resource pool linked to a queue block attaches resource items to parts or items in the queue block. Figure 4.7 represents a single stage system with the names of ExtendSim blocks used.

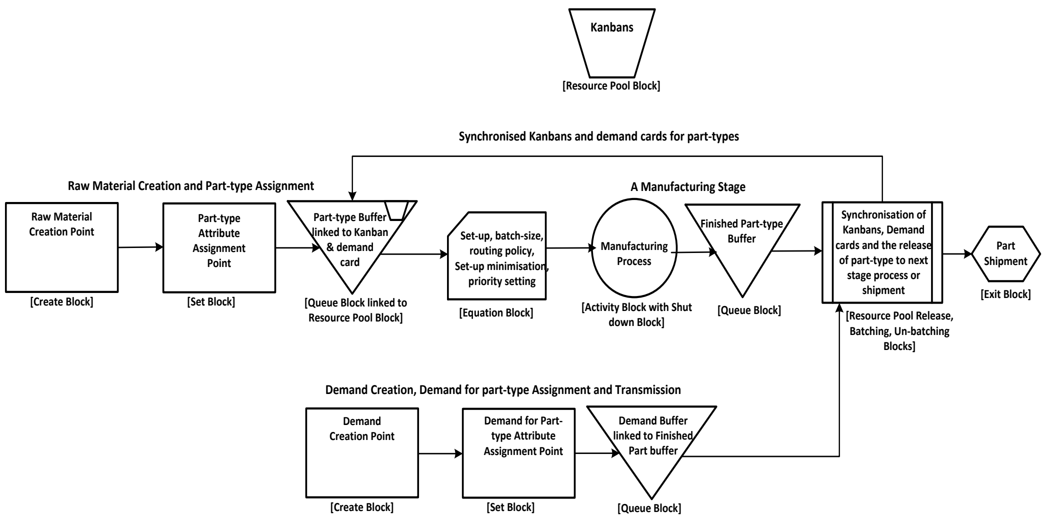


Figure 4.7: A Kanban controlled single stage system and ExtendSim blocks used

An activity block represents a machine and when combined with a queue block(s) it represents a workstation. A workstation represents a manufacturing stage and/or system. The manufacturing stage is modelled using an activity block and a queue block (output buffer).

The creation of a part-type is modelled using a create block. A create block generates items that represent parts. The parts transfer from the create-block to the set-blocks. The set block assigns part-type attribute to parts. The parts transfer to the queue blocks, which represent buffers. These part-types are raw materials and remain in the buffers for their authorisation and release into the system. The part creation events are shown in Figure 4.8 including the name of the blocks used in modelling it.

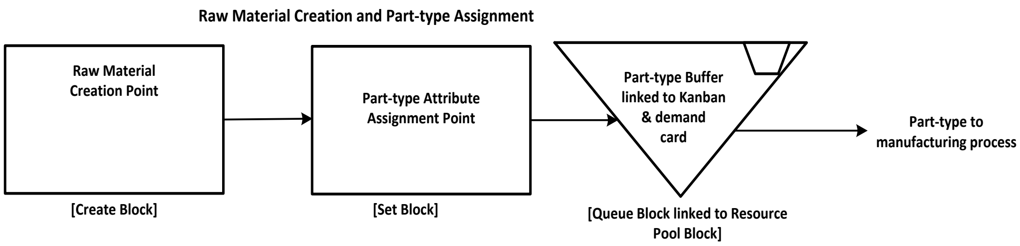


Figure 4.8: Part-type creation event in the model and the ExtendSim blocks used

Demands occurrence in the system is represented by items. Items are generated using a create block. When a demand item is generated, it is transferred to a demand queue and it requests for a finished part-type (this is also represented as an item), if a corresponding item is available it matches with demand and detaches Kanbans while leaving to the exit block (exit block represents shipment to customer). The demand items also have assigned attributes to distinguish demands for different product types. The demand item creation event is shown in Figure 4.9.

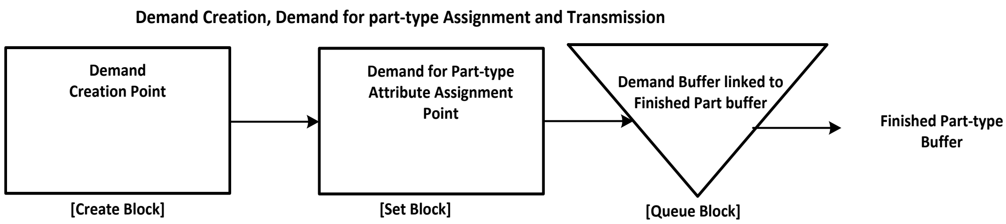


Figure 4.9: Demand creation event in the model and the ExtendSim blocks used

In order to authorise a release of parts into the system, corresponding demand items (demand information), and Kanbans are required. In modelling these events, a combination of queue blocks, resource pool block and resource pool release block, is used. The demand and the finished products with Kanbans attached are held in different queue blocks. Unattached Kanbans are kept in a resource pool block. When demand occurs in a system, it request for a release of finished product from the queue block holding finished products, if available, the resource pool release block detaches the Kanban item from the finished product, while the resource pool block linked to demand queue batches the demand item and Kanban item and transmits it upstream for replacement of the product, while the finished product leave the system through the exit block. Figure 4.10 shows the process of synchronisation of Kanban, demand and parts.

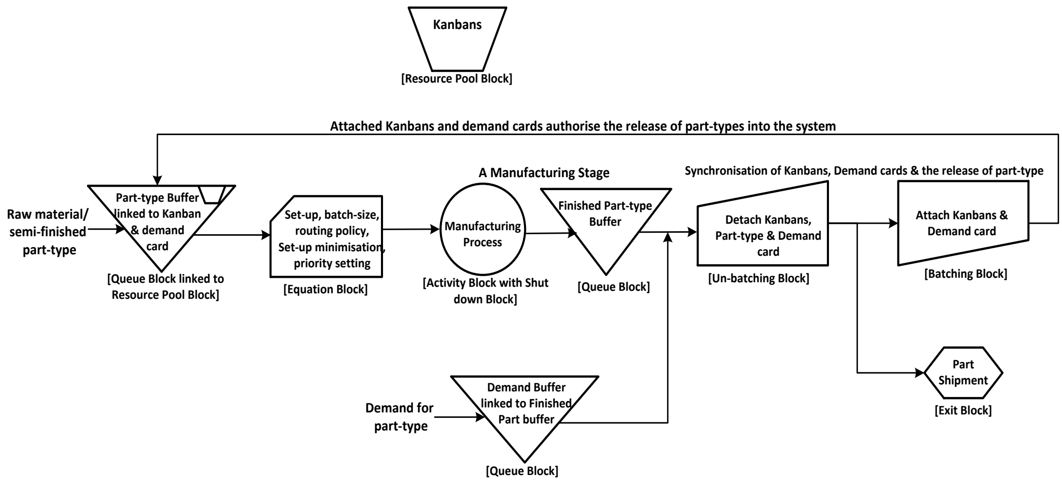


Figure 4.10: Synchronisation of demand cards and Kanbans event for release of a part-type in the model and the ExtendSim blocks used

Demand information is modelled as demand item. Demand items are generated using a create block and the items are transmitted upstream in the systems either locally or globally. In local transmission, demand items are transferred from one stage to the next, while in global transmission the demand items are transmitted to the first stage or to all stages instantaneously. An un-batching block is used to either create a multiple of demand items for transmission to the appropriate stages or to detach Kanbans, parts and demand cards. The demand items are held in demand queue block waiting for other input parameters for the release of the part into the system. Figure 4.11 represents the demand transmission.

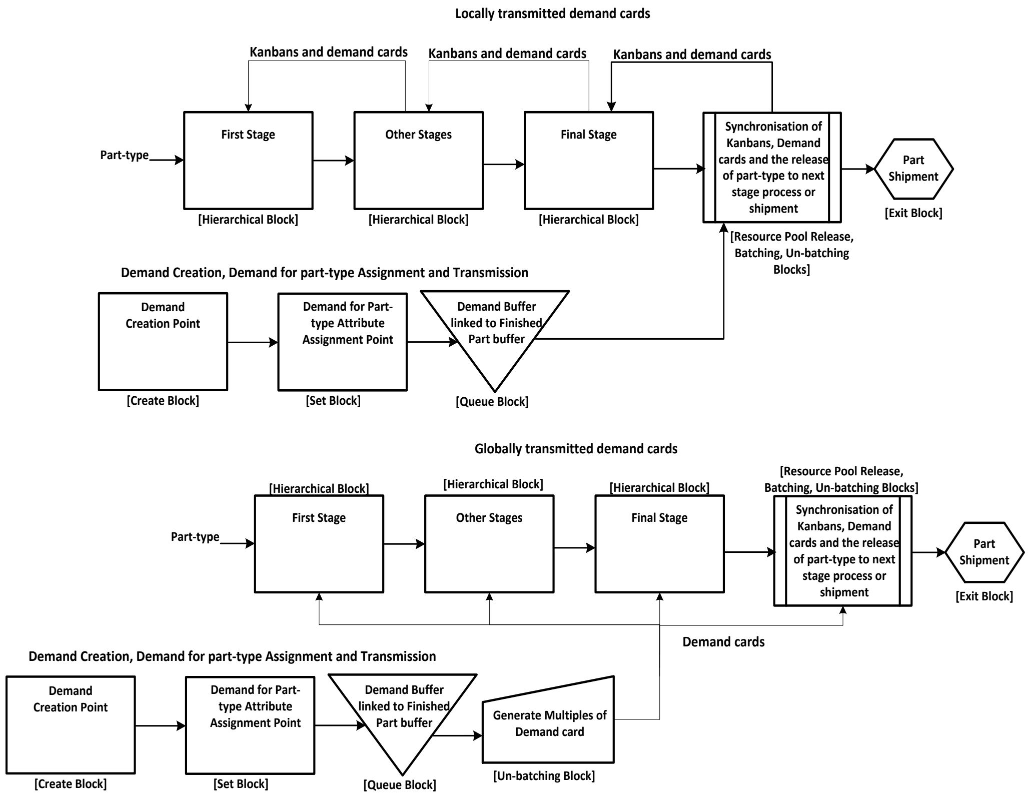


Figure 4.11: Local and global demand information transmission event in the model and the ExtendSim blocks used

Furthermore, pictorial representations of the ExtendSim blocks and the codes for set-ups, minimisation of set-ups and priority rules used here are presented in Appendix A.

4.3.1 Simulation Model Assumption

The complexity of the system was simplified in the model by removing some of the aspects of the system that are outside the scope of the study such as the transportation network. The pull PCS studied in Cases 1 and 2 are HK-CONWIP, GKCS, EKCS and BK-CONWIP.

In Case 1: The following assumptions were made in the models for simplification purposes:

- Two products are manufactured in the system using the same machines or sets of machines in a series.
- The demand profile is deterministic.
- Demands that are not satisfied within the appropriate period are logged as backlog and are served in the next period before satisfying the demand of

the next period

- There are three stages in the manufacturing system with each having a workstation.
- The three stages are assumed to have negligible setup times, such that the products are treated in the First In First Out (FIFO) order of the buffer.
- Raw materials are readily available such that constraints owing to the availability of materials are eliminated.
- The machines are assumed to have an operation dependent breakdown such that a machine can only breakdown during the time it is available for production (effective production time).
- The time for loading and unloading a workstation is negligible.
- The information flow in the system occurs within a negligible time period. Demand and authorisation card information transmissions are instantaneous

In Case 2: The following assumptions were made to focus on the relevant aspects of the system that would influence the objectives of this study:

- The system produces two family types and each family has two part-types processed on a set of machines in a serial manufacturing/assembly line configuration.
- Raw materials are readily available.
- Part-types of the first family are considered as entering the system at stage 1. The first family part-types are available in pallet batch and are processed in pallet quantity of 16 boxes (each box has 90 parts) within stages 1 and 2. They are considered as boxes in stages 3, 4, 5 and Supermarket area.
- The second family part-types enter the line at stage 3. They are considered as boxes of 120 parts each. The products are assumed to be always available and no more than 32 boxes (2 pallets) may be in the area containing these products.
- Set-up time is assumed to occur in stage 3which stops operation in stages 4 and 5, the three stages recover simultaneously after setup.
- Set-up time is considered to be negligible in stages 1 and 2.
- The breakdown of a workstation is operation dependent such that failures occur only during processing of a part. The breakdown is modelled such that any failure within stages 1 and 2 will cause operations to stop in both

stages and they recover simultaneously after maintenance is completed. Also, any failure within stages 3, 4 and 5 will cause operations to stop within those stages and they recover simultaneously after repairs.

- Demand is intermittent such that it exhibits an unpredictable pattern. Unsatisfied demands within the one week time frame are recorded as backlog and are added to the following week's demand, such that the sum of the previous backlog and the actual week's demand is served as the current week demand.
- Each stage consists of a workstation.
- There is a priority setting on each stage depending on the demand size, and day for family product production. However, any buffer that is not priority controlled or resource pool controlled is considered as First In First Out (FIFO) principle of the buffer.
- Loading and unloading operations in a workstation consume negligible time period.
- There is a negligible time frame for information flow in the system. Demand and authorisation card information transmissions are instantaneous.

4.3.2 Warm-up Period, Run Length and Number of Replications

It is important to reduce to a minimum the effect of the initial state of a system in order to make unbiased judgements about the system's performance based on the results of simulation experiments. Two approaches for reducing the influence of the initial state in a system are: (1) the deletion of the initial sets of data, considered to have been affected by transitory state of a system, (2) setting simulation into the steady state approach at the beginning of the experiment (Intelligent initialisation).

The deletion of an initial set of data approach is widely used in simulation studies. The Welch's graphical technique uses a graph to estimate the warm up period and it is simple to implement. Several studies that compared the Welch's technique to its alternatives (such as: simple time series inspection, ensemble average plots, cumulative mean rule, variance plot, the Conway rule, the modified Conway rule and autocorrelation estimator rule) often recommend it for warm up analysis because its alternatives depend on restrictive assumptions and extensive computation [95-98]. The Welch graphical technique was applied to the pull strategies under investigation, to avoid selecting a warm up period that could negatively affect the outcome of the simulation either by under-estimating (collecting biased data) or over-estimation (wasting so much steady state data) of the warm up period. The warm up analysis was carried out on all models under investigation. To avoid biased estimators for each experiment in cases 1 and 2, seven replications were used. This is because at 95% confidence intervals the mean values were found to be within 2.4% of the mean value, which is relatively small.

In Case 1, 50,000 hours run length for each model was used to determine the warm up period. The control parameters of the models were selected using sensitivity analysis (one parameter change at a time). The WIP level of the system was computed every 100 hour time period in each run to obtain a high number of observations of each data point for statistically detailed results. The Welch's technique was applied on these data with different window lengths (5, 10, 20, 30, 40) to establish appropriate window sizes that are capable to resolve the finer frequency components and provide sufficient periodograms to average, in order to reduce the variance of the overall spectrum estimate. Two different smoothing window sizes of 20 and 30 were selected for the models. Figure 4.12 provides the warm up analysis of EKCS-D-KAP (graphical representation of the warm up analysis of all PCS-KAP for case 1 can be found in Appendix B), with the lengthiest biased period and it assumes consistency from 13,800 hours. Thus, 15000 hours warm up period was selected to avoid biased data. Thirty replications of the simulation experiments with a long run of 50,000 hours per run were performed for each experiment.

In Case 2, nine weeks run length were used in determining the warm up period of the models. The changeover factor was set based on the knowledge of several trial simulations to 6 pallet quantities of product 1, 4 pallet quantities of product 2, 5 pallet quantities of product 3 and 4 pallet quantities of product 4. The Kanban settings for the stages were varied, ranging from 1 to 100. The CONWIP cards for HK-CONWIP and BK-CONWIP strategies were varied, ranging from 40 to 300. The WIP of the system was collected for every 24 hour time period for the 9 week period for each of the 7 runs. Two smoothing window-sizes 20 and 30 were used in the warm-up analysis. D-KAP EKCS, which has the longest biased period, assumed a steady state at 3 week period (360 hours) as shown in Figure 4.13 (graphs for all the models are provided in the Appendix B). However, in order to ensure that a significant number of irregular events would have occurred and have confidence that the system was in a steady-state in the experiments, a conservative warm-up period of 4 weeks (480 hours) was selected.

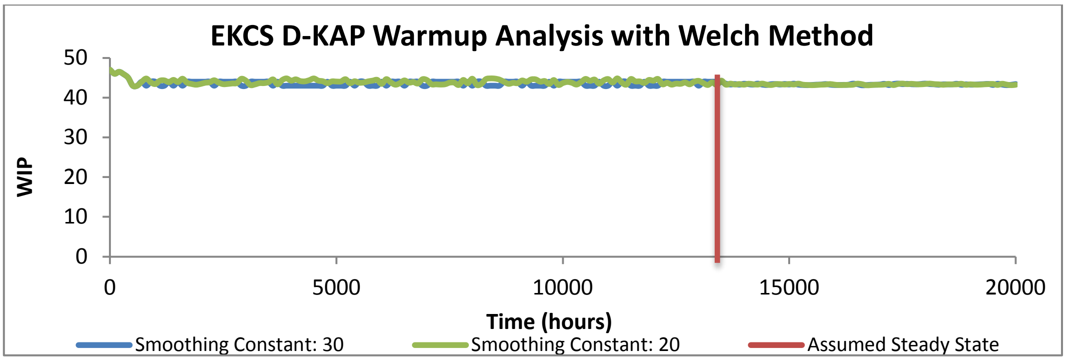


Figure 4.12: Case 1 Welch graph of EKCS D-KAP for window sizes 20 and 30

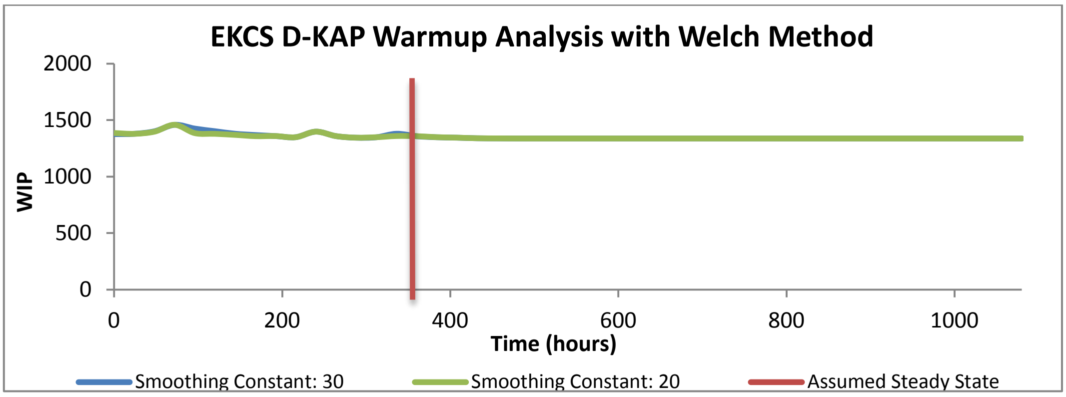


Figure 13: Case 2 Welch graph of EKCS D-KAP for window sizes 20 and 30

4.3.3 Verification and Validation of Simulation Models

It is important to verify that a simulation model represents and behaves as the system. To show that the pull model is a true representation of the actual system, the model was examined on stage bases before checking the entire model and wherever errors or inaccuracies were found, the model was reviewed and corrected.

In Case 1, each stage of the model was observed and analysed to ensure that the models behave as the system. The production capacities of each stage and of the entire model (preventive maintenance, number of products and authorisation cards) were tested and compared with the data from the real system. A defined quantity of demand was released into the real system to verify that the output corresponds to the output of the model. The quantity was varied to attest that the models represent the system. The demand was varied for the purpose of testing and verifying the production process capacity of the system in comparison with the model. The statistics were taken from each stage WIP for the comparison. The validation of most of the PCS models under consideration was based on the study of Olaitan and Geraghty [77] which compared five PCS, which confirms the accuracy of the models in comparison to the system under study. Table 4.2 shows the comparison of WIP results from models developed by Olaitan and Geraghty [77] and the models used in this work.

Table 4.2: Case 1 Comparison of WIP results for model validation

PCS-KAP	Average Total WIP from Olaitan and Geraghty [77], with minimal blocking policy at 95% SL	Average Total WIP from Current models with minimal blocking policy at 95% SL	Average Total WIP from Current models with no minimal blocking policy at 95% SL	Confidence Interval of differences between Average Total WIP of columns 2 and 3
D-KAP BSCS	48.582	Not Applicable	Not Applicable	Not Applicable
D-KAP CONWIP	47.000	Not Applicable	Not Applicable	Not Applicable
D-KAP KCS	47.764	47.557	44.465	0.207±0.284
D-KAP EKCS	46.835	46.609	36.809	0.226±0.272
S-KAP EKCS	46.252	46.112	36.71	0.140±0.153
D-KAP GKCS	44.278	44.187	37.264	0.091±0.116
S-KAP GKCS	43.832	44.024	37.241	-0.192±0.207
D-KAP HK-CONWIP	Not Applicable	46.376	38.994	Not Applicable
S-KAP HK-CONWIP	Not Applicable	46.529	38.978	Not Applicable
D-KAP BK-CONWIP	Not Applicable	43.877	32.169	Not Applicable
S-KAP BK-CONWIP	Not Applicable	43.25	31.947	Not Applicable

In case 2, to ensure that the models behave as the system, a structured walk-through of the logics used in the models was conducted with engineers and managers of the company to verify and correct the logics where necessary. A push controlled model was developed owing to the company's system currently operating push control strategy. There were four company visitations and five online meetings to verify the models. In these meetings, corrections and changes were made to the model. The production capacities of each stage and of the entire model (preventive maintenance, number of products and authorisation cards) were tested and compared with the data from the real system. A defined quantity of demand was released into the model to verify that the output corresponds to the output of the real system. The quantity was varied to attest that the models represent the system by the company's production personnel. The demand was varied for the purpose of testing, verifying and validation of the production process capacity of the system in comparison with the model. The company accepted the WIP results (see, Table 4.3) of the push model and the model was used to develop the pull controlled models by adding the Kanbans according to the strategy's control mechanism.

Table 4.3: Case 2 Comparison of WIP results for model validation

PCS	Average Total WIP from system	Average Total WIP from models	Confidence Interval of differences between Average Total WIP of columns 2 and 3	Company's Remark
Push	2725.34	2718.59	6.750±0.742	Accepted as valid data

4.4 Model Optimisation

The aim of optimising the models is to conduct experiments using the best control parameters for the pull control strategies and authorisation card policies, to achieve the best results of the models in a given scenario. Real-world manufacturing problems often contain two or more conflicting objectives requiring complex search space. In such cases a multi-objective optimisation is often favoured as it searches for optimality in problems with multiple conflicting objectives, which often results in the generation of a set of non-dominated solutions such that no enhancement can be achieved by altering any of the constraints without negatively influencing the performance of one or more of the objectives. This set of non-dominated solutions is referred to as a Pareto-optimal solution. The multi-objective optimisation has an advantage over single-objective optimisation because it provides a set of alternative solutions, which trades different objectives against each other. The non-dominated solutions are useful in supporting a decision maker with settings that will give rise to alternative solutions without re-optimised for such solutions [89, 90].

4.4.1 Evolutionary Algorithm for Pareto Optimisation

The simulation model under examination is capable of generating different output values for the same run setting based on its stochastic nature and therefore requires replications in order to evaluate the noise level and create a confidence interval around the performance measures. Similarly, the large and complex search space contributes to the need for an efficient heuristic search algorithm to optimise the parameters. Evolutionary Algorithms (EA) have been shown to be successful in optimising multi-criteria stochastic problems [99].

Evolutionary algorithms refer to a group of stochastic optimisation approaches that mimic the process of natural evolution. The three most frequently used evolutionary approaches are Genetic Algorithms (GA), Evolutionary Programming (EP) and Evolution Strategies (ES) [100]. The two main principles of Evolutionary algorithms are selection and variation. Selection refers to the struggle for resources among beings, such that the best survive and reproduce. It concentrates the search for a better region of a search space by assigning and ranking individuals' fitness. This is simulated by a stochastic selection method in evolutionary algorithms. Each individual solution has the opportunity to be members of the next generation and reproduce a defined number of times based on their quality. The second principle (variation) mimics natural capability of creating offspring based on recombination and mutation. Evolutionary algorithms are appropriate for multi-objective optimisation because EA switches between the objectives during the selection phase such that when an individual is selected for reproduction, a different objective decides the members of the population that will be copied into the mating pool. Therefore, it has the capability of capturing several Pareto-optimal solutions in one simulation run and exploit comparisons of solutions by recombination. There are numerous applications of evolutionary algorithms, especially genetic algorithm in multi-objective optimisation [101]. The universally used elements of genetic algorithms include (i) populations, (ii) selections, (iii) mutations and (iv) crossovers. GA is a statistical optimisation procedure that applies the concepts of genetics and natural selection to determine an optimal solution to a problem. The method of search in genetic algorithms involves a continuous enhancement of a solution via selection and integration of individual solutions over successive generations. It emphasises crossover over mutation. The EP and ES generally apply to the real valued representation of optimisation problems. Their emphasis is on the mutation over the crossover and applies to much smaller population sizes than GA. GA remains the most widely recognised form of EA and therefore was selected for this study.

The genetic algorithm settings include the mutation rate, the number of generations (population size) and the number of replications. The aim of the multi-objective is to establish the conditions in which any of the strategies would out-perform the rest of the strategies. This would support a decision process for managers or production personnel to co-ordinate production authorisations and manage inventory in a multi-product system while maintaining targeted or higher delivery performance (service level or backlog).

4.5 Comparison Tools And Techniques

To determine a superior pull PCS (a strategy that outperformed its alternatives), significant analyses and comparisons of experimental results are required. The techniques and tools used in this study include (i) the curvature analysis, (ii) Nelson's screening and selection of the best system, (iii) robustness analysis.

4.5.1 Curvature Analysis

The curvature of any given arc measures the degree of deviation of the curve from a straight line and measures the rate of changes of the curve in the direction of a tangent. When considering a two-dimensional curve expressed as, $y = f(x)$, the curvature functions or the signed curvature is given by [99]

$$k = \frac{\frac{d^2y}{dx^2}}{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{\frac{3}{2}}} \qquad 4.1$$

The negative or positive sign of the curvature function k shows the direction of rotation of the unit tangent vector along the curve, such that a clockwise rotation of the unit tangent vector indicates that $k<0$, while a counterclockwise rotation of the unit tangent indicates that $k>0$.

This technique will be shown by applying it on the trade-off curves of all developed simulation models. Polynomials smoothen and show inflection points on a curve. An inflection point is a position on the curve that changes from a positive radius to negative. A high order polynomial can be lumpy or smooth, owing to the nature of the curve. In this study, to obtain a smooth, and at least one inflection point on the curves, the order of polynomial was varied from first order to sixth order. A sixth order polynomial was applied to the trade-off curves of the models as, $WIP = f(Service\ Level)$. To compute the points of inflection and the corresponding service level, the curvature function will be applied to the resulted curves by superimposing it on the curves. The analysis of the curvature in this thesis will concentrate on Service Levels above 90% as industrialists are interested in achieving higher service levels.

4.5.2 Nelson's Screening and Selection Technique

The ranking and selection techniques have been shown to be useful in determining the best system in comparison studies. However, ranking and selection procedure is widely used when the number of systems for screening is relatively small. Nelson et al [102] developed a screening and selection procedure that obtains higher statistical efficiency for a large number of alternatives.

Nelson's screening and selection procedure [102] was adopted for statistical determination of a superior PCS-KAP. The procedure permits instant removal of inferior PCS-KAP during screening with no extra simulations. In the screening stage, all the survivors are grouped into a set for further screening. If the survivors' set contains only one survivor, the survivor is considered as the best strategy and/or policy without conducting further selection procedure. The performance metrics for screening and comparisons are the WIP and service levels in the system. The parameters of Nelson's combined procedure used are as follows: k, where k is the number of alternatives (the number of PCS-KAP) for screening and selection. The initial number of replications is denoted as n_0. The variance of the sample data is represented as S_i^2, while $\bar{Y}_i$ is the mean of the sample data. 90% overall confidence level for the combined procedure, that is $\alpha = 0.1$, also 95% confidence level for each of the two stage sampling procedures is given as $\alpha_0 = \alpha_1 = \frac{\alpha}{2} = 0.05$. The Rinott's integral h is given as $h = h(1 - \alpha_1, n_0, k)$. The significant difference between the best and the second-best true mean is given by ε, which indicates that with 90% overall confidence it is desired to select a system as the best system which has a mean total inventory of no more than ε, larger than the actual best system. The screening thresholds, W_{ij}, for each comparison are determined from Equation 4.2 below.

$$W_{ij} = t\left(\frac{S_i^2 + S_j^2}{n_0}\right)^{\frac{1}{2}} \text{where } t = t_{1-(1-\alpha_0)^{1/(k-1)}, n_0 - 1} \qquad 4.2$$

When the assumption is that smaller is better (in case of WIP), the survivor set, is determined by identifying all the alternative models for which the inequality given in Equation 4.3, below, holds.

$$\bar{Y}_i \leq \bar{Y}_j + max\left(0, W_{ij} - \varepsilon\right) for\ all\ j \neq i \qquad 4.3$$

The inequality in Equation 4.3 is altered as shown in Equation 4.4 assuming larger is better, as in the case of evaluating Service Level as the comparative performance metric.

$$\bar{Y}_i \leq \bar{Y}_j + max\left(0, W_{ij} + \varepsilon\right) for\ all\ j \neq i \qquad 4.4$$

If the survivor set holds more than one model then the number of extra replications required for each survivor is determined from Equation 4.5.

$$N_i = max\left(n_0, \left\lceil \left(\frac{hS_i}{\varepsilon}\right)^2 \right\rceil\right) where\ \lceil\ \rceil\ signifies\ round\ up \qquad 4.5$$

4.5.3 Robustness Analysis

The implementation of an optimal solution for the parameters of a system is found to weaken a manufacturing system's ability to respond to variations [70]. The optimal solution to a problem is vital; however the robustness of such a solution is equally important in the design of systems. The robustness and quality improvement proposed in 1980's by Taguchi [103] used various performance measures referred to as signal-to-noise ratios for minimising variations and calculating performance of products and processes [99]. The aim of Taguchi's robust design is to develop a process or product design that has minimum deviations in the presence of noise factors with respect to the performance metrics of interest. The control parameters of the process or product design should be insensitive to the environmental changes. The environment changes can occur during the processing and/or product lifetime. Hence, risk is associated with any given product design [99]. Therefore, to design a responsive manufacturing system, the robustness of the system needs adequate consideration. Taguchi [103] advocates regulating the design of products by means of Design of Experiments to ensure that the product's performance metrics become insensitive to the effects of environmental changes. Kleijnen and Gaury [70] applied this technique to analyse the robustness of production control strategies to environmental factors.

The design of experiments is vital to produce the training set for the production of the simulation models. The standard design of experiments often used is the space filling designs [104]. The aim of space filling design is to fill the space with the number of points or runs such that a broad input parameter space is sampled. It shows the performance of the simulator across the entire space of the parameters. Hence, it is required to span the full range of the inputs with a training set of runs. The traditional space filling design of experiments is the LHS technique [105].

The samples of each environmental parameter (noise factor) are used to conduct simulation experiments. The results of the scenarios would provide an estimated probability distribution of the performance measures. Comparison of any two systems can be made based on the concept of cumulative distribution function and stochastic dominance [99]. Stochastic dominance is a statistical ranking and selection technique, used in decision theory and analysis to show where one probability distribution can be ranked superior to another.

In this work, the LHS technique was applied to design experiments for PCS-KAP. A stochastic dominance test was used for comparison of the policies' cumulative distribution functions. The outcome of a stochastic dominance test is classified as first degree or second degree dominance. First degree stochastic dominance occurs when the cumulative distribution functions ($CDF_Y(x) and\, CDF_Z(x)$) of two systems ($Y\ and\ Z$) are compared with the objective function to maximise X, hence system Y has first-order stochastic dominance over system Z if

$$CDF_Y(x) \leq CDF_Z(x), for\ all\ x. \qquad 4.6$$

Conversely, system Y has second degree dominance over Z if

$$\int_b^a CDF_Y(x)dx \leq \int_b^a CDF_Z(x)dx\,, for\ all\ k \qquad 4.7$$

where a is the higher limits and b is the lower limits

CHAPTER 5: SIMULATION EXPERIMENTS, RESULTS AND EVALUATION

5.1 Introduction

This chapter compares the performance of the pull control strategies (HK-CONWIP, GKCS, EKCS and BK-CONWIP) in D-KAP and S-KAP modes. The purpose is to investigate the response of the known superior pull control strategies and the newly developed pull strategy under linear demand profile and non-linear demand profile. The outcome will provide a better understanding of the processes for selection and implementation of pull PCS especially in a multi-product manufacturing environment. A detailed description of the experimental conditions, model configurations and optimisation are presented first, followed by the simulation results and then comparison.

5.2 Simulation Set-ups and Configuration

In Case 1, to determine a practical level of loading of the production capacity, the infinite loading approach was applied [77]. Infinite loading approach places orders that exceed a system's capacity constraints, such that demand is available, while the manufacturing processes restrict production. The model was run under a simple push PCS condition under infinite loading (infinite demand is generated via the ExtendSim Create block). The model was simulated in a push mode and the mean time between items was collected from the ExtendSim information block as 5.1 hours and 5.2 hours for part-type 1 and 2 respectively. The mean time between the demands for part-type 1 was calculated as 5.61 hours, given by $110\% \times 5.1$ hours, corresponding to 90% production capacity and the other was calculated as 5.72 hours.

Factors of significant interest with respect to representation and applicability in a real life manufacturing system are the production capacity of the system, loading and the level of variability [77]. An Exponential distribution with a mean of 90 hours and 10 hours were selected for MTBF and MTTR, respectively, to achieve the required 90% production capacity availability of each workstation in the system. A normal distribution was used in modelling the mean time between demands as the demand can be considered as a combination of events from different customers. Also, it can easily be used in setting the varying levels with a combination of standard deviation and mean values. Therefore, the mean value of the demand arrival time of product 1 is 5.61 hours and 5.72 hours for product 2. The level of variability in product 1 is 50% of the mean value and product 2 is 10%, implying that the standard deviation values were calculated as 2.805 hours and 0.572 hours respectively.

In Case 2, to achieve a high level accuracy in modelling the system, the behaviour of the production capacity, the loading and the level of variability in the system were given considerable attention. The demand profile, the processing times, the setup times, and the downtimes were obtained from the automotive component manufacturing company that sponsored the project. The data were used for the experiments. The four main classifications of a demand profile based on the level of variability in the literature are (i) slow-moving, (ii) intermittent, (iii) erratic and (iv) lumpy demand profiles [106, 107]. The slowing moving demand profile has irregular demands with a similar demand size occurring at close intervals, while the intermittent demand profile has random demand with no demand occurring in a few intervals. The erratic demand profile has irregular demand sizes with a high level of variations while lumpy demand profile is characterised with zero demands in a few intervals and demand sizes with a high level of variability. The demand profile (Table 5.1) used in this study has uneven sizes with a high level of variance and is classified as erratic. There are six weeks demand profiles for each of the products. The weekly demands of each of the products are recorded in an internal database of the model.

5.2.1 Model Configuration

To evaluate the performance of the pull control strategies in both dedicated and shared Kanban allocation policies, several experiments were conducted under varying manufacturing conditions. The system configurations and settings used in the experiments in Case 1 are detailed in Table 5.2.

Table 5.1: Case 2 Weekly demand profile

Demand Dataset	Product = P	Production Week					
		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
A	P1	542	452	404	503	247	483
	P2	130	224	142	118	129	114
	P3	130	184	131	159	125	147
	P4	110	138	147	71	61	39
	Total	912	998	824	851	562	783
B	P1	503	366	413	365	381	480
	P2	147	212	147	108	112	144
	P3	115	194	128	143	169	137
	P4	121	158	131	62	61	51
	Total	886	930	819	678	723	812
C	P1	502	405	352	403	369	612
	P2	149	153	212	109	122	108
	P3	145	169	132	103	129	111
	P4	111	141	149	72	81	41
	Total	907	868	845	687	701	872
D	P1	461	450	463	493	330	445
	P2	231	156	137	116	134	170
	P3	99	145	107	97	174	101
	P4	128	161	140	81	70	78
	Total	919	912	847	787	708	794
E	P1	481	451	400	412	492	1133
	P2	308	151	146	90	221	120
	P3	103	165	92	115	137	111
	P4	118	161	130	60	77	51
	Total	1010	928	768	677	927	1415
F	P1	481	544	461	412	461	429
	P2	296	225	141	107	130	200
	P3	103	25	111	122	119	97
	P4	101	20	128	68	57	48
	Total	981	814	841	709	767	774

Table 5.2: Case 1 manufacturing system configuration

Stage	Product 1	Product 2	MTBF Exponential Distribution Mean	MTTR Exponential Distribution Mean
	Processing Time	Processing Time		
1	1.5 hours	3 hours	90 hours	10 hours
2	1.5 hours	3 hours	90 hours	10 hours
3	1.5 hours	3 hours	90 hours	10 hours
Demand	~N(5.61,2.805)	~N(5.72,0.572)		

~N = Normal distribution

In Case 2, the summary of the configurations is presented in Table 5.3. While Table 5.1 provides a detailed description of the demand data sets A to F.

Table 5.3: Case 2 manufacturing system configuration

	Product 1	Product 2	Product 3	Product 4	Maintenance: Exponential Distribution Mean		Setup Times (Hours)
Stage	Processing Times/Box (Hours)	Processing Times/Box (Hours)	Processing Times/Box (Hours)	Processing Times/Box (Hours)	MTBF (Hours)	MTTR (Hours)	
1	0.162	0.162	0	0	3.5	0.23	0
2	0.126	0.126	0	0	3.5	0.23	0
3	0.0975	0.0975	0.13	0.13	6.1	0.23	~N(0.327, 0.109)
4	0.0975	0.0975	0.13	0.13	6.1	0.23	0
5	0.0975	0.0975	0.13	0.13	6.1	0.23	0

~N = Normal distribution

5.3 Optimisation

In this thesis, the focus is on using a multi-objective optimisation block developed by Kernan and Geraghty [108] that has the capability of sampling large and complex search spaces to find the precise Pareto-optimal solution set for the simulation experiments.

5.3.1 Pareto Optimisation

The simulation model under examination is capable of generating different output values for the same run setting based on its stochastic nature and, therefore, requires replications in order to evaluate the noise level and create a confidence interval around the outcomes. The multi-objective optimisation provides a range of optimal solutions to varying control parameters. The results show the quantity of WIP required or the cost of increasing the service level from one level to another. Therefore, it supports a decision making process for selection of a set of control parameters to achieve a given service level at a given period. Also, it reduces the time required to carry-out re-optimise the control parameters of a system when changes to the service levels are requested.

Selecting appropriate control parameter is important in conducting a suitable search for a solution. To determine an appropriate mutation rate, a range of values (0.000 to 0.200) was tested. It is important to select a mutation rate for high enough solutions because it gives a wider range of local and global solutions. The mutation rate of 0.100 was selected for the experiments after testing various mutation rates ranging from 0.000 to 0.200 using D-KAP and S-KAP models of the pull PCS under investigation (see, Table 5.4). During the trial test for selection of a mutation rate, small mutation rates (ranging from 0.000 to 0.075) result in premature convergence (i.e. local optimum solutions) with a few solutions, while a higher mutation rate (ranging from 0.125 to 0.200) results in an overdue convergence, such that search converges to the global optimum while leaving out some of the local optimum solutions. The number of specific generations before termination of the search is set to 150 generations [108]. In order to have a good level of confidence from the experiments, the number of replications was set to 30 [47].

Table 5.4: Different mutation rates and number of solutions

Mutation Rate	Number of Generation	Number of Solutions
0.000	150	26
0.025	150	137
0.050	150	355
0.075	150	675
0.100	150	1487
0.125	150	1431
0.150	150	1292
0.175	150	964
0.200	150	611

5.3.2 Pareto Optimisation Results

A summary of the control parameters that achieved 95% and 100% service level of a specified Production Control Strategy and Kanban Allocation Policy (PCS-KAP) is presented in Tables 5.5 and 5.6 for Case 1 and Tables 5.7 and 5.8 for Case 2. The Pareto frontiers, showing the trade-off points between the average work-in-process inventory and the service levels achieved by individual PCS-KAP, are presented in Figures 5.1 and 5.2 for Case 1 and Case 2, respectively.

Table 5.5: Case 1 Pareto search space and optimal values of PCS-KAP at 95% service level

Pareto Decision Set at 95% Service Level			CONWIP (RV) &[O.S]	Kanban (RV) & [O.S]			Basestock (RV) & [O.S]	Total		
Stage			1 2 3	1	2	3	3	CON-WIP	Kan-ban	Base-stock
PCS	KAP	Product	10 – 50 (RV)	1 – 40 (RV)			10-40 (RV)			
HK-CONWIP	D-KAP	1 2	[21] [20]	[8] [8]	[14] [8]	N/A N/A	[21] [20]	41	38	41
	S-KAP	1 2	[40]	[9]	[16]	N/A	[21] [19]	40	25	40
GKCS	D-KAP	1 2	N/A N/A	[2] [4]	[9] [4]	[20] [20]	[21] [20]	N/A	59	41
	S-KAP	1 2	N/A	[13]	[14]	[22]	[21] [20]	N/A	49	41
EKCS	D-KAP	1 2	N/A N/A	[8] [7]	[9] [9]	[17] [22]	[22] [17]	N/A	72	39
	S-KAP	1 2	N/A	[14]	[16]	[35]	[22] [17]	N/A	65	39
BK-CONWIP	D-KAP	1 2	[20] [15]	[8] [6]	[7] [6]	N/A N/A	[19] [14]	35	27	33
	S-KAP	1 2	[32]	[13]	[13]	N/A	[16] [14]	32	26	30

[O.S] – Optimal values for the control parameters, (RV) – Range value of search, N/A - Not Applicable, Basestock levels for stages 1 and 2 are zeros

Table 5.6: Case 1 Pareto search space and optimal values of PCS-KAP at 100% service level

Pareto Decision Set at 100% Service Level			CONWIP (RV) &[O.S]	Kanban (RV) & [O.S]			Basestock (RV) & [O.S]	Total		
Stage			1 2 3	1	2	3	3			
PCS	KAP	Product	20 – 100 (RV)	10 – 60 (RV)			25-70 (RV)	CON-WIP	Kan-ban	Base-stock
HK-CONWIP	D-KAP	1	[51]	[25]	[30]	N/A	[51]	96	98	96
		2	[45]	[20]	[20]	N/A	[45]			
	S-KAP	1	[95]	[42]	[54]	N/A	[50]	95	96	95
		2					[45]			
GKCS	D-KAP	1	N/A	[28]	[23]	[57]	[54]	N/A	177	98
		2	N/A	[22]	[19]	[28]	[44]			
	S-KAP	1	N/A	[44]	[34]	[28]	[52]	N/A	106	95
		2					[43]			
EKCS	D-KAP	1	N/A	[26]	[22]	[34]	[54]	N/A	156	89
		2	N/A	[25]	[19]	[30]	[35]			
	S-KAP	1	N/A	[42]	[20]	[43]	[50]	N/A	105	86
		2					[36]			
BK-CONWIP	D-KAP	1	[53]	[23]	[27]	N/A	[50]	83	96	80
		2	[30]	[21]	[25]	N/A	[30]			
	S-KAP	1	[82]	[43]	[52]	N/A	[47]	82	95	75
		2					[28]			

[O.S] – Optimal values for the control parameters, (RV) – Range value of search, N/A - Not Applicable, Basestock levels for stages 1 and 2 are zeros

Table 5.7: Case 2 Pareto search space and optimal values of PCS-KAP at 95% service level.

Pareto Decision Set at 95% Service Level			CONWIP (RV)&[O.S]	Kanban (RV) & [O.S]			Basestock (RV) & [O.S]	Total		
Cells			1 2 3	1	2	3	3			
PCS	KAP	Product	10–350(RV)	4 - 150(RV)			10 - 160(RV)	CON-WIP	Kan-ban	Base-stock
HK-CONWIP	D-KAP	1	[119]	[17]	[18]	N/A	[119]	215	98	215
		2	[42]	[15]	[16]	N/A	[42]			
		3	[21]	N/A	[17]	N/A	[21]			
		4	[33]	N/A	[15]	N/A	[33]			
	S-KAP	1	[212]	[19]	[19]	N/A	[118]	212	56	180
		2				N/A	[42]			
		3		N/A	[18]	N/A	[18]			
		4		N/A		N/A	[34]			
GKCS	D-KAP	1	N/A	[7]	[8]	[110]	[110]	N/A	243	204
		2	N/A	[5]	[6]	[42]	[42]			
		3	N/A	N/A	[7]	[21]	[21]			
		4	N/A	N/A	[6]	[31]	[31]			
	S-KAP	1	N/A	[9]	[10]	[109]	[109]	N/A	226	198
		2				[39]	[39]			
		3		N/A	[9]	[20]	[20]			
		4		N/A		[30]	[30]			
EKCS	D-KAP	1	N/A	[7]	[8]	[117]	[107]	N/A	245	195
		2	N/A	[6]	[6]	[43]	[43]			
		3	N/A	N/A	[7]	[18]	[18]			
		4	N/A	N/A	[6]	[27]	[27]			
	S-KAP	1	N/A	[9]	[10]	[112]	[107]	N/A	228	195
		2				[43]	[43]			
		3		N/A	[9]	[18]	[18]			
		4		N/A		[27]	[27]			
BK-CONWIP	D-KAP	1	[121]	[12]	[12]	N/A	[120]	194	54	190
		2	[35]	[8]	[8]	N/A	[34]			
		3	[19]	N/A	[8]	N/A	[18]			
		4	[21]	N/A	[6]	N/A	[20]			
	S-KAP	1	[185]	[15]	[20]	N/A	[95]	185	53	161
		2				N/A	[30]			
		3		N/A	[18]	N/A	[14]			
		4		N/A		N/A	[22]			

[O.S] – Optimal values for the control parameters, (RV) – Range value of search, N/A - Not Applicable, Basestock levels for stages 1 and 2 are zeros

Table 5.8: Case 2 Pareto search space and optimal values of PCS-KAP at 100% service level

Pareto Decision Set at 100% Service Level			CONWIP			Kanban			Basestock	Changeover Factor Setting
PCS	KAP	Product/Cell	1	2	3	1	2	3	3	
HK-CONWIP	D-KAP	1		148		18	15	N/A	148	7
		2		65		17	16	N/A	65	4
		3		29		N/A	12	N/A	29	5
		4		46		N/A	6	N/A	46	3
	S-KAP	1		265		29	29	N/A	146	5
		2						N/A	55	2
		3				N/A	18	N/A	24	2
		4				N/A		N/A	40	5
GKCS	D-KAP	1		N/A		8	12	153	153	6
		2		N/A		6	8	64	64	4
		3		N/A		N/A	8	31	31	5
		4		N/A		N/A	6	41	41	3
	S-KAP	1		N/A		12	15	129	139	7
		2						49	49	3
		3				N/A	10	30	30	5
		4				N/A		40	40	5
EKCS	D-KAP	1		N/A		8	10	127	129	6
		2		N/A		8	6	53	56	4
		3		N/A		N/A	7	28	28	4
		4		N/A		N/A	6	37	37	3
	S-KAP	1		N/A		12	13	127	127	5
		2						53	53	2
		3				N/A	9	28	28	2
		4				N/A		37	37	5
BK-CONWIP	D-KAP	1		139		18	20	N/A	130	6
		2		61		10	10	N/A	40	4
		3		21		N/A	8	N/A	21	5
		4		40		N/A	7	N/A	29	3
	S-KAP	1		225		[19]	[17]	N/A	114	7
		2						N/A	34	3
		3				N/A	[14]	N/A	17	5
		4				N/A		N/A	26	3

[O.S]–Optimal values for the control parameters, (RV)–Range value of search, N/A-Not Applicable, Basestock for cells 1 and 2 are zeros

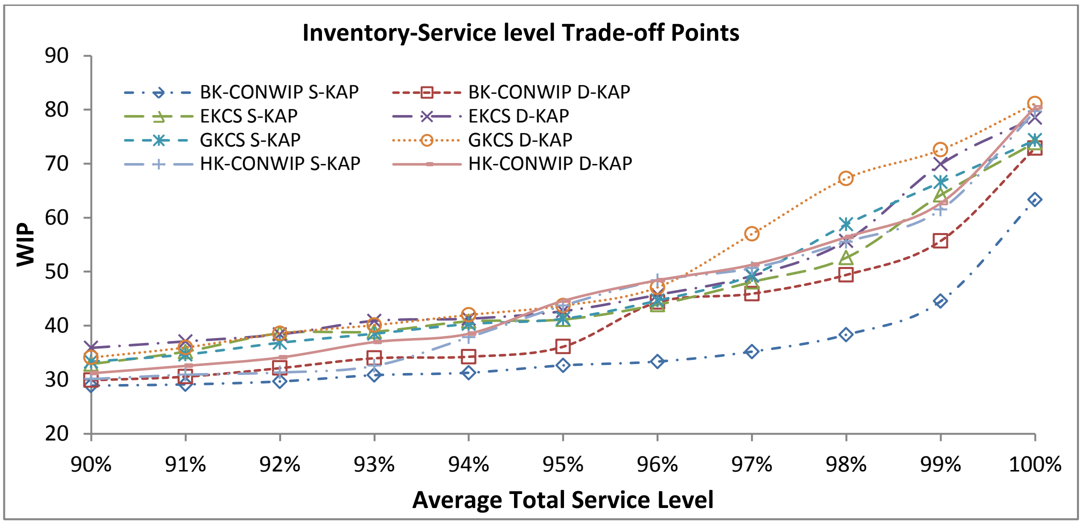


Figure 5.1: Trade-off between service level and inventory (Case 1)

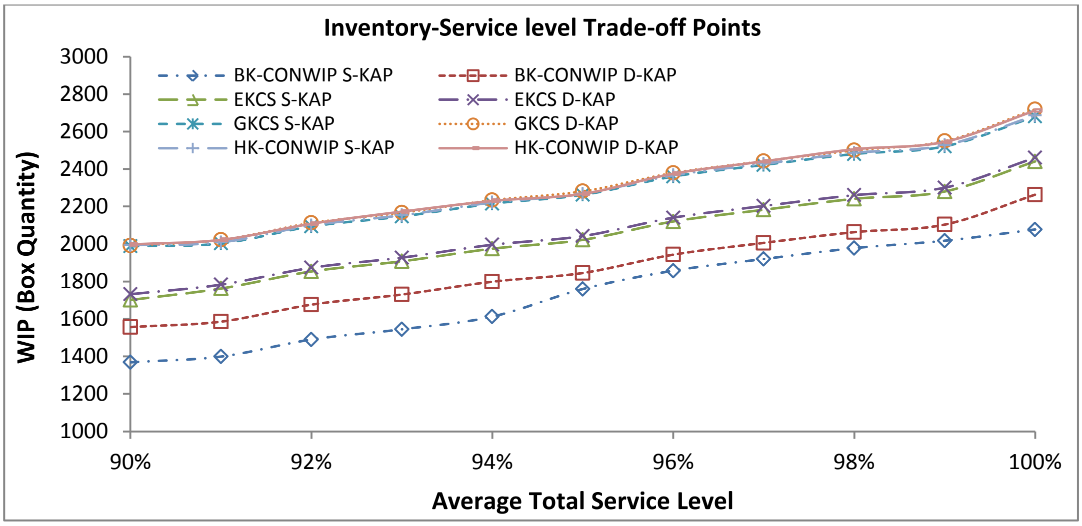


Figure 5.2: Trade-off between service level and inventory (Case 2)

5.4 Simulation Results

Four simulation experiments referred to as experiment 1, experiment 2, experiment 3, and experiment 4 were conducted using the system configuration settings, PCS-KAP optimal settings and demand profile of either Case 1 or Case 2. Table 5.9 provides a brief description of the experiments, while the examined PCS-KAP are presented in Table 5.10.

Table 5.9: Description of experiments

Experiment Number	Title/Purpose	Case studied
1	WIP of PCS-KAP at 100% service level	1
2	Effect of Erratic demand	2
3	Effect of product mix	2
4	Time to recovery after lumpy demand	2

For case 1, a simulation warm-up period of 15,000 hours, a run length of 50,000 hours and 30 simulation replications were used in conducting the experiments, while in case 2, the simulation warm-up period was set to 480 hours (equivalent to four production weeks' period), the run length was set to 1200 hours, and 30 simulation replications were conducted for each run.

Table 5.10: List of PCS-KAP compared

PCS - D-KAP	PCS - S-KAP
GKCS D-KAP	GKCS S-KAP
EKCS D-KAP	EKCS S-KAP
HK-CONWIP D-KAP	HK-CONWIP S-KAP
BK-CONWIP D-KAP	BK-CONWIP S-KAP

5.4.1 Observations from Experiment 1 Case 1

Experiment 1 Case 1 is a comparison of the PCS-KAP in a simple theoretical manufacturing system. A set of eight experiments was conducted. The models were configured to operate with stochastic demand, stochastic failure rates, negligible set-up times and deterministic service time. The system configuration and demand profile used in Experiment 1 Case 1 is provided in Table 5.2, while the control parameter settings for each PCS-KAP are the optimal values provided in Table 5.6.

The inventories at each machine and the output buffers were considered for computing the total average work-in-process inventory in the system. The aim is to examine the proportion WIP at targeted 100% service level when a multi-product flow line with the linear demand profile is controlled by the pull strategies under investigation. The average total WIP inventory in the system for each PCS-KAP is plotted in Figure 5.3.

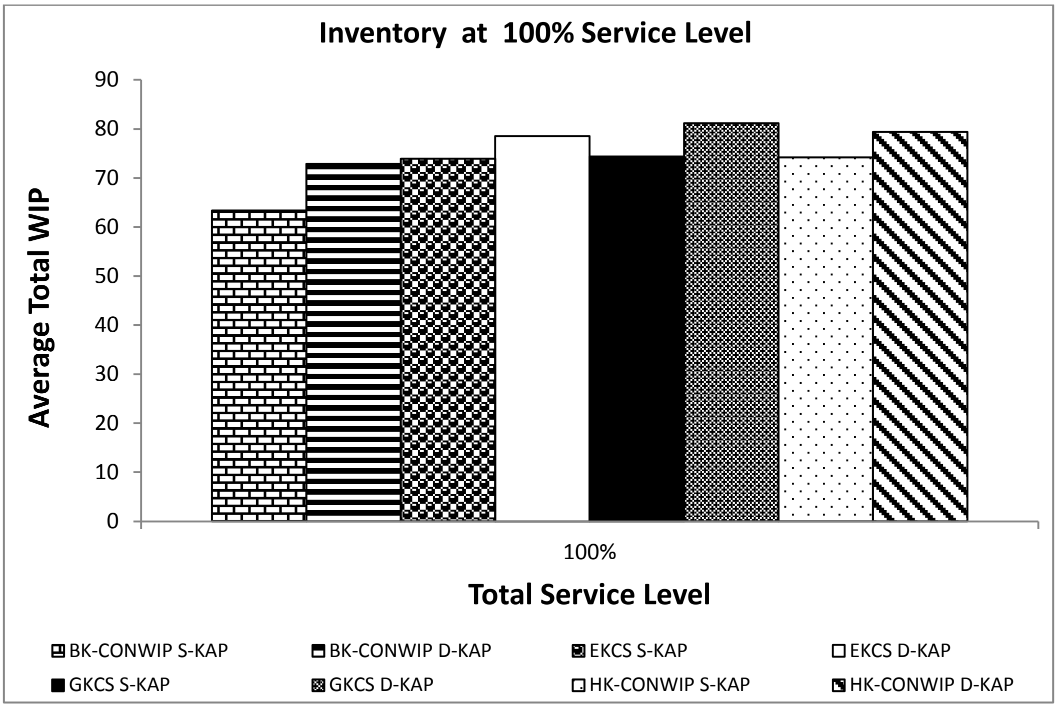


Figure 5.3: Experiment 1 Case 1 WIP level of PCS-KAP at 100% service level

Figure 5.3 shows that all PCS-KAP examined achieved different proportions of WIP inventory at 100% service level. Direct observation shows that BK-CONWIP S-KAP had the lowest WIP inventory level in the system, while GKCS D-KAP has the most WIP inventory level in the system. Taking decision on the WIP performance of the strategies based on a direct observation is premature and can result in inaccuracies. To select the PCS-KAP with the best performance in terms of WIP control, a statistical ranking and selection technique is presented in the following section.

5.4.2 Selection of Superior PCS-KAP from Experiment 1 Case 1 Results

The inventory result was screened to select a superior strategy using Nelson's screening and selection procedure. The performance metric for screening and comparisons is the average total WIP inventory level in the system. The parameters of the Nelson's ranking and selection technique used in Experiment 1 Case 1 are presented in Table 5.11.

Table 5.11: Experiment 1 Case 1 Parameters for Nelson's combined procedure

Parameter	n_0	k	α	$\alpha_0 = \alpha_1$	ε	h	t
Value	30	8	0.1	0.05	0.2	4.253	2.886

The result of the application of Nelson's combined procedure for the WIP inventory of the PCS-KAP is presented in Table 5.12. The table shows that BK-CONWIP S-KAP was selected (Keep) as a superior PCS-KAP over its alternatives. BK-CONWIP is superior to EKCS, GKCS and HK-CONWIP.

The outcome of the application of Nelson's combined procedure confirms the observation that BK-CONWIP S-KAP outperformed its alternatives. The ranking of the performance of all the PCS-KAP from 1 to 8, where 1 represents PCS-KAP with the lowest (superior PCS-KAP) average total WIP inventory in the system and 8 represents the PCS-KAP with the most (worst PCS-KAP) average total WIP inventory in the system is shown in Table 5.13.

From Figure 5.3, Tables 5.12 and 5.13, it was shown that PCS in combination with S-KAP, in general, performed better than PCS in combination with D-KAP, while BK-CONWIP performed better than EKCS, GKCS and HK-CONWIP.

Table 5.12: Experiment 1 Case 1 application of Nelson’s combined procedure for selection of the best PCS-KAP

PCS-KAP	i	n_0	$\bar{Y}_i$	S_i^2	j	W_{ij}	$\bar{Y}_i + \max(0, W_{ij} - \varepsilon)$	**Keep?**	N_i
D-KAP HK-CONWIP	1	30	79.42	0.62	2	0.677	79.680	eliminate	387
					3	0.719	81.140		
					4	0.700	74.350		
					5	0.675	78.530		
					6	0.668	73.900		
					7	0.615	72.860		
					8	0.552	63.340		
S-KAP HK-CONWIP	2	30	74.18	1.33	1	0.677	80.420	eliminate	305
					3	0.826	81.140		
					4	0.809	74.350		
					5	0.787	78.530		
					6	0.782	73.900		
					7	0.737	72.860		
					8	0.685	63.340		
D-KAP GKCS	3	30	81.14	1.58	1	0.719	80.420	eliminate	327
					2	0.826	79.680		
					4	0.845	74.350		
					5	0.824	78.530		
					6	0.819	73.900		
					7	0.776	72.860		
					8	0.727	63.340		
S-KAP GKCS	4	30	74.35	1.46	1	0.700	80.420	eliminate	313
					2	0.809	79.680		
					3	0.845	81.140		
					5	0.807	78.530		
					6	0.802	73.900		
					7	0.758	72.860		
					8	0.708	63.340		
D-KAP EKCS	5	30	78.53	1.31	1	0.675	80.420	eliminate	300
					2	0.787	79.680		
					3	0.824	81.140		
					4	0.807	74.350		
					6	0.780	73.900		
					7	0.735	72.860		
					8	0.683	63.340		
S-KAP EKCS	6	30	73.90	1.28	1	0.668	80.420	eliminate	269
					2	0.782	79.680		
					3	0.819	81.140		
					4	0.802	74.350		
					5	0.780	78.530		
					7	0.729	72.860		
					8	0.677	63.340		
D-KAP BK-CONWIP	7	30	72.86	0.98	1	0.615	80.420	eliminate	250
					2	0.737	79.680		
					3	0.776	81.140		
					4	0.758	74.350		
					5	0.735	78.530		
					6	0.729	73.900		
					8	0.624	63.340		
S-KAP BK-CONWIP	8	30	63.34	0.67	1	0.552	80.420	keep	241
					2	0.685	79.680		
					3	0.727	81.140		
					4	0.708	74.350		
					5	0.683	78.530		
					6	0.677	73.900		
					7	0.624	72.860		

Table 5.13: Experiment 1 Case 1 PCS-KAP WIP performance ranking at 100% service level

	Ranking of PCS-KAP WIP							
PCS-KAP	**BK-CONWIP S-KAP**	**BK-CONWIP D-KAP**	**EKCS S-KAP**	**HK-CONWIP S-KAP**	**GKCS S-KAP**	**EKCS D-KAP**	**HK-CONWIP D-KAP**	**GKCS D-KAP**
Ranking	1	2	3	4	5	6	7	8

5.4.3 Observations from Experiment 2 Case 2

Experiment 2 Case 2 investigates the effect of erratic demand on the performance of the PCS-KAP in a complex four product manufacturing system under deterministic service times and stochastic failure. The aim is to explore the effect of changing demands in multi-product systems across products and the response of the PCS-KAP. The average total backlog (TBL), the average total service level (TSL) of the four products, and the average total WIP inventory (TWIP) in the system are the performance metrics of interest. The demand profile used here is provided in Table 5.1, while the PCS-KAP control parameters are provided in Table 5.8. The system configurations are shown in Table 5.3. The product selection strategy employed on stage 3 was augmented to consider a set-up avoidance policy, such that, in addition to priority rules, stage 3 will also consider a minimum batch quantity production rule before a changeover, subject to availability of the current part-type.

The Pareto optimisation block was used to search for optimal solutions for the minimum run/batch quantities for each product type in each PCS-KAP (see, Table 5.8 for changeover factor optimal settings). The models were configured using the optimal settings obtained via deterministic demand dataset A and kept constant in the system while studying the behaviour of the system under changing weekly demand profiles (demand datasets B to F). TBL, TWIP and TSL of each PCS-KAP are plotted in Figure 5.4.

Observations from the results show that all PCS-KAP maintained approximately 100% service levels (and zero backlogs) for four of the demand profiles examined (demand dataset A, B, C and D). The volume of demand dataset E varies with 20% increase to the volume of demand dataset A. None of the PCS-KAP achieved 100% service level in demand dataset E. In demand dataset F, which is similar to the volume of demand dataset A, BK-CONWIP (S-KAP and D-KAP) and EKCS S-KAP achieved service level above 99%. BK-CONWIP S-KAP achieved the highest service level in demand datasets E and F, while GKCS D-KAP had the lowest service level.

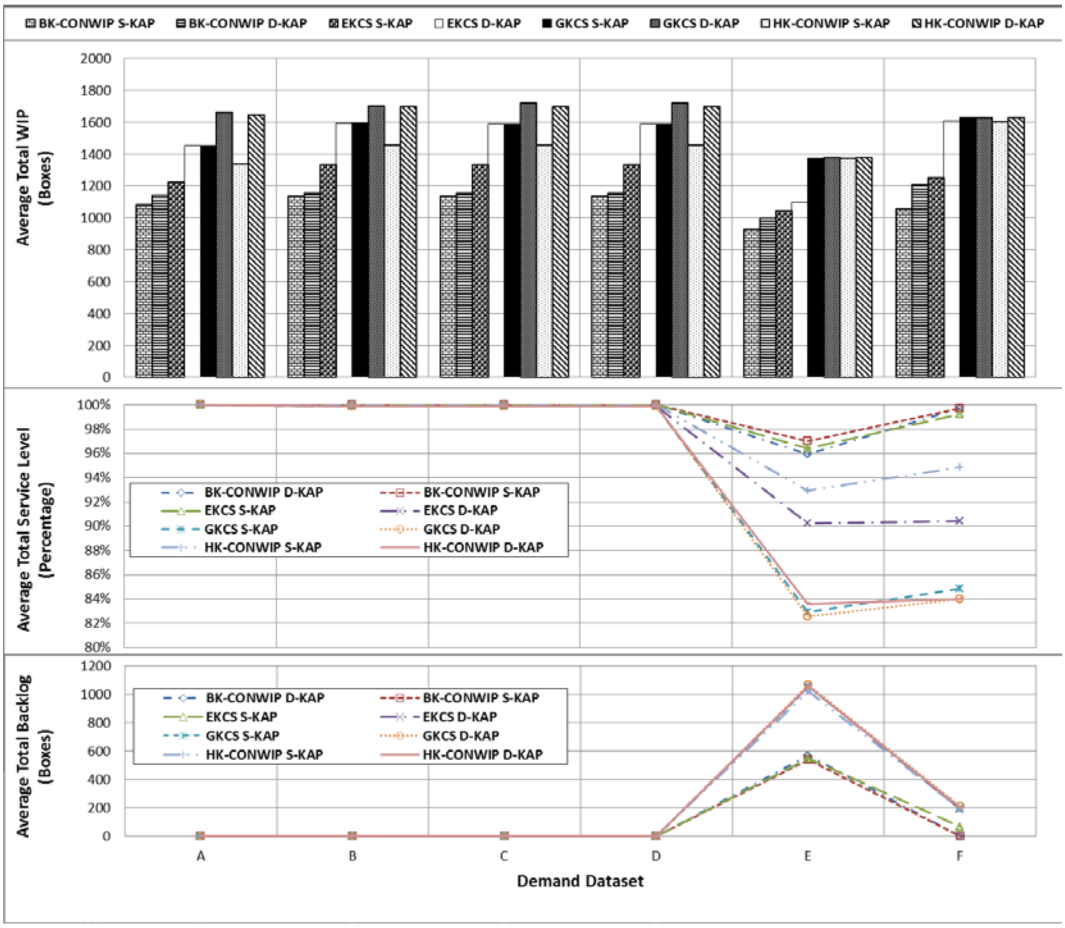


Figure 5.4: Experiment 2 Case 2 Results of TWIP, TSL and TBL of PCS-KAP

In terms of the WIP and backlog performances of the PCS-KAP, BK-CONWIP S-KAP maintained the lowest proportion of WIP and backlogs in the system, while GKCS D-KAP maintained the highest proportion of WIP. PCS in combination with S-KAP is observed to have better WIP control than PCS in combination with D-KAP, while BK-CONWIP has better WIP control than its alternatives. To confirm the observation, Nelson's combined procedure was applied to the results.

5.4.4 Selection of Superior PCS-KAP from Experiment 2 Case 2 Results

Nelson's combined procedure was applied to the average total WIP inventory, total service level and average total backlog to select the superior PCS-KAP. The control parameters of the Nelson's combined procedure used are shown in Table 5.14.

Table 5.14: Experiment 2 Case 2 Parameters for Nelson's combined procedure

Parameter	n_0	k	α	$\alpha_0 = \alpha_1$	ε	h	t
Value	30	8	0.1	0.05	30	4.253	2.886

The summary of the outcome of the application of Nelson's combined procedure for the WIP inventory for demand dataset A to F is provided in Table 5.15, while the results are provided in Appendix C.

Table 5.15: Experiment 2 Case 2 Summary of application of Nelson's combined procedure on the three performance metrics

Data-set	Perfor-mance Metrics	S-KAP BK-CONWIP	D-KAP BK-CONWIP	S-KAP EKCS	D-KAP EKCS	S-KAP GKCS	D-KAP GKCS	S-KAP HK-CONWIP	D-KAP HK-CONWIP
A	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Keep	Keep	Keep	Keep	Keep	Keep
	TSL	Keep	Keep	Keep	Keep	Keep	Keep	Keep	Keep
B	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Keep	Keep	Eliminate	Eliminate	Keep	Eliminate
	TSL	Keep	Keep	Keep	Keep	Eliminate	Eliminate	Keep	Eliminate
C	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
D	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
E	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
F	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate

Table 5.15 shows that the BK-CONWIP S-KAP is the best PCS-KAP among the PCS-KAP compared. Figure 5.4 shows that BK-CONWIP S-KAP maintained the highest service level, the lowest backlogs and the lowest WIP inventory level, while GKCS D-KAP has the lowest service level, the largest backlogs and WIP level in the system. PCS in combination with S-KAP performed better than PCS in combination with D-KAP, while BK-CONWIP outperformed its alternatives. EKCS outperformed HK-CONWIP and GKCS, while HK-CONWIP outperformed GKCS.

The ranking of the performance of all the PCS-KAP from 1 to 8, where 1 represents PCS-KAP with the lowest (superior PCS-KAP) TWIP, TBL and the highest TSL in the system and 8 represents the PCS-KAP with the most (worst PCS-KAP) average total WIP inventory in the system is shown in Table 5.16.

Table 5.16: Experiment 2 Case 2 PCS-KAP TWIP, TBL and TSL ranking

	Ranking of PCS-KAP WIP, service level and backlogs							
PCS-KAP	**BK-CONWIP S-KAP**	**BK-CONWIP D-KAP**	**EKCS S-KAP**	**HK-CONWIP S-KAP**	**GKCS S-KAP**	**EKCS D-KAP**	**HK-CONWIP D-KAP**	**GKCS D-KAP**
Ranking	1	2	3	4	5	6	7	8

5.4.5 Observations from Experiment 3 Case 2

Experiment 3 Case 2 studies the effect of product mix using a multi-product manufacturing system with a constant total demand volume, a deterministic service time, a stochastic failure and setups. The aim is to explore the effect of changing product mixes in a multi-product system across product families and within products as well as the response of the PCS-KAP. The system configuration used here is described in Table 5.3, while the control parameters of each PCS-KAP are shown in Table 5.8. The optimal settings were kept constant in the system while studying the behaviour of the system under changing product mixes. The demand profiles used are provided in Tables 5.17, 5.18 and 5.19 for tests 1, 2 and 3 respectively. The volume of the demand data set G is the same as the volume of the demand dataset A (Table 5.1). The volume of the demand dataset G was kept constant while the product mix was varied in order to derive demand dataset H, I and J. Each of the demand datasets G to J has six production weeks (week 1 to week 6).

Table 5.17: Experiment 3 Case 2 Test 1 product mixes and total demand volume

Product Mix Demand Dataset	Product	Production Week					
		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
G	P1	546	448	402	500	246	484
	P2	128	230	141	120	130	110
	P3	128	180	132	162	124	149
	P4	110	140	149	69	62	40
Total Demand Volume	Boxes	912	998	824	851	562	783
H	P1	572	498	435	526	280	507
	P2	101	170	108	94	96	87
	P3	156	220	165	179	141	157
	P4	83	110	116	52	45	32
Total Demand Volume	Boxes	912	998	824	851	562	783
I	P1	610	558	468	560	308	539
	P2	64	120	75	60	68	55
	P3	183	250	206	196	152	165
	P4	55	70	75	35	34	24
Total Demand Volume	Boxes	912	998	824	851	562	783
J	P1	127	229	140	119	129	109
	P2	547	449	403	501	247	485
	P3	110	140	149	69	62	40
	P4	128	180	132	162	124	149
Total Demand Volume	Boxes	912	998	824	851	562	783

Table 5.18: Experiment 3 Case 2 Test 2 Product mixes and total demand volume

Product Mix Demand Dataset	Product	Production Week					
		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
G	P1	473	360	330	430	200	418
	P2	92	210	124	103	119	94
	P3	201	248	188	216	159	200
	P4	146	180	182	102	84	71
Total Demand Volume	Boxes	912	998	824	851	562	783
H	P1	491	419	361	450	229	445
	P2	73	150	91	77	85	71
	P3	238	289	231	247	186	220
	P4	110	140	141	77	62	47
Total Demand Volume	Boxes	912	998	824	851	562	783
I	P1	519	470	397	485	258	469
	P2	46	110	66	52	62	47
	P3	274	328	270	262	202	235
	P4	73	90	91	52	40	32
Total Demand Volume	Boxes	912	998	824	851	562	783
J	P1	91	209	123	102	118	93
	P2	474	361	330	430	198	419
	P3	146	180	182	103	85	71
	P4	201	248	189	216	161	200
Total Demand Volume	Boxes	912	998	824	851	562	783

Table 5.19: Experiment 3 Case 2 Test 3 Product mixes and total demand volume

Product Mix Demand Dataset	Product	Production Week					
		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
G	P1	619	519	460	560	285	547
	P2	128	250	157	137	141	126
	P3	110	149	108	136	107	94
	P4	55	80	99	18	29	16
Total Demand Volume	Boxes	912	998	824	851	562	783
H	P1	646	588	501	602	324	571
	P2	92	180	116	103	102	94
	P3	128	170	132	137	113	102
	P4	46	60	75	9	23	16
Total Demand Volume	Boxes	912	998	824	851	562	783
I	P1	683	648	542	636	359	610
	P2	64	130	83	69	74	63
	P3	137	180	149	137	117	102
	P4	28	40	50	9	12	8
Total Demand Volume	Boxes	912	998	824	851	562	783
J	P1	127	249	156	136	140	125
	P2	620	519	461	560	286	548
	P3	55	80	99	18	29	16
	P4	110	150	108	137	107	94
Total Demand Volume	Boxes	912	998	824	851	562	783

The demand occurs weekly with constant total product demand volume and irregular product mixes pattern. Three sets of experiments were conducted based on varying product mixes across families. In the first set of simulation test (test 1), the product mixes across the two families are set to 70% of the overall product demand volume for family A and 30% for family B. The product mixes across the two families in test 2 are set to 60% of the total product demand volume for family A and 40% for family B, while in test 3, the product mix across the two families are set to 80% of the total product demand volume for family A and 20% for family B.

In addition, the product mix within families varies with a shift in product 1 giving rise to a shift in product 2 and a shift in product 3 giving rise to a shift in product 4, while maintaining the overall product mix across the families. The average total backlog, average total service level of the four products, and average total end of the production week inventory in the system for each PCS-KAP were plotted in Figure 5.5, for Test 1, while graphs for Tests 2 and 3 are provided in Figures 5.6 and 5.7. The responses from the tests were screened to select a superior strategy using the Nelson's screening and selection procedure.

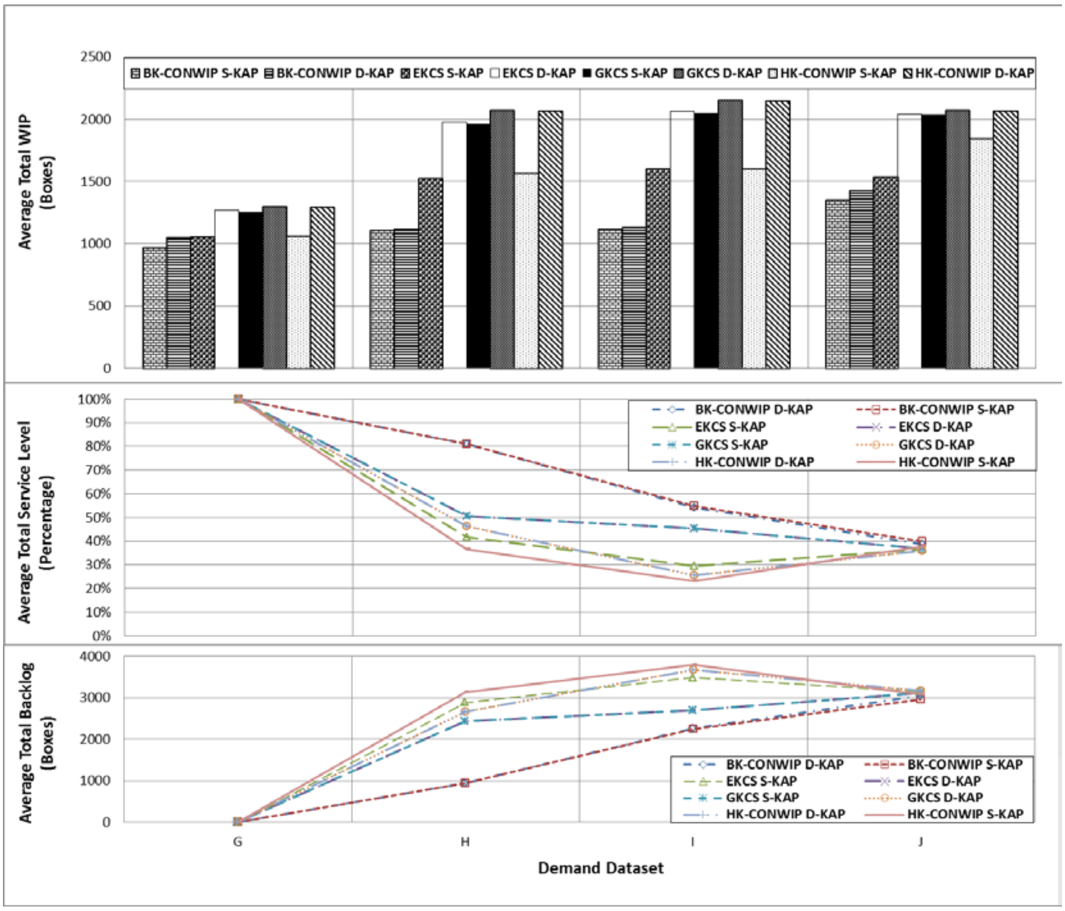


Figure 5.5: Experiment 3 Case 2 Test 1 results of TWIP, TSL and TBL of PCS-KAP

Figure 5.5 (Test 1: 70-30 % product mix across family A and B) shows that in the demand dataset G, all PCS-KAP examined achieved 100% service level and zero backlogs at different proportions of WIP inventory. BK-CONWIP S-KAP has the lowest WIP inventory level in the system, while GKCS D-KAP has the largest WIP inventory level in the system. PCS in combination with S-KAP performed better than PCS in combination with D-KAP. BK-CONWIP performed better than EKCS, HK-CONWIP and GKCS. In demand datasets H, I and J, similar observations were made showing that S-KAP outperform D-KAP and BK-CONWIP outperform its alternatives. Direct observations from tests 2 and 3 (see, Figures 5.6 and 5.7) show the same results to that of test 1. In Test 2 with 60-40 % product mix across family A and B (see, Figure 5.8), none of the PCS-KAP achieved 100% service level and zero backlogs. BK-CONWIP in both D-KAP and S-KAP modes maintain the maximum service levels and smallest backlogs in all the demand datasets, while BK-CONWIP S-KAP outperformed the alternatives with the lowest WIP inventory.

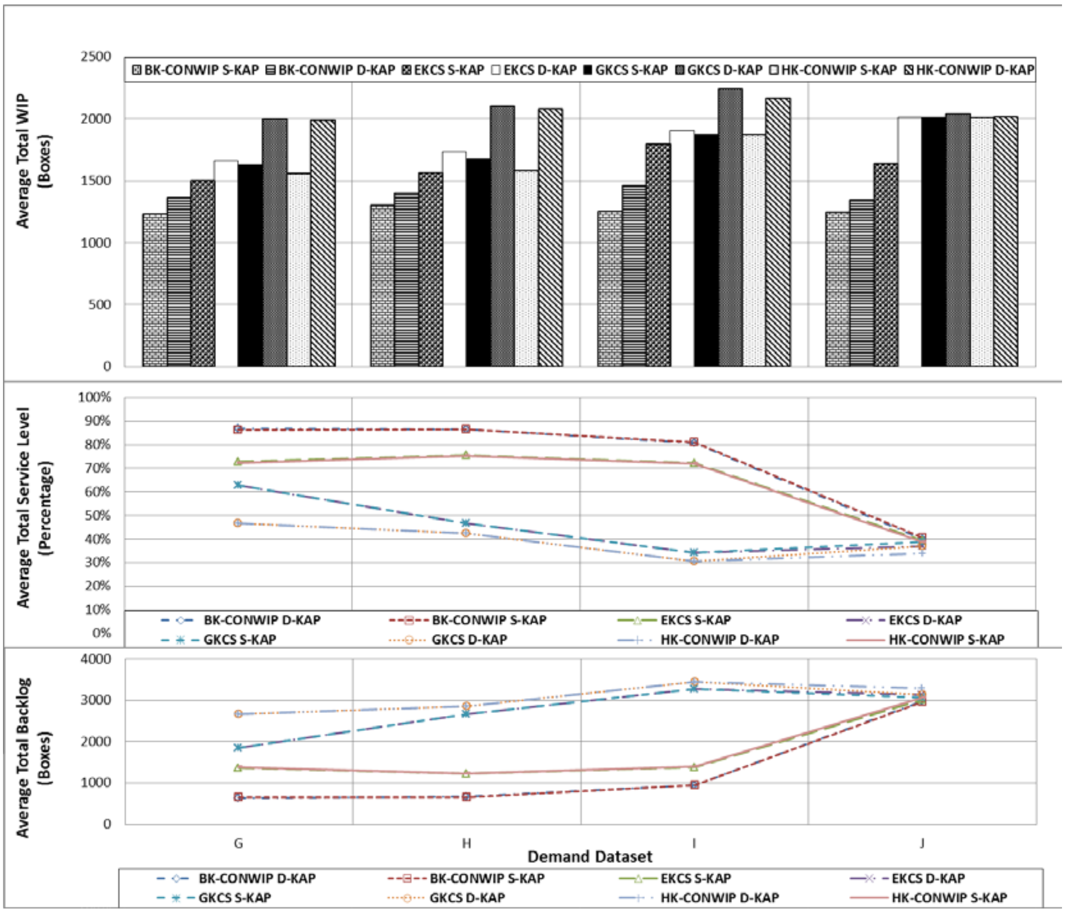


Figure 5.6: Experiment 3 Case 2 Test 2 results of TWIP, TSL and TBL of PCS-KAP

BK-CONWIP (S-KAP and D-KAP mode) is the strategy that achieved service level greater than 80% (see, Figure 5.6) in the demand dataset G, H and I. The service level performance of all the PCS-KAP in the demand dataset J ranges from 40% to 34%. PCS in combination with S-KAP outperformed PCS in combination with D-KAP. BK-CONWIP is the best performer, followed by EKCS, then HK-CONWIP while GKCS, is the worst performer. Similarly, in Test 3 with 80-20 % product mix across family A and B (see, Figure 5.7), it was observed that only BK-

CONWIP (D-KAP and S-KAP) achieved 100% total service level in the demand dataset G and maintained a higher total service level in demand datasets H, I and J over EKCS (D-KAP and S-KAP), HK-CONWIP (D-KAP and S-KAP) and GKCS (D-KAP and S-KAP).

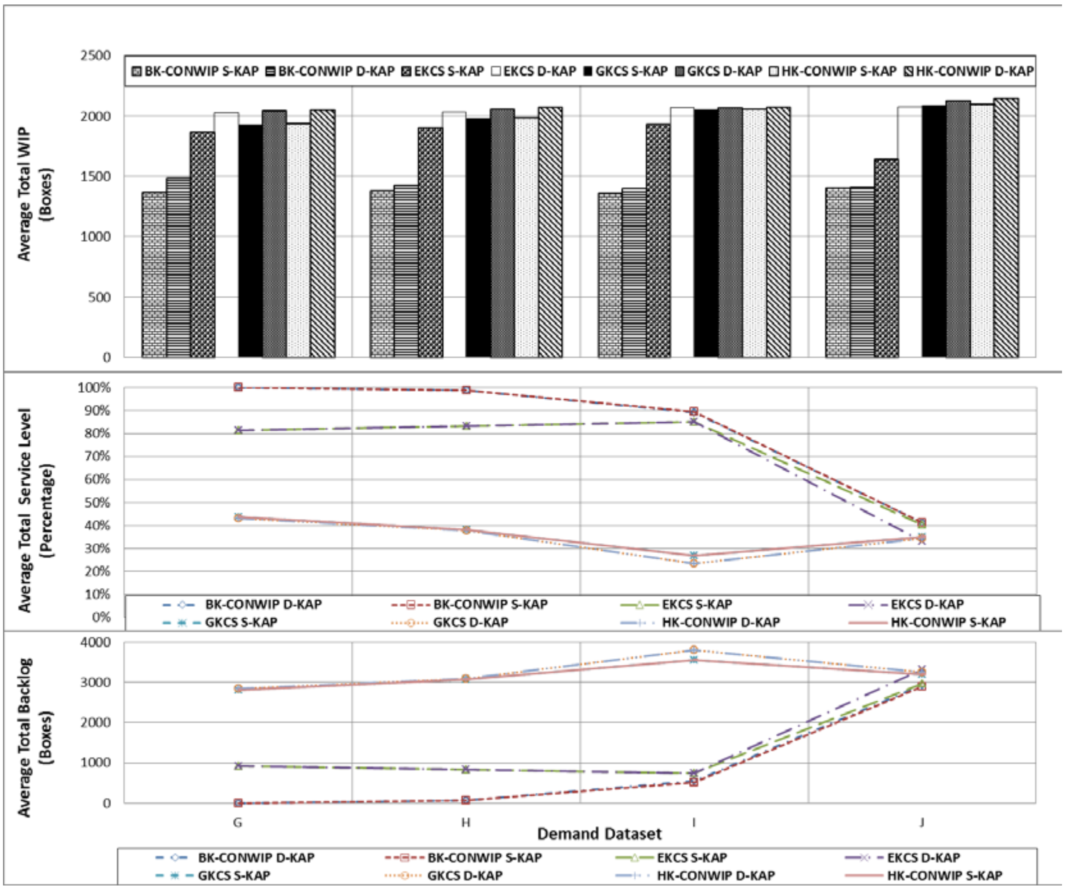


Figure 5.7: Experiment 3 Case 2 Test 3 results of TWIP, TSL and TBL of PCS-KAP

BK-CONWIP S-KAP maintained the lowest WIP inventory. BK-CONWIP outperformed EKCS while EKCS outperformed HK-CONWIP. GKCS is the worst performer. It was observed that product mixes influence the performances of the PCS-KAP.

5.4.6 Selection of Superior PCS-KAP from Experiment 3 Case 2 Results

The control parameters of the Nelson’s combined procedure used are shown in Table 5.20, while the summary of the application of Nelson’s combined procedure of the performance metrics (TWIP, TSL and TBL) to select the superior PCS-KAP for test 1 is presented in Table 5.21. Tests 2 and 3 had the same outcome and Table 5.22 represents the two tests.

Table 5.20: Parameters for Nelson's combined procedure

Parameter	n_0	k	α	$\alpha_0 = \alpha_1$	ε	h	t
Value	30	8	0.1	0.05	30	4.253	2.886

Table 5.21: Experiment 3 Case 2 Test 1-summary of application of Nelson's combined procedure on the three performance metrics

Data -set	Perfor-mance Metrics	BK-CONWIP S-KAP	BK-CONWIP D-KAP	EKCS S-KAP	EKCS D-KAP	GKCS S-KAP	GKCS D-KAP	HK-CONWIP S-KAP	HK-CONWIP D-KAP
G	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Keep	Keep	Keep	Keep	Keep	Keep
	TSL	Keep	Keep	Keep	Keep	Keep	Keep	Keep	Keep
H	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
I	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
J	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate

Table 5.22: Experiment 3 Case 2 Tests 2 and 3 -summary of application of Nelson's combined procedure on the three performance metrics

Data -set	Perfor-mance Metrics	BK-CONWIP S-KAP	BK-CONWIP D-KAP	EKCS S-KAP	EKCS D-KAP	GKCS S-KAP	GKCS D-KAP	HK-CONWIP S-KAP	HK-CONWIP D-KAP
G	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
H	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
I	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
J	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate

The outcome of the application of Nelson's combined procedure on TWIP, TSL and TBL shows that of HK-CONWIP, GKCS and EKCS in both D-KAP and S-KAP modes were eliminated ten of the twelve scenarios of Test 1. HK-CONWIP, GKCS and EKCS in both D-KAP and S-KAP modes were all eliminated in all the 24 scenarios of test 2 and test 3. They were listed as "Keep" in TSL and TBL of the demand dataset G of test 1, which is the base demand dataset used to optimise all the systems for targeted 100% service levels and zero backlogs at minimum WIP inventory. HK-CONWIP, GKCS and EKCS were eliminated for TWIP of demand dataset G. BK-CONWIP D-KAP was eliminated four times of the twelve scenarios in test 1 and was eliminated eight times of the twenty-four scenarios of tests 2 and 3. It was listed as "Keep" in all the TSL and TBL scenarios of tests 1, 2 and 3. BK-CONWIP S-KAP was selected as "Keep" in all the thirty-six scenarios of tests 1, 2 and 3 and was shown to be the only survivor of the six PCS-KAP examined for

TWIP. The performance ranking (1 to 8; where 1 is the best) of the PCS-KAP in terms of TWIP, TSL and TBL (see, Figures 5.5, 5.6, 5.7, Tables 5.21 and 5.22) is presented in Table 5.23.

Table 5.23: Experiment 3 Case 2 PCS-KAP TWIP, TBL and TSL ranking

	Ranking of PCS-KAP WIP, service level and backlogs							
PCS-KAP	**BK-CONWIP S-KAP**	**BK-CONWIP D-KAP**	**EKCS S-KAP**	**HK-CONWIP S-KAP**	**GKCS S-KAP**	**EKCS D-KAP**	**HK-CONWIP D-KAP**	**GKCS D-KAP**
Ranking	1	2	3	4	5	6	7	8

Table 5.23 shows that BK-CONWIP S-KAP was selected as the best PCS-KAP when minimum WIP inventory has higher priority for selection of a strategy and policy under varying product mixes. Furthermore, when TSL and TBL are considered as the performance metrics for the selection of PCS-KAP in a multi-product system under varying product mixes, it is evident that BK-CONWIP (both D-KAP and S-KAP) will outperform the alternatives. BK-CONWIP has a higher flexibility in responding to varying product mixes in a system under constant total product demand volume, while BK-CONWIP in combination with S-KAP respond to variation with lower WIP than BK-CONWIP D-KAP.

5.4.7 Observations from Experiment 4 Case 2

Experiment 4 Case 2 investigates the PCS-KAP recovery period after a lumpy demand in a multi-product manufacturing system under stochastic setups, intermittent deterministic demand and deterministic service time with stochastic failure. The aim is to investigate the length of time that individual PCS-KAP take in recovering after a lumpy demand. The system configuration for experiment 4 is provided in Table 5.3, while the control parameter settings for each PCS-KAP are the optimal values as shown in Table 5.8. Two demand datasets (K and L) used here are provided in Table 5.24. The system configuration and the PCS-KAP control settings were kept constant while examining PCS-KAP behaviour when a lumpy demand (first week of demand dataset L) occurs in a system. TWIP, TBL and TSL of each PCS-KAP in the system were plotted in Figure 5.8, while the weekly cumulative backlogs was plotted and shown in Figures 5.9, 5.10 and 5.11 for end of week 1, week 5 and week 6 (see, Appendix D for weeks 2, 3 and 4 results), to describe the position of backlogs in the system.

Table 5.24: Experiment 4 Case 2 Demand profile

Demand Dataset	Product	Production Week					
		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
K	P1	542	452	404	503	247	483
	P2	130	224	142	118	129	114
	P3	130	184	131	159	125	147
	P4	110	138	147	71	61	39
Total Demand Volume	Boxes	912	998	824	851	562	783
L	P1	1133	542	452	404	503	247
	P2	220	130	224	142	118	129
	P3	211	130	184	131	159	125
	P4	154	110	138	147	71	61
Total Demand Volume	Boxes	1718	912	998	824	851	562

Table 5.24, shows a lumpy demand that occurred in week 1 of demand dataset L (at 120 hour time period) of the six-week period. The demand data of week 2 to week 6 of demand dataset B (Table 5.1) are the same as the demand dataset K of week 1 to week 5, which is the demand dataset used to search for the optimal solution settings in each PCS-KAP. Each PCS-KAP is expected to recover after a lumpy demand data in week 1. However, the period taken by individual PCS-KAP to recover is observed and the PCS-KAP with minimum recovery period is considered as the best PCS-KAP. Figure 5.8 shows that BK-CONWIP S-KAP maintains the lowest WIP inventory level, followed by BK-CONWIP D-KAP, next is EKCS S-KAP, then HK-CONWIP S-KAP, next is GKCS S-KAP, then EKCS D-KAP, followed by HK-CONWIP D-KAP, while GKCS D-KAP has the most WIP inventory level in the system. PCS in combination with S-KAP performed better than PCS in combination with D-KAP. BK-CONWIP outperformed all the alternatives. EKCS outperformed HK-CONWIP and GKCS, while HK-CONWIP outperformed GKCS.

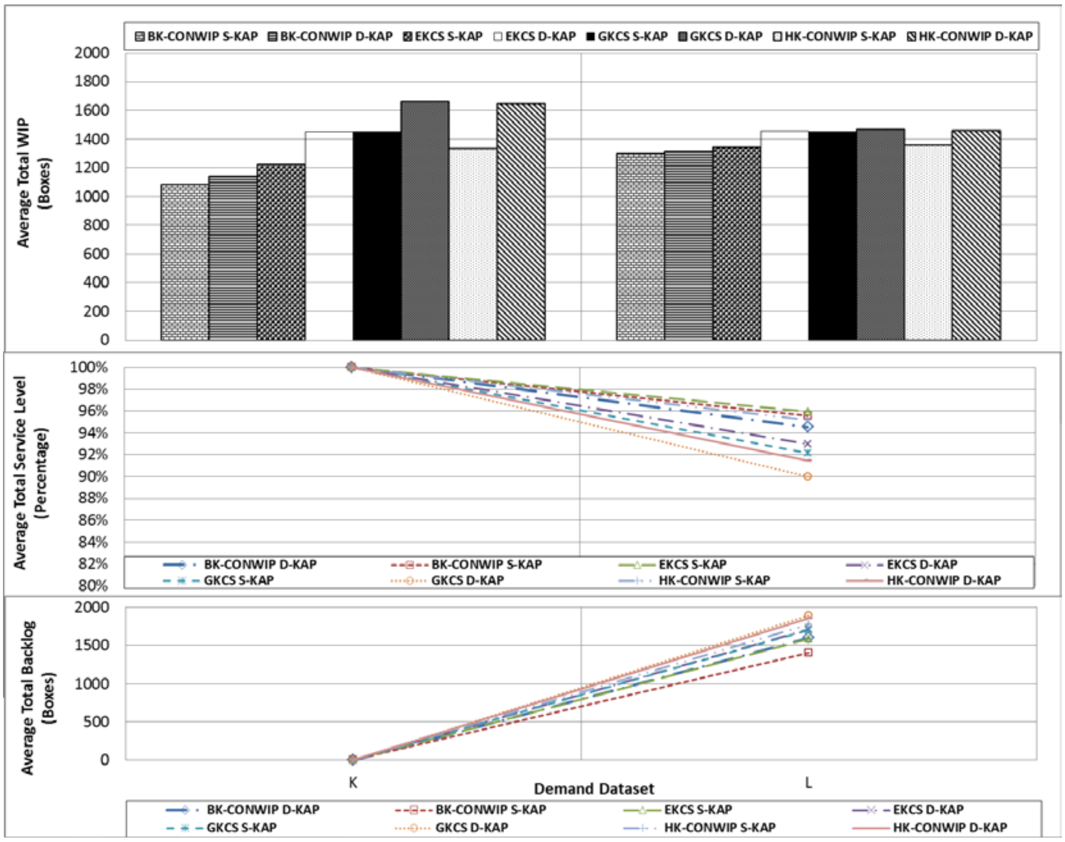
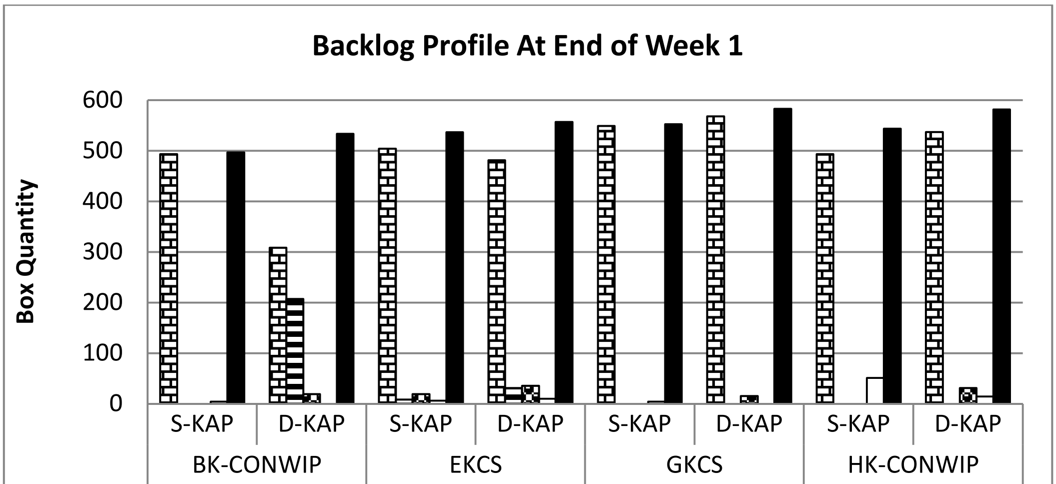
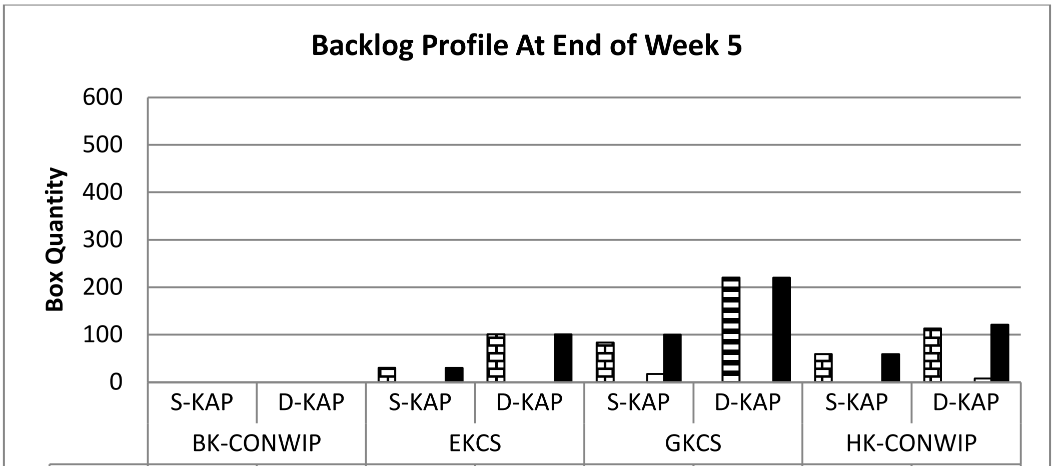


Figure 5.8: Experiment 4 Case 2 Results of TWIP, TSL and TBL of PCS-KAP



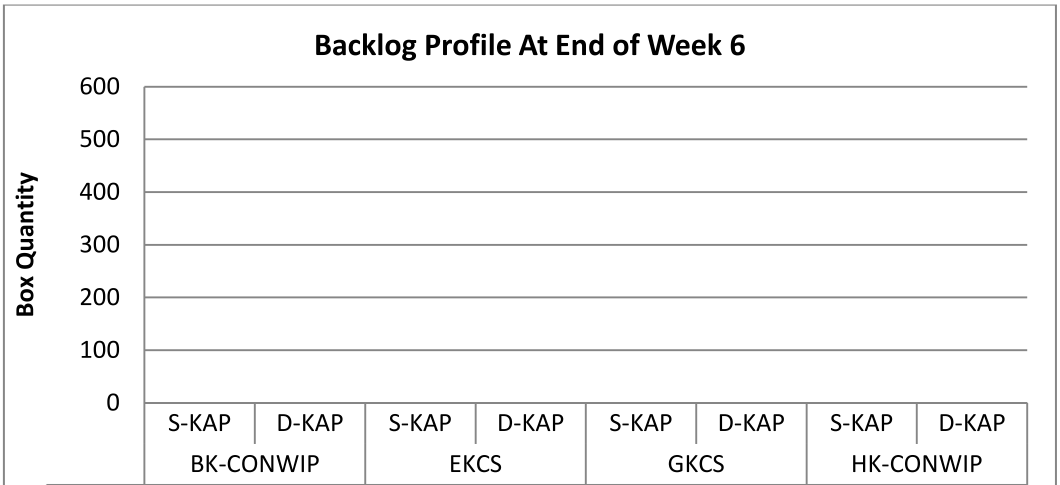
	BK-CONWIP		EKCS		GKCS		HK-CONWIP	
	S-KAP	D-KAP	S-KAP	D-KAP	S-KAP	D-KAP	S-KAP	D-KAP
P1	493	308	504	481	549	568	493	537
P2	0	207	8	31	0	0	0	0
P3	0	19	19	35	0	15	0	31
P4	4	0	6	10	4	0	51	14
Total	497	534	537	557	553	583	544	582

Figure 5.9: Experiment 4 Case 2 End of the week 1 backlog positions



	BK-CONWIP S-KAP	BK-CONWIP D-KAP	EKCS S-KAP	EKCS D-KAP	GKCS S-KAP	GKCS D-KAP	HK-CONWIP S-KAP	HK-CONWIP D-KAP
P1	0	0	30	101	83	0	59	113
P2	0	0	0	0	0	220	0	0
P3	0	0	0	0	0	0	0	0
P4	0	0	0	0	17	0	0	8
Total	0	0	30	101	100	220	59	121

Figure 5.10: Experiment 4 Case 2 End of the week 5 backlog positions



	BK-CONWIP S-KAP	BK-CONWIP D-KAP	EKCS S-KAP	EKCS D-KAP	GKCS S-KAP	GKCS D-KAP	HK-CONWIP S-KAP	HK-CONWIP D-KAP
P1	0	0	0	0	0	0	0	0
P2	0	0	0	0	0	0	0	0
P3	0	0	0	0	0	0	0	0
P4	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0

Figure 5.11: Experiment 4 Case 2 End of the week 6 backlog positions

From the observations drawn from the backlogs position at the end of each week (see, Figure 5.9, Figure 5.10, Figure 5.11 and Appendix D), BK-CONWIP recovered better than its alternatives. The BK-CONWIP in both D-KAP and S-KAP modes recovered in 5 weeks (600 hours) period. While HK-CONWIP, EKCS and GKCS recovered in 6 weeks (720 hours) period. BK-CONWIP S-KAP has the smallest total backlog in weeks 1 to 6, while GKCS D-KAP has the biggest number of backlogs in the system. In week 5, BK-CONWIP in both S-KAP and D-KAP modes achieved total recovery and had zero backlogs, followed by EKCS S-KAP with 30 boxes (backlogs), then HK-CONWIP S-KAP with 59 boxes, next is GKCS S-KAP with 100 boxes (backlogs), followed by EKCS D-KAP with 101 boxes, and HK-CONWIP D-KAP with 121 boxes, while GKCS D-KAP has the biggest number of backlogs (220 boxes) in the system. In week 6, the remaining PCS-KAP recovered and achieved zero backlogs in the system. PCS in combination with S-KAP was observed to outperform PCS in combination with D-KAP in quick recovery, while BK-CONWIP outperformed its alternatives as it recovered earlier than the rest.

5.5 Curvature Analysis

The graphs from the application of the trade-off curves of all PCS-KAP obtained from the Pareto Optimisation Curves of Service Level against Work-In-Process inventory (POCSLWIP) of both Case 1 and Case 2 are provided in Appendix E. However, the graph of the Case 1 BK-CONWIP S-KAP curvature analysis is presented in Figure 5.12 for example. The focus of the curvature analysis is on the service levels, ranging from 90% to 100% because practitioners and decision makers are interested in such higher service level range.

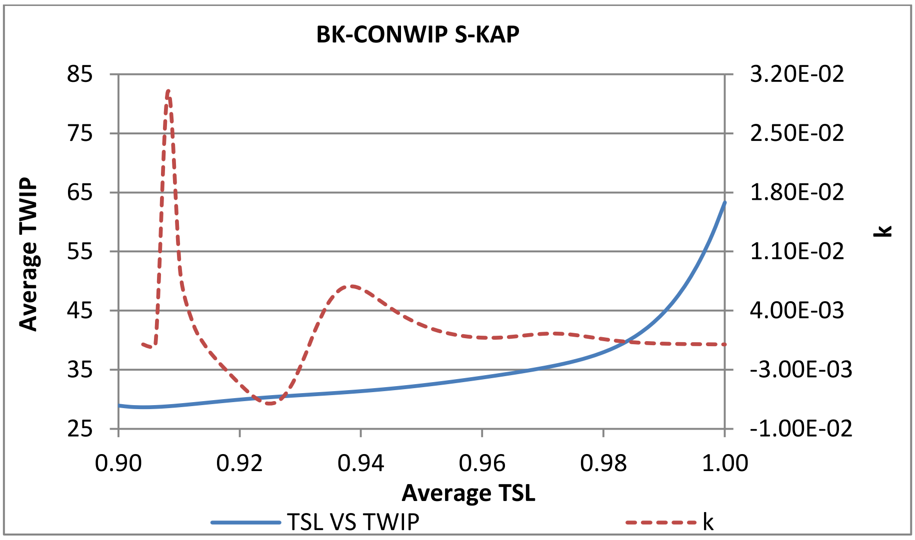


Figure 5.12: Case 1 BK-CONWIP S-KAP curvature analysis plot

The observation of the curvature functions of the PCS-KAP (see, Appendix E) in Case 1 (for the curvature for the average total work-in-process inventory and the average service level) suggests that the decision makers should set the parameters of the PCS-KAP to achieve the following performance metrics as shown in Table 5.25.

Table 5.25: Case 1 Performance metrics achievable at low WIP cost

PCS-KAP	Average TSL (%)	Average TWIP
BK-CONWIP D-KAP	93.7	33.22
BK-CONWIP S-KAP	94.3	31.13
HK-CONWIP D-KAP	92.1	33.87
HK-CONWIP S-KAP	92.7	30.75
EKCS D-KAP	91.2	37.68
EKCS S-KAP	94.8	41.57
GKCS D-KAP	93.4	40.84
GKCS S-KAP	94.2	40.52

Similarly, the parameters of the PCS-KAP for Case 2 should be set to achieve the following performance metrics as shown in Table 5.26.

Table 5.26: Case 2 Performance metrics achievable at low WIP cost

PCS-KAP	Average TSL (%)	Average TWIP
BK-CONWIP D-KAP	98.8	2090.79
BK-CONWIP S-KAP	99.0	2011.12
HK-CONWIP D-KAP	98.6	2523.84
HK-CONWIP S-KAP	99.0	2514.07
EKCS D-KAP	98.6	2299.52
EKCS S-KAP	98.6	2259.03
GKCS D-KAP	98.8	2526.54
GKCS S-KAP	98.6	2519.18

From the above stated inflection points (see Figure 5.12, Appendix E and Tables 5.25 & 5.26) onward, diminishing returns are evident such that the cost of increasing the service level becomes more expensive in terms of the proportion of WIP required to achieve such an increased service level.

The results of the curvature analysis of the Pareto frontier curves clearly show that the S-KAP models in both cases 1 and 2 outperformed the D-KAP models. The BK-CONWIP S-KAP model is superior to the other models because it maintained a lower WIP inventory level throughout the curve. The GKCS D-KAP model maintained the highest WIP inventory, making it the worst system among the eight models in cases 1 and 2. The poor performance of the D-KAP models is largely attributed to a large number of the authorisation cards used in releasing product-types into the system. Releasing a large amount of product-types increases the WIP inventory in a system. Furthermore, when considering the curvature functions of each Pareto frontier are slower in S-KAP models than the D-KAP models. This indicates that there is a much more stable and linear relationship between the two performance metrics, WIP and Service Level of S-KAP models than the D-KAP models, indicating that the WIP level changes slower in S-KAP models than D-KAP models.

5.6 Summary

In this chapter, four pull control strategies (HK-CONWIP, GKCS, EKCS and BK-CONWIP) in D-KAP and S-KAP modes were examined and compared using various manufacturing conditions (linear and non-linear demands, simple and complex systems, demand volume and product mix). In both simple and complex manufacturing flow lines, PCS combined with S-KAP outperformed the same PCS when combined with D-KAP in terms of maximising service level while minimising WIP. Also, PCS that transmits demand information globally to all stages (BK-CONWIP and EKCS) outperformed their alternatives (HK-CONWIP and GKCS). In all the examined cases, BK-CONWIP maintained the best performer in achieving a maximum service level with the lowest WIP inventory in comparison to its alternatives. Similarly, BK-CONWIP S-KAP dominates its alternatives.

The performance of the PCS-KAP varies significantly in various conditions such as when the system is subject to linear demand, non-linear demand, product mix, lumpy demand (failure recovery period). The performance difference is attributed to the WIP control mechanism and the manner in which demand information is transmitted in these pull controlled systems.

The outcomes of these examinations highlights that BK-CONWIP in combination with S-KAP is a promising PCS-KAP with the capability of achieving a high service level with a minimal WIP at various manufacturing conditions such as (product volume and mix variabilities) than its alternatives.

CHAPTER 6: ROBUSTNESS ANALYSIS

6.1 Introduction

Experience with the comparison of the PCS-KAP in multi-product manufacturing systems based on results (see chapter 5) obtained from multi-objective optimisations and simulation studies on theoretical and empirical case studies shows that the S-KAP models outperformed the D-KAP models, while BK-CONWIP outperformed EKCS, GKCS and HK-CONWIP. Nonetheless, changes in demand and system parameters negatively influence the behaviour of these PCS-KAP. According to Kleijnen and Guary [70], optimisation of a strategy for a certain scenario and taking a decision about its performance based on the outcome of the optimal solution of that particular scenario is too risky. A manufacturing system is often subjected to environmental and/or system changes that may include low to high variations in the properties of the distributions of processing times, machine unreliability (MTBF & MTTR) and demand inter-arrival rates. If these changes are not adequately catered for in a production control strategy, it will result in increased production waste, poor product quality and poor service level. Consequently, it is necessary to create a good solution that is robust to these changes rather than an optimal solution that is sensitive to environmental or system changes.

This chapter examines and compares the performance of the pull production control strategies and Kanban allocation policies with consideration to risk using two different multi-product manufacturing systems; Case1- is a theoretical serial manufacturing line with negligible set-up times and moderate demand variation, while Case 2- is an industrial case from the sponsoring company of a complex assembly line with significant set-up times and erratic demand profiles. A detailed description of the experimental conditions, model configurations and optimisation is presented first, followed by the design of experiments, next is results and then comparison.

6.2 Design of Experiment for Simulation Models

To design a responsive manufacturing system, the robustness level of the system's control parameters needs adequate consideration. The robustness analysis method generates practical decision factors via the Latin Hypercube Sampling (LHS) technique. JMP (http://www.jmp.com/uk/index.shtml) from SAS was used to design the experiments in accordance with the Latin hypercube sampling technique. ModelRisk from Vose Software (http://www.vosesoftware.com/) was used to conduct the analysis of the stochastic dominance tests. The factors were varied within the range of $\pm5\%$ of the base values (see, Tables 6.1 to 6.4). The experiments were designed with ten factors in case 1 and with thirty factors in case 2. The factors considered are as follows: In case 1, four demand variability factors and six processing rate variability factors, while in case-2, twenty-four demand variability factors and six processing rate variability factors. Tables 6.1 and 6.2 provide details of the boundary conditions with the base values, the minimum range values and the maximum range values of the ten factors used in the design of the LHS experiment in Case-1, while Tables 6.3 and 6.4 detail the boundary conditions for Case-2. 100 samples were selected from each of the factors within $\pm5\%$ percent range of the base value. In Case-1, the run length of 50,000 hours and 30 replications were applied in carrying out the simulation of the 100 samples and a run length of 10 weeks period and 30 replications were used in Case-2.

Table 6.1: Case-1 boundary conditions for demand variability for design of LHS experiments

Demand (Environmental Variability) Factor	Product 1	Product 2
Mean (Normal Distribution)	5.61 [5.26, 5.96]	5.72 [5.65, 5.79]
Standard Deviation (Normal Distribution)	2.805 [2.52, 3.09]	0.572 [0.29, 0.86]

[R.V] – Range values for the Factors (range from -5% to +5% of base value)

Table 6.2: Case-1 boundary conditions for system variability for design of LHS experiments

Processing (System variability) Factor	Stage 1	Stage 2	Stage 3
Mean Time before Failure (Exponential Distribution)	90 [78.5, 103]	90 [78.5, 103]	90 [78.5, 103]
Mean Time before Failure (Exponential Distribution)	10 [8.72, 11.5]	10 [8.72, 11.5]	10 [8.72, 11.5]

[R.V] – Range values for the Factors (range from -5% to +5% of base value)

Table 6.3: Case-2 boundary conditions for system variability for design of LHS experiments

Factors/ Stages	Stages 1 & 2	Stages 3, 4 & 5
Mean time before Failure (Exponential Distribution)	3.5 [3.05, 4.01]	6.1[5.32, 6.99]
Mean time to repair (Exponential Distribution)	0.23 [0.21, 0.26]	0.23 [0.21, 0.26]
Changeover: Mean (Normal Distribution)	N/A	0.3267 [0.3130, 0.3404]
Changeover: Standard Deviation (Normal Distribution)	N/A	0.1088 [0.0915, 0.1242]

N/A- Not Applicable, [R.V] – Range values for the Factors (range from -5% to +5% of base value)

Table 6.4: Case-2 boundary conditions for demand variability for design of LHS experiments

Product	Range Setting	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
	Base value	115	194	128	143	169	137
1	-5% of Base	109	184	122	136	161	130
	+5% of Base	121	204	134	150	177	144
	Base value	121	158	131	62	61	51
2	-5% of Base	115	150	124	59	58	48
	+5% of Base	127	166	138	65	64	54
	Base value	503	366	413	365	381	480
3	-5% of Base	478	348	392	347	362	456
	+5% of Base	528	384	434	383	400	504
	Base value	147	212	147	108	112	144
4	-5% of Base	140	201	140	103	106	137
	+5% of Base	154	223	154	113	118	151

6.3 Performance Evaluation of the Strategies and Policies

The total service level and the average total work-in-process inventory are the performance metrics used in the comparison of the pull production control strategies and Kanban allocation policies (S-KAP and D-KAP) investigated. An incremental range of 5% was applied in constructing the cumulative distribution function plots of the average total service level and average total work-in-process inventory of the two cases. The comparison of the strategies was conducted for the entire distribution to give consideration to achieving service level because of high or low work-in-process inventory in the system.

6.3.1 Comparison of the PCS-KAP via Total Service Level

The average total service level achieved by PCS-KAP under environmental and systems variability are compared. PCS-KAP with relatively high average total service level are considered as superior to PCS-KAP with low average total service level in any given multi-product systems. Figures 6.1 and 6.2 provide descriptions of the cumulative distribution function of the average total service level in cases 1 and 2 respectively.

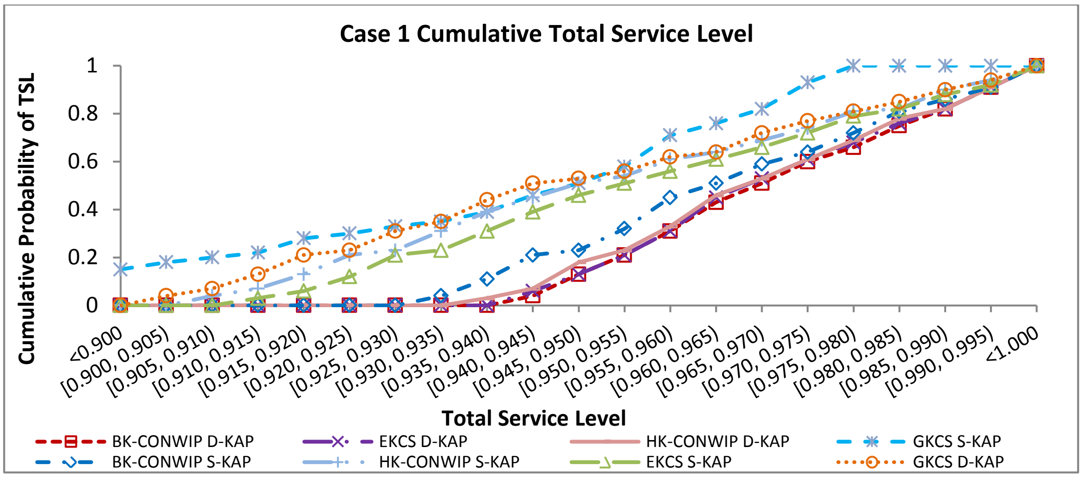


Figure 6.1: Case-1 average total service level cumulative distribution function graph

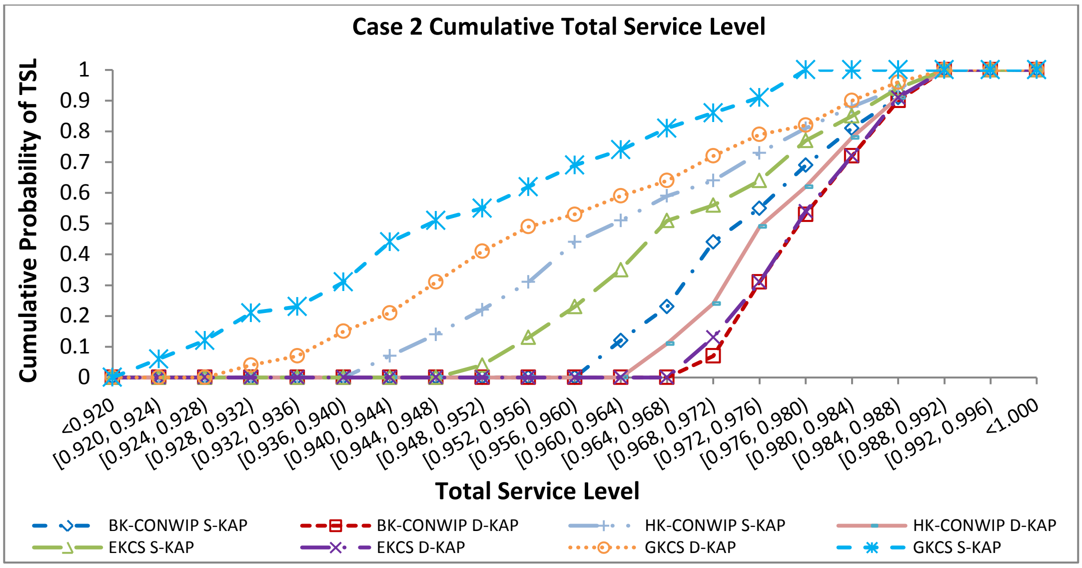


Figure 6.2: Case-2 average total service level cumulative distribution function graph

The result of the total service level cumulative distribution function graph for case-1 (Figure 6.1) shows BK-CONWIP D-KAP with the highest total service level than its alternatives. The lowest average total service level that occurred in BK-CONWIP D-KAP is 94.2 per cent and it was considered as the best performer in comparison to BK-CONWIP S-KAP, EKCS (S-KAP and D-KAP), HK-CONWIP (S-KAP and D-KAP) and GKCS (S-KAP and D-KAP). Table 6.5 shows the lowest, mean and maximum percentage of the total service level achieved by PCS-KAP and their rankings with 1 representing the best performer, and 8 is considered as the worst performer.

Table 6.5: Case-1 statistical description of the simulation result data

PCS-KAP	BK-CONWIP D-KAP	EKCS D-KAP	HK-CONWIP D-KAP	BK-CONWIP S-KAP	EKCS S-KAP	HK-CONWIP S-KAP	GKCS D-KAP	GKCS S-KAP
Minimum	94.2%	94.1%	93.9%	93.2%	91.4%	90.6%	90.0%	84.2%
Mean	97.1%	97.0%	96.9%	96.6%	95.6%	95.2%	94.9%	93.8%
Maximum	100%	100%	100%	100%	100%	100%	100%	100%
Rank/position	1	2	3	4	5	6	7	8

Similarly, the result (Figure 6.2) of the cumulative distribution function graph of the average total service level in case-2 shows the same results as the case1. D-KAP BK-CONWIP maintained the highest average total service level when compared to its alternatives. Therefore, BK-CONWIP D-KAP is selected as the best performer in terms of service level, while GKCS S-KAP is the worst performer with the lowest total service level. The minimum, average and maximum total service levels and ranking positions achieved by PCS-KAP are presented in Table 6.6.

Table 6.6: Case-2 statistical description of the simulation result data

PCS-KAP	BK-CONWIP D-KAP	EKCS D-KAP	HK-CONWIP D-KAP	BK-CONWIP S-KAP	EKCS S-KAP	HK-CONWIP S-KAP	GKCS D-KAP	GKCS S-KAP
Minimum	97.0%	96.9%	96.5%	96.0%	95.0%	94.0%	93.0%	92.0%
Mean	98.0%	97.9%	97.7%	97.5%	97.0%	96.5%	96.0%	95.0%
Maximum	99.0%	99.0%	99.0%	99.0%	99.0%	99.0%	99.0%	99.0%
Rank/position	1	2	3	4	5	6	7	8

From the results in Figure 6.2 and Table 6.6, D-KAP BK-CONWIP is presented as the best PCS-KAP, followed by D-KAP HK-CONWIP, while the third best performer is D-KAP EKCS, followed by S-KAP BK-CONWIP, then S-KAP EKCS, next is S-KAP HK-CONWIP, and D-KAP GKCS, while S-KAP GKCS was identified as the worst performer. BK-CONWIP D-KAP is the superior PCS-KAP.

A Stochastic Dominance test was conducted for the average total service level of all the PCS-KAP in both cases 1 and 2. The results of the total service level dominance tests are presented in Tables 6.9 and 6.10 for case-1 and 2 respectively. Table 6.9 shows a majority of first order dominance outcomes with an exception of one. A first order dominance is true, if the comparison of the values of the cumulative distribution functions (CDF) of any two PCS-KAP has the CDF of one of the PCS-KAP less than or equal to CDF of the second PCS-KAP for all sampled data. BK-CONWIP D-KAP has first order dominance (1d) over its alternatives, resulting in the selection of BK-CONWIP D-KAP as the best performer, while

GKCS S-KAP is the worst PCS-KAP in terms of service level.

- D-KAP EKCS stochastically dominates, HK-CONWIP D-KAP, BK-CONWIP S-KAP, EKCS S-KAP, GKCS D-KAP, GKCS S-KAP in a first order dominance, but was dominated by BK-CONWIP D-KAP.
- HK-CONWIP D-KAP has first order dominance over BK-CONWIP S-KAP, EKCS S-KAP, GKCS D-KAP, GKCS S-KAP and HK-CONWIP S-KAP, but was dominated by BK-CONWIP D-KAP and EKCS D-KAP.
- The comparison between GKCS D-KAP and GKCS S-KAP shows that GKCS D-KAP stochastically dominates GKCS S-KAP in a second degree (2d) dominance.
- D-KAP GKCS has second order dominance over S-KAP GKCS.

Similar results were obtained in case 2 (Table 6.10) with BK-CONWIP D-KAP as the best performer and S-KAP GKCS as the worst performer. All PCS-KAP compared returned first order dominance. The ranking of the PCS-KAP based on their service level performance for cases 1 and 2 is presented in Table 6.7, with 1 representing the best performer and 8 representing the worst performer.

Table 6.7: Cases 1 & 2 ranking of PCS-KAP based on service level performance

PCS-KAP	**BK-CONWIP D-KAP**	**EKCS D-KAP**	**HK-CONWIP D-KAP**	**BK-CONWIP S-KAP**	**EKCS S-KAP**	**HK-CONWIP S-KAP**	**GKCS D-KAP**	**GKCS S-KAP**
Case 1 ranks	1	2	3	4	5	6	7	8
Case 2 ranks	1	2	3	4	5	6	7	8

To present detailed results of the stochastic dominance test, the PCS-KAP are represented using alphabets as shown in Table 6.8, while the dominance test results for cases 1 and 2 are provided in Tables 6.9 and 6.10 respectively.

Table 6.8: Representation of PCS-KAP by alphabets

PCS-KAP	**BK-CONWIP D-KAP**	**BK-CONWIP S-KAP**	**HK-CONWIP D-KAP**	**HK-CONWIP S-KAP**	**EKCS D-KAP**	**EKCS S-KAP**	**GKCS D-KAP**	**GKCS S-KAP**
Symbol	A	B	C	D	E	F	G	H

Table 6.9: Case 1 result of PCS-KAP service level dominance test

Dominance	B	C	D	E	F	G	H
A	A 1d over B	A 1d over C	A 1d over D	A 1d over E	A 1d over F	A 1d over G	A 1d over H
B		C 1d over B	B 1d over D	E 1d over B	B 1d over F	B 1d over G	B 1d over H
C			C 1d over D	E 1d over C	C 1d over F	C 1d over G	C 1d over H
D				E 1d over D	F 1d over D	D 1d over G	D 1d over H
E					E 1d over F	E 1d over G	E 1d over H
F						F 1d over G	F 1d over H
G							G 2d over H

1d= is 1st degree dominance, 2d= is 2nd degree dominance

Table 6.10: Case 2 result of PCS-KAP service level dominance test

Dominance	B	C	D	E	F	G	H
A	A 1d over B	A 1d over C	A 1d over D	A 1d over E	A 1d over F	A 1d over G	A 1d over H
B		C 1d over B	B 1d over D	E 1d over B	B 1d over F	B 1d over G	B 1d over H
C			C 1d over D	E 1d over C	C 1d over F	C 1d over G	C 1d over H
D				E 1d over D	F 1d over D	D 1d over G	D 1d over H
E					E 1d over F	E 1d over G	E 1d over H
F						F 1d over G	F 1d over H
G							G 1d over H

1d= is 1st degree dominance

6.3.2 Comparison of PCS-KAP via Total Work-in-process Inventory

The average total work-in-process inventory of individual PCS-KAP was compared to select the PCS-KAP with least work-in-process inventory in a system. Figures 6.3 and 6.4 provide graphical descriptions of the cumulative distribution functions in cases 1 and 2 respectively, while Figures 6.5 and 6.6 presents the average work-in-process inventory probability histogram. Tables 6.11 and 6.12 provide details the minimum, average and maximum average total WIP inventory and ranking positions achieved by PCS-KAP in cases 1 and 2.

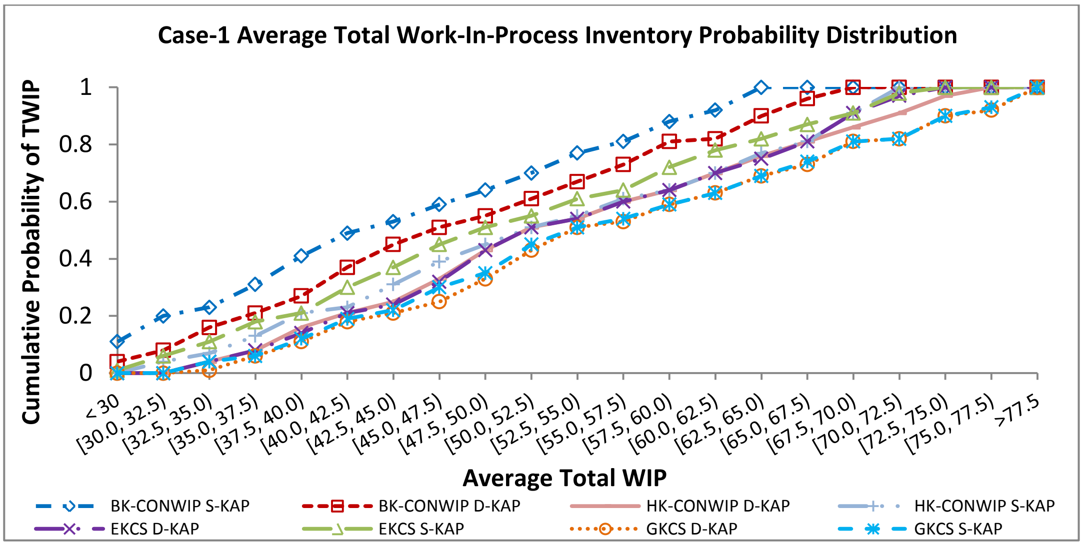


Figure 6.3: Case-1 average total WIP inventory probability distribution graph

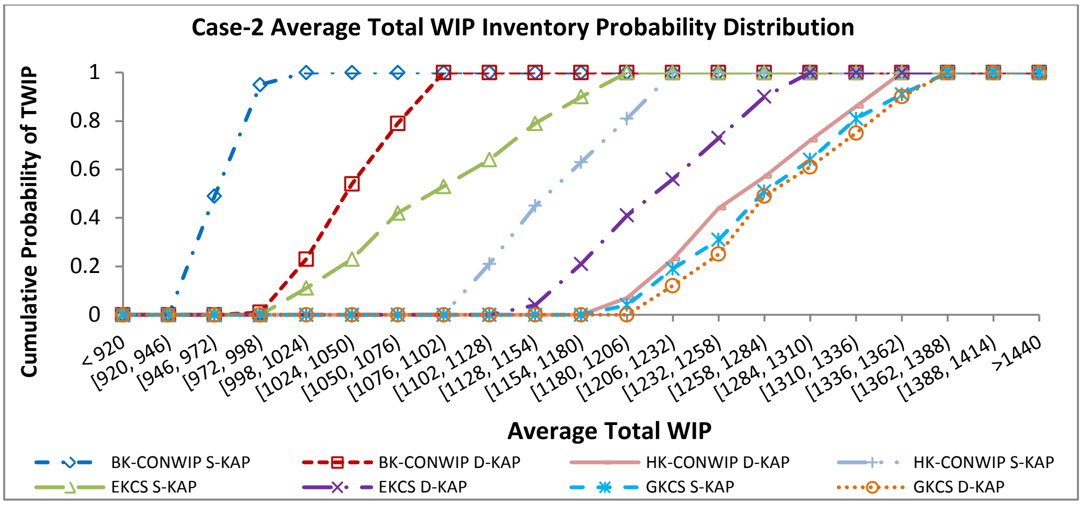


Figure 6.4: Case-2 average total WIP inventory probability distribution graph

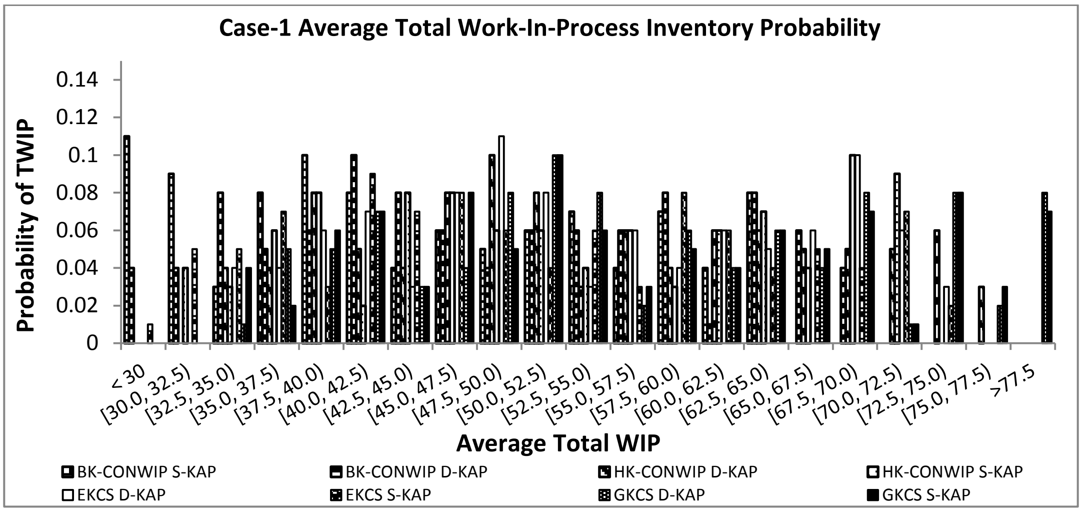


Figure 6.5: Case-1 average total WIP inventory probability distribution histogram

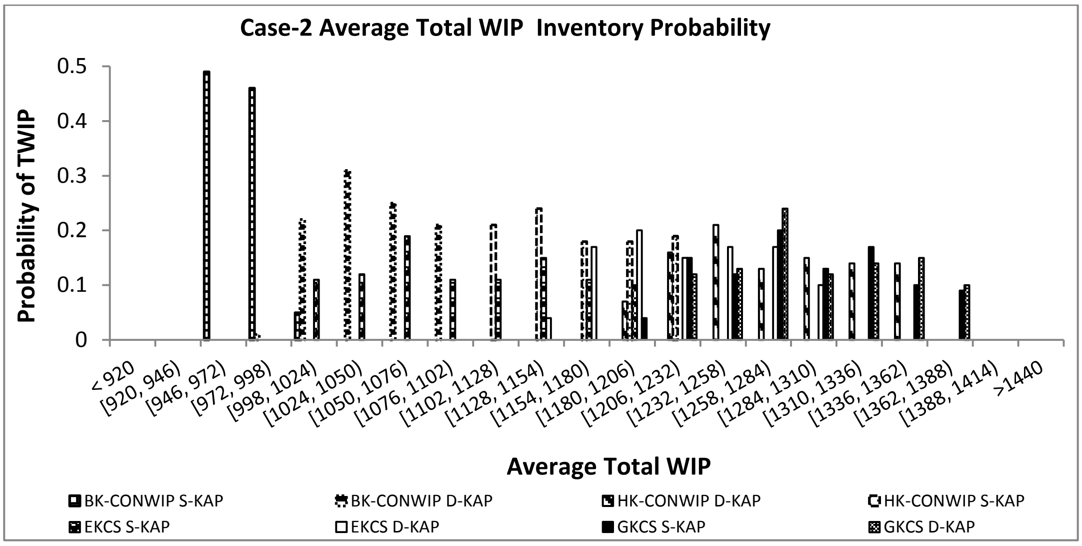


Figure 6.6: Case-2 average total WIP inventory probability distribution histogram

Table 6.11: Case-1 statistical description of TWIP results

PCS-KAP	BK-CONWIP S-KAP	BK-CONWIP D-KAP	EKCS S-KAP	HK-CONWIP S-KAP	EKCS D-KAP	HK-CONWIP D-KAP	GKCS S-KAP	GKCS D-KAP
Minimum	25.10	28.09	29.80	32.80	33.00	33.70	34.00	34.60
Mean	44.76	48.25	51.09	54.09	54.19	56.03	56.67	56.98
Maximum	64.67	68.66	72.64	75.64	75.64	78.62	79.62	79.62
Rank/position	1	2	3	4	5	6	7	8

Table 6.12: Case-2 statistical description of TWIP results

PCS-KAP	BK-CONWIP S-KAP	BK-CONWIP D-KAP	EKCS S-KAP	HK-CONWIP S-KAP	EKCS D-KAP	HK-CONWIP D-KAP	GKCS S-KAP	GKCS D-KAP
Minimum	949.52	997.57	1000.45	1102.29	1150.34	1190.39	1200.40	1210.39
Mean	974.40	1048.05	1098.80	1165.23	1224.10	1273.98	1286.45	1293.98
Maximum	999.58	1099.14	1198.33	1228.93	1298.75	1358.58	1373.54	1378.58
Rank/position	1	2	3	4	5	6	7	8

The results of the average total work-in-process inventory when robustness were considered in the systems (see, Figures 6.5 and 6.6) indicate that GKCS maintained the highest level of WIP inventory when compared to the level of WIP inventory achieved by its alternatives in cases 1 and 2. Therefore, GKCS is the least desired strategy in both cases. BK-CONWIP S-KAP had the lowest total average WIP inventory in both cases, implying that it is a better choice when the proportion of WIP inventory generated by PCS-KAP in a system is considered as a deciding factor for the selection of a PCS-KAP. Conversely, GKCS D-KAP has the highest level of WIP inventory in both cases, suggesting that it is the worst strategy. BK-CONWIP S-KAP is ranked the best performer with lowest WIP inventory, followed by BK-CONWIP D-KAP, then EKCS S-KAP, next is HK-CONWIP S-KAP, followed by EKCS D-KAP and HK-CONWIP D-KAP. GKCS S-KAP is ranked seventh, while GKCS D-KAP is the worst performer.

The stochastic dominance test is designed for maximisation such that it returns individual PCS-KAP with the biggest value of the sampled data as the one with dominance over the alternatives. However, the minimisation of WIP is required in this study. As a result of this, the PCS-KAP with the smallest value of WIP is considered as superior to the alternatives. Therefore, in reporting the dominance test conducted on the average total WIP inventory of the two cases (1 and 2), the PCS-KAP with least dominance over the rest is considered as superior, while the PCS-KAP with the most dominance is considered as the worst PCS-KAP. The outcome of the dominance tests for cases 1 and 2 are presented in Tables 6.13 and 6.14 respectively.

Table 6.13: Case 1 result of PCS-KAP WIP dominance test

Dominance	B	C	D	E	F	G	H
A	B 1d over A	A 1d over C	A 1d over D	A 1d over E	A 1d over F	A 1d over G	A 1d over H
B		B 1d over C	B 1d over D	B 1d over E	B 1d over F	B 1d over G	B 1d over H
C			D 1d over C	E 1d over C	F 1d over C	C 1d over G	C 1d over H
D				D 1d over E	F 1d over D	D 1d over G	D 1d over H
E					F 1d over E	E 1d over G	E 1d over H
F						F 1d over G	F 1d over H
G							G 1d over H

1d= is 1st degree dominance

Table 6.14: Case 2 result of PCS-KAP WIP dominance test

Dominance	B	C	D	E	F	G	H
A	B 1d over A	A 1d over C	A 1d over D	A 1d over E	A 1d over F	A 1d over G	A 1d over H
B		B 1d over C	B 1d over D	B 1d over E	B 1d over F	B 1d over G	B 1d over H
C			D 1d over C	E 1d over C	F 1d over C	C 1d over G	C 1d over H
D				D 1d over E	F 1d over D	D 1d over G	D 1d over H
E					F 1d over E	E 1d over G	E 1d over H
F						F 1d over G	F 1d over H
G							G 1d over H

1d= is 1st degree dominance

The TWIP stochastic dominance test result obtained in case 1 is the as in case 2 (Tables 6.13 and 6.14). In both cases, the following observations are made:

- GKCS D-KAP has first degree dominance over BK-CONWIP (D-KAP and S-KAP), HK-CONWIP (D-KAP and S-KAP), EKCS (D-KAP and S-KAP) and GKCS S-KAP, which implies that GKCS D-KAP is the worst performer.
- GKCS S-KAP has first order dominance over BK-CONWIP (D-KAP and S-KAP), HK-CONWIP (D-KAP and S-KAP) and EKCS (D-KAP and S-KAP). It is the second worst performer.

The ranking of the PCS-KAP based on their WIP performance for cases 1 and 2 is presented in Table 6.15, with 1 representing the best performer and 8 representing the worst performer.

Table 6.15: Cases 1 & 2 ranking of PCS-KAP based on WIP performance

PCS-KAP	**BK-CONWIP S-KAP**	**BK-CONWIP D-KAP**	**EKCS S-KAP**	**HK-CONWIP S-KAP**	**EKCS D-KAP**	**HK-CONWIP D-KAP**	**GKCS S-KAP**	**GKCS D-KAP**
Case 1 ranks	1	2	3	4	5	6	7	8
Case 2 ranks	1	2	3	4	5	6	7	8

CHAPTER 7: DISCUSSION

7.1 Discussion

The documented effective performance of PCS in single product manufacturing systems [7-9, 14] and ineffective performance of these strategies in multi-product systems [15, 16, 77] led to the development of S-KAP as an alternative to D-KAP. The findings of Baynat et al. [16] showed that a PCS combined with S-KAP outperforms the same PCS when combined with D-KAP in a system with negligible instabilities. However, the literature shows that KCS, CONWIP, BSCS, HK-CONWIP in combination with S-KAP cannot operate naturally. The documented failure of KCS, CONWIP, BSCS, HK-CONWIP to operate in the S-KAP mode [15, 16, 77] and the poor performance of these PCS-KAP in multi-product systems with varying demands, processing requirements, and highly engineered products in small batches [7-9] motivated this study. This work agreed with the findings of these studies and has advanced their works by developing a technique that allows PCS to operate in S-KAP mode and a new PCS that is capable of a quick response to varying demand sizes in multi-product manufacturing systems.

It was shown that the tight coupling between the demand information and the production authorisation card (Kanbans) will cause a multi-product pull controlled system to hold a large proportion of WIP. The ability to decouple the demand information and the Kanbans in a few production stages, commencing from the final stage gives a strategy an ability to operate S-KAP while retaining its underlying characteristics. PCS in combination with S-KAP has better WIP control than PCS in combination with D-KAP (see, Chapter 5: Figures 5.5 to 5.12 and Tables 5.12, 5.17 and 5.23). The superior performance of the PCS in combination with S-KAP over its alternative is attributed to the decoupling of demand information and the Kanbans. It results in the release of unattached Kanbans that are kept in the Kanbans' initial position without releasing a part into the system except for the occurrence of demands. It is important to have a high unattached Kanbans because it responds to surge in the demand volume and when the demand reduces to an anticipated level, the unattached Kanbans return to their original position with no additional WIP in the system. This confirms the analysis of the simulation results in Chapter 5 regarding the poorer performance of the PCS with D-KAP over PCS with S-KAP.

The development of BK-CONWIP provides a pull control strategy that operates with a small basestock level (Tables 5.4, 5.5, 5.6 and 5.7) to maintain a small WIP level, assuming an anticipated demand occurs and relatively a bigger Kanbans planned to respond to a surge in demand. The rapid response to demand in BK-CONWIP is attributed to the manner in which the demand information is transmitted in the system. Therefore, the transmission of demand information in a pull controlled multi-product system influences the productivity level in the system. The effective WIP control of BK-CONWIP is attributed to the use of CONWIP cards which has a stronger WIP control than KCS.

In the selection of an appropriate PCS for a simple and a complex manufacturing flow lines, GKCS is the least effective PCS regarding its WIP and service level performances, while BK-CONWIP has the most effective service level and WIP control. There was a significant difference in WIP and service level performances between BK-CONWIP and the alternatives. The superior performance of BK-CONWIP over its alternatives is attributed to the manner of transmission of the demand information (global transmission to all stages and total decoupling of demand information from the PAC) and the use of CONWIP cards and Kanbans for WIP control. BK-CONWIP, EKCS and HK-CONWIP outperformed GKCS. The three PCS uses global demand information transmission resulting in their performance better than GKCS. In a GKCS controlled system demand information is transmitted upstream in a stage by stage approach, starting from the final stage until it reaches the initial stage. HK-CONWIP globally transmits the demand information to the initial stage using the CONWIP cards. HK-CONWIP performed better than GKCS because of its global demand information transmission. EKCS globally transmits demand information onto all stages, making it to perform better than HK-CONWIP.

Consequently, GKCS's poor performance relative to its alternatives is largely attributed to delay in demand information. This confirms the outcome and analysis of the simulation experiments in Chapter 5. WIP Cap of CONWIP mechanism is important in reducing the WIP level in systems examined in this thesis. It limits

WIP of the system such resulting in restriction of high WIP level in the system. When the WIP Cap is used in combination with global demand information transmission onto all stages, the PCS performs better than its alternatives. BK-CONWIP in both S-KAP and D-KAP modes outperformed EKCS.

The comparison analysis in Chapter 5 confirms that PCS combined with S-KAP outperformed PCS combined with D-KAP. Similarly, it was shown that PCS that uses global demand information flow to all stages in a system (BK-CONWIP and EKCS) outperformed PCS that uses global demand information flow to the initial stage (HK-CONWIP) and PCS that uses local demand information flow (KCS).

The robustness analysis in Chapter 6, reveals that PCS combined with D-KAP outperformed PCS combined with S-KAP, when service level is the main consideration for the selection of PCS-KAP for a system under environmental and system variabilities. However, when WIP is the main factor for the selection of PCS-KAP, PCS combined with S-KAP outperformed PCS combined with D-KAP.

The higher service level performance of PCS combined with D-KAP over PCS combined with S-KAP is basically attributed to fact that the control mechanism PCS combined with D-KAP, diversifies its resources (as the saying goes: do not put all eggs in one basket), such that individual product type has its specific resource pool and can absorb its own environmental and system variabilities better than having all resources in one pool as the overall environmental and system variabilities would negatively influence its performance. It is important to note that PCS combined with D-KAP have larger Kanbans than PCS combined with S-KAP (Tables 5.4 to 5.7). In the presence of variabilities, the large quantity of Kanbans in PCS combined with D-KAP absorbs the effect of the variability depending on the level of variations. The negative effect of the large quantity of Kanbans in PCS combined with D-KAP is that WIP level is higher than in PCS combined with S-KAP.

The performance of the PCS-KAP in the simulation studies were analysed and presented in Table 7.1. This analysis provides the service level and WIP performance rankings of the PCS-KAP owing to manufacturing conditions such as demand profile, product mix failure recovery and environmental variabilities. The

PCS-KAP are ranked from 1 to 8, with 1 representing the best PCS-KAP (selected for a given condition), while 8 represents the worst PCS-KAP.

Table 7.1:Comparative analysis of PCS-KAP (1 = best, 8 = worst)

		Manufacturing Conditions									
		Linear Demand		Non-Linear Demand		Product Mix		Failure Recovery		Environmental & System Variability	
PCS	KAP	SL	WIP	SL	WIP	SL	WIP	SL	WIP	SL	WIP
BK-CONWIP	S-KAP	1	1	1	1	1	1	1	1	4	1
	D-KAP	2	2	2	2	2	2	2	2	1	2
EKCS	S-KAP	3	3	3	3	3	3	3	3	5	3
	D-KAP	6	6	6	6	6	6	6	6	2	5
HK-CONWIP	S-KAP	4	4	4	4	4	4	4	4	6	4
	D-KAP	7	7	7	7	7	7	7	7	3	6
GKCS	S-KAP	5	5	5	5	5	5	5	5	8	7
	D-KAP	8	8	8	8	8	8	8	8	7	8

It was shown that in all the experiments, PCS in combination with S-KAP are more flexible and respond to varying demand quicker than PCS combined with D-KAP when the system is subjected to little or no environmental changes, resulting in an effective minimisation of WIP while maximising service level. Similarly, in the presence of variability, PCS combined with S-KAP has better WIP control than PCS combined with D-KAP. However, when service level is the factor for selection of a PCS-KAP, PCS combined with D-KAP is selected as the best performer. Furthermore, BK-CONWIP outperforms its alternatives in all cases. BK-CONWIP combined with S-KAP is selected as the best PCS-KAP regarding WIP control and maximisation of service levels in systems with anticipated variability. In systems with unexpected variability, it is also selected as the best PCS-KAP for WIP control. However, if maximisation of service level is the priority for PCS-KAP selection, then BK-CONWIP combined with D-KAP is selected as the best PCS-KAP.

7.2 Summary

In this thesis, a comprehensive analysis of the existing pull control strategies and pull production card policies was carried out. An approach that modifies pull control strategies that failed to naturally operate S-KAP was proposed and a new pull production control strategy was developed. BK-CONWIP combines the WIP Cap technique in CONWIP, the global information flow technique in BSCS, the stage WIP control technique in KCS (except for the final stage) and push control mechanism for the final stage of a system.

The analyses and simulation studies conducted showed that BK-CONWIP is flexible and robust in varying manufacturing conditions. It significantly outperformed its alternatives under the same conditions in terms of WIP inventory, backlogs and service levels (see, Figures 5.5 to 5.12 and Tables 5.12 to 5.23). It was shown that PCS in combination with S-KAP use lower PAC (i.e. Kanbans or CONWIP cards) and basestock level than PS in combination with D-KAP in a multi-product manufacturing environment (see, Tables 5.4, to 5.7). Also, PCS combined with S-KAP responds to surge in demand quicker than PCS combined with D-KAP.

The comparison analysis in Chapter 6 reveals the flexibility and robustness of BK-CONWIP in the presence of unstable demands resulting from unanticipated changes (environmental and system variabilities). This is the major advantage of BK-CONWIP over the alternatives. BK-CONWIP not only performs significantly better than the alternative, but it is more robust than the alternatives in the presences of variabilities.

7.3 Practical Implications for Practitioners and Academia

This research has practical implications to both manufacturing organisations and supply chain organisations. The actual demands drive the manufacturing systems, achieving a high service level with a minimal WIP inventory. For instance, the make-to-order policy, of which the company (a major global automotive electronics component manufacturer) sponsoring this project is a leading organisation. The company operates a make-to-order policy and has a one-week period to deliver products to its customers from the time the order is accepted. A majority of its suppliers has three weeks lead time to deliver parts to the company. To maintain its business philosophy, the company requires its suppliers to have a warehouse sufficient enough for the production of its products and close to its manufacturing plant. However, it does not share the cost of the inventory in its suppliers' warehouses until it withdraws the inventory from the warehouse to its plant. The problem here is how much inventory will suffice the needs of the company since the actual demand fluctuates and custom-made parts are sometimes required? Therefore, if suppliers fill their warehouses with inventory to have enough inventory. Any change in product design will induce a large quantity of waste owing to obsolete inventory. The demand profile fluctuates, implying that if the supplier has a less inventory than required, the make-to-order company will experience lost sales. The recommendation of this thesis is that the implementation of BK-CONWIP (S-KAP and D-KAP) permits the suppliers to have an instantaneous view of real time demand information (the global information flow technique) of all its customers, resulting in a quick response to varying demands. Also, the implementation of BK-CONWIP S-KAP over its alternatives will effectively reduce the WIP inventory by using a fewer number of PAC to authorise the minimal required inventory in the warehouse than its alternatives. Furthermore, the CONWIP mechanism of BK-CONWIP will ensure that inventory is only at the final stage of the system (CONWIP maintains WIP at the final stage). Therefore, both the company and its suppliers will maintain minimal WIP inventory while maximising service level by implementing BK-CONWIP. This reduces cost, production waste and improves company's competitiveness.

The implications of this research to academia with roles such as production planning, designing, operations of control strategies in any organisation. At any given service level in multi-product systems, the S-KAP models of any PCS maintain a lower WIP inventory in a system than the D-KAP models. This is because of the capability of sharing resources in S-KAP, resulting in the S-KAP models having a fewer PAC than the D-KAP models. Also, in the four PCS (S-KAP and D-KAP) examined, GKCS was the worst performer. This is attributed to the delay, which occurs during the communication of the demand information onto the initial stage (local information flow approach). The recommendation of this thesis is that to design a PCS for manufacturing systems, a global information flow approach onto all stages should be considered. This approach allows all the stages to quickly respond to demand information. BK-CONWIP and EKCS were shown to respond to demand information faster than HK-CONWIP and GKCS. BK-CONWIP is consistently the best performer in all the examined cases. It is recommended that BK-CONWIP be implemented in combination with S-KAP for systems with anticipated environmental and system variations, while BK-CONWIP should be implemented in combination with D-KAP for systems having unexpected environmental and system variations.

CHAPTER 8: CONTRIBUTION AND FUTURE RESEARCH WORK

8.1 Conclusion and Contributions

The work in this thesis has advanced the works of Baynat et al. [16]; Olaitan and Geraghty [77] in proffering a solution to PCS that failed to operate S-KAP naturally and the studies of Marek et al. [7]; Krishnamurthy et al. [9] by developing a robust PCS for WIP control and rapid response manufacturing. The main contributions of this thesis are listed as follows:

- A comprehensive framework for modification of pull control strategies to operate shared Kanban allocation card policy was proposed. The parameters with significant effect on the control mechanism of pull control strategies were identified.
- A new pull production control strategy (BK-CONWIP) was designed and developed that is capable of quick response to demand variations in a multi-product system. It was proved via multi-objective optimisation and simulation comparison that BK-CONWIP is more robust and superior to its alternatives in any manufacturing conditions.
- A table has been developed (Table 7.1) to assist decision makers to select the best PCS-KAP for multi-product manufacturing systems. It was shown that BK-CONWIP combined with S-KAP should be selected for all the manufacturing conditions examined, except when service level is the priority for selection of PCS-KAP for systems under environmental and system variabilities. Then, BK-CONWIP combined with D-KAP is selected as the best PCS-KAP.

8.2 Future Research Work

Additional research on (i) the performance comparison of pull control strategies and production authorisation card policies in a complex tiered mixed model assembly line with custom-made and highly engineered product types in small batches under different demands and processing time requirements, and (ii) evaluation of BK-CONWIP in multi-tiered supply chain. These studies will provide clearer guidance for operation managements in selection and implementation of pull production control strategies under non robust and robust conditions for production and supply chain managements.

It is my suggestion that BK-CONWIP as a promising control strategy would outperform the alternatives based on its proven WIP control technique and quick response to demand variability. Further study could be in the area of performance comparison of a large number of product types in complex production line having varying order due dates, lost sales, uncorrelated processing times, finite capacity, and sequence independent set-up times with uncertainty in demand variability, typical of a complex food processing industry.

Even though the work presented here has focused mainly on the impact of erratic demand on the performance of pull production control strategy and Kanban allocation policies in multi-product manufacturing/assembly systems. The approach adopted was to optimise the control parameters of each pull production control strategy and Kanban allocation policy given assumptions regarding the demand, the failure and the repair distributions. Additional steps in this research will continue in the direction of development of pull production control strategy with the capability to respond quickly to demand in order to address the issue of poor performance of pull production control strategy during high variations in terms of product mix and volume.

Other works and Papers

During the course of this work, other contributions are made in various areas. These contributions are listed below as follows:

[1] Tutor/Demonstrator, (2011 to 2014), "MM584 Manufacturing Systems Simulation Tutorial Class" School of Mechanical and Manufacturing Engineering, Dublin City University (DCU), Ireland.

[2] Tutor/Demonstrator, (2011 to 2014), "MM485 Operations Research Methods Tutorial Class" School of Mechanical Engineering, DCU, Ireland.

[3] Company Seminar, (2013), "Operation Research Paper Presentation" Methode Electronics Malta Limited, Company Presentation, Mriehel, Qormi, Malta.

[4] Company-work Presentation, (2013), "Evaluation of Push and Pull PCS on C170 Ignition Start Assembly Plant under Erratic Demand variability" Methode Electronics Malta Limited, Company Presentation, Mriehel, Qormi, Malta

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[9] Onyeocha, C.E., Khoury, J. & Geraghty, J. (2013), "Evaluation of Multi-product Lean Manufacturing Systems with Setup and Erratic Demand", *Computers & Industrial Engineering*, (currently under review)

[10] Onyeocha, C.E., Wang, J., Khoury, J. & Geraghty, J. (2013), "Comparison of Deterministic and Stochastic Models of Pull Controlled Multi-Product Assembly-Line under Erratic Demand with Consideration for Robustness", *Annals of Operations Research* (currently under review)

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APPENDIX A

PCS Model Parts and ExtendSim Blocks

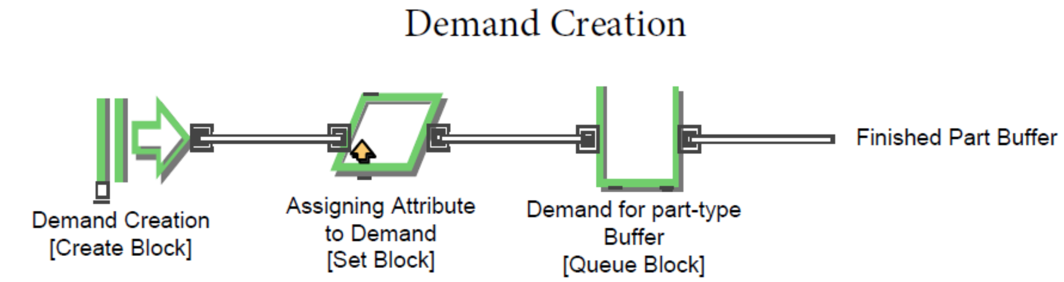


Figure A.1: Demand creation event in ExtendSim model

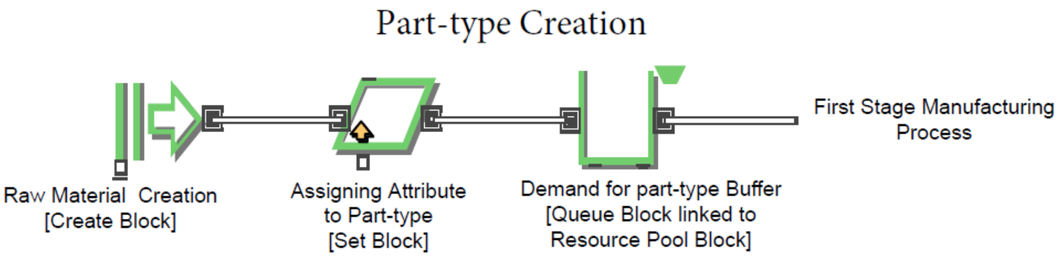


Figure A.2: Part type creation event in ExtendSim model

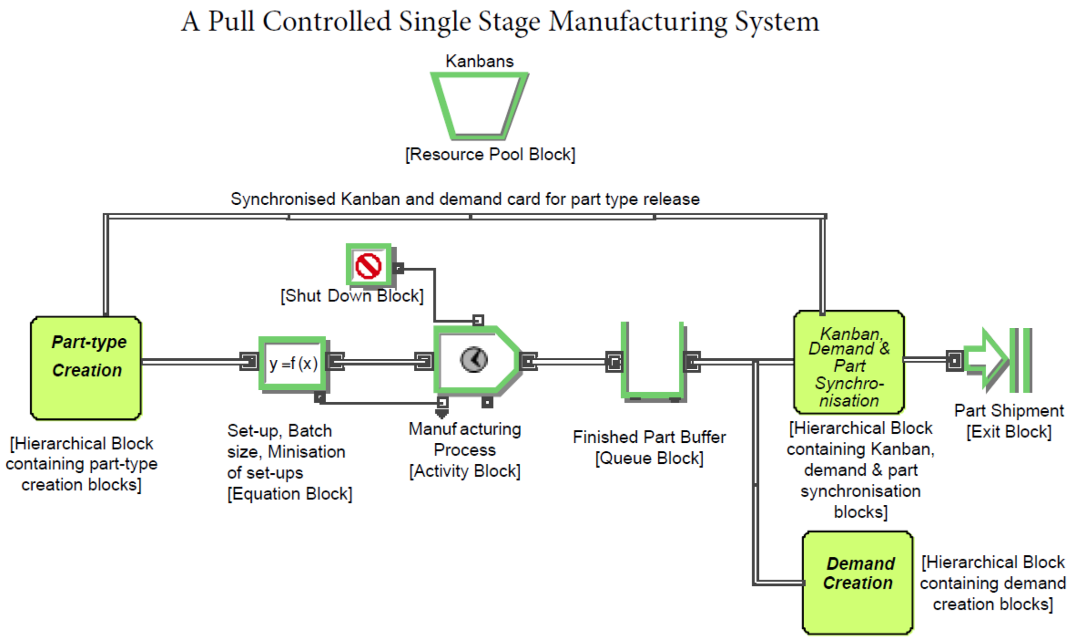


Figure A.3: ExtendSim model of a pull controlled single stage manufacturing system

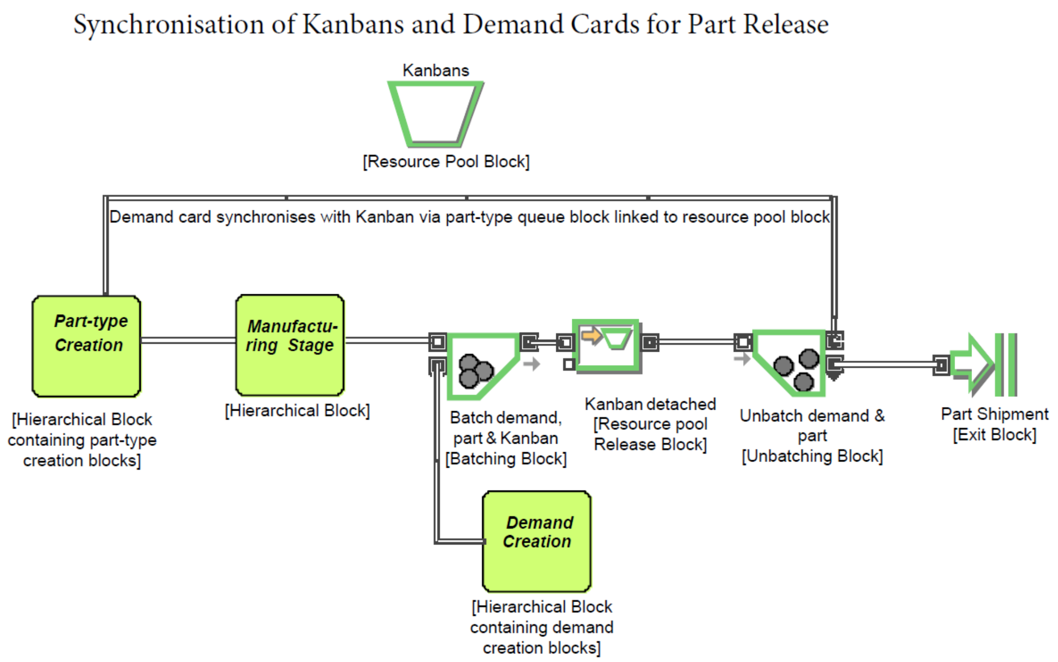


Figure A.4: Synchronisation of Kanbans and demand cards for part release

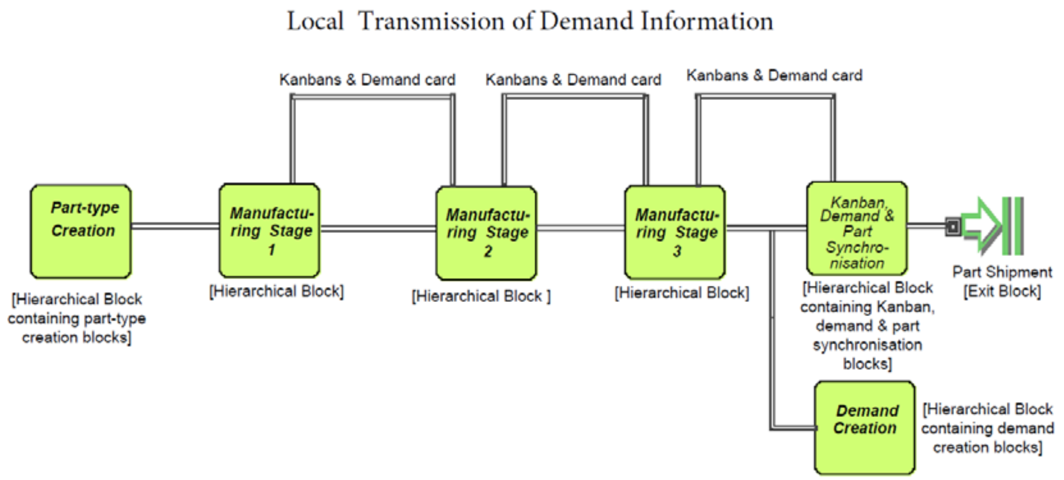


Figure A.5: Local transmission of demand information

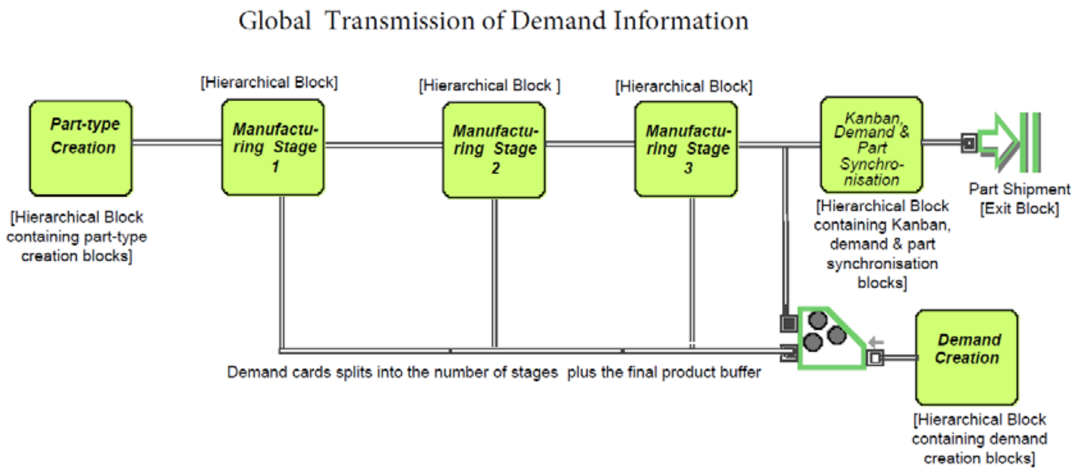


Figure A.6: Global transmission of demand information

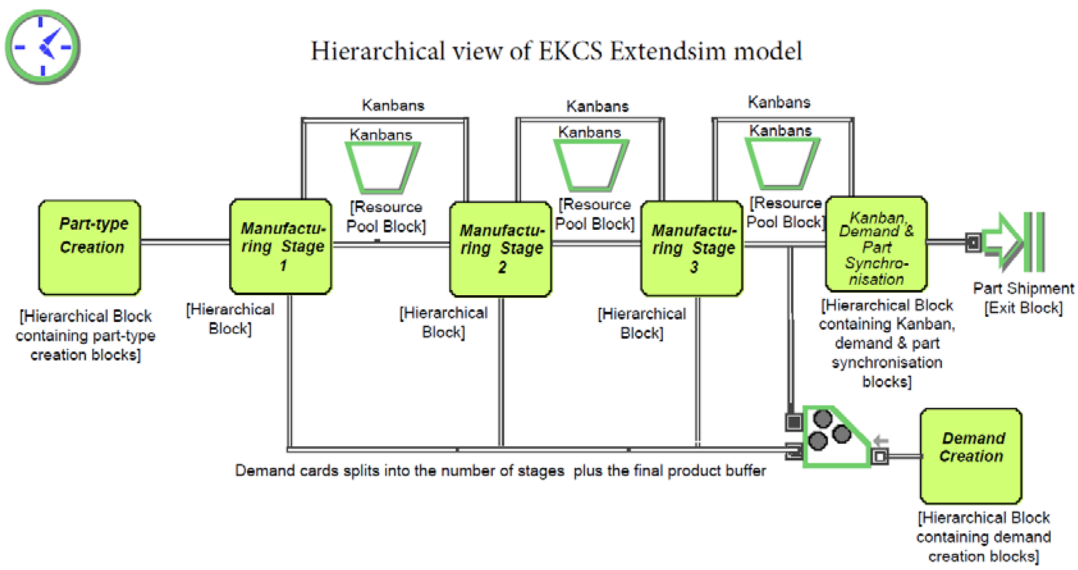


Figure A.7: ExtendSim model of EKCS controlled 3 stage manufacturing system

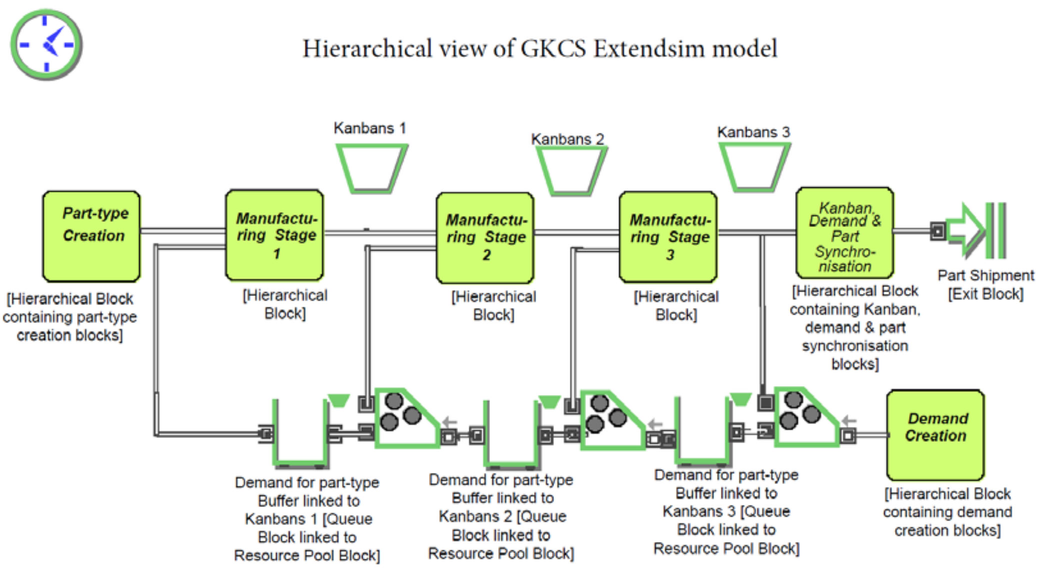


Figure A.8: ExtendSim model of GKCS controlled 3 stage manufacturing system

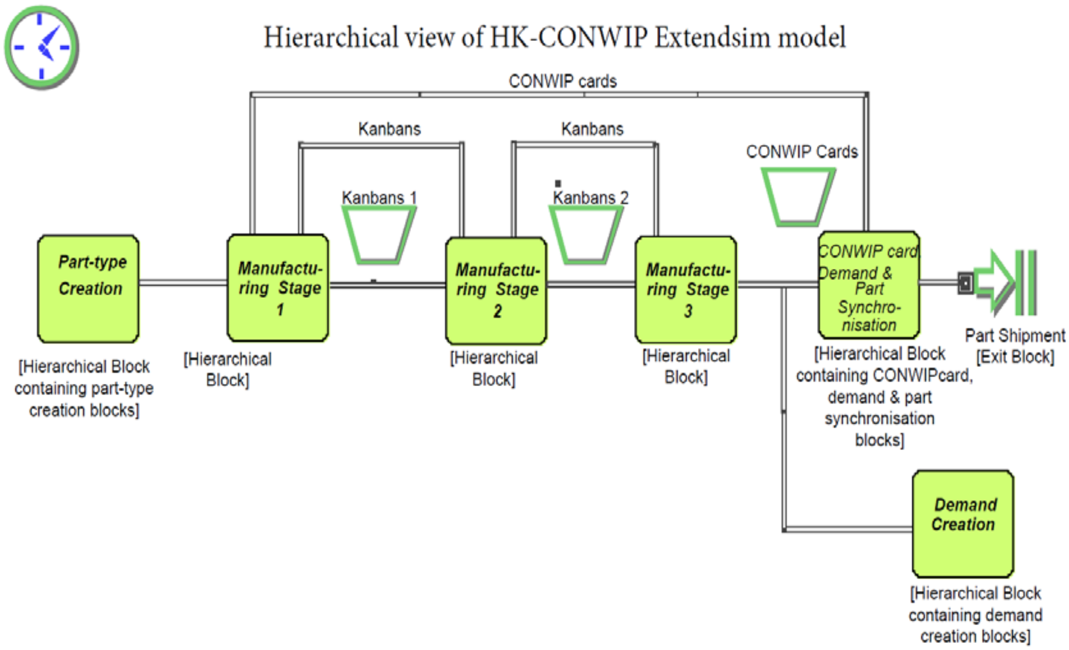


Figure A.9: ExtendSim model of HK-CONWIP controlled 3 stage manufacturing system

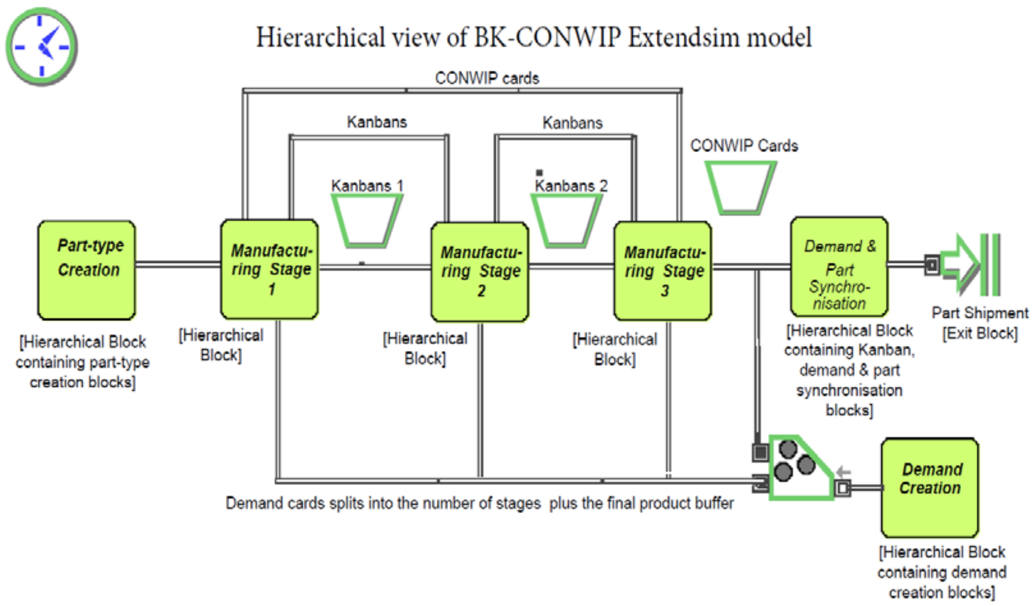


Figure A.10: ExtendSim model of BK-CONWIP controlled 3 stage manufacturing system

APPENDIX B

Warm up Analysis of PCS-KAP

Case 1 graphs

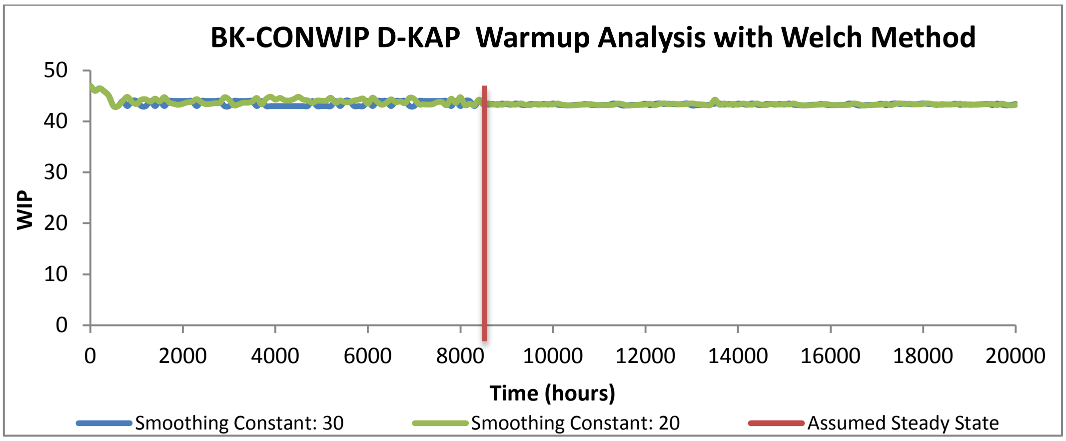


Figure B.1: Case 1 Welch graph of BK-CONWIP D-KAP for window sizes 20 & 30

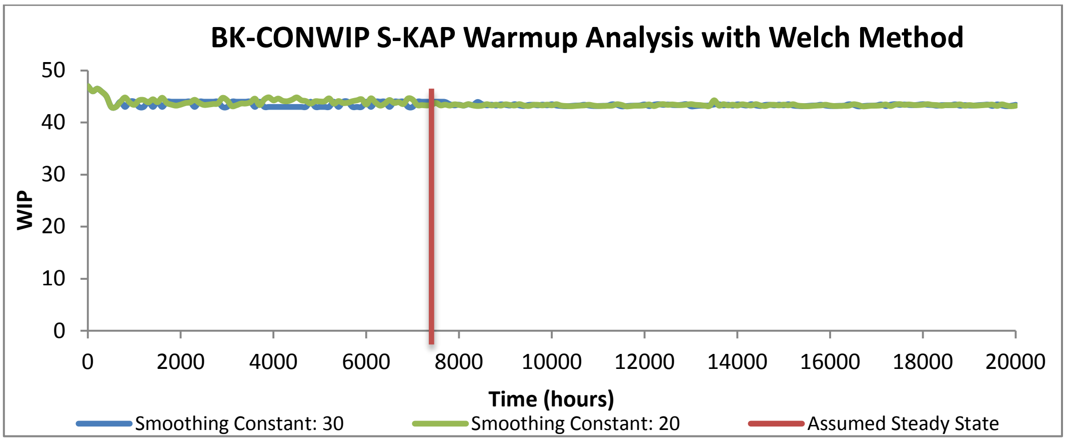


Figure B.2: Case 1 Welch graph of BK-CONWIP S-KAP for window size 20 & 30

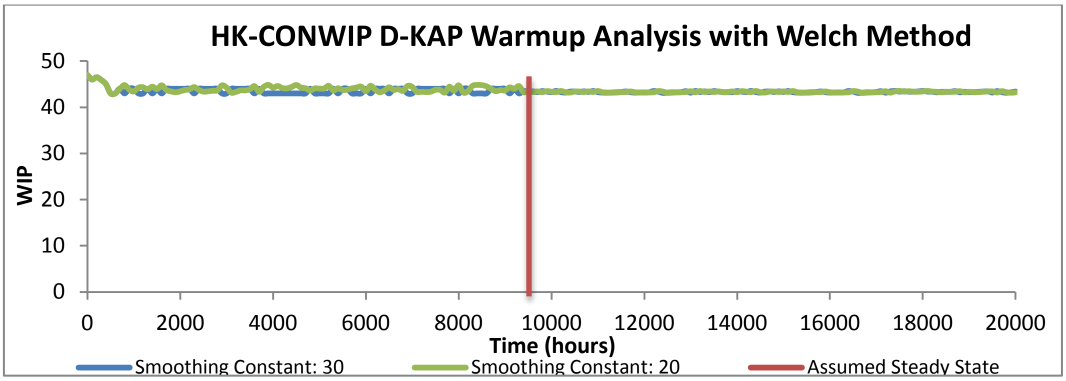


Figure B.3: Case 1 Welch graph of HK-CONWIP D-KAP for Window Sizes 20 & 30

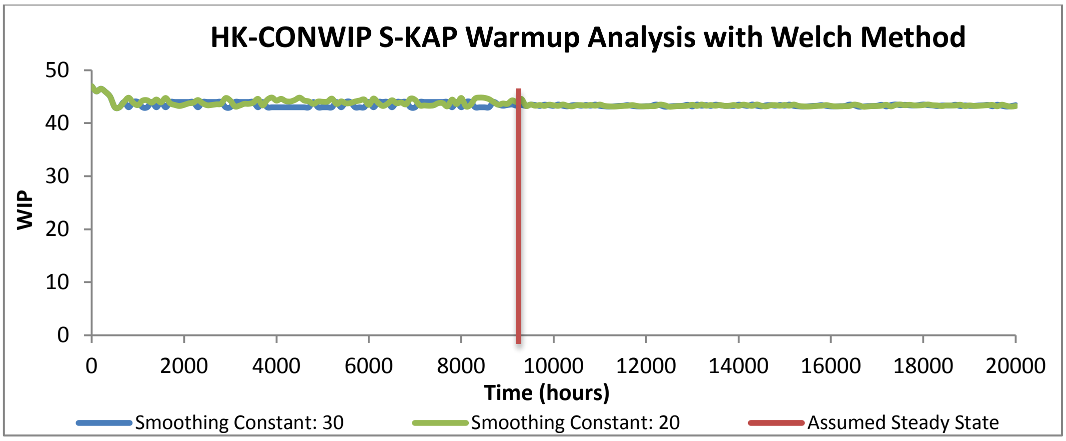


Figure B.4: Case 1 Welch graph of HK-CONWIP S-KAP for Window Sizes 20 & 30

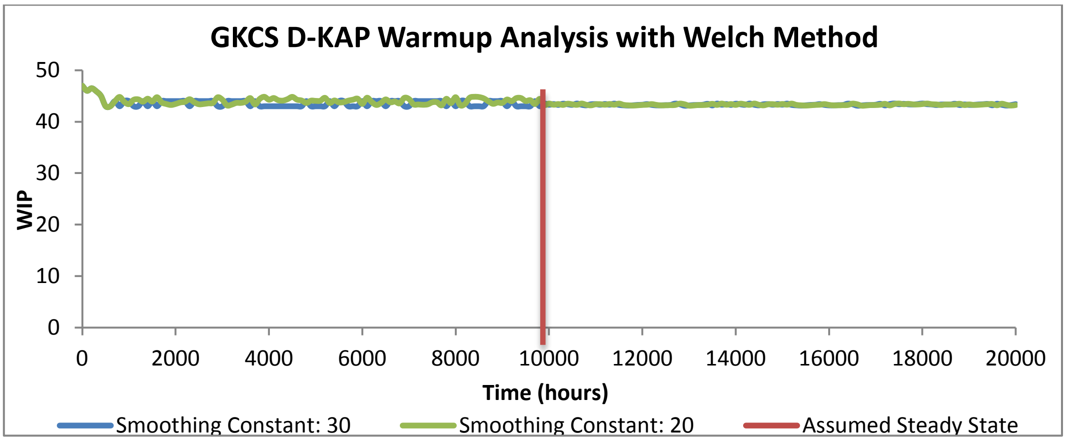


Figure B.5: Case 1 Welch graph of GKCS D-KAP for Window Sizes 20 & 30

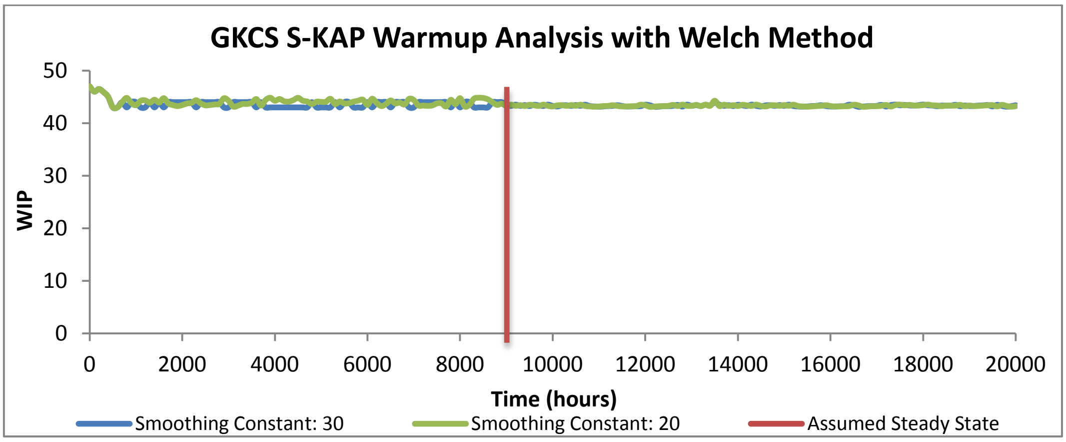


Figure B.6: Case 1 Welch graph of GKCS S-KAP for Window Sizes 20 & 30

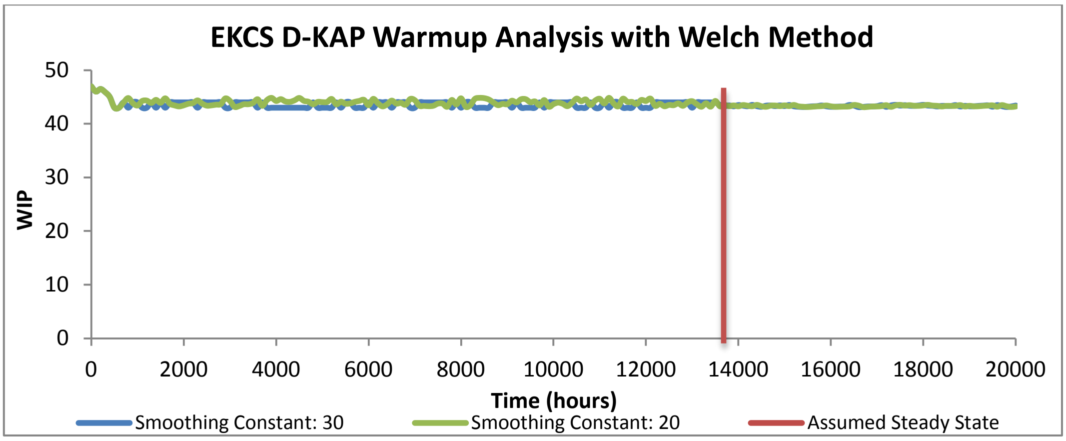


Figure B.7: Case 1 Welch graph of EKCS D-KAP for Window Sizes 20 & 30

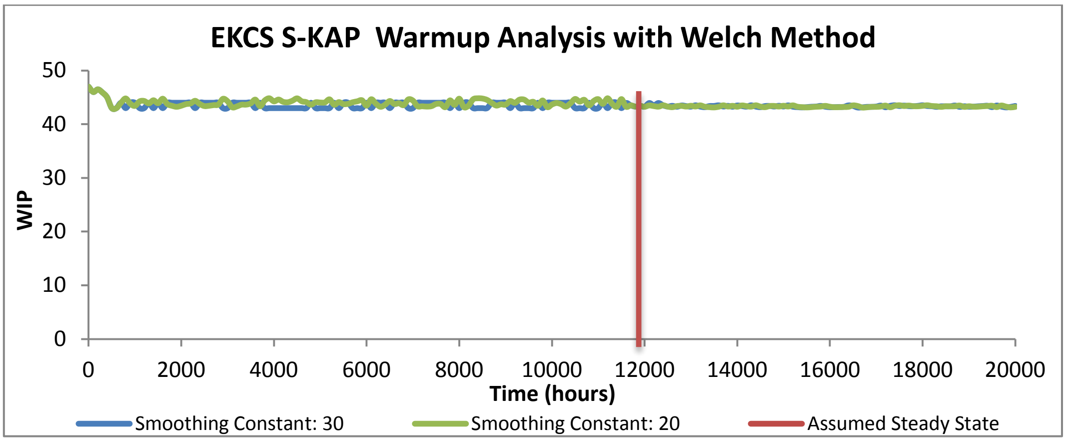


Figure B.8: Case 1 Welch graph of EKCS S-KAP for Window Sizes 20 & 30

Case 2 graphs

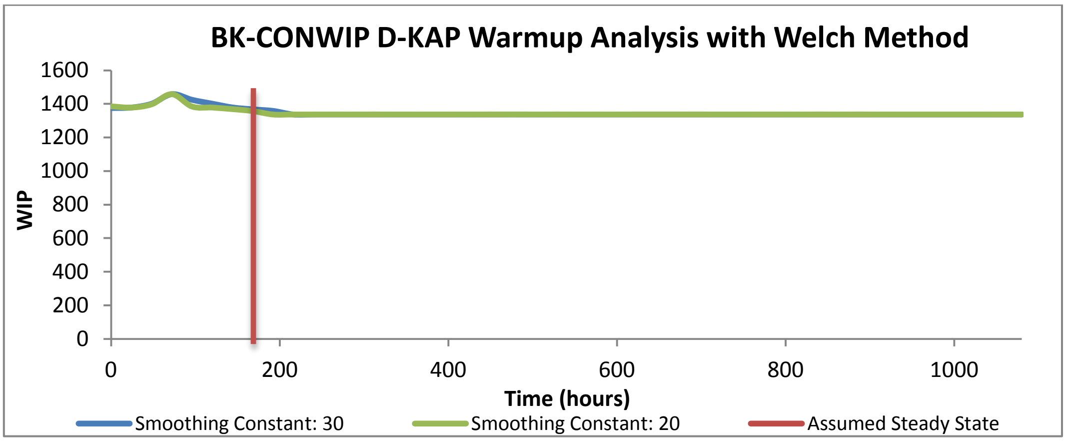


Figure B.9: Case 2 Welch graph of BK-CONWIP D-KAP for Window Sizes 20 & 30

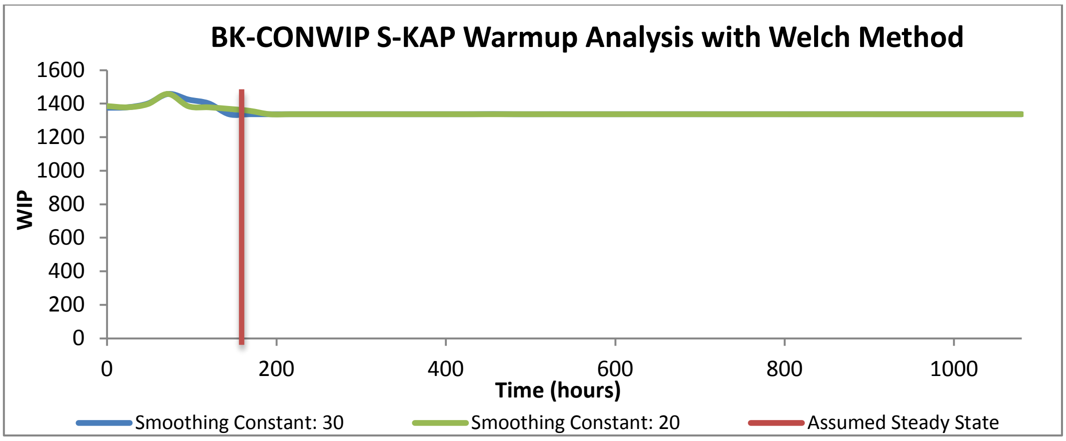


Figure B.10: Case 2 Welch graph of BK-CONWIP S-KAP for Window Sizes 20 & 30

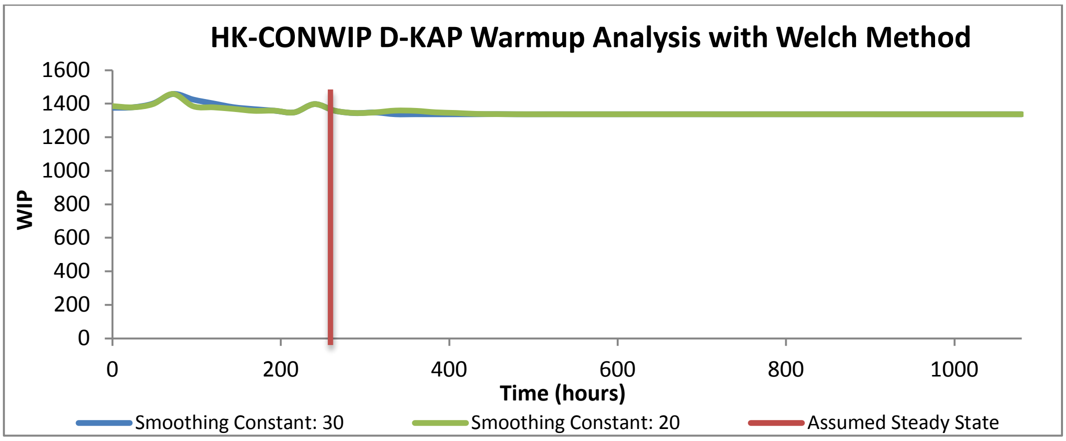


Figure B.11: Case 2 Welch graph of HK-CONWIP D-KAP for Window Sizes 20 & 30

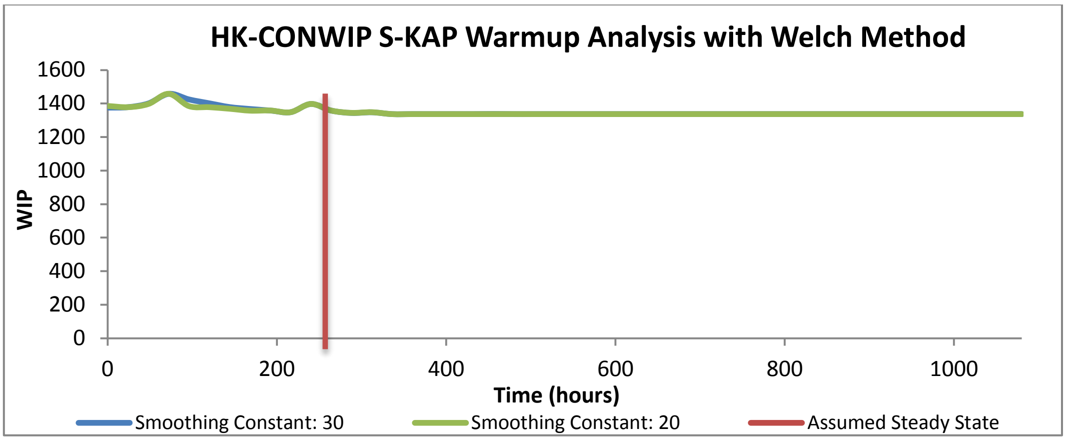


Figure B.12: Case 2 Welch graph of HK-CONWIP S-KAP for Window Sizes 20 & 30

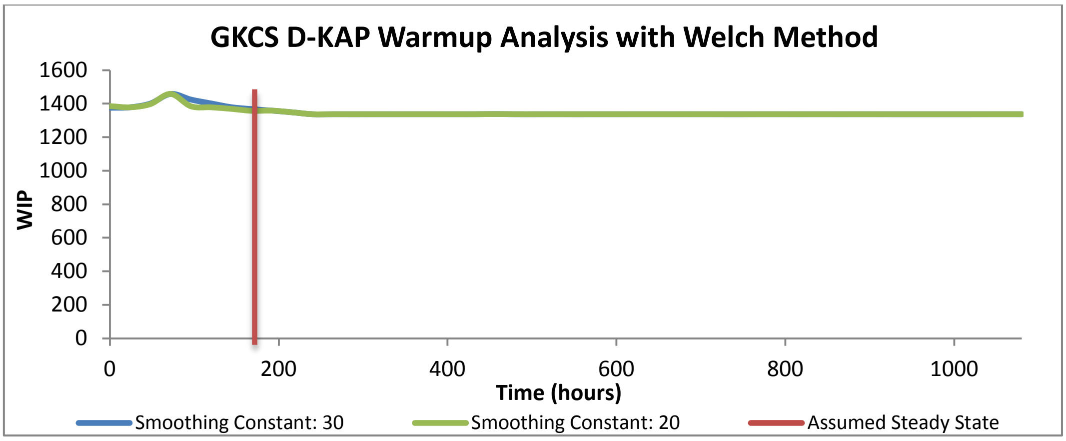


Figure B.13: Case 2 Welch graph of GKCS D-KAP for Window Sizes 20 & 30

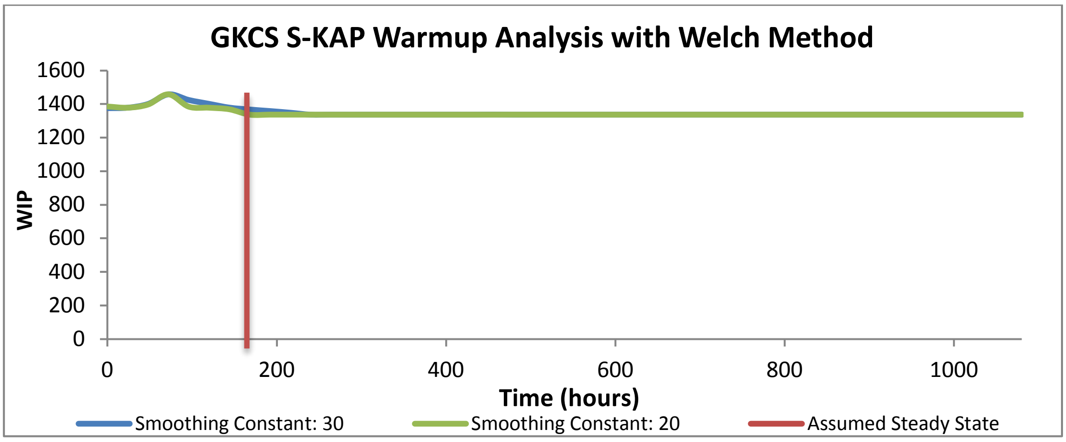


Figure B.14: Case 2 Welch graph of GKCS S-KAP for Window Sizes 20 & 30

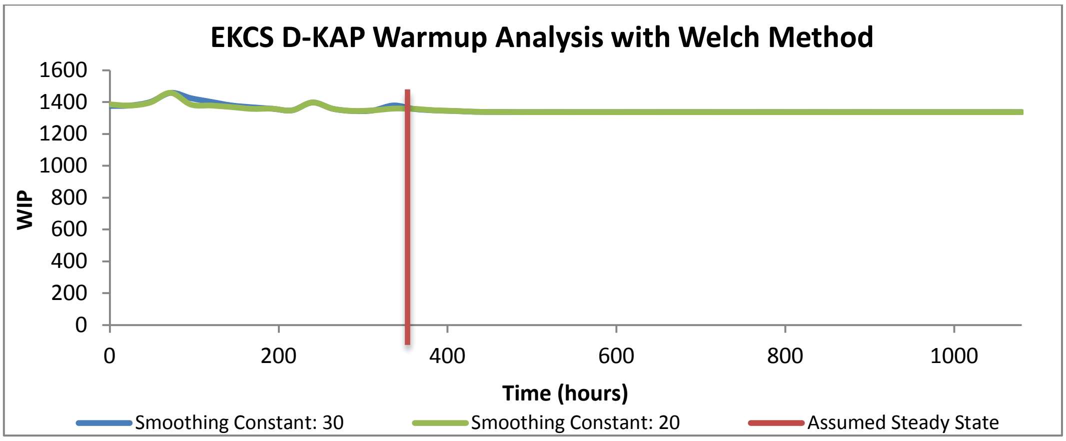


Figure B.15: Case 2 Welch graph of EKCS D-KAP for Window Sizes 20 & 30

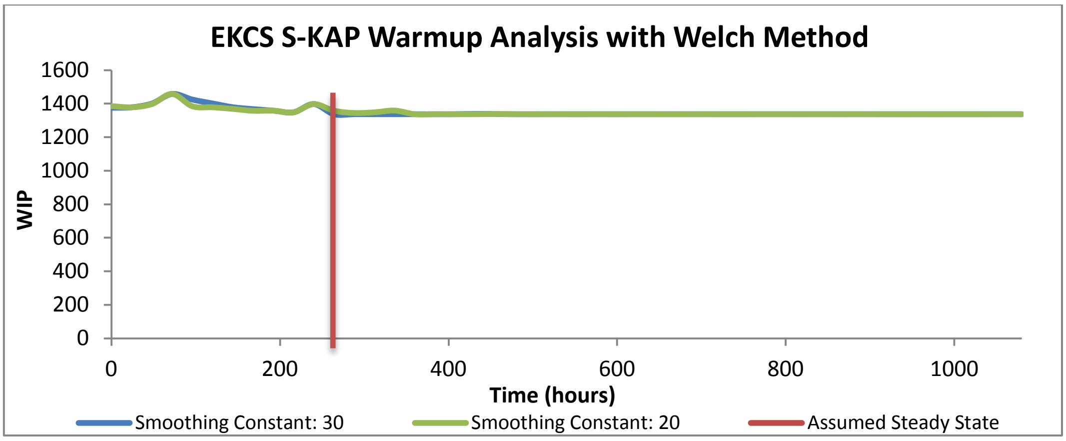


Figure B.16: Case 2 Welch graph of EKCS S-KAP for Window Sizes 20 & 30

APPENDIX C

Application of Nelson's Combined Procedure

Table C.1: Experiment 2 Case 2 Application of Nelson's combined procedure for screening and selection of the best PCS-KAP

PCS-KAP	i	n_0	$\bar{Y}_i$	S_i^2	j	W_{ij}	$\bar{Y}_i + \max(0, W_{ij} - \varepsilon)$	Keep?	N_i
HK-CONWIP D-KAP	1	30	1759.50	18893.80	2	1.182	1760.8	eliminate	584
					3	17.193	1761.32		
					4	11.833	1750.17		
					5	36.431	1343.631		
					6	17.193	1225.59		
					7	11.833	1141.32		
					8	36.431	1091.871		
HK-CONWIP S-KAP	2	30	1753.80	18021.01	1	1.182	1791.5	eliminate	419
					3	17.009	1761.32		
					4	11.651	1750.17		
					5	36.481	1343.681		
					6	17.193	1225.59		
					7	11.833	1141.32		
					8	36.431	1091.871		
GKCS D-KAP	3	30	1761.32	18987.38	1	17.193	1791.5	eliminate	447
					2	17.009	1760.8		
					4	13.537	1750.17		
					5	34.053	1341.253		
					6	17.009	1225.59		
					7	11.651	1141.32		
					8	36.481	1091.921		
GKCS S-KAP	4	30	1750.17	18859.01	1	11.833	1791.5	eliminate	592
					2	11.651	1760.8		
					3	13.537	1761.32		
					5	35.779	1342.979		
					6	17.193	1225.59		
					7	11.833	1141.32		
					8	36.431	1091.871		
EKCS D-KAP	5	30	1337.20	20985.78	1	36.431	1797.931	eliminate	754
					2	36.481	1767.281		
					3	34.053	1765.373		
					4	35.779	1755.949		
					6	17.009	1225.59		
					7	11.651	1141.32		
					8	36.481	1091.921		
EKCS S-KAP	6	30	1225.59	20182.04	1	17.193	1791.5	eliminate	631
					2	17.193	1760.8		
					3	17.009	1761.32		
					4	17.193	1750.17		
					5	17.009	1337.2		
					7	13.537	1141.32		
					8	34.0.53	1089.493		
BK-CONWIP D-KAP	7	30	1141.32	17824.63	1	11.833	1791.5	eliminate	587
					2	11.833	1760.8		
					3	11.651	1761.32		
					4	11.833	1750.17		
					5	11.651	1337.2		
					6	13.537	1225.59		
					8	35.779	1091.219		
BK-CONWIP S-KAP	8	30	1085.44	17830.12	1	36.431	1797.931	keep	523
					2	36.431	1767.231		
					3	36.481	1767.801		
					4	36.431	1756.601		
					5	36.481	1343.681		
					6	34.053	1229.643		
					7	35.779	1147.099		

Table C.2: Experiment 2 Case 2 Application of Nelson's combined procedure for selection of the best PCS-KAP

PCS-KAP	i	n_0	$\bar{Y}_i$	S_i^2	j	W_{ij}	$\bar{Y}_i + \max(0, W_{ij} - \varepsilon)$	**Keep?**	N_i
HK-CONWIP D-KAP	1	30	1759.50	18893.80	2	1.182	1760.8	eliminate	584
					3	17.193	1761.32		
					4	11.833	1750.17		
					5	36.431	1343.631		
					6	17.193	1225.59		
					7	11.833	1141.32		
					8	36.431	1091.871		
HK-CONWIP S-KAP	2	30	1753.80	18021.01	1	1.182	1791.5	eliminate	419
					3	17.009	1761.32		
					4	11.651	1750.17		
					5	36.481	1343.681		
					6	17.193	1225.59		
					7	11.833	1141.32		
					8	36.431	1091.871		
GKCS D-KAP	3	30	1761.32	18987.38	1	17.193	1791.5	eliminate	447
					2	17.009	1760.8		
					4	13.537	1750.17		
					5	34.053	1341.253		
					6	17.009	1225.59		
					7	11.651	1141.32		
					8	36.481	1091.921		
GKCS S-KAP	4	30	1750.17	18859.01	1	11.833	1791.5	eliminate	592
					2	11.651	1760.8		
					3	13.537	1761.32		
					5	35.779	1342.979		
					6	17.193	1225.59		
					7	11.833	1141.32		
					8	36.431	1091.871		
EKCS D-KAP	5	30	1337.20	20985.78	1	36.431	1797.931	eliminate	754
					2	36.481	1767.281		
					3	34.053	1765.373		
					4	35.779	1755.949		
					6	17.009	1225.59		
					7	11.651	1141.32		
					8	36.481	1091.921		
EKCS S-KAP	6	30	1225.59	20182.04	1	17.193	1791.5	eliminate	631
					2	17.193	1760.8		
					3	17.009	1761.32		
					4	17.193	1750.17		
					5	17.009	1337.2		
					7	13.537	1141.32		
					8	34.0.53	1089.493		
BK-CONWIP D-KAP	7	30	1141.32	17824.63	1	11.833	1791.5	eliminate	587
					2	11.833	1760.8		
					3	11.651	1761.32		
					4	11.833	1750.17		
					5	11.651	1337.2		
					6	13.537	1225.59		
					8	35.779	1091.219		
BK-CONWIP S-KAP	8	30	1085.44	17830.12	1	36.431	1797.931	keep	523
					2	36.431	1767.231		
					3	36.481	1767.801		
					4	36.431	1756.601		
					5	36.481	1343.681		
					6	34.053	1229.643		
					7	35.779	1147.099		

Table C.3: Experiment 3 Case 2 Summary of application of Nelson's combined procedure on the three performance metrics

Data-set	Perfor-mance Metrics	BK-CONWIP S-KAP	BK-CONWIP D-KAP	EKCS S-KAP	EKCS D-KAP	GKCS S-KAP	GKCS D-KAP	HK-CONWIP S-KAP	HK-CONWIP D-KAP
A	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Keep	Keep	Keep	Keep	Keep	Keep
	TSL	Keep	Keep	Keep	Keep	Keep	Keep	Keep	Keep
B	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Keep	Keep	Eliminate	Eliminate	Keep	Keep
	TSL	Keep	Keep	Keep	Keep	Eliminate	Eliminate	Keep	Keep
C	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate
D	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
E	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
F	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
Sum mary	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate

Table C.4: Experiment 3 Case 2 Application of Nelson's combined procedure for screening and selection of the best PCS-KAP

PCS-KAP	i	n_0	$\bar{Y}_i$	S_i^2	j	W_{ij}	$\bar{Y}_i + \max(0, W_{ij} - \varepsilon)$	**Keep?**	N_i
					2	1.182	1269.9		
					3	17.193	1295.3		
					4	11.833	1257.29		
HK-CONWIP D-KAP	1	30	1301.44	1494.63	5	36.431	1066.981	eliminate	330
					6	17.193	1051.93		
					7	11.833	1055.64		
					8	36.431	973.851		
					1	1.182	1301.44		
					3	17.009	1295.3		
					4	11.651	1257.29		
HK-CONWIP S-KAP	2	30	1269.90	1487.14	5	36.481	1067.031	eliminate	329
					6	17.193	1051.93		
					7	11.833	1055.64		
					8	36.431	973.851		
					1	17.193	1301.44		
					2	17.009	1269.9		
					4	13.537	1257.29		
GKCS D-KAP	3	30	1295.30	1596.30	5	34.053	1064.603	eliminate	359
					6	17.009	1051.93		
					7	11.651	1055.64		
					8	36.481	973.901		
					1	11.833	1301.44		
					2	11.651	1269.9		
					3	13.537	1295.3		
GKCS S-KAP	4	30	1257.29	1413.51	5	35.779	1066.329	eliminate	347
					6	17.193	1051.93		
					7	11.833	1055.64		
					8	36.431	973.851		
					1	36.431	1307.871		
					2	36.481	1276.381		
					3	34.053	1299.353		
EKCS D-KAP	5	30	1060.55	1092.19	4	35.779	1263.069	eliminate	418
					6	17.009	1051.93		
					7	11.651	1055.64		
					8	36.481	973.901		
					1	17.193	1301.44		
					2	17.193	1269.9		
					3	17.009	1295.3		
EKCS S-KAP	6	30	1051.93	1191.51	4	17.193	1257.29	eliminate	374
					5	17.009	1060.55		
					7	13.537	1055.64		
					8	34.0.53	971.473		
					1	11.833	1301.44		
					2	11.833	1269.9		
					3	11.651	1295.3		
BK-CONWIP D-KAP	7	30	1055.64	1227.35	4	11.833	1257.29	eliminate	235
					5	11.651	1060.55		
					6	13.537	1051.93		
					8	35.779	973.199		
					1	36.431	1307.871		
					2	36.431	1276.331		
					3	36.481	1301.781		
BK-CONWIP S-KAP	8	30	967.42	1014.96	4	36.431	1263.721	keep	201
					5	36.481	1067.031		
					6	34.053	1055.983		
					7	35.779	1061.419		

Table C.5: Experiment 3 Case 2 Test 1-summary of application of Nelson's combined procedure on the three performance metrics

Data-set	Perfor-mance Metrics	BK-CONWIP S-KAP	BK-CONWIP D-KAP	EKCS S-KAP	EKCS D-KAP	GKCS S-KAP	GKCS D-KAP	HK-CONWIP S-KAP	HK-CONWIP D-KAP
A	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Keep	Keep	Keep	Keep	Keep	Keep
	TSL	Keep	Keep	Keep	Keep	Keep	Keep	Keep	Keep
B	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
C	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
D	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
Sum mary	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate

Table C.6: Experiment 3 Case 2 Test 2-summary of application of Nelson's combined procedure on the three performance metrics

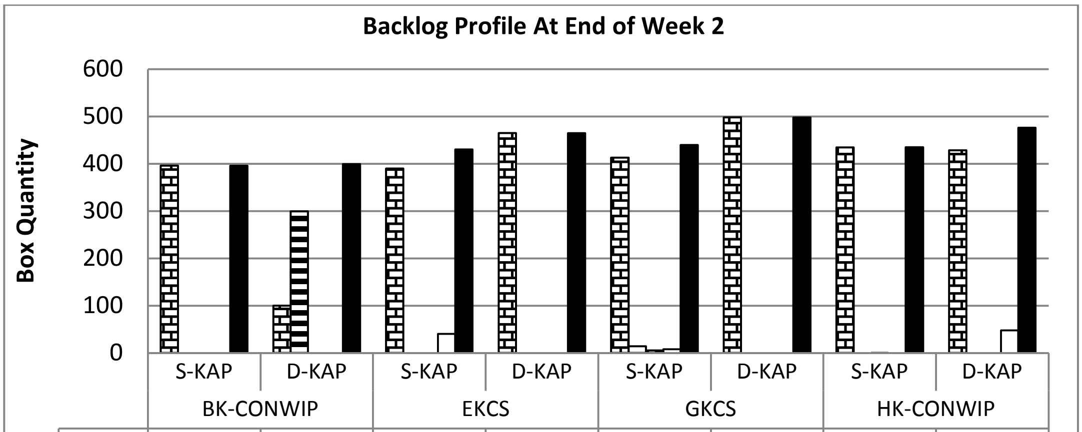
Data-set	Perfor-mance Metrics	BK-CONWIP S-KAP	BK-CONWIP D-KAP	EKCS S-KAP	EKCS D-KAP	GKCS S-KAP	GKCS D-KAP	HK-CONWIP S-KAP	HK-CONWIP D-KAP
A	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
B	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
C	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
D	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
Sum mary	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate

Table C.7: Experiment 3 Case 2 Test 3-summary of application of Nelson's combined procedure on the three performance metrics

Data-set	Perfor-mance Metrics	BK-CONWIP S-KAP	BK-CONWIP D-KAP	EKCS S-KAP	EKCS D-KAP	GKCS S-KAP	GKCS D-KAP	HK-CONWIP S-KAP	HK-CONWIP D-KAP
A	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
B	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
C	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
D	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
Sum mary	TWIP	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TBL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate
	TSL	Keep	Keep	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate	Eliminate

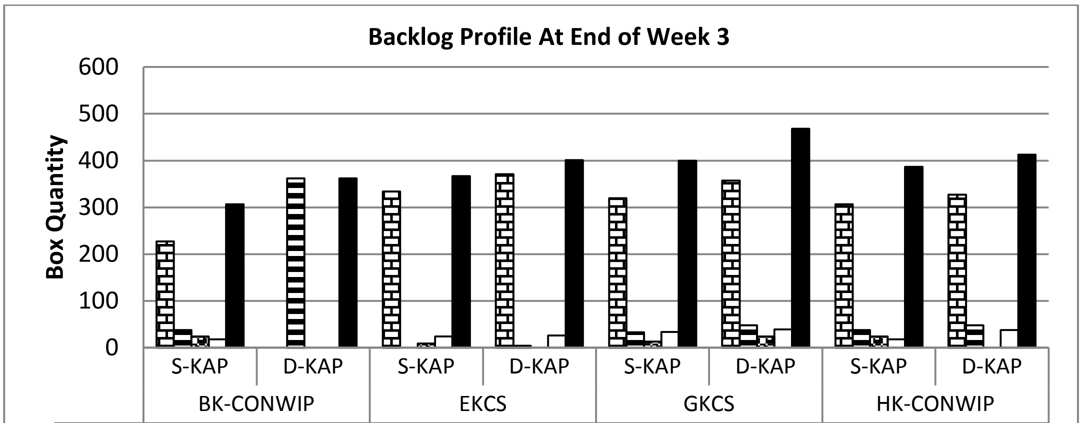
APPENDIX D

PCS-KAP Results of End of the Week Backlog Position



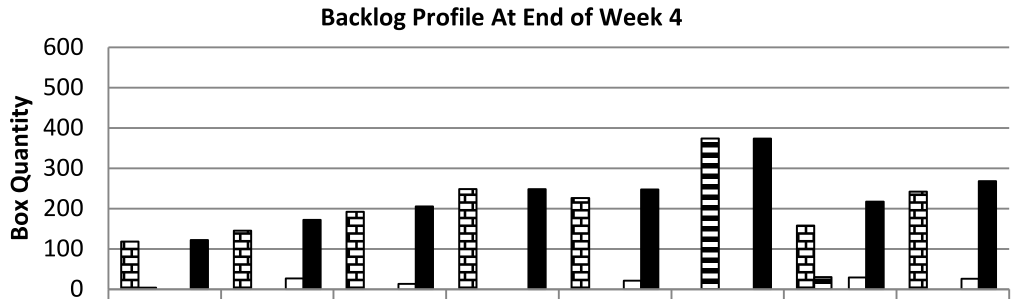
	BK-CONWIP S-KAP	BK-CONWIP D-KAP	EKCS S-KAP	EKCS D-KAP	GKCS S-KAP	GKCS D-KAP	HK-CONWIP S-KAP	HK-CONWIP D-KAP
P1	396	100	390	465	413	498	434	428
P2	0	299	0	0	14	0	0	0
P3	0	0	0	0	5	0	1	0
P4	0	0	40	0	8	0	0	48
Total	396	399	430	465	440	498	435	476

Figure D.1: Experiment 4 Case 2 End of the week 2 backlog positions



	BK-CONWIP S-KAP	BK-CONWIP D-KAP	EKCS S-KAP	EKCS D-KAP	GKCS S-KAP	GKCS D-KAP	HK-CONWIP S-KAP	HK-CONWIP D-KAP
P1	227	0	334	371	320	357	307	327
P2	38	362	0	4	33	48	38	48
P3	24	0	9	0	13	24	24	0
P4	18	0	24	26	34	39	18	38
Total	307	362	367	401	400	468	387	413

Figure D.2: Experiment 4 Case 2 End of the week 3 backlog positions



	BK-CONWIP S-KAP	BK-CONWIP D-KAP	EKCS S-KAP	EKCS D-KAP	GKCS S-KAP	GKCS D-KAP	HK-CONWIP S-KAP	HK-CONWIP D-KAP
P1	118	145	192	248	226	0	158	242
P2	4	0	0	0	0	374	30	0
P3	0	0	0	0	0	0	0	0
P4	0	27	13	0	21	0	29	26
Total	122	172	205	248	247	374	217	268

Figure D.3: Experiment 4 Case 2 End of the week 4 backlog positions

APPENDIX E

Curvature Analysis

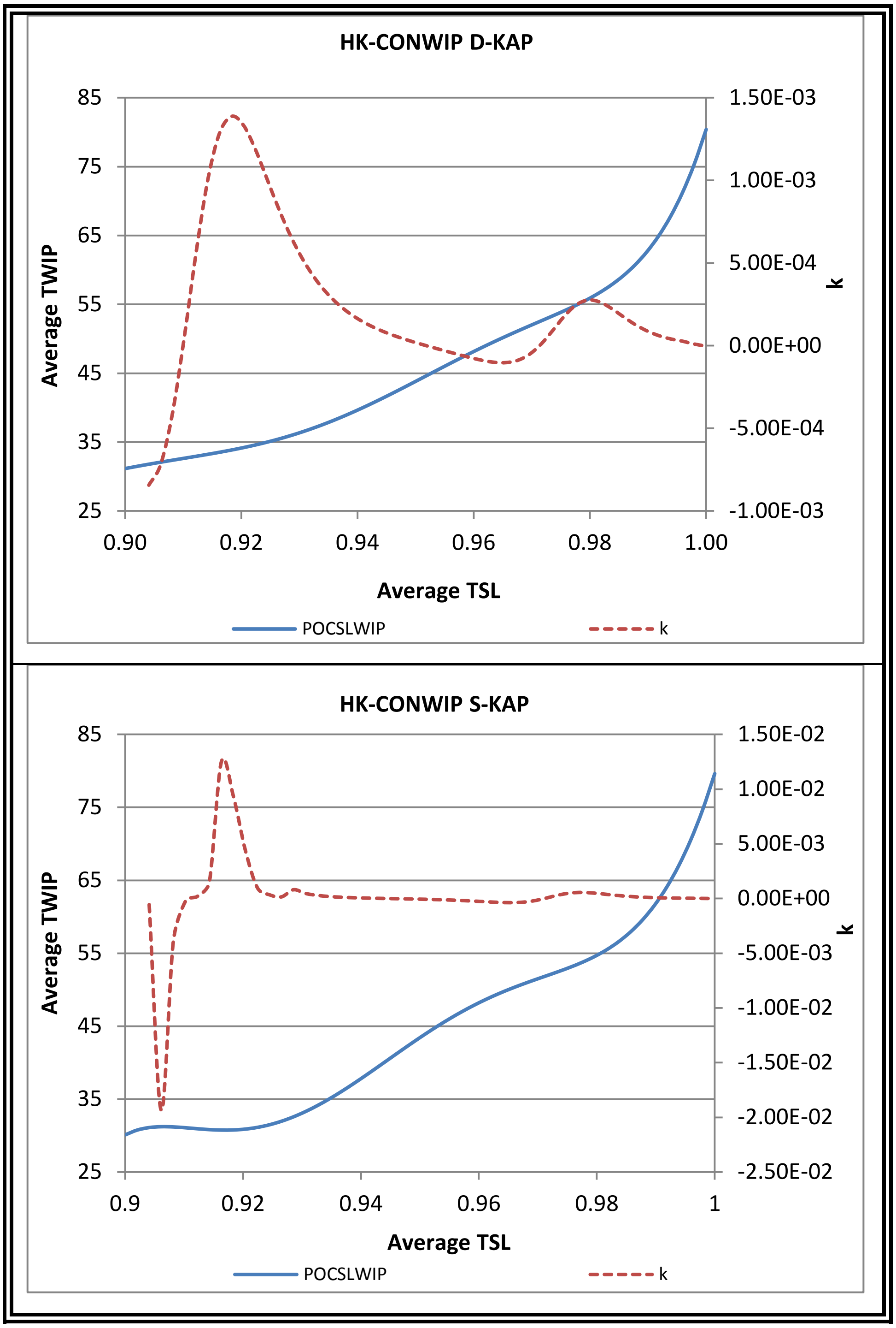


Figure E.1: Case 1 HK-CONWIP curvature analysis plot

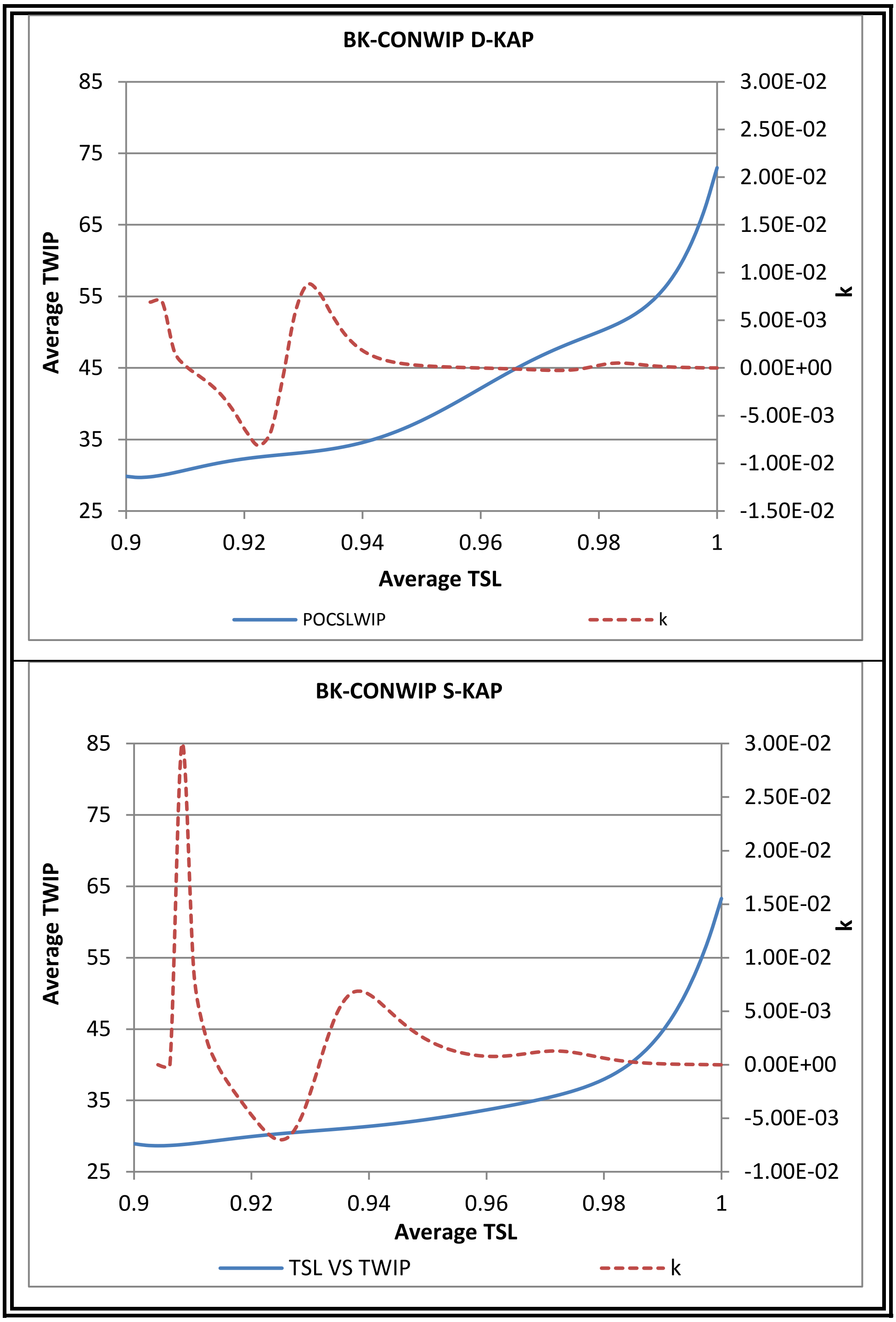
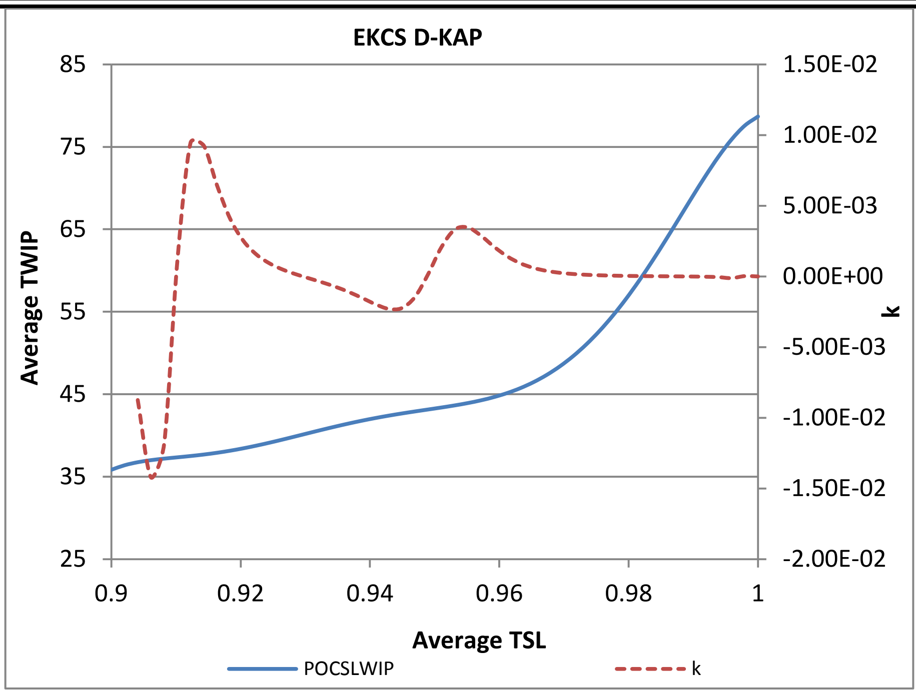


Figure E.2: Case 1 BK-CONWIP curvature analysis plot



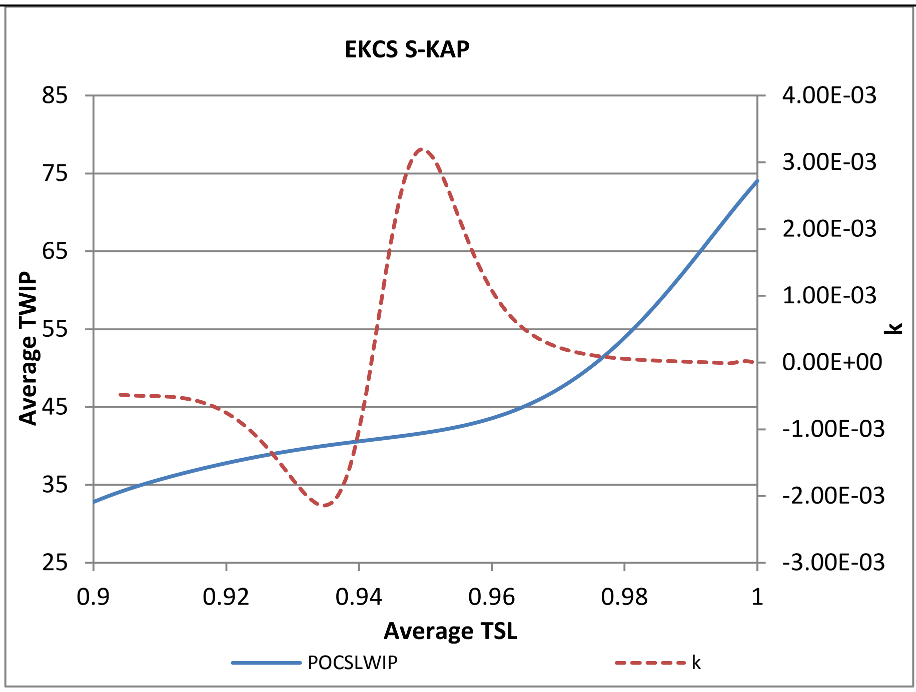


Figure E.3: Case 1 EKCS curvature analysis plot

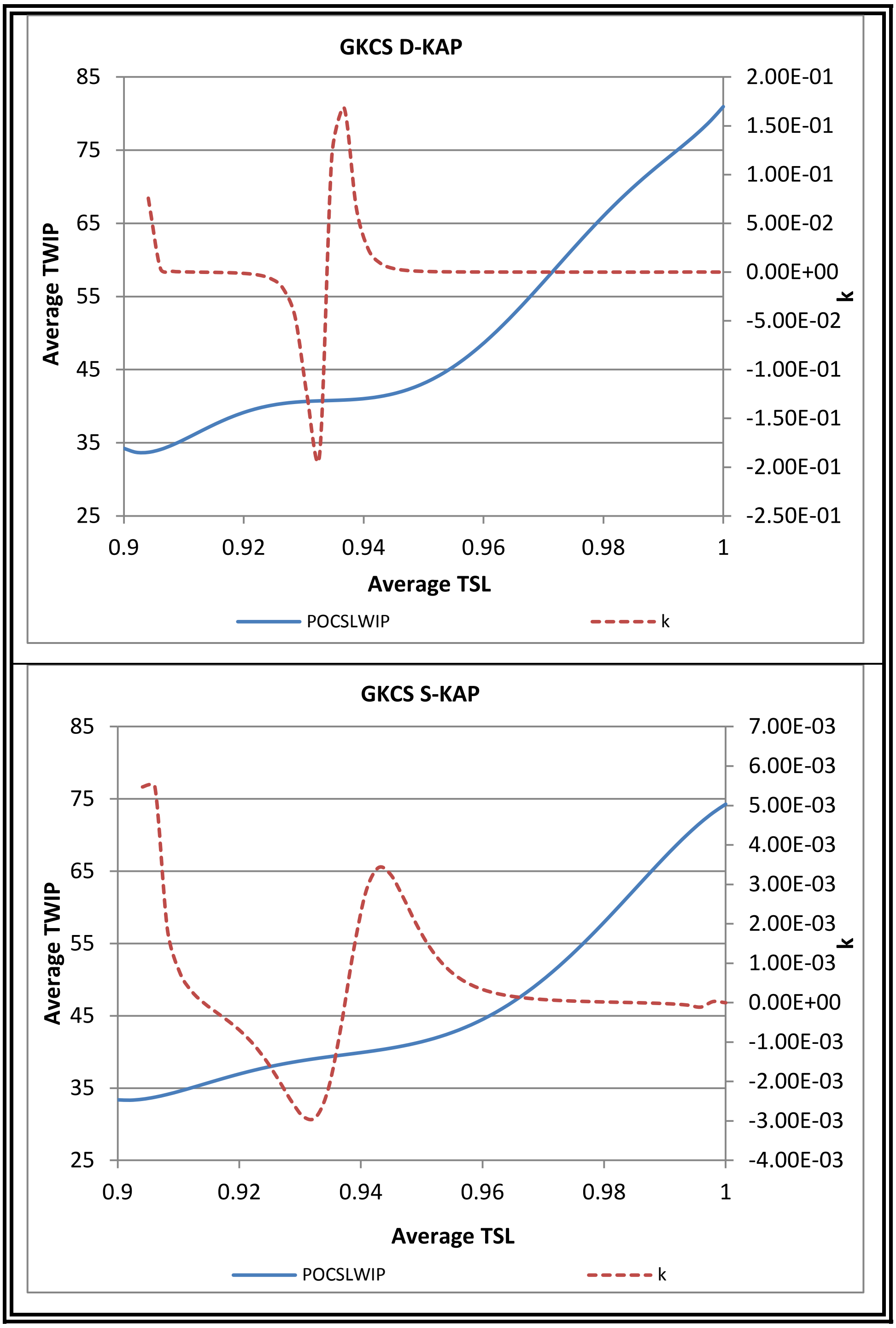


Figure E.4: Case 1 GKCS curvature analysis plot

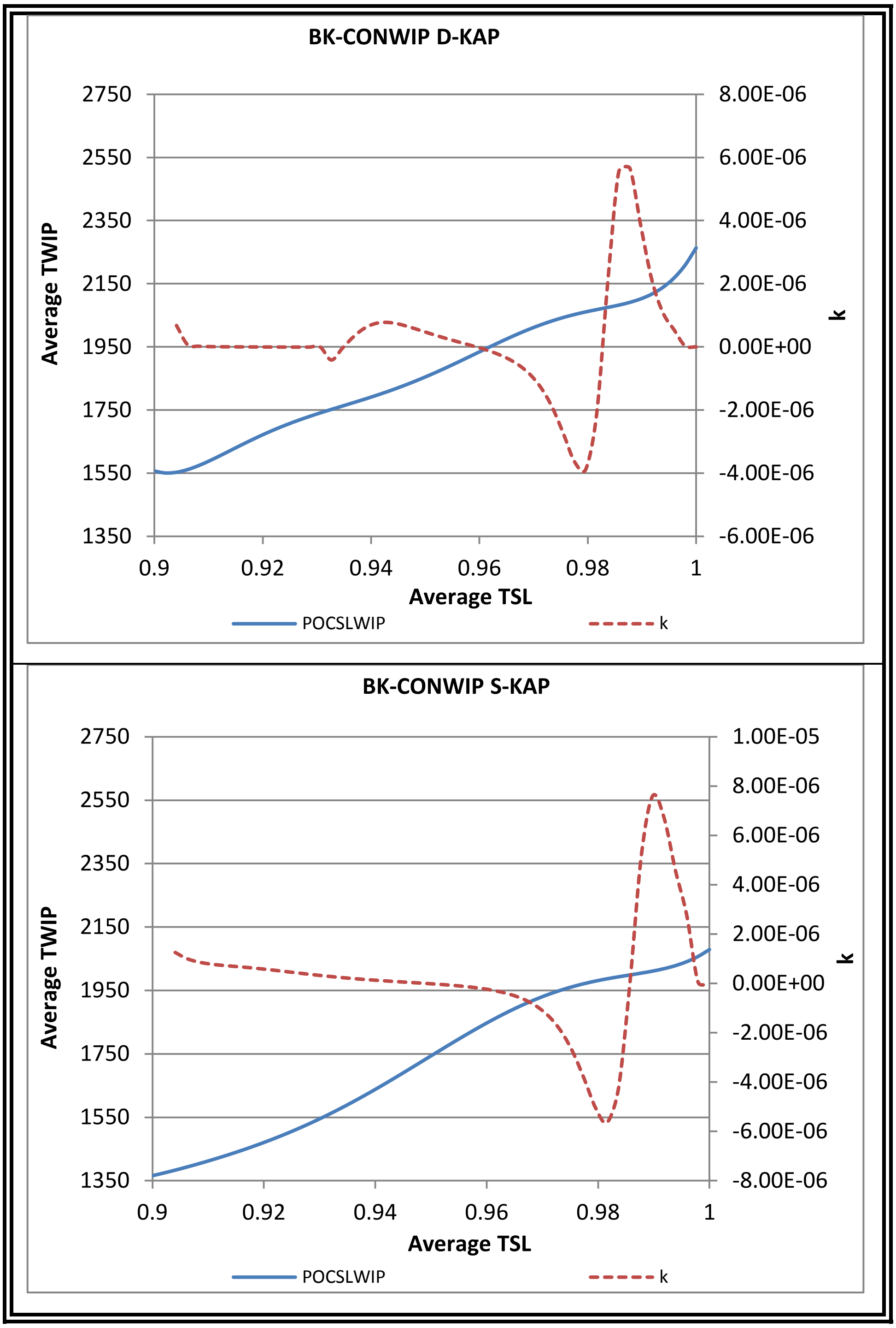


Figure E.5: Case 2 BK-CONWIP curvature analysis plot

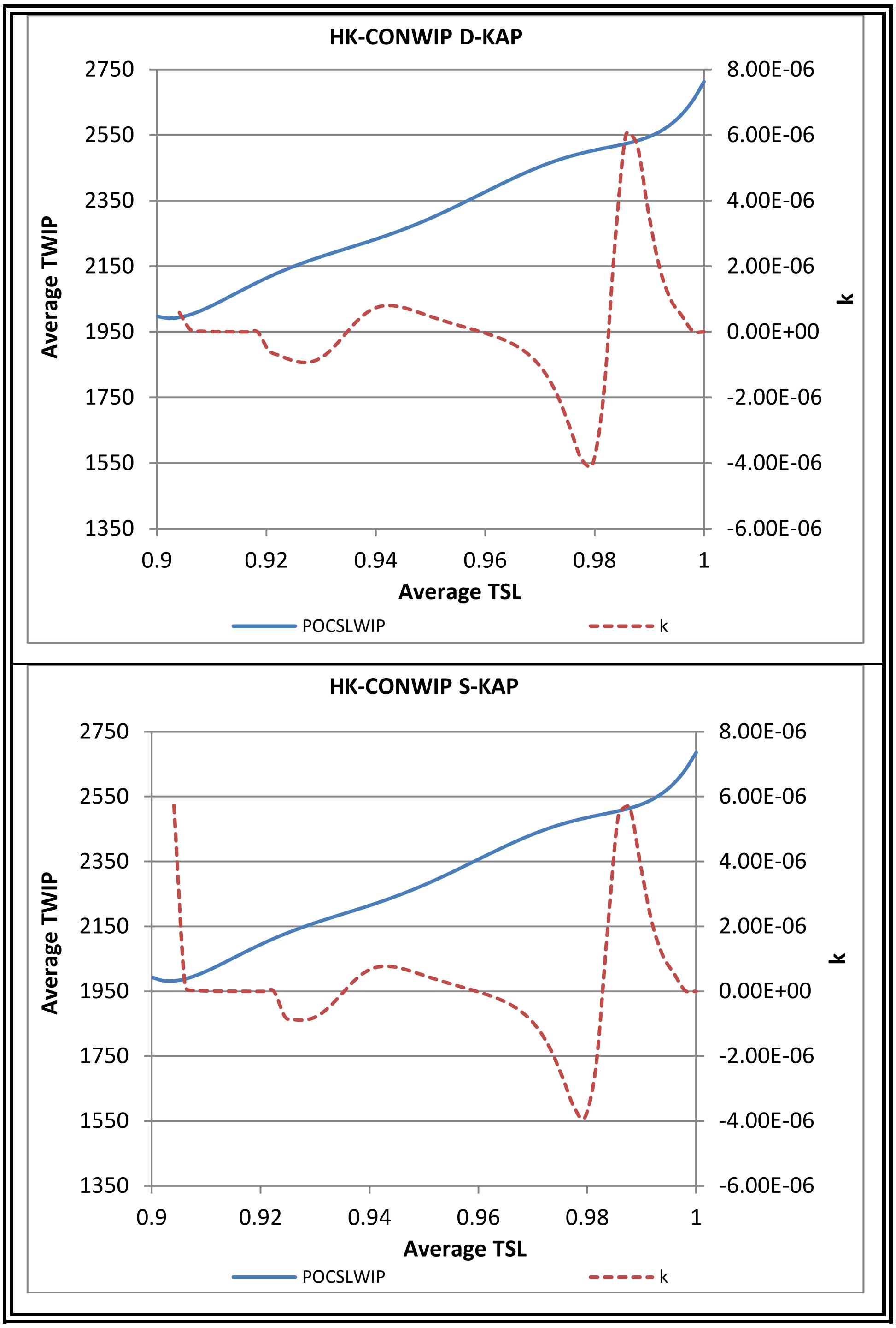


Figure E.6: Case 2 HK-CONWIP curvature analysis plot

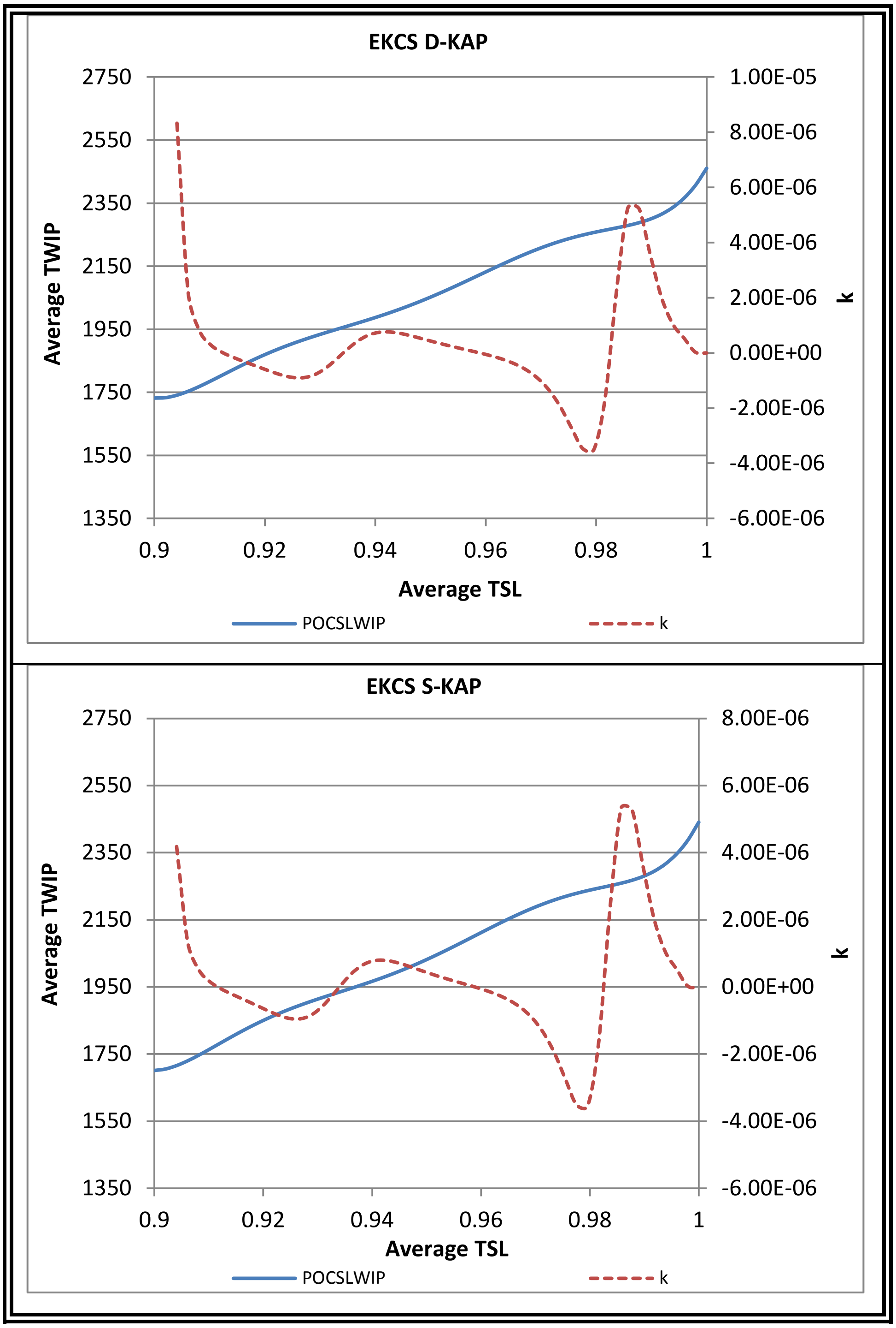
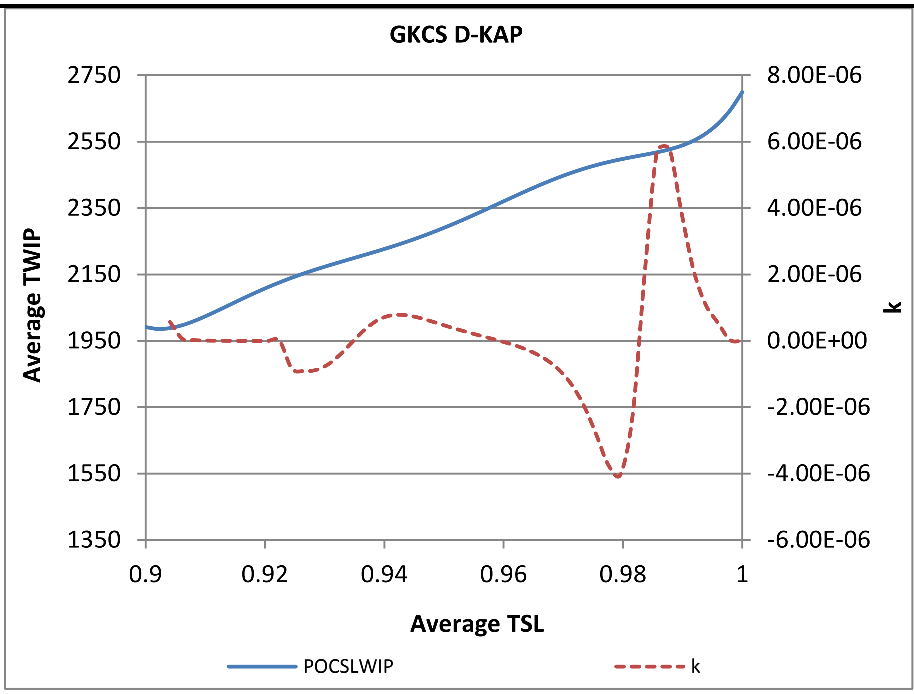


Figure E.7: Case 2 EKCS curvature analysis plot



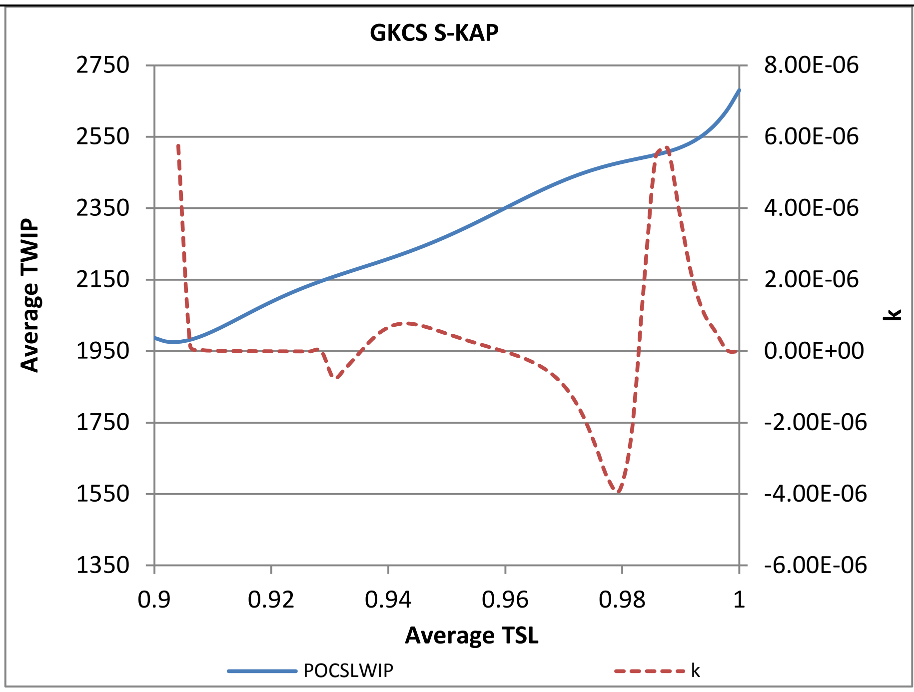


Figure E.8: Case 2 GKCS curvature analysis plot

APPENDIX F

Software Products Used

[1] ExtendSim Software version 8.0.2 (2011),
Imagine That Inc., San Jose, C.A.,
United States of America.
www.extendsim.com

[2] JMP® Statistical Discovery™. version 10.(2011)
SAS Institute Inc. 2012.
SAS Campus Drive
Building T
Cary, NC 27513
1.919.677.8000
(www.jmp.com),

[3] Vose Software. ModelRisk 5. (2012); version 5.1.0.0.
Franklin Rooseveltlaan 348
Gent, 9000
Belgium
www.vosesoftware.com/

[4] Excel 2010
Microsoft Corporation 1 Microsoft Way Redmond WA
USA
http://www.microsoft.com