INVESTIGATION OF WIP MANAGEMENT FOR CONTROL OF SEMICONDUCTOR MANUFACTURING SEGMENTS

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PhD

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INVESTIGATION OF WIP MANAGEMENT FOR CONTROL OF SEMICONDUCTOR MANUFACTURING SEGMENTS

By

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LIST OF ACRONYMS/ABBREVIATIONS

ABC	Artificial Bee Colony
Ca	Coefficient of Variation of Arrivals
CONWIP	Constant Work In Process
CR	Critical Ratio
CRN	Common Random Number
CT	Cycle Time
DBR	Drum Buffer Rope
EDD	Earliest Due Date
Fab	Wafer Fabrication Facility
FCFS	First Come First Serve
FIFO	First In First Out
GA	Genetic Algorithm
GPOLCA	Paired-Cell Overlapping Loops of Cards with Authorization
HL/MRP	High-Level Materials Requirements Planning
IC	Integrated Circuit
ICMR	Irish Centre for Manufacturing Research
ICONWIP	Inter arrival time CONWIP
IDep	Insulation Deposition
IEtch	Insulation Etch
IPol	Insulation Planarization-Insulation Thickness
LAlign	Pattern Alignment Check
LCONWIP	Looped CONWIP
LDim	Pattern Dimension Check-Etch Dimension Check
LDS	Least Dynamic Slack

LIFO	Last In First Out
LPat	Lithography Patterning
LRPT	Longest Remaining Processing Time
m-CONWIP	Multiple CONWIP
MDep	Metal Deposition-Pad Deposition
MEtch	Metal Etch-Pad Etch
Minifab	Intel Five Machine Six Step Mini-Fab
MRP	Materials Requirements Planning
MTBA	Mean Time Between Arrivals
MTBF	Mean Time Between Failures
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
POLCA	Paired-Cell Overlapping Loops of Cards with Authorization
RWash	Resist Removal
SA	Starvation Avoidance
SiO_2	Silicon Dioxide
SRPT	Shortest Remaining Processing Time
SST	Shortest Setup Time
TBA	Time Between Arrivals
TCheck	Thickness Check-Check
TH	Throughput Rate
TTF	Time to Failure
TTR	Time to Repair
U	Utilisation
U*	Fab Utilisation
U_{max}	Maximum Utilisation

UofA	Utilisation of Availability
V	Variance
VDep	Via Deposition
VPol	Via Planarization
WIP	Work In Process
WR	Workload Regulating
WSPW	Wafer Start Per Week

Ingy A. El-Khouly

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ABSTRACT

The process of wafer fabrication is arguably the most technologically complex stage in semiconductor manufacturing. This manufacturing environment has a number of unusual features. Probably re-entrancy of lots and unbalanced production facilities are two of the most important and unique features of semiconductor wafer fabrication facilities (fabs) that necessitate lot flow control and effective scheduling. Flow control is achieved by a lot release control strategy which specifies when new lots are to be released into the fab. This work starts with analysing the effect of controlling lot releases on a set of performance metrics. Most popular push and pull control strategies were first used to control lot releases in the Intel Five Machine Six Step Minifab. Then a representative segment of an existing wafer fabrication facility operating with the latest technologies used in the semiconductor manufacturing, which captures the challenges involved in scheduling these complex manufacturing systems. Afterwards, based on review of literature and a classification of lot release control strategies, different lot release control strategies were selected and tested to evaluate and compare their effect on the performance metrics. These tests were conducted using simulation models that have been developed for both the Minifab and the representative segment. Results of the simulation study has shown that pull lot release control strategies can achieve same throughput rate with lower cycle times and work-in-process (WIP) levels compared to traditional push systems. However, further analysis of arrivals variability and WIP distribution has shown that the performance metrics can be further improved by reducing the variability of arrivals; this is done by modifying the CONWIP to control the release of lots into the model and reduce the interarrival variability (ICONWIP). Moreover, further analysis showed that application of these strategies lead to unbalanced distribution of WIP across the

segment. To address this, a Looped CONWIP (LCONWIP)strategy which balances this load by looking the WIP in each re-entrant loop, was developed. This improves the performance while maintaining a balanced load across the line. The results of the simulation have shown that ICONWIP outperforms both LCONWIP and the traditional CONWIP at reducing the WIP levels and cycle times.

1 INTRODUCTION

Semiconductor manufacturing is facing an increasing worldwide competition and is a rapidly growing industry. It has been demonstrated that the number of transistors on integrated circuits doubles approximately every 2 years. Consequently new technologies appear that lead to a rapid obsolescence of products, an increasing pressure on the cost of wafers due to worldwide competition, and high customer requirements in terms of quality [1].

A significant feature of semiconductor wafer fabrication is the re-entrant flow of wafers; where, a wafer revisits the same machines several times to produce different layers. This is because the different wafer layers require a similar fabrication process and also due to the fact that in semiconductor wafer fabrication the machines used in the production line are extremely expensive and comprise 70% of the total cost of the fabrication facility [2].

Semiconductor wafer fabrication is considered to be one of the most difficult manufacturing environments to control [3]. Millions of dollars are tied up in capital equipment, therefore equipment utilisation is of great importance [4, 5].

Objectives like throughput rate, cycle time, WIP, and utilisation must be improved to push the technological development and secure the existence of semiconductor manufacturers in a rapid growing global market especially in the frontend of the semiconductor manufacturing processes, which is the wafer fabrication. Consequently, reducing inventories, decreasing cycle time, and improving the utilisation of resources are very important issues in this industry [6]. Thus, any reductions in cycle time can cause substantial productivity improvements and eventually lead to a capacity increase at no investment cost. Therefore, cycle time improvements become strategic targets for companies that want to maintain competitive advantages [7].

Since it is preferable that wafers are always available to be processed; in general, wafers are pushed into the production line rather than released dependent on the state of the production facility. Hence, wafers end up spending most of the time in queues waiting for machines to become available, and consequently high equipment utilisation is maintained. Pushing wafers also results in high levels of work-in-process inventory (WIP) and long cycle times.

However, the selection, implementation and management of the appropriate manufacturing control system can play an important role towards meeting the rapidly changing market needs and to pay off the prohibitively expensive investment [3, 8].

Literature focuses on two approaches: high utilisation of expensive equipment and reduction of cycle times. The end results of the approach that focuses on the utilisation is high levels of WIP, long and variable cycle times due to waiting for an available machine in long queues at stations, poor due date performance, and considerable expediting to get the right products from the fab, in spite of maintaining high utilisation of equipment [4]. It should be noted that this approach is commonly applied in most of the semiconductor wafer fabrication facilities to make the maximum use of the expensive equipment.

The other approach focuses on reducing the cycle times, which is considered as a key performance criterion, since reducing cycle time can decrease WIP for any given level of throughput rate, and improve the fab's ability to respond to market fluctuations [9].

In this work, both approaches are applied to the Intel Five-Machine Six Step Mini-Fab (Minifab) that is selected as a test bed because it captures some of the challenges involved in the re-entrant semiconductor wafer fabrication facilities. Experiments and analysis of CONWIP simulation results of the Minifab show that there is high variability in the arrival of lots. As a result, a new lot release control strategy (named ICONWIP) is proposed which regulates the arrivals to the Minifab and reduces its variability of arrivals. Results of simulation experiments and analysis of the ICONWIP strategy have shown that cycle times and WIP levels can be reduced while still achieving the same target throughput level. It was also noticed that by setting deterministic inter-arrival times of lots introduction for push strategy better performance is attained when compared to CONWIP, further analysis has shown that is due to the fact that the only stochastic inputs to the

Minifab are the inter-arrival times and emergency breakdowns at one station only, yet; ICONWIP outperforms the other strategies.

Consequently, it is decided to test the applicability of the proposed ICONWIP strategy on larger models that include a greater number of machines, more processing steps and, exhibits complexity and variability characteristics more typical of real fabs.

Therefore, a representative segment based on an existing wafer fabrication facility [1] operating with the latest technologies used in semiconductor manufacturing has been selected and defined with the assistance of the Irish Centre for Manufacturing Research "ICMR", which works with a number of fabs and research institutes in Ireland and Europe to address the significant challenges involved in operating and controlling fabs. The Segment captures most of the challenges involved in real fabs such as high re-entrancy, complex batching and sampling, variable breakdowns…etc. Simulation results of the Segment have shown that ICONWIP outperforms CONWIP (which is in turn better than a push strategy) by reducing the WIP levels and cycle times.

When applying CONWIP to the Segment, it was apparent that WIP can be totally held at one or more stations due to the lengthy breakdowns. This wasn't evident in the Minifab; however, this occurred in the Segment due to the larger number of machines, the greater number of processes, high re-entrancy, and higher variability of time to failure and time to repair of stations. This unbalanced WIP distribution across the Segment is another issue that is addressed in this work. Different lot release control strategies that are based on a classification presented in this work were tested using simulation; namely:

- Checking the effect of using another lot release control strategy existing in literature, this strategy is from the bottleneck station control class (DBR).
- Testing the impact of combining a strategy from the multi-station control class (CONWIP) and the bottleneck station control class (DBR).

[1]Referred to as the Segment throughout the remaining text.

- Assessing the performance of the Segment using a modified CONWIP lot release control strategy termed Looped CONWIP (LCONWIP), which is a strategy from the variation and hybrid strategies class.

1.1 AIM AND OBJECTIVES OF THE WORK

1.1.1 Aim of the Work

The aim of this work is to improve the performance of a representative segment of an existing wafer fabrication facility operating with the latest technologies used in the semiconductor manufacturing by applying new lot release control strategies resulting from either combining or modifying lot release control strategies existing in literature.

1.1.2 Objectives of the Work

The objectives of this work include the following:

- Proposing a representative segment of an existing wafer fabrication facility operating with the latest technologies used in the semiconductor manufacturing that will be used as a test bed in literature.

- Assessing the effect of applying different push and pull strategies on the performance of the Minifab and the Segment.

- Evaluating the impact of applying two modified CONWIP lot release control strategies; one of them is developed and applied on the Minifab and then tested on the Segment, and the other one is developed and tested on the Segment only.

- Testing the effectiveness of developing a hybrid strategy by combining lot release control strategies in improving the performance of the Segment.

1.2 THESIS OUTLINE

The report consists of nine chapters and three appendices.

Chapter two covers a review of literature offering background and related work to this research.

Chapter three gives an overview to the research methodology applied in this work.

Chapter four presents a full description of the Minifab, along with the experiments, results and analysis that leads to proposing the ICONWIP lot release control strategy.

Chapter five covers a detailed description of the more representative system under study; the overall objectives together with the data collection are also presented.

Chapter six details the development of the simulation model, model verification and validation, moreover, a brief description of the modifications made to the model to represent applying different lot release control strategy.

Chapter seven includes the detailed experiments, results, and analysis including a preliminary analysis of the Segment and testing the applicability of the ICONWIP on the Segment. Moreover, further analysis to CONWIP results that leads to testing combining CONWIP and DBR, also LCONWIP lot release control strategy is proposed.

Chapter eight presents the discussions.

Chapter nine covers the conclusions and recommendations for future work.

Finally, the appendices include:

- Articles published in peer reviewed conferences as part of this work.
- Anonymised representative data from semiconductor manufacturing machines which operate in the same manner as those in the Segment to establish the mean time between failures for different classes of machine.
- The average utilisation of stations reported from the models at the end of every week for all the strategies tested.

2 LITERATURE REVIEW

This chapter starts with an introduction to semiconductor manufacturing in general with a focus on the complexity, inherent specifically in wafer fabrication. Then, manufacturing control systems are discussed and different lot release control strategies are presented. Afterwards a deeper review on previous research work relevant to one of the lot release control strategies presented is undertaken. Followed by an overview of modelling and simulation, which is an effective approach to analyse and predict the dynamic behaviour of such a complex system, with a detailed section describing the steps of the simulation study followed in this work. Finally, conclusions of the most important findings based on the review of literature are presented.

2.1 SEMICONDUCTOR MANUFACTURING

Semiconductor manufacturing is probably one of the most intensive manufacturing processes, not only for its complexity but for the amount of capital invested [10]. Semiconductors are all around us. They control the computers used to conduct business, the phones and mobile devices for communication, the cars and planes for transportation from place to place, the machines that diagnose and treat illnesses, the military systems for protection, and the electronic gadgets used to listen to music, watch movies and play games [11].

2.1.1 Semiconductor Industry Outlook

Not only does semiconductor technology make these devices possible, it also makes them more compact, less expensive, and more powerful. For example, in 1984, mobile phones weighed about 0.9 kg, cost around $4,000, and held a charge for only about 30 minutes of talk time. In 2014, smartphones are about 0.15 kg, cost consumers about $200, stay charged for around 8 hours of talk time, and come equipped with many added features such as advanced cameras and data packages [11].

Therefore, much of the electronics industry is based on semiconductor sales, which observed a significant progress over the past 20 years as presented in Figure 2-1, mainly as a result of the growing demand for the integrated circuit (IC) chips built using semiconductors. In fact, most other industries including the aerospace, communications, consumer electronics and automobile industry, rely heavily on IC chips, and in many ways the semiconductor is a fundamental basis of global technological improvement [12].

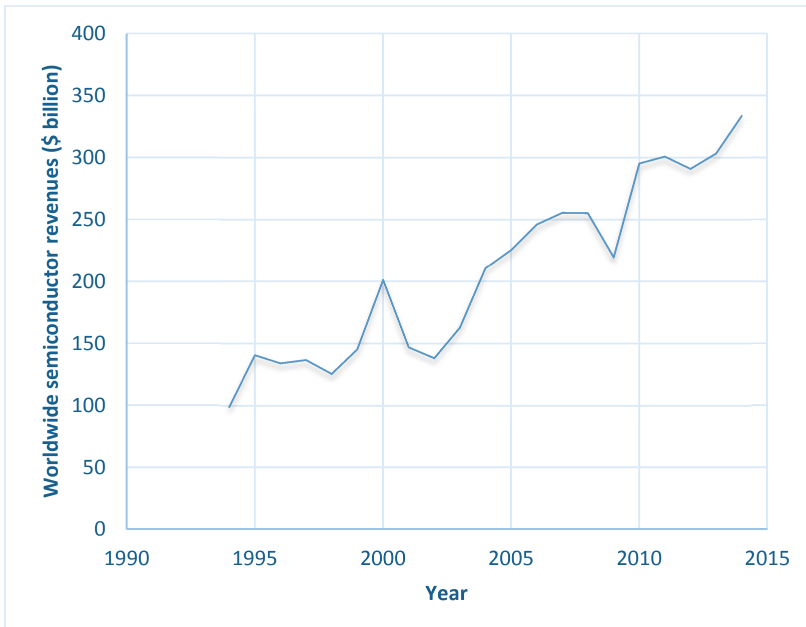

Figure 2-1: Increase in global semiconductor sales from 1994 to 2014 [13].

2.1.2 Stages in Semiconductor Manufacturing

Generally, the manufacturing of IC chips involves four major processes separated into two main categories; front-end manufacturing and back-end manufacturing [2] as shown in Figure 2-2.

- Front-end manufacturing includes the first two processes (wafer fabrication and wafer probe), which are dedicated to building the ICs in the silicon wafer as well as performing preliminary tests.

- Back-end manufacturing includes the second two processes (chip assembly and final test), that are focused on packaging of the ICs and testing functionality and performance.

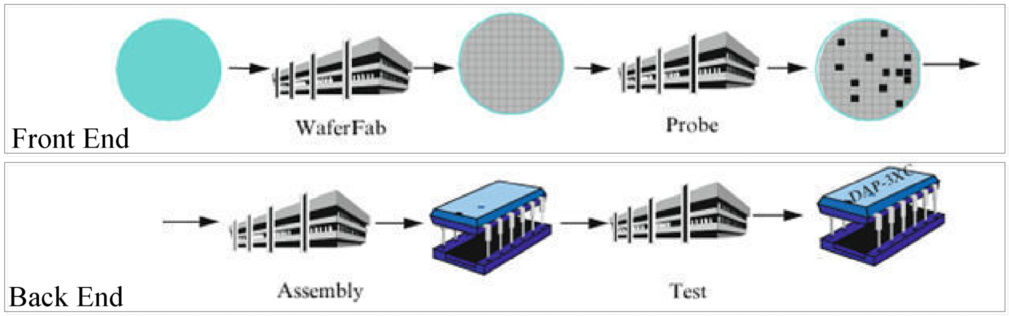

Figure 2-2: Major processes of semiconductor manufacturing, modified from [2].

2.1.3 Wafer Fabrication

Wafer fabrication is the most technologically sophisticated and capital intensive phase in semiconductor manufacturing. It is argued to be one of the most complex manufacturing processes found today. The wafer fabrication process is a complex process requiring several steps by special machines [1]. Figure 2-3 shows a description of the main steps of the wafer fabrication, which are as follows [14]:

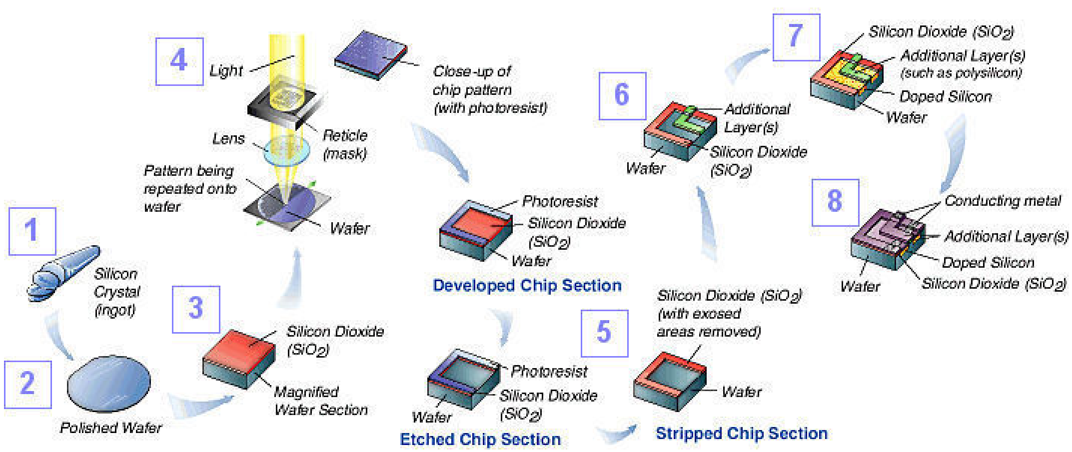

Figure 2-3: Wafer fabrication process [14].

1. To make wafers, silicon ingots are firstly sliced into wafers.

2. Each wafer is then polished to remove even the tiniest scratches and impurities as chips are built into this surface.

3. Deposition of a layer of silicon dioxide (SiO_2) is grown on the wafer. Later channels will be etched or otherwise formed into the dielectric for conducting materials. More layers of SiO_2 may also be deposited in later steps in the process as layers of circuits are added.

4. Photolithography, lithography for short, is a key step in the wafer fabrication process and is used to create the circuit patterns on a chip. Exposure to light in lithography causes portions of the resist to “harden”.

5. Etching then takes place where the “non-hardened” resist is washed away in a series of steps. The “hardened” resist by lithography is then stripped off so that the material underneath forms a three dimensional pattern on the wafer.

6. Several lithography and etch steps are repeated, building subsequent layers of various patterned materials on the wafer to form the multiple layer of circuit patterns on a single chip.

7. Doping process is used in certain areas of the wafer to control the flow of electricity through a chip.

8. Finally, all the millions of individual conductive pathways must be connected in order for the chip to function. This includes vertical interconnections between the layers as well as horizontal interconnections across each layer of the chip.

Although the process might seem to be similar to other manufacturing processes, yet it is characterized by its high technological complexity. It usually involves several hundreds of processing steps. Moreover, since the number of operations that have to be carried out exceeds the number of available machines, several of these operations are done at the same machines, resulting in visiting the same station several times. A manufacturing system having this feature is called a re-entrant flow line (see Figure 2-4) [2].

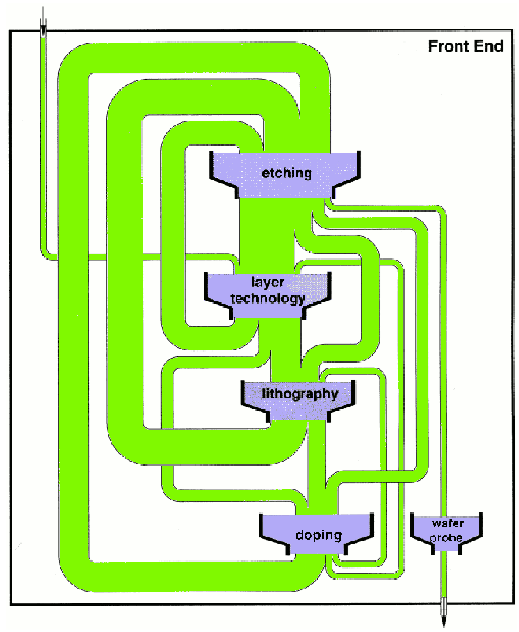

Figure 2-4: Re-entrant material flow, modified from [14].

Concisely, the success of a semiconductor manufacturing facility is determined by its ability to produce the right parts, at the right time, with the right quality in an extremely competitive environment. Although changes in technology such as larger wafer sizes and smaller chips have enhanced productivity, the highly complex nature of semiconductor manufacturing, if not managed properly, can result in high levels of WIP, long cycle times, and poor due-date performance [15]. Therefore, it is decided to study the manufacturing control systems in order to implement the most appropriate strategies that can improve the semiconductor wafer fabrication facility performance [3, 8].

2.2 MANUFACTURING CONTROL SYSTEMS

Manufacturing Control Systems can be classified into either push systems or pull systems. Generally, a push system is considered as an open system, which is based on demand forecast and has no feedback loop within its mechanism, whereas, a pull system is considered as a closed system that has a feedback loop within its mechanism [4, 16]. Although, most real world systems are actually hybrids or mixtures of push and pull [17], in this section pure push and pure pull systems are discussed to show the operating principles of both systems.

2.2.1 Push versus Pull

Push and Pull systems operate in opposite sense and have their own advantages and disadvantages [18]. The mechanism that triggers the movement of lots in the system distinguishes the push and the pull systems, as displayed in Figure 2-5.

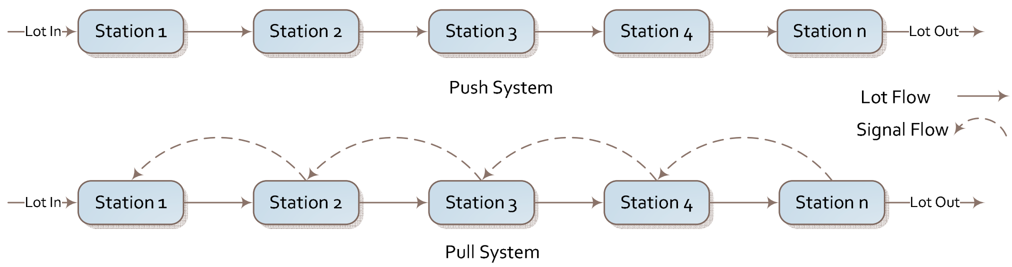

Figure 2-5: Push and Pull systems.

Basically, a push system releases a lot into the production line precisely when called to do so by an exogenous schedule driven by forecasts, and the release time is not modified according to what is happening in the process itself [17]. Briefly, Push systems are those where lots, when processing in a station is complete, are pushed to the following station for either processing or storage and hence throughput rate is controlled (providing that throughput rate is lower than bottleneck rate) and WIP is observed [18-21].

In contrast, a pull system only allows a lot to be released into the production line when a signal generated by a change in line status calls for it. Hence, the trigger for lot releases comes from outside a push system but from inside a pull system. [17]. Concisely, Pull systems are those where the entry of one lot is triggered by a signal from inside the production line, and the lot is pulled by the successive station instead of being pushed by the previous station and hence WIP is controlled and throughput rate is measured [18, 20, 21].

From the control perspective of WIP (pull) versus the control of throughput rate (push), Hopp and Spearman found that WIP is easier to control than throughput rate for two reasons [22]:

- First, WIP is directly observed while throughput rate cannot be observed directly and is controlled with respect to capacity which is estimated to specify the input rate.

- Second, WIP is a more robust control than throughput rate. For example, in a push system if the specified input rate is less than the capacity, then throughput rate is equal to input rate. If not, throughput is equal to capacity and WIP accumulates causing WIP explosion if unchecked regularly, and consequently cycle times can increase dangerously (as noted by Little's law that is given in Equation 2-1 and originally found in [23]). Thus, if the estimated capacity is incorrect the input can easily exceed the true capacity. However, this problem is avoided in a pull system because WIP is controlled and there is a limit on the maximum amount of WIP. Therefore, errors in setting WIP levels will degrade the performance of pull systems less than errors in estimating capacity will hurt the performance of push systems.

$$WIP = TH \times CT \qquad \text{Equation 2-1}$$

Where;

WIP is the work-in-process,

TH is the throughput rate, and

CT is the cycle time.

As mentioned earlier, most real-world systems have aspects of both push and pull. For instance, if a lot is scheduled to be released, but is held back because the production line is considered too congested, then the effect is a hybrid push-pull system. On the other hand, if a pull system generates a signal to release a lot but the release is delayed because of expected lack of demand for the lot (i.e. it is not called for in the master production schedule), then this is also a hybrid system [17].

2.2.2 Advantages and Disadvantages of Push and Pull Production Systems

A push system is based on long term demand forecast and lots are pushed through the production line, from the production upstream to the production downstream, this may enable the system to reduce delivery lead time since many semi-finished or finished products are available [19]. Though, releasing lots to a very congested line, only to have them get stuck somewhere in the middle may result in a loss of flexibility in several ways. First, lots that have been partially completed can't easily incorporate engineering (e.g. design) changes. Second, high WIP levels impede priority or scheduling changes, as lots may have to be moved out of the production line to make way for a high-priority lot. Third, if WIP levels are high, lots must be released to the production line well in advance of their due dates. Finally, because customer orders become less certain as the planning horizon is increased, the system may have to rely on forecasts of future demand to determine releases. Since, forecasts are never as accurate as one would like, this reliance serves to further degrade performance of the system [17].

A pull system that establishes a WIP cap can prevent these negative effects and thereby enhance the overall flexibility of the system. By preventing, release of lots when the factory is overly congested. This will facilitate engineering and priority/ scheduling changes. Also, releasing lots as late as possible will ensure that releases are based on right customer orders to the greatest extent possible. The net effect will be an increased ability to provide responsive customer service [17].

Therefore, in designing manufacturing control systems it is very critical to determine an effective or preferably the 'optimal' mechanism controlling the material flow within the system. In literature, these mechanisms are referred to as material flow control mechanisms, production and material flow control strategies, flow control policies, or, lot release control strategies, which is preferred in this work, because in semiconductor manufacturing, materials are moved on a lot basis. The following section describes some of these strategies.

2.3 LOT RELEASE CONTROL STRATEGIES

As mentioned previously, the flow of lots to the production line is controlled in pull systems by using lot release control strategies. In this work these strategies are classified based on how lots are controlled over the system. The diagram in Figure 2-6 shows that classification with the strategies falling under each class and reviewed in this work.

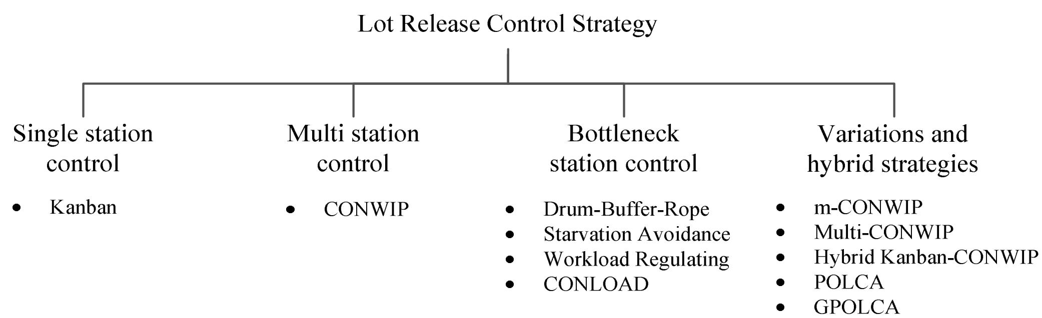

Figure 2-6: Classification of lot release control strategies.

In the above mentioned classification, lots are released to the production line based on a single station control, multi station control (up to all stations in a production line), bottleneck station control, or variations and hybrid strategies of the previously mentioned controls. A discussion of the lot release control strategies in each of these classes is given in the following sections.

2.3.1 Single Station Control

At single station control strategy every station in the production line has a loop that signals to call for a change in the production status. Where, the number of loops that cover the production line must be equal to the number of stations. Thus, a lot is released to the production line if a signal is generated due to a change in any of the stations status. An example of single station control strategy reviewed in this work is Kanban.

Kanban

A Kanban system is a simple system that relies on cards (Kanban in Japanese means card or ticket) to pull material into a production line when needed. The card has information about which lot to be released [24].

Figure 2-7 illustrates the mechanism of the Kanban lot release control strategy showing the backward signal flow from each station to the buffer before it that authorizes the release of lots to that station. Hence, Kanban can set WIP to a maximum level at every station based on the number of cards used.

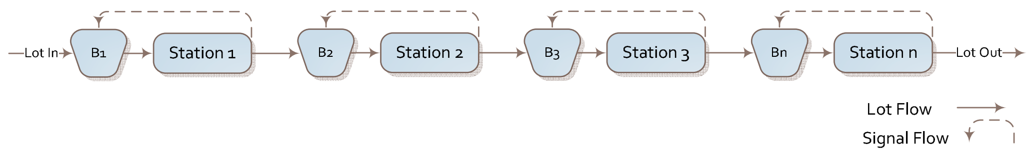

Figure 2-7: Kanban lot release control strategy.

Based on a literature review conducted in 2007 [18], different research work has been carried out to determine the optimum number of cards that can improve a set of performance measures such as WIP, cycle time, throughput rate… etc. Simulation, queuing models, mathematical models were among the methodologies and techniques reviewed.

Unfortunately, Kanban is not applicable to many manufacturing environments, it is pointed out that Kanban is dedicated to repetitive manufacturing; it will not work in a shop controlled by orders with short production runs, or significant set-ups, or scrap loss, or large, unpredictable fluctuations in demand, or even custom designs [25-30]. For this reason, Kanban has been subjected to ad hoc modifications to improve its performance, and 32 of these are reviewed in [31].

2.3.2 Multi Station Control

In multi-station control strategy, all the stations in the production line are grouped to have a single loop that trigger to call for a change in the production status. An Example of multi-station control strategy studied in this work is CONWIP lot release control strategy and is described in the following section.

CONWIP

CONWIP was first proposed in 1990 by Spearman *et al.* [26] as an alternative pull strategy to Kanban and argued that CONWIP offers the same advantages of Kanban with greater flexibility in terms of applicability to a wider variety of production environments. Since that time it has received a great deal of attention from researchers [32].

CONWIP is the simplest way to constraint the WIP level of a production line (generally referred to as establishing WIP cap). It sets a limit on the WIP level and simply does not allow releases into the line whenever the WIP is at or above the limit. This results in a *WIP* level that is nearly constant; hence, the strategy is called CONWIP (constant work in process) [17]. Figure 2-8 illustrates how CONWIP controls the WIP level over the production line. The figure shows that authorisation of lot release happens as soon as another lot departs and an authorisation signal is sent to the beginning of the line.

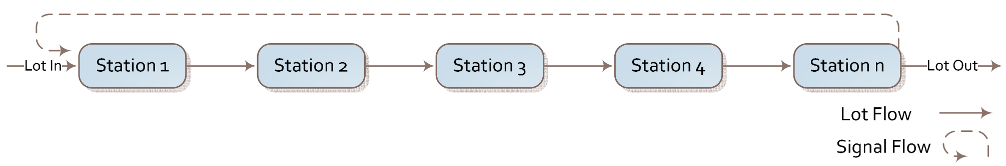

Figure 2-8: CONWIP lot release control strategy.

As mentioned earlier, CONWIP shares the advantages of Kanban; in addition, previous studies have reported that CONWIP has the following advantages over Kanban [33]:

- It is robust concerning changes in the production environment.
- It is flexible regarding introduction of new products, changes in the product mix.
- It provides higher throughput rate for same WIP level than Kanban.

CONWIP has a number of limitations that results in developing modified CONWIP lot release control strategies; 15 variations of CONWIP were recently reviewed in

2014 that addressed different limitations of CONWIP [34]. The conclusion of the review is that although CONWIP system is one of the most popular pull systems, it still suffers from some limitations and there are still several future research opportunities in that regard. Some of the review's conclusions that are relevant to this work include:

- CONWIP controls the WIP level of the line at an aggregated level and that total WIP level doesn't give any indication of WIP distribution across the stations of the system. This means that WIP levels (queue length) at stations can repeatedly increase dramatically at bottlenecks (defined as stations with low production rates or stations with repetitive failures). Overcoming that limitation is by controlling the WIP levels at the bottleneck stations (discussed in the next section).

- CONWIP can be combined with other lot release control strategies. This variation addresses the need for maintaining a fixed level of inventory at crucial sections of a production line and guaranteeing a better distribution of WIP across the production (discussed in Section 2.3.4).

- A single loop CONWIP system for controlling a production line is unsuitable (especially in product mix environments); hence, one of the most common modification that was observed in that review is splitting the single loop system into a number of loops controlling different number of stations (discussed in Section 2.3.4).

2.3.3 Bottleneck Station Control

In Bottleneck station control strategies there is one loop from the start of the line up to the bottleneck station that signals to call for a lot release. If a signal is generated due to a change in bottleneck station status, a lot is released to the production line. It should be mentioned that Prakash and Chin [34] considered this type of control strategies as a variation of CONWIP; as CONWIP does not take into account is the impact of the bottleneck station may have on the performance of a system [16]; however, in this work it is decided to consider them as an independent class.

Examples of bottleneck station control strategies considered in this work are: Drum-Buffer-Rope, Starvation Avoidance, Workload Regulating, and CONLOAD, which are reviewed in the following sections.

Drum-Buffer-Rope (DBR)

The DBR is a Theory of Constraint approach introduced by Goldratt, it has 3 main components. The "Drum" is the control point of this system, or main constraint. It is the process that has the least amount of excess capacity (bottleneck rate) and controls the total throughput rate of the system. To avoid the starvation of the bottleneck a protection time "Buffer" is maintained before the drum. Finally, the "Rope" signals the releasing of lots to the shop floor [35-43].

In DBR, when a lot completes processing by the bottleneck station, another lot with the bottleneck's rate is released at the start of the production line [4, 16, 26]. Hence, it controls the WIP up to the bottleneck station [15, 44], as presented in Figure 2-9. It should be noted that DBR is more general than CONWIP in that it can be applied to pure job shop manufacturing systems whereas CONWIP cannot. However, when both applied to flow lines, they have nearly similar results [26].

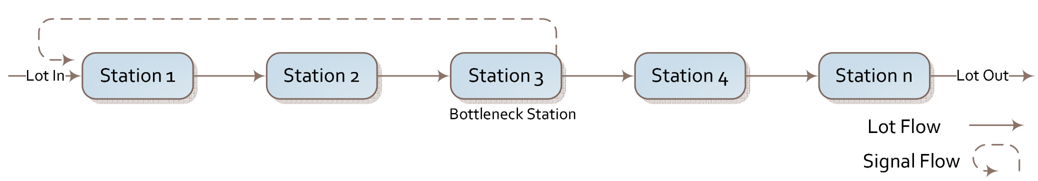

Figure 2-9: DBR lot release control strategy.

DBR has produced excellent results across a wide variety of manufacturing environments. It has been implemented as a manual system and is quite successful in providing increased system throughput rate, significant reductions in cycle times and work-in-process inventories, and improved due date performance [4]. As a result DBR is became popular in many manufacturing industries, especially semiconductor manufacturing [44], although, its implementation is not straight forward in semiconductor manufacturing due to the presence of re-entrant flow [38, 43].

Starvation Avoidance

This is a lot release strategy, in which a new lot is released into the shop floor to avoid starvation of a bottleneck station. In this rule, a new lot is released when virtual inventory at the bottleneck station falls down to a predetermined value. This rule can only be directly applied to a system with single bottleneck station producing a single product type [4, 45, 46].

Workload Regulating

Workload Regulating (WR) or sometimes called CONWORK, is applied to take into consideration the system loading situation and how much work a single lot will create for a bottleneck. Where, the total of processing times at the bottleneck that is currently represented by the lots being processed in the production line is measured. A lot is released to the production line if the current workload plus the total amount of bottleneck processing times of this lot is less than a given limit. As soon as it is released the workload is increased by the sum of bottleneck processing times of this lot, and each time a lot leaves the bottleneck station the workload is decreased by its bottleneck processing time [47]. Briefly, a new lot is released to the system when the sum of the remaining processing times, at any bottleneck station, over all lots in the fab falls below a critical value [4, 45, 46, 48]. This strategy was compared to others, and showed significant impact on the performance of the cycle time [4]. Though, this strategy provides a better picture of the loading situation of the system, it does not reflect how the load is distributed over time [47].

CONLOAD

CONLOAD is a lot release control strategy developed by Rose to overcome some performance problems of traditional lot release control strategies like CONWIP and WR during product mix changes at semiconductor manufacturing. Where, it is stated that CONWIP and WR are not capable to avoid overload because of their lack in tracking the current load situation of the system accurately enough, and that CONLOAD takes into consideration how much load is added to a single machine or a group of machines by a particular lot to decide on releasing this lot into the fab [47].

CONLOAD is a simple extension of WR, instead of considering the amount of work for the bottleneck station, the load for the bottleneck station is computed (the sum of bottleneck processing times of the lot divided by the average cycle time of lots of this product type). A new lot is allowed to enter the system if the current bottleneck load plus the load introduced by the new lot is less than a predetermined level. Each time a lots enters the line, the bottleneck load is increased by the lots load, and each time a lot leaves the line, it is decreased by the same amount [47].

CONLOAD varies from CONWIP, WR, and other lot release control strategies, in that the predetermined level that controls the releasing of lots is a natural constant of the system, while, that of the others are usually determined by simulation. The predetermined level is the target utilisation of the bottleneck station multiplied by the number of bottleneck machines. For instance, if the maximum bottleneck load should be 95% and the bottleneck consists of 4 machines, then the predetermined level is 3.8. The only parameters that have to be determined in advance by simulation or queuing analysis are the average cycle times for each lot [47].

In conclusion, CONLOAD out-performs CONWIP and WR with respect to keeping the bottleneck utilisation at a desired level and to provide a smooth evolution of the WIP. Also, it reduces the variations in cycle times and smooth's the lot departure process of the system [47].

2.3.4 Variations and Hybrid Strategies

Variations and hybrid strategies is either a modification to an existing lot release control strategy or a combination of more than one strategy to achieve sustainable improvements in performance over a single strategy. Examples of variations and hybrid strategies reviewed in this work are: m-CONWIP, Multi-CONWIP, Hybrid Kanban-CONWIP, Paired-Cell Overlapping Loops of Cards with Authorization (POLCA), and Generic Paired-Cell Overlapping Loops of Cards with Authorization (GPOLCA), which are briefly discussed in the following sections.

m-CONWIP

m-CONWIP, where *m* stands for multiple CONWIP, is a lot release control strategy that regulates releasing lots to manufacturing systems having more than one route, where, a CONWIP loop for every routing is introduced to control the release of lots as displayed in Figure 2-10.

Hence, it is considered as route specific control lot release strategy [49, 50]. It should be noted that m-CONWIP balances the workload among the routings by constraining the number of lots that are released separately to each route [50].

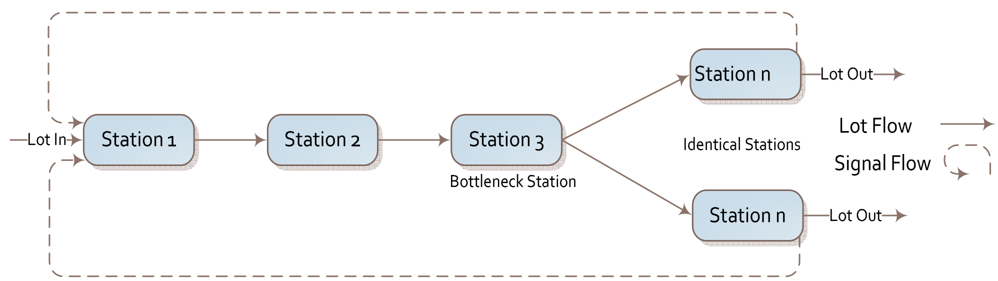

Figure 2-10: m-CONWIP lot release control strategy.

Germs *et al* [50] analysed the cycle time performance at a make-to-order manufacturing system under the control of CONWIP, m-CONWIP, and POLCA (Paired-Cell Overlapping Loops of Cards with Authorization) taking into consideration workload balancing capabilities, they concluded that cycle time was successfully reduced and that workload balancing capability exists for m-CONWIP and POLCA but not for CONWIP.

Multi-CONWIP

Multi-CONWIP (also known as segmented CONWIP) mixes between the Kanban and CONWIP, in which the WIP cap is controlled by a number of loops, each loop has a constant WIP level independent from the other as presented in Figure 2-11. The number of loops must be more than one loop (CONWIP) and less than the number of stations (Kanban). This lot release control strategy can be found in real manufacturing, such as semiconductor manufacturing [51, 52].

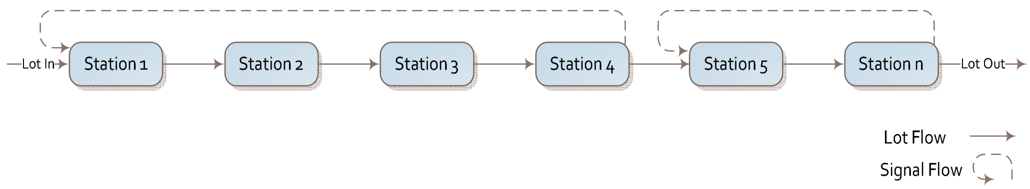

Figure 2-11: Multi-CONWIP lot release control strategy.

It should be noted that the first loop must include the first station, the last loop must include the last station, and all other stations must be part of loops.

Hybrid Kanban-CONWIP

Hybrid Kanban-CONWIP was introduced by Bonvik *et al.* [53] in order to overcome the disadvantages of loose coordination between production stages in a CONWIP line. They also stated that the hybrid strategy proposed is a better way than the minimal blocking strategy in facilitating machine recovery from failures and keeping bottlenecks working even if there are failed machines downstream.

In Hybrid Kanban-CONWIP, as in CONWIP, an overall cap is placed on the amount of inventory allowed in the manufacturing system. In addition, inventory is controlled using kanban cards in all stations except the last station as shown in Figure 2-12. CONWIP can be considered as special case of Hybrid Kanban-CONWIP, in which there is an infinite number of kanban cards distributed to each station [54].

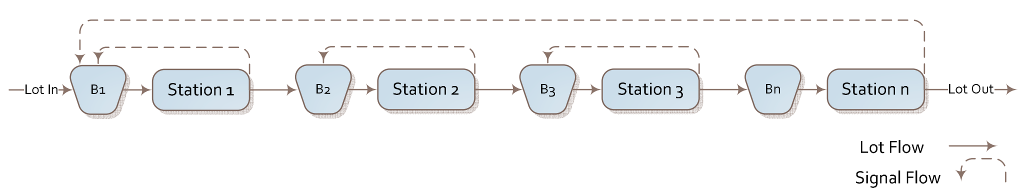

Figure 2-12: Hybrid Kanban-CONWIP lot release control strategy.

As a further variation to CONWIP, Hybrid Kanban-CONWIP was combined with DBR and applied to an assembly production line. Simulation results showed that the method was indeed able to solve the bottleneck problem effectively, enhanced the productivity, and reduced the delay time of the line [40].

Paired-Cell Overlapping Loops of Cards with Authorization (POLCA)

POLCA is a hybrid push-pull strategy that combines the best features of card based pull systems and push systems for quick response manufacturing (QRM) [28-30, 42]. The QRM strategy is best applied at companies that make custom designed products in small batches (or even one of a kind), and companies that don't custom design each product, but still have such a wide variety of options and combinations of specifications that they cannot afford to store inventory for all these options at various stages of their manufacturing system [27-30, 35, 42].

POLCA uses signal cards, called POLCA cards to communicate and control the lot movement between cells (stations) in order to authorize the progress of a lot. The release of lots is authorized by specifying the release dates using high-level Materials Requirements Planning system (HL/MRP), which might be accomplished by calculations from the due date and planned lead times. Similar to an MRP system, there are times when each cell may begin work on a particular lot. However, unlike in a standard push system where a cell should start work at that time, POLCA simply authorizes the beginning of the work, but the cell cannot start unless the corresponding POLCA card is available [27-30, 35, 42].

Although this may seem similar to Kanban, however there are some important differences. First, the POLCA cards are only used to control movement between cells, not within cells (For material control between workstations within a cell, cells have the freedom to use various other procedures) [28-30, 35]. Second, the POLCA provides a route specific control of the lot flow, while Kanban provides a product specific control. In other words, in POLCA the cards are assigned to pairs of cells instead of being specific to the product type, as in Kanban. The third difference from Kanban is that the POLCA cards for each pair of cells stay with a lot during its journey through both cells in the pair before they loop back to the first cell in the pair [27-30], and an additional card needs to be attached to the lot before entering the second cell of the first pair to signal the availability of capacity at the first cell of the second pair within the routing [27, 49].

Generic Paired-Cell Overlapping Loops of Cards with Authorization (GPOLCA)

GPOLCA is an adaptation of the POLCA mechanism developed as part of the QRM strategy [20]. GPOLCA requires that a released lot must possess cards for all POLCA loops in its complete routing before processing may begin at its first cell [25].

The characteristic of GPOLCA, non-existent in POLCA is that, GPOLCA releases lots only after the GPOLCA cards necessary by a lot at each pair of cells in the job's routing become available and are allocated to the lot. POLCA, on the other hand, undertakes the lot release as long as cards for the first pair of cells in the job's routing are available [20].

2.4 CONWIP

This section is dedicated to review of previous research work on CONWIP specifically. The review included journals and conference proceedings retrieved from electronic databases such as EI Engineering Village, IEEE Xplore, ScienceDirect, and Web of Science, the search term included "CONWIP".

Based on a literature review conducted in 2003 [32], different research work of CONWIP has been carried to study one or more of three topics. This classification is used here to group the relevant previous work under the following:

- Applicability of CONWIP to a manufacturing environment, either by real implementation or by development of computer simulation models for existing manufacturing systems.
- To determine the optimum WIP level as a decision variable that can improve a set of performance measures using different solution techniques such as simulation, optimisation, mathematical techniques… etc.
- Comparing the performance of CONWIP to push or other pull systems, in order to evaluate the performance of CONWIP to be better or worse than the compared systems based on given performance measures.

2.4.1 Applicability of CONWIP to a Manufacturing Environment

Based on literature, CONWIP has been applied to different manufacturing environments and also implemented successfully in different industries. CONWIP has been reported to work best for balanced production lines running in a steady state already [47]. Still, it has been applied to job shop manufacturing [55], multi-product environment [56], and multi-product assembly system [57].

Based on the literature review and to the best of our knowledge, unlike DBR that was implemented in real wafer fabrication facilities [37, 43, 58], CONWIP has not been applied other than application of a simplified CONWIP mechanism in terms of the output feedback mechanism. This simplified CONWIP has been tested in a wafer fabrication facility using simulation. Although results showed that the fab performance can be improved when applying the CONWIP; yet, authors of this work suggested that further research should be conducted to develop a fully functional CONWIP lot release control strategy in wafer fabrication facilities [4].

2.4.2 Determining the Optimum WIP Level as a Decision Variable

Based on the description of the basic (original) CONWIP lot release policy, it is clear that the only variable that needs to be determined is the WIP level that results in optimum performance of the production line. Different research work has been developed to that end such as the development of a mathematical model and an application of an artificial bee colony (ABC) optimisation algorithm to find the optimum WIP level for a multi-product multi-machine serial production line in order to minimize cycle time [59] and the development of deterministic approaches to define the optimum WIP level that maximises throughput rate using minimum WIP level in a flow production line [60].

Multi-CONWIP lot release control strategy problem, which was discussed earlier as one of the variants of CONWIP, has also attracted the attention of researchers to due to the computational complexity of determining the number of segments of a production line and the WIP level of each segment. Evolutionary simulation optimisation [51] and an evaluation method combined with a genetic algorithm [52] has been successfully applied in semiconductor assembly and test factories. Although multi-CONWIP strategy outperformed CONWIP and Kanban when applying the evolutionary simulation optimisation [51]; yet, the computational complexity and the efficiency of the proposed methods in solving these problems were addressed as potential future research opportunities.

It should be noted that setting the WIP level in either the CONWIP or any of its variations is considered as the main decision variable; yet, another important issue that has been addressed in literature is whether that level is set statically; meaning that the level is set once, or dynamically; meaning that the WIP level can change depending on the state of the system (for example to meet unexpected demand with higher throughput rates). Setting the WIP level once is referred to as "card setting"; while, setting the WIP level dynamically is referred to as "card controlling". A card control for CONWIP procedure has been suggested and experiments showed that card control produces competitive results when compared to card setting; however, under a make to order environment [61]. Other work related to dynamic CONWIP level includes optimisation using simulation of simple production lines to optimise the parameters used to control the line [62]. Also, adaptive CONWIP has been modelled as a stochastic queueing network and applied to a hybrid production system with two discrete processes that undertake manufacturing and remanufacturing activities [63].

2.4.3 Comparing the Performance of CONWIP to Push or Other Pull Systems

Performance of CONWIP has been compared to push systems or other pull systems using various analytical and simulation methods in literature.

CONWIP performance of throughput rate and WIP has been compared to push using simulation and applied to unidirectional flow line, with no re-entrancy or rework. Results showed that when there is high variability in the arrivals CONWIP is better than Push; however, Push can perform better than CONWIP when lots are released on a constant interval [64].

The performance of CONWIP and Kanban was also compared in a make to order environment and simulation was used to evaluate the impact of applying both strategies on the mean and standard deviation of cycle times and confirmed that CONWIP outperforms Kanban [65]. Furthermore, CONWIP system achieved a less average WIP than Kanban given the same rate of throughput when applied to a tree-shaped multi-stage assembly system; on the other hand, when applied to a simple serial production line Kanban is superior to CONWIP [66].

Simulation was also used to compare the impact of CONWIP and DBR on the performance of a back-end semiconductor manufacturing flow line. Findings of that work is that DBR can outperform CONWIP mainly due to the ability of DBR in distinguishing the bottleneck(s) and placing greater control over the portion of the system that directly influences the bottleneck; however, DBR loses this advantage when bottleneck(s) starts shifting [44]. Also, application of CONWIP to unbalanced lines with distinct bottlenecks has been compared to DBR and showed that performance of the lines mainly depend on the characteristics of the line in terms of the position of the bottleneck [16, 67].

Furthermore, the impact of combining different dispatching rules with Push was compared to combining these dispatching rules to CONWIP lot release strategy in two realistic semiconductor test bed fabs. Simulation results and analysis showed that the cycle times reported from Push outperformed CONWIP in both fabs. Also, it showed that most rules failed to outpace FCFS (First Come First Serve) in CONWIP, thus supporting the FCFS recommendation of Hopp and Spearman [15].

Impact of combining dispatching rules with CONWIP on the performance of wafer fabrication facilities on the average throughput rate and cycle time along with the variability in these measures has been tested on Wein's model, which is a fictitious wafer fab using data gathered the Hewlett-Packard Technology Research Centre Silicon fab [68] and the Minifab model [69]. Both studies have been carried using simulation and both confirmed that the lot release policy is the dominant factor in improving the performance of both fabs.

Multi-CONWIP discussed in the previous section was compared to CONWIP by evaluating their impact on the performance of semiconductor assembly lines. Simulation results showed that multi-CONWIP outperforms CONWIP and was capable of achieving same throughput rate (target obtained from simulation of base model) at higher WIP levels (higher by 0.6%) and lower cycle times (lower by 0.4%) [70].

It is noticed that since the application environment is highly complex, the only reasonable approach to demonstrating the effectiveness was to use modelling and simulation. Therefore, it is effective to use simulation to analyse and predict the dynamic behaviour of complex systems.

Moreover, simulation has become a popular technique for developing production schedules in a manufacturing environment. Also, it offers the advantage of developing a feasible and accurate schedule in shorter computation times compared to some of the other techniques [9].

2.5 MODELLING AND SIMULATION

Simulation can be defined as the process of designing a model of a real system and conducting experiments with this model for the purpose of either understanding the behaviour of the system or evaluating various strategies for the operation of the system. It is the ability to mimic the dynamics of the real system that gives simulation its structure, its function, and its unique way to analyse results [71]. Discrete event simulation is the modelling of systems in which the state variables change only at a discrete set of points in time [72].

Simulations are often used to analyse systems that are too complicated to tackle via analytic methods such as calculus, standard probability and statistics, or queuing theory [73]. It is a powerful tool for the evaluation and analysis of new system designs, modifications to existing systems and proposed changes to control systems and operating rules [74].

Discrete event simulation is particularly effective in the analysis and prediction of the behaviour of complex dynamic systems, meaning that it is the ideal tool to develop a test bed to determine the effectiveness of the policies developed in this work. Moreover, simulation offers the advantage of developing a feasible and accurate schedule in shorter computation times compared to some other techniques [9].

The steps of a simulation study may be summarized in four phases, each consisting of different steps, as presented in Figure 2-13 [74], and discussed in the following sections. It must be noted that although the figure shows the steps to be carried out independently, most of the time several steps are performed concurrently (e.g. model conceptualization and data collection, verification and validation…).

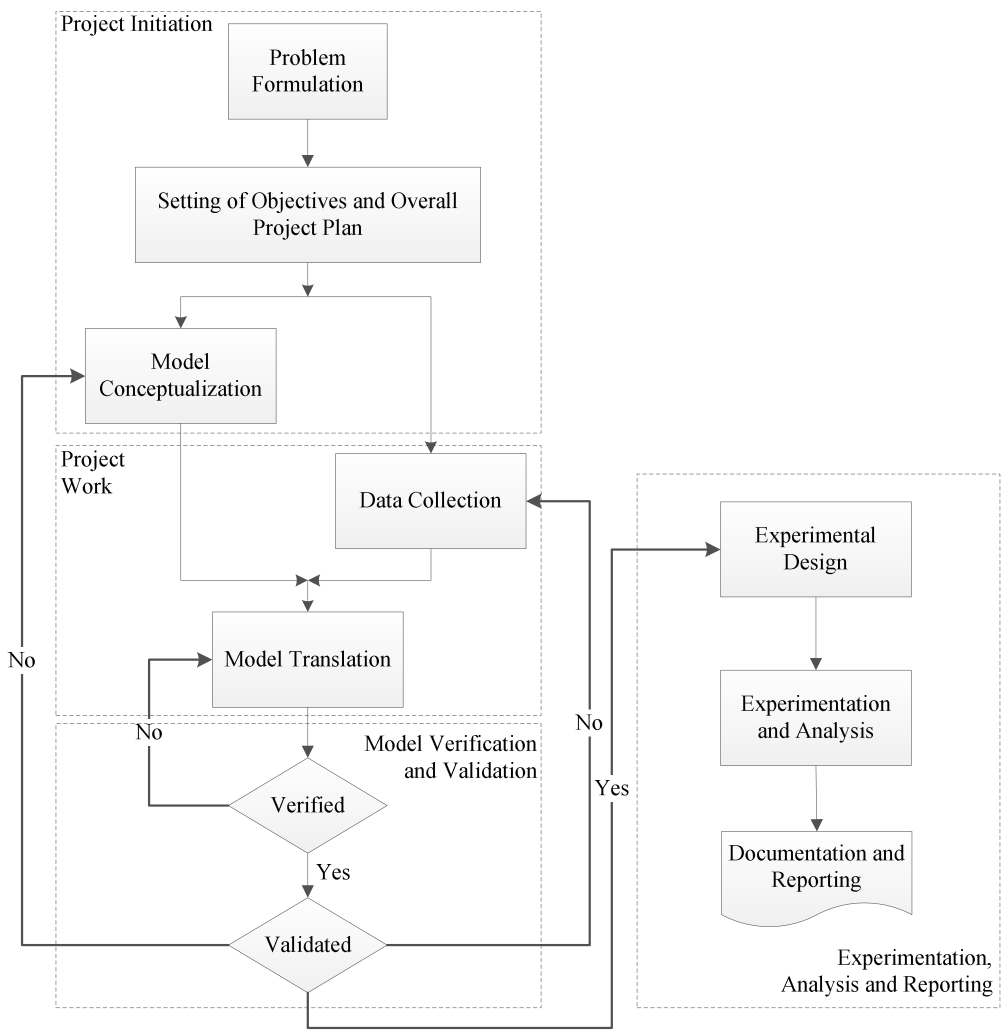

Figure 2-13: Steps in a simulation study, modified from [72].

2.5.1 Project Initiation

The first phase of a simulation study is the project initiation that starts with formulating the problem, setting the objectives, and performance measures to be evaluated. Then the details of the modelling assumptions and data requirements should be provided to the simulation analyst in order to set the project plan with time and cost estimates. Based on the project plan, it is decided either to proceed with the simulation study, or perhaps to expand or limit its scope [74].

Afterwards is the model conceptualization, which is a non-software representation to the system to be developed describing the objectives, inputs, outputs, assumptions and simplifications of the system [75]. The end results of this phase are the project plan and the conceptual model.

2.5.2 Project Work

This phase consists of data collection and model translation. The end result of this phase is a working model that is subjected to verification and validation in the next phase.

Data Collection

The first step in gathering data is to determine the data required for building the model; these can be categorized as structural data, operational data, and numerical data [76].

- Structural Data: Structural data involve all of the objectives in the system to be modelled. This includes such elements as entities (lots), resources (machines), and locations (stations). Structural information basically describes the layout or configuration of the system and identifies the entities that are processed.

- Operational Data: Operational data explain how the system operates. Operational data consist of all the logical or behavioural information about the system such as routings, schedules, down time behaviour, and resource allocation. If the process is structured and well controlled, operational information is easy to define.

- Numerical Data: Numerical data provide quantitative information about the system. Examples of numerical data include capacities, arrival rates, activity times, and time between failures. Some numerical values are easily determined, such as resource capacities and working hours. Other values are more difficult to assess, such as time between failures or routing probabilities.

Usually the simulation analyst constructs the model while the data collection is progressing. Also, the required data format must be accurately defined, to facilitate introducing the data to the developed model. Furthermore, the probability distributions for any random variables must be defined at this stage. Finally, data on the performance of the real system, which can be used for validation purposes, must be collected (if the real system exists) [14].

Model Translation

In this step the model is developed by translating the conceptual model constructed in phase 1 into a computer-recognizable form, an operational computer simulation model [14]. There are a number of simulation packages that are available as commercial-off-the-shelf (COTS) software. Based on a recent review of simulation software in 2009, over 40 products are available in the market offered by 26 vendors [77]. Usually selection of the correct simulation package is based on different criteria such as; model-building features, runtime environment, animation and layout features, output features, and vendor support and product documentation [72].

2.5.3 Model Verification and Validation

In this phase the simulation analyst verifies and validates the model. If problems are found, the model or the data, or both, are corrected.

Verification

Verification concerns the operational model, which makes sure that the model is operating as intended by the system-analyst, and ensuring that the computer programming and implementation of the conceptual model are correct [78].

It is highly advisable that verification takes place as a continuing process and not to wait until the entire model is completed to begin the verification process [14].

Validation

Validation is the determination that the conceptual model is an accurate representation of the real system, and that the model can be substituted for the real system for the purposes of experimentations. An ideal way to validate the model is to compare its output to that of the real system; where, a simulation model of the existing system is developed and its output data are compared to those from the existing system itself [79].

Three steps (levels) of validation can be followed: face validation, validation of model assumptions, and input/output transformations validation [72].

- Face validation: The first goal of the simulation modeller is to construct a model that appears reasonable on its face to model users and others who are knowledgeable about the real system being simulated. This validation takes place without deep investigation and is usually carried out using the animation capabilities of the simulation model.

- Validation of model assumptions: Model assumptions fall into two general classes: structural assumptions and data assumptions.

  - Structural assumptions involve questions of how system operates and usually involve simplifications and abstractions of reality. It is concerned with the validation of the resources (stations, machines…etc.).

  - Data assumptions should be based on the collection of reliable data and correct statistical analysis of the data. It is done by conforming the input model variables that are generated randomly represents the actual variables.

- Input/output transformations validation: In this phase of the model validation, the model accepts values of the input parameters and transforms these inputs into output measures of performance. This validation is done by comparing these output measures to that of the real system.

2.5.4 Experimentation, Analysis and Reporting

The purpose of this phase is to meet the objectives set in the project initiation either to evaluate or/and compare the performance measures of the system. It consists of three main steps; experimental design, experimentation and analysis, and documentation and reporting. These are discussed in the following sections.

Experimental Design

Many of the classic experimental designs can be used in simulation studies and the goal will influence the way the study should be conducted [80]. Carefully planned simulation studies can yield valuable information without an undue amount of computational effort. A wide variety of approaches, methods, and analysis techniques, known collectively as experimental design, have the principal goals of estimating how changes in input factors affect the results, or responses of the experiment. Experimental design can specifically determine [81]:

- How sensitive are outputs to changes in inputs?
- Which inputs are important? Which are not?
- What is the best combination of inputs?

It should be noted that simulations may be either terminating or nonterminating. A terminating simulation is one for which there is a natural event that specifies the simulation run time, and the performance measures for such simulation may also be known as transient simulations (for example a bank that closes at the end of a day or a call centre that operates for specific hours a day). However, a nonterminating simulation is one for which there is no natural event to specify the simulation run time, where the long run behaviour is studied when it is operating normally. Assuming that these simulations will reach a steady state and that performance is measured at that state; hence, these simulations are said to be steady state simulations (for example a manufacturing facility that operates continuously and the aim of the simulation is to evaluate its long term performance measure) [82-85]. Since, this work focuses on simulating wafer fabrication facilities that are said to run indefinitely with no obvious terminating event; thus, the simulation in this research belongs to the nonterminating one.

Three major pitfalls in output data analysis have been pointed out [83] , two of them are discussed in this section and the third one is related to the following section:

- Analysing simulation output data from one run, which might result in a gross underestimation of variances and standard deviations.
- Failure to have a warm up period for steady state analysis.
- Failure to determine the statistical precision of simulation output statistics by the use of a confidence interval.

For each scenario that is to be simulated, decisions need to be made concerning the simulation parameters, which include: length of the simulation run, the warm-up period, and the number of replications [14, 72, 79]. The following subsection discusses the approaches used in setting the simulation parameters in this study.

<u>Length of the Simulation Run</u>

Although there is no definitive way of picking the simulation run time at nonterminating simulation and needs to be determined by the model user [75]; however, the simulation run time should be much larger than the warmup period [86].

<u>Warm-Up Period</u>

Before a simulation can be run, one must provide initial conditions for all of the simulation's state variables. Such a choice of initial conditions can have an impact on the simulation output. Thus, initialization problems can lead to errors, particularly in steady state output analysis. The technique most often suggested to deal with that problem is called warming up the model or initial data deletion. The idea is to delete some number of observations from the beginning of a run and to use only the remaining observations, as the observations near the beginning of the simulation may not be very representative of steady state behaviour due to the choice of initial conditions [82-84].

In literature there are several techniques to determine the warmup period, and they are classified in to: Graphical methods, Heuristics approaches, statistical methods, Initialization bias tests, and hybrid methods [75]. In this work the Welch method, that is considered as the most general graphical technique for determining the warmup period [82, 86], is discussed here.

In order to determine the warmup period using the Welch's method, which is based on the calculation and plotting of moving averages, the following steps are carried out [75, 82]:

- Make a series of n replications (at least 5) each of a simulation run time m (where m is large). Let Y_{ji} be the i^{th} observation from the j^{th} replication ($j = 1,2, \dots n; i = 1,2, \dots m$).

- Calculate the average of the performance measure across the replications for each period using Equation 2-2.

$$\bar{Y}_i = \sum_j^n \frac{Y_{ji}}{n} \qquad \text{Equation 2-2}$$

  For $i = 1, 2, \dots m$.

- To smooth out the high frequency oscillations in $\bar{Y}_{1,}\bar{Y}_{2,} \dots$, the moving average is further calculated based on a window size w (start with w = 5) using Equation 2-3.

$$\bar{Y}_i(w) = \begin{cases} \dfrac{\sum_{s=-(i-1)}^{i-1} \bar{Y}_{i+s}}{2i-1} & if\ i = 1, \dots w \\ \dfrac{\sum_{s=-w}^{w} \bar{Y}_{i+s}}{2w+1} & if\ i = w+1, \dots, m-w \end{cases} \qquad \text{Equation 2-3}$$

Where; w is the window size and is a positive integer such that $w \leq [m/4]$.

- Plot $\bar{Y}_i(w)$ for $i = 1, 2, \dots m - w$ and choose l (warmup period).
- If the plotted data is not smooth increase the size of w and repeat the previous 2 steps.
- Identify the warmup period (l) as the point where the time-series becomes flat.

In using Welch's method the aim should be to select the smallest w that gives a reasonably smooth line. Although selecting a larger w will give a smoother line, it also tends to give a longer estimate to the warmup period, which wastes the data collected from a simulation run and; hence, has implications for the simulation run time. It is also recommended that the value of w should not be more than a quarter of the total observations [75].

Number of Replications

A replication is a run of a simulation that uses specific streams of random numbers. Multiple replications are performed by changing the streams of random numbers that are referenced and re-running the simulation. The aim is to produce multiple samples in order to obtain a better estimate of mean performance. There are three approaches to determine the number of replications required for a simulation study: a rule of thumb, a graphical method and a confidence interval method [75].

In this work the graphical method will be used to identify the number of replications required in this study. This approach is to plot the cumulative mean of the performance measure from a series of replications. It is recommended that at least 10 replications are performed initially. As more replications are performed the graph should become a flat line. The number of replications required is defined by the point at which the line becomes flat. Performing more replications beyond this point will only give a marginal improvement in the estimate of the mean value. If the line does not become flat more replications are needed [75].

Experimentation and Analysis

Experimentations and analysis, are used to estimate measures of performance for the scenarios that are being simulated [14, 72].

As the input processes driving a simulation are usually random variables (e.g., inter-arrival times, processing times, and breakdown times); the output variables from the simulation will also be stochastic. Thus, runs of the simulation only yield estimates of measures of system performance (e.g., the mean throughput rate, cycle time and WIP). These estimators are themselves random variables, and are therefore subject to sampling error. As a result, these estimates could, in a particular simulation run, differ greatly from the corresponding true characteristics for the model. The net effect is that there could be a significant probability of making inaccurate inferences about the system under study [83, 84]. Therefore, when comparing alternative scenarios one should decide which scenario is better. This is not simply a case of comparing the mean values of the performance measures to see which one is the best [75].

When comparing two systems (alternatives) more accurate approaches should be applied such as: developing confidence intervals with specified precision, independent sampling, and common random numbers (CRN) [72]. Relying on confidence intervals and checking whether intervals overlap or not, is not quite an accurate approach to compare alternatives [87].

Independent sampling and CRN techniques are essentially paired-t tests the difference between the two techniques is that the first compares the output of two systems using different random numbers; while, the second technique uses a variance reduction technique (CRN), which compares two systems using the same random numbers. The systems under study in this work exhibit high randomness in its input parameters; therefore, the CRN technique is used to control that randomness.

However, the paired *t*-confidence interval is used to compare two scenarios. When comparing many scenarios there are statistical methods for choosing the best one. Nelson *et al.* [88] proposed a method the combines screening procedure with Rinott's two-stage sampling procedure for selecting the best scenario.

This method starts with the screening procedure that generates a survivor set, which must include at least one of the scenarios. If the survivor set only has one scenario, that scenario is selected as the best and the procedure terminates. However, if there is more than one survivor, Rinott's two stage sampling procedure is then applied to members of the survivor set in order to determine the best scenario[89].

In order to select the best scenario using Nelson's combined method, the following steps are carried out [88, 89]:

- Set the overall confidence level $1-\propto$, confidence level $1-\propto_o$ for the screening procedure, and $1-\propto_1$ for the Rinott's procedure such that $\propto_o+\propto_1=\propto$. A convenient choice is $\propto_o=\propto_1=\propto/2$.

- Select the critical constant t for the screening procedure using Equation 2-4 when CRN are used, and Equation 2-5 when CRN are not used.

$$t = t_{1-\alpha_o/(k-1),n_o-1} \qquad \text{Equation 2-4}$$

$$t = t_{(1-\alpha_o)^{1/k-1},n_{o-1}} \qquad \text{Equation 2-5}$$

  Where;

  k is the number of scenarios,

  $n_o$is the number of replications, and

  t is value from student's t-distribution with $1-\alpha_o/(k-1)$ degree of freedom and a significant level of n_o-1.

- Select the critical constant h for the Rinott's procedure using Equation 2-6.

$$h = h_{1-\propto_1, n_o, k} \qquad \text{Equation 2-6}$$

Where; h is Rinott's constant.

- Specify a practically significance difference (ε) of the performance measure to be improved.

- Compute the means ($\bar{Y}_i$) and variances (${S_i}^2$) of the performance measures for each scenario.

  For $i = 1,2,3 \dots k$.

- Calculate the screening thresholds (W_{ij}) using Equation 2-7 when CRN are used, and Equation 2-8 when CRN are not used.

$$W_{ij} = t \left(\frac{{S_{ij}}^2}{n_o} \right)^{1/2} \qquad \text{Equation 2-7}$$

$$W_{ij} = t \left(\frac{{S_i}^2 + {S_j}^2}{n_o} \right)^{1/2} \qquad \text{Equation 2-8}$$

  For $j \neq i$.

- Construct the survivor set using Equation 2-9 assuming smaller performance measure is better and Equation 2-10 assuming greater performance measure is better.

$$\bar{Y}_i \leq \bar{Y}_j + \max(0, W_{ij} - \varepsilon) \qquad \text{Equation 2-9}$$

$$\bar{Y}_i \geq \bar{Y}_j - \max(0, W_{ij} - \varepsilon) \qquad \text{Equation 2-10}$$

- If the survivor set includes one scenario that scenario is selected as the best and the procedure terminates. However, if there is more than one survivor, Rinott's two stage sampling procedure is then applied to members of the survivor set in order to determine the best scenario, and the number of additional replications required for each survivor is determined from Equation 2-11.

$$N_i = \max\left(n_o, \left\lceil\left(\frac{hS_i}{\varepsilon}\right)^2\right\rceil\right) \qquad \text{Equation 2-11}$$

Where; $\lceil . \rceil$ implies roundup.

Documentation and Reporting

Documentation is necessary for numerous reasons. If the simulation model is going to be used again by the same or different analysts, it may be necessary to understand how the simulation model operates. This will provide confidence in the simulation model so that the model users and policy makers can make decisions based on the analysis.

In addition, if the model is to be modified, this can be greatly facilitated by adequate documentation. The result of all the analysis should be reported clearly and concisely. This will enable the model user to review the final formulation, the alternatives that were addressed, the criterion by which the alternative systems were compared, the results of the experiments, and the analyst recommendations, if any [72].

2.6 CONCLUSIONS OF LITERATURE

Semiconductor wafer fabrication manufacturing uses push systems to make maximum use of expensive tools; it is considered better having lots waiting for processing, rather than to have a machine waiting for a lot. However, controlling the release of lots optimally to the shop floor can have a significant effect on the performance of the fab.

Focusing on CONWIP showed that CONWIP has a number of drawbacks and limitations that resulted in developing either a variation of CONWIP or a combined strategy with CONWIP which is more likely to achieve sustainable improvements in the performance. The recent review of CONWIP in 2014 confirmed that CONWIP system is one of the most popular pull systems. Still, several papers confirmed that

CONWIP doesn't control WIP distribution across the stations of the system, CONWIP can be combined with other lot release control strategies to achieve better performance, and that a single loop CONWIP system for controlling a production line might be unsuitable in some manufacturing environments. This lead to review different control strategies reported in literature that addresses these limitations. The review has shown the diverse nature of the application of different control strategies, with different outcomes in manufacturing.

Further review of CONWIP has been conducted and concentrates on the applicability of CONWIP in different manufacturing environments, determining the optimum WIP level, and comparison of CONWIP to other manufacturing control systems. The most important findings of that review are listed as follows:

- CONWIP has been reported to work best for balanced production lines running in a steady state already.
- Limited application to real wafer fabrication facilities; only application of a simplified CONWIP mechanism in terms of the output feedback mechanism.
- Optimisation of WIP levels to either minimize cycle time or to maximise throughput rate using minimum WIP level as the commonly used performance measures of production lines.
- Other work showed that the performance measure was minimisation of WIP levels to achieve the same rate of throughput.
- Optimisation using simulation of dynamic CONWIP and adaptive CONWIP strategies; yet, application was to simple production lines due to the computational complexity associated with the problem.
- When high variability in arrivals exists, CONWIP is better than Push; however, Push can perform better than CONWIP when lots are released on a constant interval.
- CONWIP compared to other release strategies showed that:
  - CONWIP can outperform Kanban.

    - CONWIP is better than Push given that arrivals are of high variability.
    - Push can be better than CONWIP if lots are released deterministically.
    - DBR can outperform CONWIP; however this depends on the location of the bottleneck and whether the bottleneck is shifting or not.

- Combining dispatching rules with CONWIP showed that dispatching rules has a minimal effect on the performance of a production line.

- Simulation has been used in most of the literature reviewed as an effective tool to analyse and compare the dynamic behaviour of complex production systems operating under different manufacturing control systems.

In this work two limitations of CONWIP are addressed, the first is related to the variability of Lot Arrivals to a system applying CONWIP. Since, the arrival of lots to a system depends on the departure of lots from the system; thus, highly variable inter-departure times will result in highly variable inter-arrival times as well. Consequently, highly variable inter-arrival times will induce variability throughout the production line, which degrades the performance of the line in terms of cycle times and WIP levels of the production line (as will be discussed in details in Section 4.7). To overcome this drawback ICONWIP lot release control strategy is proposed that regulates the arrival of lots to the system and reduces the variability associated with it.

The second drawback is relevant to the distribution of WIP across the stations of a system. Queues in front of stations can repeatedly build-up at stations with low production rates (bottlenecks) or stations with repetitive failures. As a result, DBR lot release control strategy is applied to control the WIP forming at bottlenecks; moreover, a hybrid CONWIP/DBR lot release control strategy is tested also to combine the advantages of both CONWIP and DBR. Finally, to control the distribution of WIP over stations where queues are likely to accumulate (referred to as critical stations in this work), LCONWIP lot release control strategy is proposed to reduce individual WIP levels at critical stations and improve the performance of the system.

3 RESEARCH METHODOLOGY

3.1 RESEARCH TOOL

As mentioned earlier, simulation has been used in most of the literature reviewed to analyse complex production systems that are too complicated to tackle via analytic methods. It is particularly effective in the analysis and prediction of the behaviour of complex dynamic systems. Therefore it is the ideal tool to develop a test bed to determine the effectiveness of the strategies developed in this research.

In this work ExtendSim™ is selected as the simulation environment to be used for developing all simulation models described in details in the upcoming chapters. That's partly because ExtendSim™ was available as a grant for research purposes and also because of the following features [90]:

- Ability to divide the model into hierarchical sections.
- Ability to effectively manage model data through built-in databases.
- Different mathematical and logical equations can be easily defined in a variety of equation-based blocks.
- Automatic and informative visual feedback by animation of blocks and entity flows.

3.2 RESEARCH SCOPE

Although several lot release control strategies are found in literature, yet CONWIP is still regarded as one of the most popular pull strategies. In this work two limitations of CONWIP are addressed, the first is related to the variability of Lot Arrivals to a system applying CONWIP. Since, the arrival of lots to a system depends on the departure of lots from the system; thus, highly variable inter-departure times will result in highly variable inter-arrival times as well. Consequently, highly variable inter-arrival times will induce variability throughout the production line, which degrades the performance of the line in terms of cycle times and WIP levels of the production line (as will be discussed in details in Section 4.7). To overcome this drawback ICONWIP lot release control strategy is proposed that regulates the arrival of lots to the system and reduces the variability associated with it.

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3.3 CASE STUDIES

This work started with one of the most popular models used by researchers, which is the Minifab model. Although the Minifab captures some of the challenges involved in a re-entrant fab; however, it has a limited number of stations, machines and steps. Thus, it was unable to address the second limitation of CONWIP, which is the unbalanced WIP distribution across the stations.

Furthermore, the Minifab was developed during the 1990s; therefore, a representative segment of an existing wafer fabrication facility operating with the latest technologies used in the semiconductor manufacturing was developed in collaboration with the ICMR.

Compared to the Minifab, this Segment includes greater number of stations and machines with greater number of steps. Also, the Segment addresses the significant challenges involved in operating current highly re-entrant wafer fabs such as high re-entrancy, complex batching processes, sampling, and stochastic variable breakdowns derived from actual data of similar machines.

3.4 RESEARCH EXPERIMENTS

Experimental work in this research addresses two drawbacks of CONWIP; the first is related to the arrivals variability (applied to both the Minifab and Segment), and the second addresses the unbalanced distribution of WIP across the stations (applied to the Segment only). Briefly, the Minifab scenarios address the arrivals variability, and the Segment scenarios are divided in to two groups: Group I scenarios that address the arrival variability, and Group II scenarios that address the distribution of WIP across the stations as summarised in Figure 3-1.

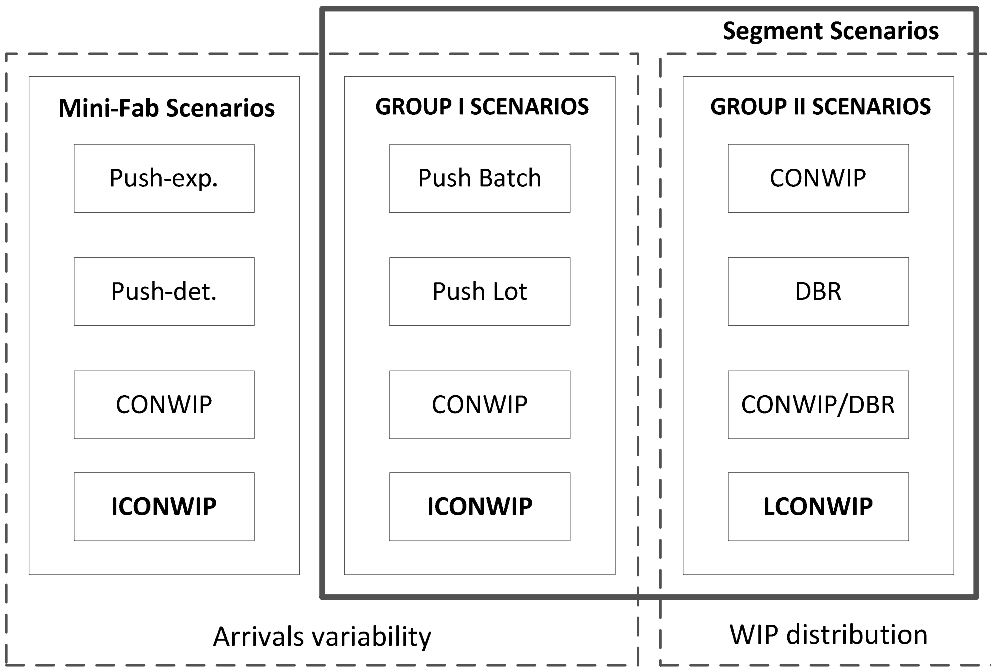

Figure 3-1: Summary of experimental work.

As previously mentioned in literature, Push can perform better than CONWIP when lots are released on a constant interval [64]. So, experiments in this work start with testing the effect of applying different Push strategies on the behaviour of Minifab. Comparison of Push using exponential inter-arrival times and deterministic ones helps to show whether or not the performance of the Minifab will improve using the deterministic inter-arrival times. Also, analysis of behaviour of Minifab under deterministic input will help in understanding the reason for that improvement.

These two Push strategies are then compared to CONWIP control applied to the Minifab. Simulation results show that deterministic Push strategy can actually outperform CONWIP confirming what was presented in [64]. Further analysis of simulation results, specifically inter-arrival variability, has shown that there is much higher variability in the arrival of lots under CONWIP when compared to Push deterministic and this variability adversely affects the lot cycle time. As a result, in an attempt to reduce this arrival variability, the ICONWIP lot release control strategy is proposed which regulates the arrivals to the Minifab and reduces the variability of arrivals.

Due to the limited number of stations, machines and steps of the Minifab, it is not possible to demonstrate the impact of the unbalanced WIP distribution across the stations. A representative Segment of a semiconductor fabrication process has been developed with the ICMR. This Segment includes a greater number of machines and stations, more processing steps and exhibits the increased complexity (sampling for quality control) and variability (e.g. machine breakdowns) that are typical characteristics of real fabs than can be included in the Minifab. The same comparative study of applying different Push behaviours and the proposed ICONWIP strategy is applied to the model of the Segment to ensure that it exhibits the same behaviour as the Minifab. However, based on the operational data supplied by the ICMR, lot introduction applied to the Segment under a Push policy should be based on a single event where all of the lots for the day are loaded immediately one after the other. While this is deterministic in the schedule, the extended interarrival time between the last lot on any day and the first lot on the next means that there is a distribution associated with this activity. The purely deterministic method for lot introduction for Push is to introduce the individual lots at regular time intervals throughout the day. In both cases, the number of lots introduced should be 19 lots per day on average to meet the required throughput of 3325 wafer starts per week.

When applying CONWIP to the Segment an unbalanced WIP profile can arise as much of the WIP can be held at one or two stations due to the lengthy breakdowns. Therefore, modifications to CONWIP by combining it with other lot release control strategies are required to overcome this unbalanced WIP distribution issue. DBR was reported in literature to result in better performance of fabs when compared to CONWIP and actually balance the WIP distribution along the line [44]. Although it was also reported that DBR is not effective in balancing WIP in all lines and that this depends on the characteristics of the line and the position of the bottleneck [16, 67]; however, DBR was first simulated to test its effectiveness in improving the distribution of WIP and reducing the unbalancing effect induced by CONWIP. Simulation results showed that DBR did not manage to balance the distribution of WIP across the stations of the Segment due to the nature of the Segment; where, the last step performed on the bottleneck station is Step 41 out of a total of 46 steps. Hence, most of the line was controlled by a single WIP cap loop as in CONWIP; confirming what was mentioned in [16, 67]. Next, in an attempt to improve the results of both CONWIP and DBR a hybrid strategy of both is tested (as suggested by the work in [34]), which is the CONWIP/DBR lot release strategy. Finally, controlling WIP levels at bottleneck or critical stations by adding WIP caps to these stations using the developed LCONWIP strategy; in order to balance the distribution of WIP across the stations of the Segment.

To conclude, the following summarizes the experimental work in the sequence they are carried out in this research:

A. MINIFAB SCENARIOS

1. Push scenarios (Section 4.6.3).
2. CONWIP scenarios (Section 4.6.4).
3. ICONWIP scenarios (Section 4.8).

B. SEGMENT SCENARIOS

I. Group I scenarios:

1. Push scenarios (Section 7.5).
2. CONWIP scenarios (Section 4.6.4).
3. ICONWIP scenarios (Sections 4.87.7 &.7.7)

II. Group II scenarios:

1. DBR scenarios (Section 7.10).
2. Hybrid CONWIP/DBR scenarios (Section 7.11).
3. LCONWIP scenarios (Section 7.12).

4 INTEL FIVE MACHINE SIX STEP MINI-FAB

As mentioned previously, simulation models for semiconductor wafer fabrication are considered important tools for supporting the decision making process in manufacturing operations. However, due to the complexity of these systems, usually simpler models of semiconductor wafer fabrication facilities are used as a test bed for evaluating different manufacturing control strategies.

Of the most popular models used by researchers is the Minifab model [6, 10, 25, 69, 91-104]. In spite of the fact that this model is of a relatively small size; yet, it captures some of the challenges involved in scheduling re-entrant wafer fabrication facilities.

Simulation models were developed for the Minifab to evaluate the impact of dispatching rules on a set of predetermined performance measures [105-107]; also, other simulation models evaluated the impact of changing lot release policies on the Minifab performance [108, 109].

4.1 MINI-FAB DESCRIPTION

4.1.1 An Overview of the Mini-Fab

The Minifab is a result of collaborative efforts between Arizona State University and Intel researchers and features six processing steps and five machines distributed in three stations, as shown in Figure 4-1.

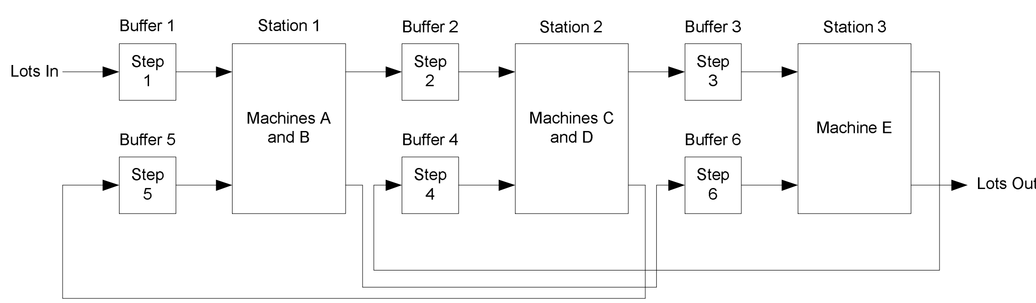

Figure 4-1: The Intel five machine six step Minifab [92].

The following sections will present a brief description[2] of the most important features of the Minifab that will be addressed in this work.

4.1.2 Products and Test Wafer Volumes

The term "Wafer Starts Per Week" (WSPW) represents the number of wafers introduced to the fab each week, where a single lot equals 24 wafers. On average 84 lots are introduced to the fab each week (2016 WSPW); where, the fab operates two 12-hours shift a day, 7 days a week.

The 84 lots introduced to the fab per week are of three types; standard product (Pa) starts 51 lots per week, standard product (Pb) starts 30 lots per week, and testing product (TW) starts 3 lots per week.

Two production operators are available for 540 minutes each per shift. Each operator gets two 60 minutes breaks and one 60 minutes meeting/training session per shift, and the two operators do not have to synchronize their off time in any way.

One maintenance technician is available for 600 minutes per shift. This technician gets two 45 minutes breaks and one 30 minutes meeting/training session per shift that do not have to synchronise with the off time of the operators. Note that no pre-emption can occur with personnel. Once they begin a task, that task must complete before any other task can begin.

4.1.3 Stations and Equipment Set Description

Station 1 of the Mini-Fab Model

Station 1 has 2 machines; machine A and machine B, which serve steps S_1 and S_5. Each machine run includes a load time which requires an operator at the beginning of a run and includes an unload time which requires an operator at the end of a run. Loading takes 20 minutes and unloading takes 40 minutes for each step. Within a given run of machine A or machine B, the same operator has to perform

[2]Full description can be found at http://aar.faculty.asu.edu/research/intel/papers/fabspec.html.

both the loading and the unloading tasks. There is a 75 minutes preventive maintenance every 24 hours (2 shifts) a day for each machine.

Machines in Station 1 batch 3 lots at a time. When batching at S_1 and S_5 certain rules restrict batching different lot types together; importantly, it is never acceptable to mix lots waiting for S_1 and lots waiting for S_5 into the same batch.

Batching rules at station 1 are as follows:

- When batching step 1, one can mix products and one test lots. For example, Pa/Pa/Pa, Pa/Pa/Pb, Pa/Pa/TW, Pa/Pb/TW, Pb/Pb/TW, Pb/Pb/Pa, Pb/Pb/Pb are acceptable.
- However, when batching step 5, one cannot mix products, but one can mix one test lot. For example, Pa/Pa/Pa, Pa/Pa/TW, Pb/Pb/TW, Pb/Pb/Pb is acceptable, but Pa/Pa/Pb, Pa/Pb/TW, Pb/Pb/Pa is not acceptable.
- It is never acceptable to mix lots waiting for S_1 and lots waiting for S_5 into the same batch.

Station 2 of the Mini-Fab Model

Station 2 has 2 machines; machine C and machine D, which serve steps S_2 and S_4. Loading takes 15 minutes and unloading takes 15 minutes for each step. Within a given run of machine C or machine D, the same operator does not have to perform both loading and unloading operations.

There is a 120 minute preventive maintenance event every 12 hours shift for each machine. In addition, emergency maintenance happens randomly every 24 to 76 hours on average; but, the repair, once started, takes on average 6 to 8 hours for each machine.

Station 3 of the Mini-Fab Model

Station 3 has only one machine, machine E, which serves steps S_3 and S_6. Loading and unloading tasks take 10 minutes for each step. Within a given run of machine E, the same operator has to perform both the loading and unloading.

There is a 30 minutes preventive maintenance every 12 hours shift. Machine E serves both Step S_3 and Step S_6, which can be Product Pa, Product Pb or a test wafer. Consequently, three types of lot changes can occur each requiring a setup time as follows:

- In one possibility, the lot type stays the same and the step changes (S_3 to S_6 or S_6 to S_3), this takes 10 minutes.
- In another possibility, the step stays the same and the lot type changes (among Pa, Pb, and TW), this takes 5 minutes.
- In the third possibility, both the step and the lot type change (for example, going from Pa on S_6 to Pb on S_3), this takes 12 minutes.

Note that all setup times are symmetric (for example, going from Pa/S_3 to TW/S_3 or going from TW/S_3 to Pa/S_3 both take 5 minutes). Table 4-1 summarizes the parameters of the three stations with their machines, steps, processing rates, loading, unloading and production operators.

Table 4-1: Summary description of Minifab parameters.

<table>
<tr><th>Station</th><th>Machine</th><th>Step</th><th>Processing time (minutes)</th><th>Loading (minutes)</th><th>Unloading (minutes)</th><th>Operator(s)</th></tr>
<tr><td rowspan="2">1</td><td rowspan="2">A /B</td><td>1</td><td>225</td><td rowspan="2">20</td><td rowspan="2">40</td><td rowspan="2">PO1</td></tr>
<tr><td>5</td><td>255</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">C/D</td><td>2</td><td>30</td><td rowspan="2">15</td><td rowspan="2">15</td><td rowspan="2">PO1/PO2</td></tr>
<tr><td>4</td><td>50</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">E</td><td>3</td><td>55</td><td rowspan="2">10</td><td rowspan="2">10</td><td rowspan="2">PO2</td></tr>
<tr><td>6</td><td>10</td></tr>
</table>

4.1.4 Basic Capacity Analysis

Table 4-2 presents the utilisation of each station based on the production of six lots. This is achieved by dividing the available time (minutes per shift) of each station by the time required to produce the six lots (minutes per shift). It is clear from the table that station 3 (machine E) has the highest utilisation; hence, this machine is the bottleneck machine.

Table 4-2: Utilisation of the three stations.

Station	Machine	Time Available (minutes/shift)	Step	Time Required (minutes/shift)	Utilization
1	A	682.5	S_1	570	87.9%
	B	682.5	S_5	630	
	Total	1365	Total	1200	
2	C	540	S_2	360	77.8%
	D	540	S_4	480	
	Total	1080	Total	840	
3	E	690	S_3	450	91.3%
			S_6	180	
			Total	630	

4.1.5 List of Assumptions

Some revisions and assumptions have been made to the Minifab, these include:

- Neither maintenance technicians nor operators required for loading and unloading are modelled.
- No rework is needed.
- This model does not include travel times.
- Rules for lot batching at station 1 are simpler.
- Tool processing times are deterministic.
- Lots of 24 wafers is the unit being processed by tools.
- Minutes are the time units.

4.2 DATA COLLECTION

The process of building the model depends on a set of data that can be categorized into three main groups: structural, operational, and numeric.

4.2.1 Structural Data

The structural data are the three stations (locations) with their five machines (resources), where:

- Station 1 has two machines, machine A and machine B.
- Station 2 has two machines, machine C and machine D.
- Station 3 has only one machine, machine E.

These machines are used to process three types of lots which are the standard product (Pa), standard product (Pb), and testing product (TW).

4.2.2 Operational Data

The operational data is the data related to:

- The routing of the six processing steps to produce a lot (S_1, S_2, S_3, S_4, S_5, and S_6).
- The preventive and emergency maintenance.
- The batching of the three lots at a time in station one. The rule that apply to batching is that mixing lots waiting for S_1 and lots waiting for S_5 into the same batch is never acceptable.
- The setup times of machine E in station three. In one possibility, the lot type stays the same and the step changes (S_3 to S_6 or S_6 to S_3), in another possibility, the step stays the same and the lot type changes (among Pa, Pb, and TW), in the third possibility, both the step and the lot type change (for example, going from Pa on S_6 to Pb on S_3).

4.2.3 Numerical Data

The numerical data is the data concerning the input values and distributions and their parameters. These values can either be deterministic (constant) or stochastic (probabilistic); these are presented as follows:

Deterministic Data

The processing time of the steps with their loading and unloading times are as shown in Table 4-3.

Table 4-3: Summary of loading, unloading, and processing times.

Step Number	1	2	3	4	5	6
Processing time (minutes)	225	30	55	50	255	10
Loading (minutes)	20	15	10	20	15	10
Unloading (minutes)	40	15	10	40	15	10

In station 1 there is 75 minutes scheduled maintenance every 24 hours (2 shifts) for each machine (machine A and machine B), in station 2 there is a 120 minutes scheduled maintenance every 12 hours shift for each machine (machine C and machine D), in station 3 there is a 30 minutes scheduled maintenance every 12 hours shift as summarized in Table 4-4.

Table 4-4: Summary of scheduled maintenance.

Station	Machine	Up Time (minutes)	Down Time (minutes)	Frequency (minutes)
1	A/B	1365	75	1440
2	C/D	600	120	720
3	E	690	30	720

As mentioned earlier, due to the existence of only one machine at station 3, product changeovers results in different setup times. Table 4-5 is the setup matrix for machine E showing the setup times needed for all possible types of step/product type changeover. When the lot type stays the same and the step changes (S_3 to S_6 or S_6 to S_3), this takes 10 minutes, when the step stays the same and the lot type changes (among Pa, Pb, and TW) this takes 5 minutes, when both the step and the lot type change (for example, going from Pa on S_6 to Pb on S_3) this takes 12 minutes.

Table 4-5: Setup time matrix.

		To					
		Pa/S_3	Pb/S_3	TW/S_3	Pa/S_6	Pb/S_6	TW/S_6
From	Pa/S_3	0	5	5	10	12	12
	Pb/S_3	5	0	5	12	10	12
	TW/S_3	5	5	0	12	12	10
	Pa/S_6	10	12	12	0	5	5
	Pb/S_6	12	10	12	5	0	5
	TW/S_6	12	12	10	5	5	0

Stochastic Data

The developed model is stochastic due to the following random inputs (listed in Table 4-6):

- The inter-arrival of items is exponentially distributed with a mean of 120 minutes, which is equivalent to 84 lots per week (2016 WSPW).

- The three different product types produced Pa, Pb, and TW follow an empirical distribution with probabilities 0.61, 0.36, and 0.03; respectively.
- The unscheduled breakdowns for machines C and D at station 2 are uniformly distributed with a minimum of 24 hours and a maximum of 76 hours. The repair time is also uniformly distributed with a minimum of 6 hours and a maximum of 8 hours.

Table 4-6: Summary of stochastic data.

<table>
<tr><th>Input Data</th><th>Distribution</th><th colspan="2">Parameters</th></tr>
<tr><td>Lot generation
(Inter arrival time)</td><td>Exponential</td><td colspan="2">Mean = 120 minutes/lot</td></tr>
<tr><td rowspan="4">Product type;
Pa = 1
Pb = 2
TW = 3</td><td rowspan="4">Empirical</td><td>Value</td><td>Probability</td></tr>
<tr><td>1</td><td>0.61</td></tr>
<tr><td>2</td><td>0.36</td></tr>
<tr><td>3</td><td>0.03</td></tr>
<tr><td>Unscheduled breakdown
(machines C and D)</td><td>Uniform</td><td colspan="2">Min = 1,440 minutes
Max = 4,560 minutes</td></tr>
<tr><td>Repair time
(machines C and D)</td><td>Uniform</td><td colspan="2">Min = 360 minutes
Max = 480 minutes</td></tr>
</table>

4.3 MODEL VERIFICATION

Model verification is the process of ensuring that the computer programming and implementation of the conceptual model are correct.

This step was carried out using ExtendSim's reporting and animation capabilities of the different building blocks of the model to ensure that the model is working as intended.

The verification process was held continually during model development to ensure that the model was working properly after any modification to the model and before moving to the next modification.

4.4 MODEL VALIDATION

As mentioned previously, there are three types of model validation, face validation, validation of model assumptions, and input/output transformation validation.

Face validation mainly involved animation to confirm that the lots are being processed in the sequence mandated by the Minifab, three lots are batched before processing at station one, and that machines are subjected to the different maintenance stoppages.

Validation of model assumptions fall into two general classes: structural assumptions and data assumptions.

- The structural assumptions took place by validating the number of stations with their machines. In station one, there are two machines A and B. In station two, there are two machines C and D. In station three, there is only one machine, machine E.

- The data assumptions was done by investigating the input model variables that are generated randomly in the model and making sure that they represent the actual variables, like the number of lots generated per week, percentage of each product type generated, and the availability of machines.

Finally, input/output transformation validation was done by comparing the output of the constructed model with respect to capacities, utilisations, and availability of the machines to those reported at the Minifab website mentioned before.

4.5 EARLY RESEARCH WORK

At the early stage of this research a simulation model of the Minifab is developed using the ExtendSim™ v8.0. An optimisation solution is examined for the operation of the Minifab under two approaches, and the details of this study can be found in [104].

Briefly, this model is capable of running eight different dispatching rules at the bottleneck station with different CONWIP levels applied to the whole line. The dispatching rules that are applied to the bottleneck station are: First In First Out (FIFO), Last In First Out (LIFO), Shortest Remaining Processing Time (SRPT), Longest Remaining Processing Time (LRPT), Earliest Due Date (EDD), Critical Ratio (CR), Least Dynamic Slack (LDS), and Shortest Setup Time (SST).

Two different approaches to find the optimal CONWIP level/dispatching rule combination are employed. Both are based on the optimisation using simulation concept; where, the model is run repeatedly with different combinations of CONWIP level and dispatching rules. Optimisation using simulation aims to find the best combination of these two variables that will maximize throughput and minimize cycle time.

The two approaches examined use a similar search technique that is based on genetic algorithms. However, they differ in the way the objective function is defined.

The first considers employing an evolutionary algorithm to the multi objective optimisation by weighting each of the objectives in order to obtain a single objective function. This requires some a-priori or external knowledge of the relative importance of the competing objectives and results in a single solution that may be considerably sensitive to the weights.

By contrast, the second uses a pareto-optimal genetic algorithm to develop a true multi-objective solution to the same problem. Here no a-priori or external knowledge is required and the decision maker is presented with a set of non-dominated solutions to assist in selection of the most appropriate solution to implement. Both solutions are developed using discrete event simulation models built in ExtendSim™.

From this study, it is concluded that optimisation using simulation has advantages and disadvantages. One of the key advantages is that it combines the flexibility of simulation with the intelligence of optimisation without requiring a detailed derivation of a mathematical model. On the other hand, one of the observed disadvantages is that the optimisation strives to find the best possible solution within a given space of the solutions.

The results of the first approach confirmed that combining the SRPT dispatching rule with the CONWIP level of 12 lots is the best solution. This is done under the assumption that both throughput and cycle time are of the same importance and thus are given the same weight.

However, if the decision maker is not satisfied with the results, then the weights assigned to each objective should be changed accordingly and the model should be run all over again. The weighting used will be based on the knowledge of those familiar with the operational performance of the system and the relative importance of one measure over the other.

Whereas, the results of the second approach gives a set of solutions that the decision maker can choose from. In case that both objectives have the same weight, then, the best solution is also a combination of SRPT dispatching rule with CONWIP 12 lots. This is the same solution obtained using the evolutionary algorithm. However, this technique offers the decision maker greater flexibility in determining the alternative that best suits his/her requirements. Therefore, one can select a solution without running the whole model again, hence, it is considered to be time saving.

Since the two measures under study are conflicting in nature and to eliminate the sensitivity of giving importance to one measure over the other; either by assigning weights to the measures in a utility function, or by selecting a solution from a set of solutions; therefore, it is decided to better have one single objective that will work on achieving same TH with better CT and WIP, resulting in an overall improvement. The remaining of this work will discuss in details how to achieve this objective with different WIP management experiments.

4.6 MINI-FAB EXPERIMENTS

Based on the single objective mentioned earlier, it is recommended to investigate the WIP management of the Minifab and analyse its results in order to improve its performance. The following sections will discuss in details a set of experiments that will achieve this goal.

4.6.1 Performance Measures

The performance measures that are evaluated in the Minifab experiments include:

- *Throughput rate*, which is the number of finished lots per week. This is reported as the average of weekly throughput rate means reported from a number of replications $\overline{\overline{(TH)}}$.

- *Cycle time,* which is the time spent to produce one lot starting from entering the fab to begin with Step 1 (S_1) and ending with leaving the fab after finishing Step 6 (S_6). This is reported as mean of the cycle time reported for each lot over the run averaged based on the outcomes of a number of replications ($\overline{\overline{CT}}$).

- *Work in process*, this is the number of lots that entered the fab and still being processed. Which is reported as the mean of the instantaneous WIP level reported throughout the run and averaged based on the outcomes of a number of replications ($\overline{\overline{WIP}}$).

The objective of these experiments is to manage WIP efficiently to achieve the same TH with less WIP levels and; hence, shorter CT.

4.6.2 Simulation Parameters

The simulation parameters that must be defined for any simulation experiment are the simulation runtime, warmup period, and number of replications (Section 2.5.4). The upcoming sections will focus on determining these parameters.

Setting the Length of the Simulation Run

Although there is no definitive way of picking the simulation run time for nonterminating simulations (which is the type of models developed in this work); and that the simulation run time should be generally larger than the warmup period and needs to be determined by the model user. Thus, it is decided to set the simulation runtime with 2 years (1,048,320 minutes).

Determining the Warmup Period

In order to determine the warmup period (l) using Welch's method ten replications are carried out; each simulation run time covers a period of 2 years

(104 weeks) resulting in 104 observations (m) for the weekly throughput reported from each replication.

Different window sizes (w) are tried ($\mathrm{w}=5, \mathrm{w}=10, \mathrm{w}=15, \mathrm{w}=20$) to calculate the moving average of the mean weekly throughput until the plot of the moving average becomes reasonably smooth as shown in Figure 4-2. Based on that plot and using a window size of 20, it is clear that the plot becomes almost flat after a warmup period of 22 weeks.

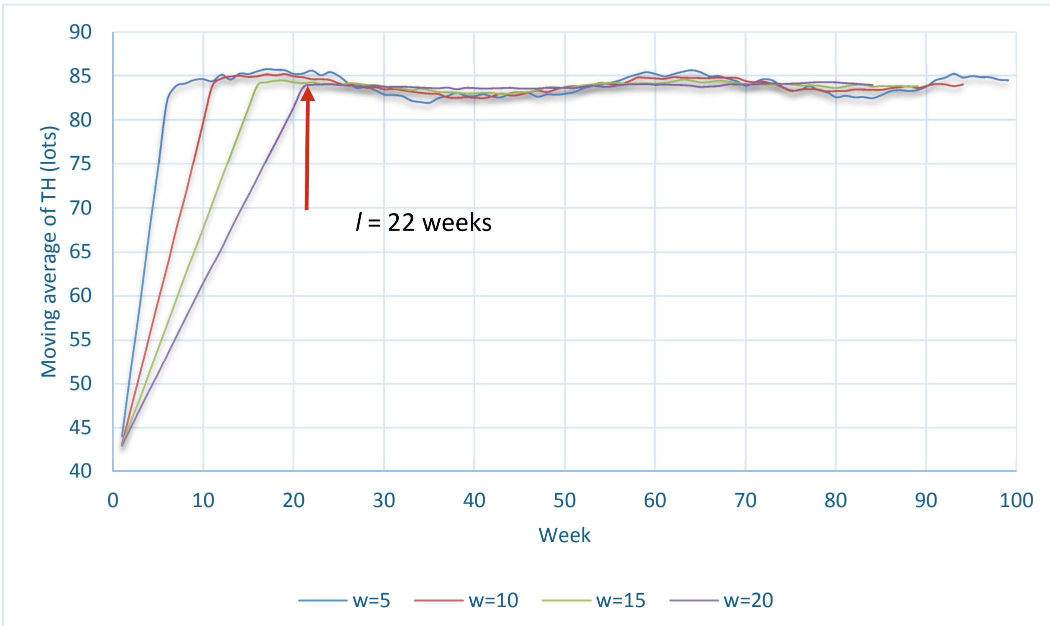

Figure 4-2: Moving average of weekly TH at w=5, w=10, w=15, w=20.

Selecting the Number of Replications

To select the number of replications required for this study 40 replications are carried out; again, each of 2 years. The results for mean throughput per week and mean cycle time are reported. In addition, the warmup period that is determined in the previous section is used in these runs and the results obtained from the first 22 weeks for throughput and cycle time are deleted. Figure 4-3 shows a graph of the cumulative mean data. Based on the plot of cumulative points, it is clear that the line becomes almost flat after 15 replications for both measures of performance;

hence, this will be the recommended number of replications for the experimentation work to follow.

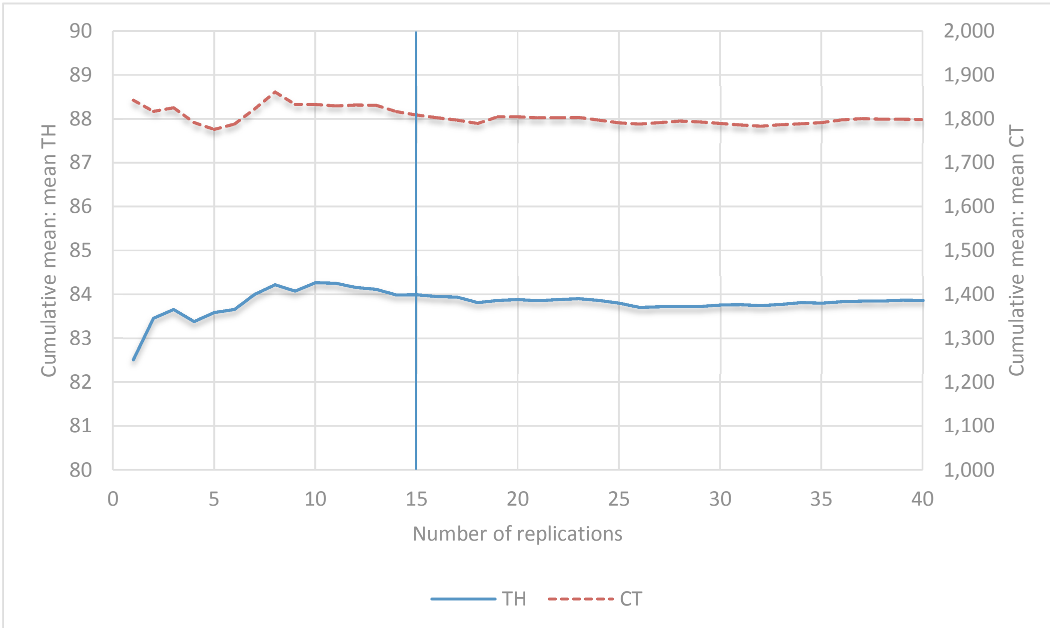

Figure 4-3: Cumulative mean of mean TH per week and mean CT.

In conclusion, it is decided that 15 replications are needed, each replication covers a simulation run time of 2 years, and with a warmup period of 22 weeks. Also, CRN is used; where, same random seeds are applied to all scenarios.

4.6.3 Push Scenarios

Two Push scenarios are tested based on different lots introduction behaviour, the first is an exponential input (Push-exp.) and the second is a deterministic input (Push-det.).

Although it is given that 84 lots per week are introduced to the Minifab, which means that a lot is introduced to the model every 120 minutes. However, different input values for inter arrival times of lots to both scenarios are tested as explained in the following sections.

Push with Exponential Input

As modelled previously, a lot is introduced to the Minifab with a mean of an exponential distribution of 120 minutes. In this section a number of simulations are carried out with different mean time between arrivals (MTBA) distributed exponentially.

Starting with a mean of 120 minutes and decreasing 1 minute for every simulation until reaching 107 minutes, the CT and WIP are incredibly increasing and thus no further simulations are tried. Table 4-7 presents the mean for the TH, CT and WIP averaged based on the outcomes of the 15 replications for every mean time between arrivals tested.

Table 4-7: Results of Push with exponential input at different mean time between arrivals.

MTBA (minutes)	$\overline{\overline{TH}}$ (lots)	$\overline{\overline{CT}}$ (minutes)	$\overline{\overline{WIP}}$ (lots)
120	84.09	1,813	15.66
119	84.84	1,876	16.32
118	85.60	1,960	17.16
117	86.31	2,044	18.03
116	87.06	2,133	18.93
115	87.80	2,266	20.25
114	88.55	2,430	21.87
113	89.35	2,623	23.76
112	90.16	2,944	26.82
111	90.95	3,433	31.49
110	91.76	4,152	38.30
109	92.49	5,341	49.50
108	93.18	7,344	68.45
107	93.52	10,847	101.73

It is clear from the results that as the mean time between arrivals decreases TH and CT increase, this is because lots are introduced faster to the Minifab and more lots are produced, thus these lots are pushed and accumulated at the queues resulting in more WIP that leads to longer CT.

Push with Deterministic Input

The other Push scenario mentioned earlier is presented in this section, a number of simulations with deterministic time between arrivals (TBA) are conducted beginning with 120 minutes and reducing a minute for every simulation until reaching 107 minutes. The results of these simulations are presented in Table 4-8.

Table 4-8: Results of Push with deterministic input at different time between arrivals.

TBA (minutes)	$\overline{\overline{TH}}$ (lots)	$\overline{\overline{CT}}$ (minutes)	$\overline{\overline{WIP}}$ (lots)
120	84.00	1,161	9.61
119	84.71	1,185	9.96
118	85.44	1,191	10.10
117	86.17	1,200	10.28
116	86.91	1,213	10.48
115	87.67	1,229	10.71
114	88.43	1,252	10.99
113	89.21	1,280	11.32
112	90.01	1,312	11.70
111	90.82	1,351	12.17
110	91.65	1,397	12.72
109	92.48	1,456	13.36
108	93.33	1,558	14.42
107	94.20	1,857	17.36

To compare the performance of both Push scenarios an operating curve to show the trade-off between TH and CT is developed and presented in Figure 4-4.

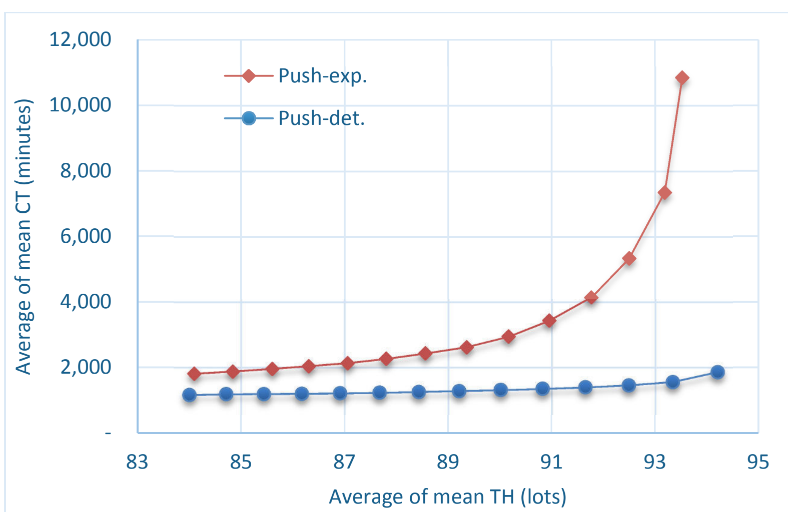

Figure 4-4: Operating curve of Push with exponential and deterministic inputs.

It is clear from the graph that the performance of the Minifab with deterministic input is better than Push with exponential input, same TH is consistently achieved with shorter CT for all arrival rates tested with simulation. This is because switching from exponential input to deterministic input reduced the amount of variability of inter arrival times of lots introduced to the Minifab, which consequently reduces the flow variability to stations downstream.

4.6.4 CONWIP Scenarios

When applying CONWIP as a lot release control strategy the WIP level to use must first be set. This is achieved by referring back to the results of the Push scenarios with deterministic input that gives a minimum WIP of 9.61 lots. This will be the starting WIP level to test using simulation; CONWIP level = 9.

Fifteen experiments are carried out by incrementing the CONWIP level by incrementing the CONWIP level by 1 lot for every experiment until reaching CONWIP level 21 lots. The results of these experiments are given in Table 4-9.

Table 4-9: CONWIP scenarios- Summary of results.

CONWIP level	$\overline{\overline{TH}}$ (lots)	$\overline{\overline{CT}}$ (minutes)	$\overline{\overline{WIP}}$ (lots)
9	76.55	1,185	8.50
10	80.63	1,250	9.50
11	85.71	1,294	10.50
12	88.78	1,363	11.50
13	89.94	1,457	12.50
14	91.98	1,534	13.50
15	93.10	1,624	14.50
16	93.62	1,723	15.50
17	93.99	1,823	16.50
18	94.24	1,925	17.50
19	94.29	2,031	18.50
20	94.34	2,137	19.50
21	94.33	2,244	20.50

By investigating the previously shown results, it is clear that by increasing the CONWIP level TH increases and accordingly CT and WIP increase until the increase of TH is minimal when compared to the increase of CT and WIP.

4.6.5 Push and CONWIP

To compare the performance of Push with deterministic input (as agreed to be better than the Push with exponential input in the previous section) to CONWIP, an operating curve showing the trade-off between TH and CT is presented in Figure 4-5.

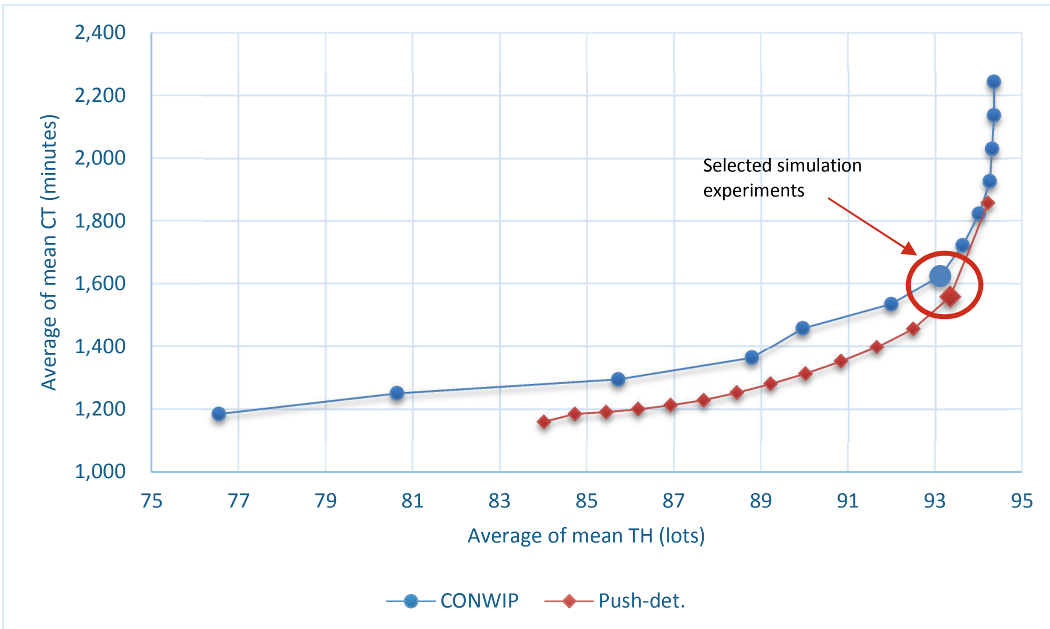

Figure 4-5: Operating curve of Push with deterministic input and CONWIP.

The figure shows that Push with deterministic input is performing better than CONWIP. To better comprehend the nature of the difference in performance between the two scenarios, a simulation experiment from each scenario is selected (selected simulation experiments have enlarged data points in Figure 4-5) and analysis is under taken.

At Push-det., this simulation experiment is the one that introduces a lot every 108 minutes to the Minifab, whereas at CONWIP, it is the one with CONWIP level 15. Revising Table 4-8 and Table 4-9, it is clear that both scenarios produce 93 lots per week, which will be the target TH in this study. However, at Push the CT is 1,557.93 minutes and at CONWIP the CT is 1,624.18 minutes.

Figure 4-6 shows a sample of the TBA of lots at Push-det. and CONWIP. At Push-det. the arrival of lots is regulated every 108 minutes since it is a deterministic input. However, at CONWIP there is high variability of Lot Arrivals. Also, it is noticed that the minimum inter-arrival time is 30 minutes which is the sum of loading, unloading and processing times of step 6 at station 3 (refer to Table 4-3). This is due the fact that a lot is introduced to the Minifab as soon as a lot is departed after its completion at station 3. Hence, the inter-arrival time of lots at CONWIP depends on the inter-departure time from the last station. This justifies the better performance of Push-det. over CONWIP.

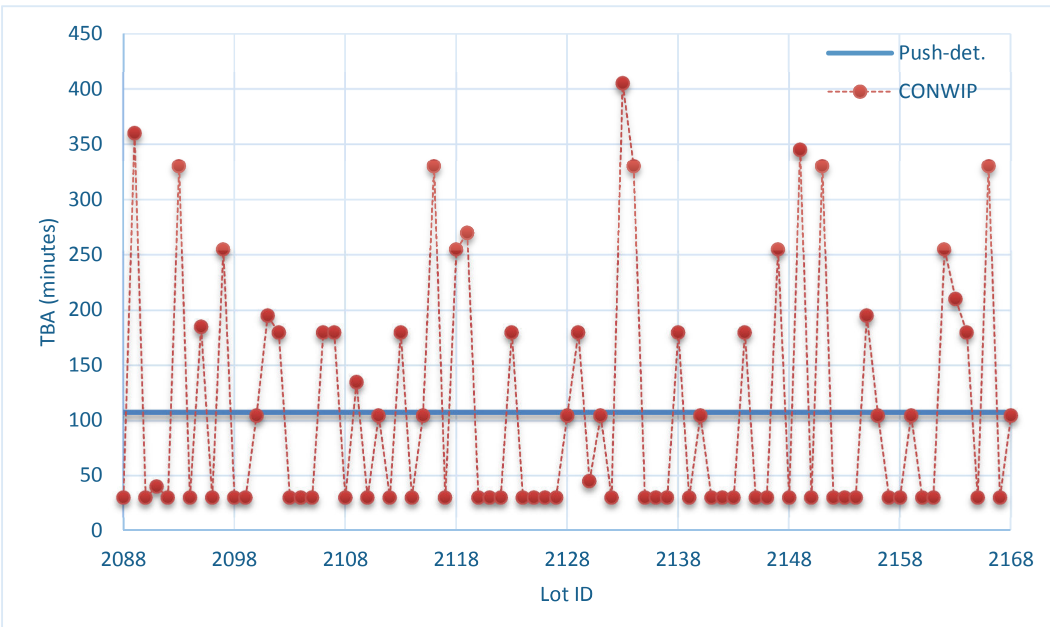

Figure 4-6: Time between arrivals of lots for Push-det. and CONWIP.

Also, it should be noted that this variability of arrivals affects the coefficient of variation of arrivals (c_a) to the three stations of the Minifab. The results of both scenarios are given at Table 4-10, and it is obvious from the results that Push-det. has lower c_a at all the stations.

Table 4-10: Mean c_a to the three stations at Push and CONWIP.

Scenario	c_{a_1}	c_{a_2}	c_{a_3}
Push-det.	0.629	0.801	0.843
CONWIP	0.863	0.850	0.967

Therefore, Push under deterministic conditions performs better than CONWIP as one of the most popular lot release control strategies of Pull. The next section will propose a modification to CONWIP lot release control strategy in order to improve its performance by regulating its arrivals to reduce the variability.

4.7 ICONWIP-PROPOSED LOT RELEASE CONTROL STRATEGY

To improve the effect of CONWIP on the performance of the Minifab, a new lot release control strategy named ICONWIP, where the first "I" stands for Inter-arrival time, is introduced. This strategy works on regulating the arrival of lots to the production line. Whenever a lot leaves the production line, a signal is given to authorize the release of a new lot. However, this lot is not released until a predetermined time interval has passed since the previous lot was released. In other words, two conditions are required to release a new lot:

- First, the departure of a lot from the production line.
- Second, a minimum predetermined time interval must pass between any 2 arrivals.

To understand the difference between CONWIP and ICONWIP, at CONWIP when a lot departs from the production line at time t_i, a new lot is immediately released to the line as shown in Figure 4-7.

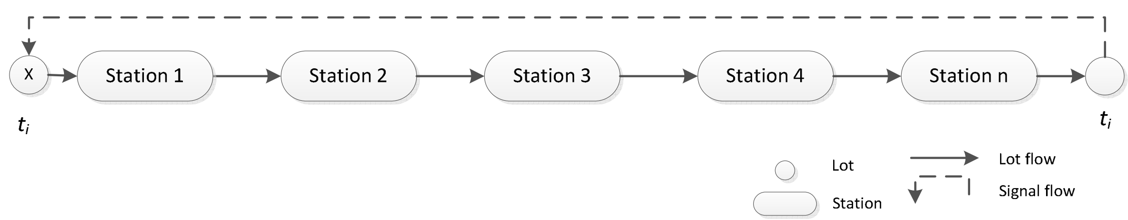

Figure 4-7: CONWIP lot release control strategy.

Whereas at ICONWIP, upon the departure of a lot from the production line at time t_i, a new lot (x) is ready to be released (as in CONWIP); yet, the arrival time of the last lot ($x-1$) introduced to the line at time t_{i-1} must first be checked. If the inter arrival time between lot x and lot $x-1$ is greater than a predetermined time interval known as minimum time between arrivals and denoted by (τ), then a signal is given to authorize the release of the new lot. Else, the new lot is delayed until that time interval (τ) passes, at that instance a signal is given to authorize the release of the new lot as shown in Figure 4-8.

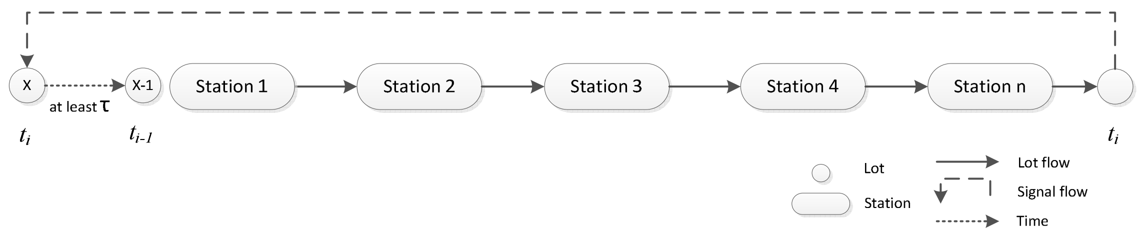

Figure 4-8: ICONWIP lot release control strategy.

4.7.1 Problem Formulation

To formulate the problem, the decision variables, objective function and constraints are to be defined as follows:

Decision Variables

There are two decision variables:

- N: number of lots at CONWIP level.
- τ: minimum time between arrivals to release a new lot.

Objective function

Min (Z) = CT

Constraints

$TH \geq TH^*$

$t_i \geq t_{i-1} + \tau$

$WIP \leq CL\ (N)$

N is integer

N and $\tau \geq 0$

Where;

TH^* is the target TH,

t_i is the arrival time of lot x,

t_{i-1} is the arrival time of lot $x-1$,

τ is the minimum time between arrivals, and

CL is the CONWIP level.

4.7.2 ICONWIP and Variability of Arrivals

The variability of arrivals to a production line affects the variability of arrivals to all stations. This is because the starting point for studying flows is the arrival of lots to a single station, and the departures of this station will in turn be arrivals to next stations (see Equation 4-1). Also, it should be mentioned that a low coefficient of variation of arrivals indicate regular or evenly spaced arrivals, while a high coefficient of variation of arrivals indicate uneven or burst arrivals [17].

$$c_a\,(i+1) = c_d(i) \qquad \text{Equation 4-1}$$

Where;

c_a is the coefficient of variation of inter arrival times,

c_d is the coefficient of variation of departure, and

i is the station number.

Therefore, regulating the arrival of lots to a production line will reduce the variability of arrivals to it and consequently will reduce the variability of arrivals to all stations.

To better understand the relation between variability of arrivals and improving cycle time, there is a need for Equation 4-2. This equation computes the waiting time in queue and it separates into three terms: a dimensionless variability term V, a utilisation term U, and a time term T, also it is referred to as VUT equation[17].

$$CT_q = \left(\frac{{c_a}^2 + {c_e}^2}{2}\right) \times \left(\frac{u}{1-u}\right) \times t_e \qquad \text{Equation 4-2}$$

Where;

CT_q is the waiting time in queue,

c_a is the coefficient of variation (CV) of inter arrival times,

c_e is the coefficient of variation (CV) of effective process time,

u is the utilisation of station, and

t_e is the mean effective process time.

It should be noted that this study will focus on the variability term V of the VUT equation. It will work on regulating the arrival of lots that will result in reducing Ca and consequently reduce the waiting time in queue and though improve CT. Referring to little's law (Equation 2-1) at constant TH, WIP is reduced with lower CT.

4.8 ICONWIP SCENARIOS

To apply ICONWIP two decision variables are required, the first is the CONWIP level, which is selected at the previous section to be 15 lots that achieved the target TH (93 lots per week). The second decision variable is the minimum time between arrivals (min TBA) that should pass between any 2 arrivals.

It should be noted that if the min TBA is 0 minutes then a lot is released to the Minifab as soon as a lot is departed, which is the CONWIP lot release control strategy discussed in the previous section. However, if a lot delays for even a minute waiting for a signal until it is released then it is the new proposed rule ICONWIP.

109 simulations are carried out starting from min TBA 0 minutes which describes CONWIP behaviour to min TBA 108 minutes which is the selected value of the Push deterministic input, and their results are presented in Figure 4-9.

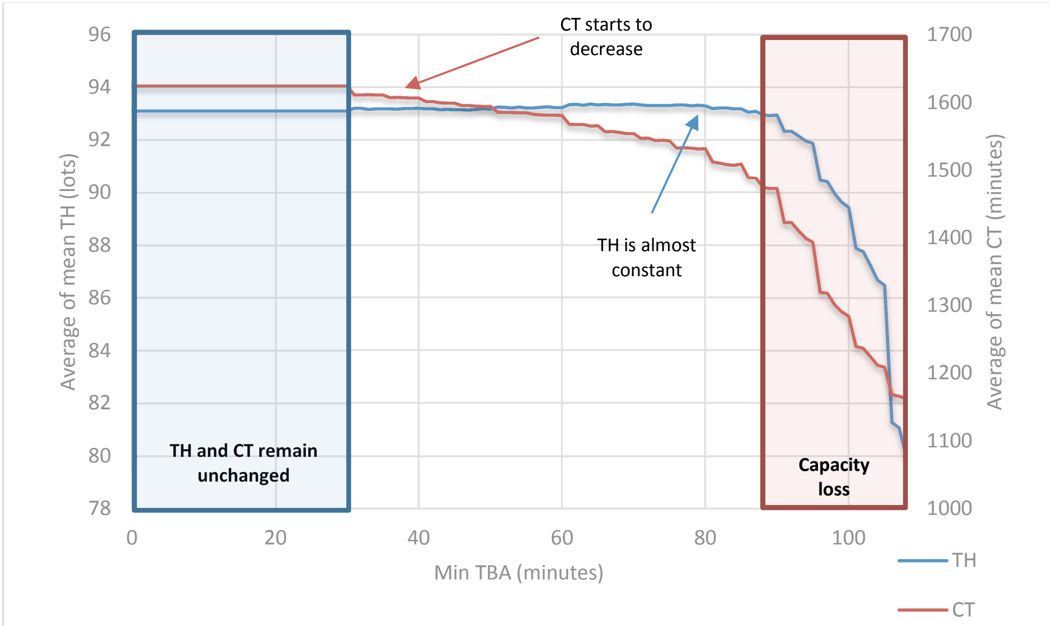

Figure 4-9: Results of ICONWIP 15 for min TBA from 0 to 108 minutes.

It is obvious that from min TBA 0 to 30 minutes TH and CT are not changing, therefore CONWIP and ICONWIP have the same performance. This is because the minimum inter arrival time of lots at CONWIP is 30 minutes (refer to Section 4.6.5, and Figure 4-6). Afterwards TH is almost steady and CT is decreasing until min TBA 87 minutes, then both measures are decreasing.

Consequently, it is agreed that the best performance of the Minifab when applying ICONWIP15 with min TBA 87 minutes results in 93.09 lots per week for TH with CT 1,487.81 minutes.

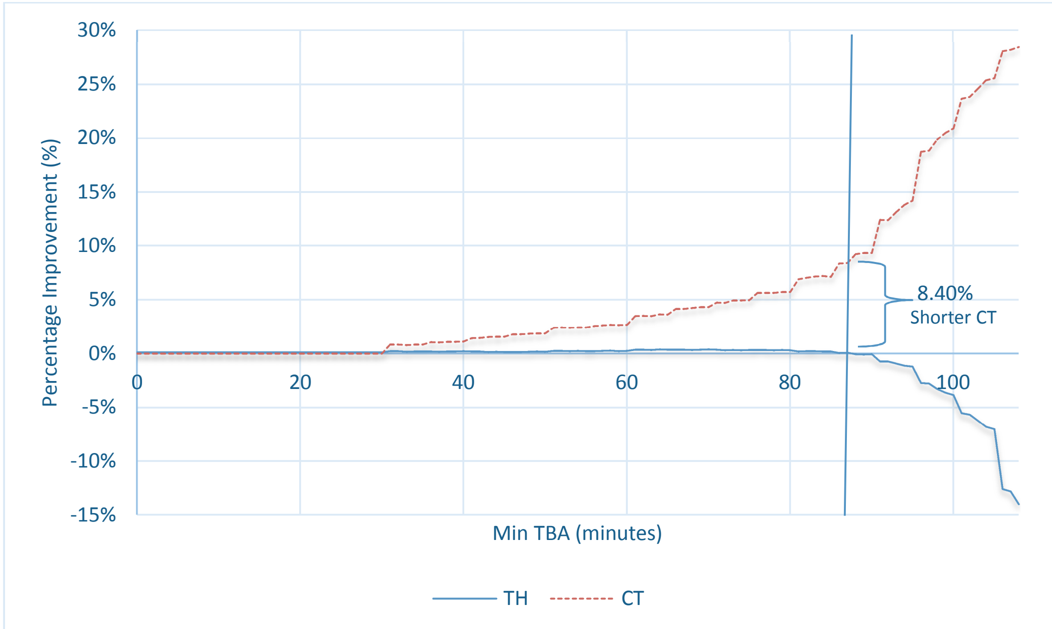

Figure 4-10: Percentage improvement of CT under ICONWIP when compared to CONWIP.

Figure 4-10 presents the percentage improvement of CT at ICONWIP15 when compared to CT of CONWIP15. It shows that the same TH is achieved with 8.4% improvement in CT at ICONWIP15 and min TBA 87 minutes.

To ensure that the best CONWIP level and min TBA are selected for the ICONWIP, other simulation experiments are tested with CONWIP levels 14 and 16 and the same min TBA (from 0 to 108 minutes) are applied for each CONWIP level. The results show that at ICONWIP14 the target TH is not achieved and the maximum TH attained is 92.29 lots with min TBA 77 minutes, whereas at ICONWIP16 the target TH is reached with min TBA 92 minutes but with longer CT when compared to ICONWIP15 as presented in Figure 4-11.

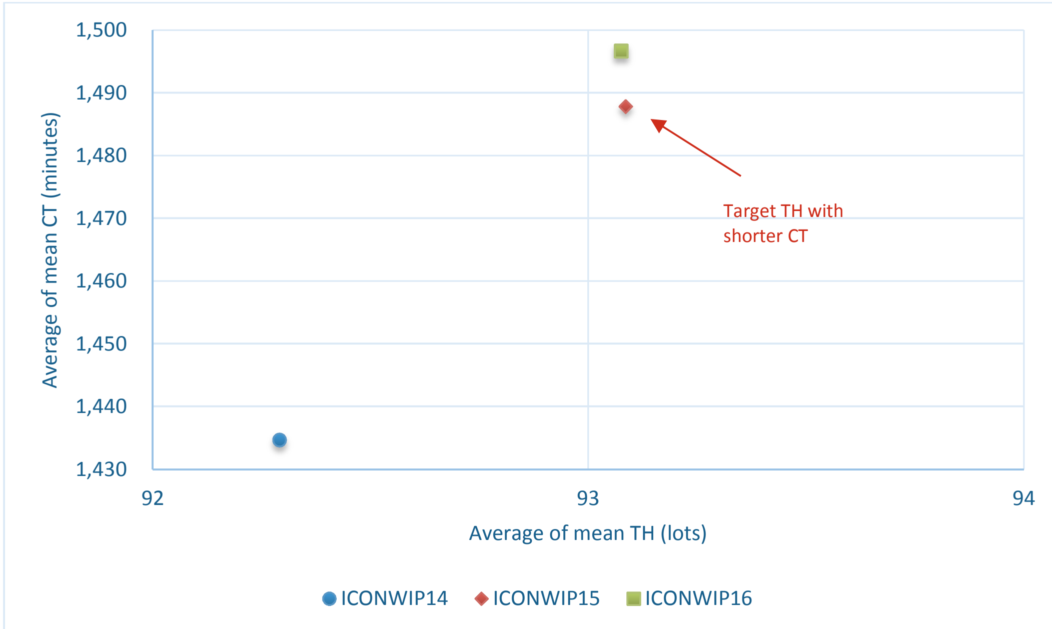

Figure 4-11: Results of selected experiments under ICONWIP14, 15, and 16.

4.9 PUSH, CONWIP AND ICONWIP

To compare Push-det., CONWIP and ICONWIP a summary of results to the 15 replications is given in Table 4-11. It is clear that the TH is achieved by the three scenarios; moreover, ICONWIP results in the lowest mean of mean CT, and mean of mean WIP.

Table 4-11: Summary of results to the 15 replications of Push, CONWIP and ICONWIP.

Scenario	$\overline{\overline{TH}}$ (lots)	$\overline{\overline{CT}}$ (minutes)	$\overline{\overline{WIP}}$ (lots)
Push-det.	93.33	1,558	14.42
CONWIP	93.10	1,624	14.50
ICONWIP	93.09	1,488	13.56

Figure 4-12 presents a sample of time between arrivals at Push-det., CONWIP and ICONWIP. It is obvious that Push-det. has the lowest variability when compared to CONWIP and ICONWIP, and this is due to the deterministic input used in the model tested.

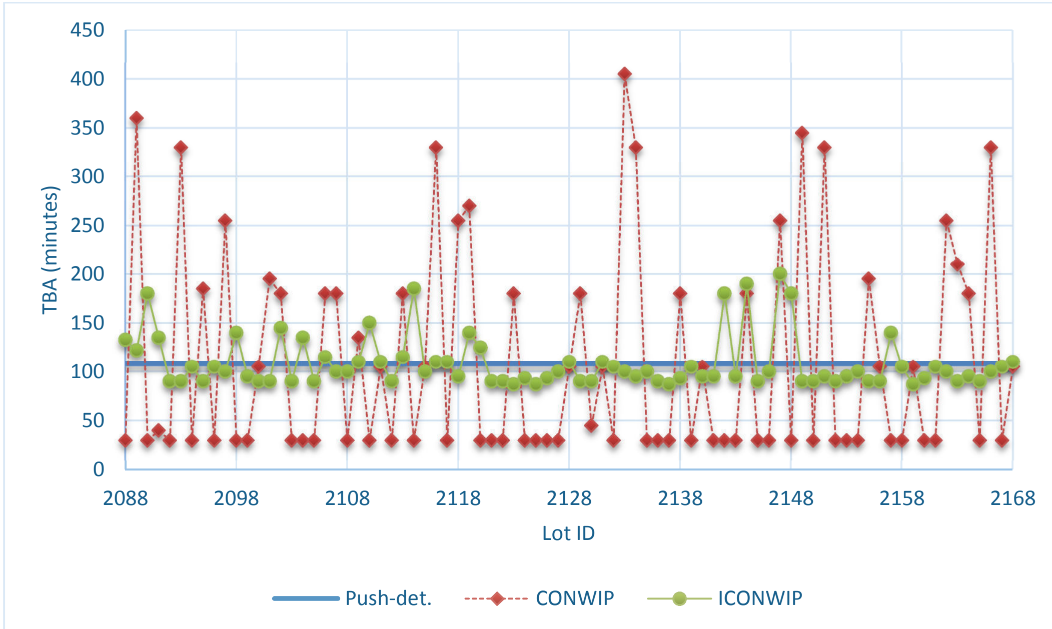

Figure 4-12: Time between arrivals of lots for Push-det., CONWIP and ICONWIP.

It is clear that ICONWIP has less variability at the arrival of lots when compared to CONWIP. For the sample shown, the inter-arrival time ranges from 87 to 200 minutes. This is because the ICONWIP is targeting the minimum time between arrivals and not the maximum, adding a floor to the inter arrival times. Lots with more than 87 minutes between the arrivals are released to the Minifab upon the departure of another lot after checking that more than 87 minutes has passed since the previous lots are released.

As mentioned earlier that this variability of arrivals affects c_a to the three stations of the Minifab, the results of the three scenarios are given in Table 4-12. It is observable from the results that Push-det. has the lowest c_a at all the stations. ICONWIP has better performance than CONWIP regarding c_a at the three stations.

Table 4-12: Mean c_a to the three stations for Push-det., CONWIP and ICONWIP.

Scenario	c_{a_1}	c_{a_2}	c_{a_3}
Push-det.	0.629	0.801	0.843
CONWIP	0.863	0.850	0.967
ICONWIP	0.668	0.810	0.861

4.10 SELECTION OF THE BEST MINI-FAB SCENARIO

To confirm the results attained from the previous sections, Nelson's combined method discussed in Section 2.5.4 (Subsection Experimentation and Analysis) is applied here to select the best Mini-fab scenario. Table 4-13 shows the parameters and constants required for this application.

Table 4-13: Parameters and Constants for Nelson's method of Mini-Fab scenarios.

Parameter	Value	Constant	Value
$\propto$	0.05	t	3.069
k	4	h	3.285
n_o	15	ε	1

The selected practically significant difference value of ε =1 indicates that, with 95% confidence, the mean cycle time (which is approximately 1 day) of the selected scenario is less than 1 minute longer than the actual best system.

Table 4-14 presents the outcomes of the Nelson's combined method when applied on the Mini-Fab scenarios. It is shown that there is only one survivor ICONWIP, thus this is the best scenario and the procedure is terminated.

Table 4-14: Results from Nelson's combined method- Mini-Fab scenarios.

Scenario	i	$\bar{Y}_i$	${S_i}^2$	j	W_{ij}	$\bar{Y}_j + \max(0, W_{ij} - \varepsilon)$	Decision
Push-exp.	1	7,344	24,933,090	2	4,094	5,623	Eliminate
				3	4,096	5,690	
				4	4,095	5,553	
Push-det.	2	1,558	1,021	1	4,094	11,409	Eliminate
				3	24.05	1,624	
				4	26.11	1,488	
CONWIP	3	1,624	10.50	1	4,096	11,410	Eliminate
				2	24.05	1,558	
				4	2.97	1,488	
ICONWIP	4	1,488	4.07	1	4,095	11,409	Keep
				2	26.11	1,558	
				3	2.97	1,624	

4.11 CONCLUSIONS OF MINI-FAB EXPERIMENTS

Although it is given that 84 lots per week are introduced to the Minifab; however, testing different input values for inter arrival times between lots results in better throughput rates, and 93 lots per week is selected to be the target TH to the all scenarios tested in this work. Table 4-15 presents the mean for the TH, CT and WIP averaged based on the outcomes of the 15 replications; ($\overline{\overline{TH}}, \overline{\overline{CT}},\ and\ \overline{\overline{WIP}}$) respectively. The results show that the target TH is attained with major differences in the remaining performance measures.

Table 4-15: Results of Minifab experiments.

Scenario	$\overline{\overline{TH}}$ (lots)	$\overline{\overline{CT}}$ (minutes)	$\overline{\overline{WIP}}$ (lots)
Push-exp.	93.18	7,344	68.45
Push-det.	93.33	1,558	14.42
CONWIP	93.10	1,624	14.50
ICONWIP	93.09	1,488	13.56

Comparing Push-exp. and Push-det., both scenarios produced a $\overline{\overline{TH}}$ of 93 lots per week; still the $\overline{\overline{CT}}$ and $\overline{\overline{WIP}}$ of Push-det. are better than Push-exp. as follows:

- $\overline{\overline{CT}}$ is reduced from 7,344 to 1,558 minutes per lot gaining 78.79% better performance.
- $\overline{\overline{WIP}}$ is decreased from 68.45 to 14.42 lots resulting in 78.93% improvement.

Therefore, switching from exponential input to deterministic input reduced the variability of arrivals to the first station of the Minifab that results in lower variability of arrivals through all the stations downstream and consequently improved all the performance measures under study as well as reduced all the variances of the measures.

Applying CONWIP to the Minifab tempted a source of arrival variability, that degrades the performance of the Minifab when compared to that achieved with Push-det., although both scenarios produced 93 lots per week for $\overline{\overline{TH}}$ and 14.5 lots for $\overline{\overline{WIP}}$; yet the $\overline{\overline{CT}}$ increased from 1,558 to 1,624 minutes per lot degrading the $\overline{\overline{CT}}$ performance with 4.24%.

The issue of arrival variability leads to the proposal of ICONWIP that regulates the release of lots to the Minifab. The results presented in Table 4-15 confirms that ICONWIP is the best strategy applied to the Minifab, and it improved the performance of the Minifab over CONWIP as follows:

- ICONWIP reduced $\overline{\overline{CT}}$ from 1,624 to 1,488 minutes per lot leading to better performance with 8.37%.
- $\overline{\overline{\text{WIP}}}$ is decreased from 14.5to 13.56 lots resulting in 6.48% lower WIP.

Finally, Comparing Push-det. and ICONWIP is undertaken, both scenarios produced 93 lots per week for $\overline{\overline{TH}}$ with an increase of $\bar{V}_{TH}$ at ICONWIP over Push-det. Thus, all the other measures of ICONWIP are better than Push-det. as follows:

- $\overline{\overline{CT}}$ is reduced from 1,558 to 1,488 minutes per lot improving the performance with 4.49.
- $\overline{\overline{\text{WIP}}}$ is decreased from 14.42 to 13.56 lots resulting in 5.96% better performance.

After comparing all the experiments tested on the Minifab, it is concluded that ICONWIP is outperforming CONWIP as well as Push with deterministic input. Therefore, it is recommended to apply the same methodologies tested on larger models that include greater number of machines, more processing steps and exhibits more complexity and variability as well as to test the applicability of the proposed ICONWIP lot release control strategy.

5 WAFER FABRICATION FACILITY UNDER STUDY

As mentioned in the previous chapter that the most popular models used by researchers is the Minifab, because it captures some of the challenges involved in a re-entrant fab; however, it has a limited number of stations, machines and steps.

Also, Wein's model is widely used [38, 91, 110, 111], it has been a benchmark for many semiconductor manufacturing studies. Most of the parameters of the model are derived from the data gathered at the Hewlett-Packard Technology Research Centre Silicon fabrication, which is a large R&D facility in Palo Alto, CA. Also, other studies used reduced models of real wafer fabrication facilities [9, 15, 101, 102, 112]. Although Wein's model has larger number of stations including greater number of machines that are exposed to random breakdowns, and greater number of steps are required to complete a production of a lot which results in higher re-entrancy when compared to Minifab; however, it does not include any of the complex batching and sampling processes found in real fabs.

In this work, a representative segment of an existing wafer fabrication facility operating with the latest technologies used in the semiconductor manufacturing is under study. This Segment has been defined with the assistance of the ICMR, which works with a number of wafer fabrication facilities and research institutes in Ireland and Europe to address the significant challenges involved in operating highly re-entrant semiconductor manufacturing lines.

5.1 DATA COLLECTION

The process of building the model depends on a set of data that can be categorized into structural, operational, and numerical data. These data are presented in details in the following sections.

5.1.1 Structural Data

The Segment under study is composed of 12 stations. Each station performs a specific operation and is composed of different number of identical machines as shown in Table 5-1.

Table 5-1: A summary of the structural data.

Station		Operation Description	No. of Machines
No.	Type		
1	MDep	Metal Deposition-Pad Deposition	2
2	TCheck	Thickness Check-Check	2
3	LPat	Lithography Patterning	4
4	LAlign	Pattern Alignment Check	2
5	LDim	Pattern Dimension Check-Etch Dimension Check	3
6	MEtch	Metal Etch-Pad Etch	3
7	RWash	Resist Removal	2
8	IDep	Insulation Deposition	3
9	IPol	Insulation Planarization-Insulation Thickness	2
10	IEtch	Insulation Etch	5
11	VDep	Via Deposition	3
12	VPol	Via Planarization	2

The unit flowing in the Segment and requiring use of the available machines/stations is a lot of 25 wafers and presenting a single product type. If any machine is not available (processing another lot or down), lots are allowed to wait and form queues in front of the station of that machine.

5.1.2 Operational Data

Lots visit different stations following a specific routing; where, some lots are subjected to sampling at the measurement stations, others may follow batching rules, as well as the machines within the stations are exposed to breakdowns. Exemplifications of the operational data included in this work are provided in the following sections.

Routing of Lots

The Segment features 46 processing steps and 33 machines distributed in 12 stations; hence, each lot visits the same station more than once (re-entrant flow) in order to complete its processing as presented in Figure 5-1.

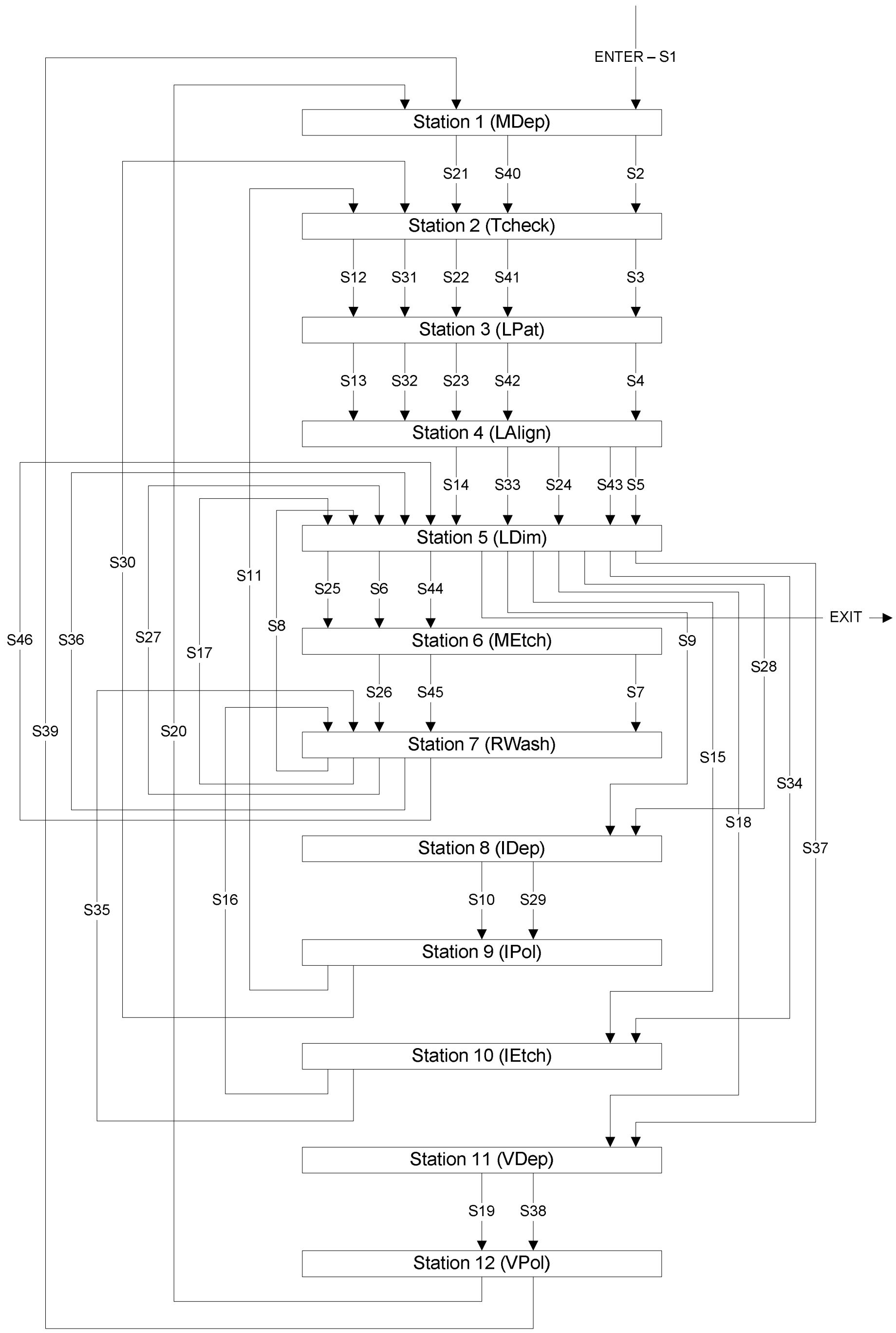

Figure 5-1: The routing of the selected segment of a wafer fabrication facility.

Sampling at Measurement Stations

There are three sampling stations at the Segment, these stations are: LDim, TCheck, and LAlign, where each station has its rule for sampling as follows:

- At LDim : Sampling rate is 2/3 initial remains sampling, where 2 lots are sampled and the third lot skip the sampling process, but here a lot that is sampled once should be sampled each time it visits the station on the same machine that was used for sampling before. Also, it should be noted that when a lot skips sampling it is never sampled.

- At TCheck and LAlign: Sampling rate is also based on total count as shown below; however, the conditions of whether to sample a lot or not, and of sampling the same lot on the same machine do not apply. Selecting a lot for sampling simply depends on arrival; a lot that is sampled once can skip sampling another time it revisits the station and vice versa.

  - Sampling rate for TCheck is 2/3 total count, where two lots are sampled and the third lot skip the sampling process.

  - Sampling rate for LAlign is 3/4 total count, where three lots are sampled and the fourth lot skip the sampling process.

Batching Stations

In the Segment there is a cascaded batch, where batches are allowed to be formed up to a maximum allowable batch size and then are cascaded through the machine [12]. The cascaded batch is found at RWash and IEtch stations; where, 2 lots of the same step are batched and then cascaded through the machines.

5.1.3 Numerical Data

The numerical data is the data concerned with values for example: loading to the production line, processing times, run rates, mean time to failure (MTTF), mean time to repair (MTTR), and transport times, these values can either be deterministic (constant) or stochastic (probabilistic), these are presented as follows:

Deterministic Data

Every day 19 lots are loaded to the production line, within each of the 12 stations all machines have the same nominal run rate in terms of the number of lots they can process, with the station run rate being the sum of the machine run rates. Table 5-2 presents the processing times of each step for every lot in minutes.

Table 5-2: A summary of processing times.

Station		Steps Served by Each Station	Processing Time (minutes per lot)
No.	Type		
1	MDep	S_1, S_{20}, S_{39}	23.07
2	TCheck	S_2, S_{11}, S_{21}, S_{30}, S_{40}	0.681
3	LPat	S_3, S_{12}, S_{22}, S_{31}, S_{41}	36.6
4	LAlign	S_4, S_{13}, S_{23}, S_{32}, S_{42}	1.2
5	LDim	S_5, S_8, S_{14}, S_{17}, S_{24}, S_{27}, S_{33}, S_{36}, S_{43}, S_{46}	0.857
6	MEtch	S_6, S_{25}, S_{44}	42.9
7	RWash	S_7, S_{16}, S_{26}, S_{35}, S_{45}	7.89
8	IDep	S_9, S_{28}	60
9	IPol	S_{10}, S_{29}	30
10	IEtch	S_{15}, S_{34}	100
11	VDep	S_{18}, S_{37}	60
12	VPol	S_{19}, S_{38}	30

Stochastic Data

The developed model is stochastic because there is a transport time for lots between all stations that is triangularly distributed with a minimum of 6 minutes, a maximum of 12 minutes, and a peak of 9 minutes.

There are a number of alternatives for modelling downtimes and failures: first, it can be ignored, second, it may not be modelled explicitly but processing times are increased in appropriate proportion, third, constant values for time to failure and time to repair can be used, and finally, statistical distributions for time to failure and time to repair may be used [72].

In the Segment statistical distributions for time to failure (TTF) and time to repair (TTR) are used. It is assumed that the each machine is individually subjected to random failure and random repair times based on exponential distributions which provides a good statistical model [72], and was used by [48, 110, 113-115].

To establish the MTTF and MTTR of the Segment, “Up and Down” time raw data provided by similar semiconductor manufacturing machines with process characteristics which match the different types of processing in the Segment are used. It be should be noted that the availability exhibited by the real machines is not used directly the segment under study, rather the mean time between failures (MTBF) from the data is used to establish the mean frequency of the “failure-repair” cycle for the machine.

The following steps show in details how these values are derived:

1. An anonymised dataset of machine status from a working fab was provided. The event time information from the machines relating to changing status from “Available” to “In Repair” were transformed into a list of “up” and “down” interval pairs. As this data was extracted to cover a period of production time, only complete events were considered in this analysis. For each station the MTBF values were as shown in Table 5-3 (Details of calculating MTBF can be found in Appendix B).

Table 5-3: Calculating MTBF for Each Station.

Station Type	Time between consecutive failure events (hours)							Sample size	MTBF (hours)
MDep	39.51	93.09	46.57	...	121. 8	204.2	155.8	244	88.09
TCheck	71.17	23.58	10.29	...	10.87	35.27	3.01	257	50.09
LPat	61.82	97.82	15.55	...	181.5	97.98	181.3	251	84.72
LAlign	71.17	23.58	10.29	...	10.87	35.27	3.01	257	50.09
LDim	28.68	83.15	15.43	...	68.09	335.7	166.5	161	107.2
MEtch	61.82	97.82	15.55	...	181.5	97.98	181.3	251	84.72
RWash	31.91	23.66	5.67	...	32.54	3.11	10.41	1,379	12.67
IDep	39.51	93.09	46.57	...	121.8	204.2	155.8	244	88.09
IPol	14.62	12.30	25.34	...	28.18	24.78	34.07	1,245	18.35
IEtch	61.82	97.82	15.55	...	181.5	97.98	181.3	251	84.72
VDep	39.51	93.09	46.57	...	121. 8	204.2	155.8	244	88.09
VPol	14.62	12.30	25.34	...	28.18	24.78	34.07	1,245	18.35

2. Availability (A) level, which is the fraction of time the machine is up and available for processing is given by the Equation 5-3 [17]. Figure 5-2 shows a timing diagram illustrating up and down events. It is clear from the figure that the MTBF covers one up and down event is thus the sum of the MTTF and MTTR resulting in Equation 5-2.

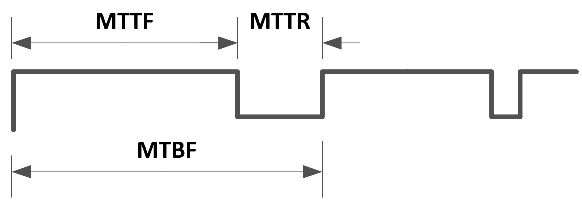

Figure 5-2: Timing diagram.

$$A = \frac{MTTF}{MTTF + MTTR} \qquad \text{Equation 5-1}$$

$$A = \frac{MTTF}{MTBF} \qquad \text{Equation 5-2}$$

3. MTBF is then combined with the availability provided to determine MTTF and MTTR, using Equation 5-3 and Equation 5-4; respectively, resulting values of both MTTF and MTTR are presented in Table 5-4.

$$MTTF = MTBF\ X\ A \qquad \text{Equation 5-3}$$

$$MTTR = MTBF\ X\ (1 - A) \qquad \text{Equation 5-4}$$

Table 5-4: Generating MTTF and MTTR.

Station Type	A	MTBF (hours)	MTTF (hours)	MTTR (hours)
MDep	0.76	88.09	66.95	21.14
TCheck	0.97	50.09	48.58	1.50
LPat	0.84	84.72	71.17	13.56
LAlign	0.97	50.09	48.58	1.50
LDim	0.96	107.24	103.42	4.31
MEtch	0.77	84.72	65.24	19.49
RWash	0.96	12.67	12.17	0.51
IDep	0.83	88.09	73.11	14.97
IPol	0.92	18.35	16.88	1.47
IEtch	0.75	84.72	63.55	21.18
VDep	0.82	88.09	72.23	15.86
VPol	0.79	18.35	14.50	3.85

5.1.4 Summary of Data Collection

As mentioned earlier the numerical data can either be deterministic (constant) or stochastic (probabilistic), Table 5-5 gives a summary of all the input data to the model.

Table 5-5: Summary of input data.

Input Data		Distribution	Parameters
Segment loading (Push Batch)		Deterministic	19 lots every day
Travel times		Triangular	Minimum=6, Maximum=12, and Peak=9 minutes.
MDep station	Processing times	Deterministic	23.07 minutes
	Time to failure	Exponential	Mean=4016.73 minutes
	Time to repair		Mean=1268.44 minutes
TCheck station	Processing times	Deterministic	0.681 minute
	Time to failure	Exponential	Mean=2914.8 minutes
	Time to repair		Mean=90.15 minutes
	Sampling Rate	Deterministic	1/3 total count
LPat station	Processing times	Deterministic	36.6 minutes
	Time to failure	Exponential	Mean=4270.35 minutes
	Time to repair		Mean=813.39 minutes
LAlign station	Processing times	Deterministic	1.2 minutes
	Time to failure	Exponential	Mean=2914.8 minutes
	Time to repair		Mean=90.15 minutes
	Sampling Rate	Deterministic	1/4 total count
LDim station	Processing times	Deterministic	0.857 minute
	Time to failure	Exponential	Mean=6205.33 minutes
	Time to repair		Mean=258.56 minutes
	Sampling Rate	Deterministic	1/3 initial remains sampling
MEtch station	Processing times	Deterministic	42.9 minutes
	Time to failure	Exponential	Mean=3914.49 minutes
	Time to repair		Mean=1169.26 minutes
RWash station	Processing times	Deterministic	7.89 minutes
	Time to failure	Exponential	Mean=729.93 minutes
	Time to repair		Mean=30.41 minutes
IDep station	Processing times	Deterministic	60 minutes
	Time to failure	Exponential	Mean=4386.69 minutes
	Time to repair		Mean=898.48 minutes
IPol station	Processing times	Deterministic	30 minutes
	Time to failure	Exponential	Mean=1013.02 minutes
	Time to repair		Mean=88.09 minutes
IEtch station	Processing times	Deterministic	100 minutes
	Time to failure	Exponential	Mean=3812.81 minutes
	Time to repair		Mean=1270.94 minutes
VDep station	Processing times	Deterministic	60 minutes
	Time to failure	Exponential	Mean=4333.84 minutes
	Time to repair		Mean=951.33 minutes
VPol station	Processing times	Deterministic	30 minutes
	Time to failure	Exponential	Mean=869.88 minutes
	Time to repair		Mean=231.23 minutes

The objective of this work is to improve the performance of the Segment by achieving the same TH while minimizing the CT and WIP, as well as monitoring the U of the resources.

5.1.5 Basic Capacity Analysis

The Segment features 46 processing steps and 33 machines distributed in 12 stations as mentioned earlier. It operates two 12-hours shifts a day, 7 days a week.

It should be noted that in reality lots size differs from one fab to another and may differ in the same fab; however, in this work, it is assumed to be fixed at 25 wafers per lot, and only one product type is considered.

Basic capacity analysis is used to estimate the theoretical throughput rate per week, in order to know the maximum daily loading of the production line. This is achieved by testing different loadings per week to check whether the fab has enough capacity to produce the applied load given the maximum allowable capacity. To fulfil this, an important feature of the Segment is first presented in the following sections.

Utilisation

The utilisation of a station is denoted by U, and it is defined as the fraction of time it is not idle for lack of WIP. This includes the fraction of time the station is working on lots or has lots waiting but is unable to work on them due to a machine failure, or other detractor. Thus, U can be computed as in Equation 5-5, where the where the effective production rate is defined as the maximum average rate at which the station can process lot, considering the effects of failures, and all other detractors that are relevant over the planning period of interest [17].

$$U_i = \frac{r_{a_i}}{r_{e_i}} \quad \text{Equation 5-5}$$

Where;

r_{a_i} is the arrival rate at the station, and

r_{e_i} is the effective production rate of the station.

Assuming the Segment has enough capacity to produce the number of wafers introduced to the line per week, then the arrival rate at each station is the WSPW multiplied by the number of times a wafer visits that station [68].

Referring to the definition of the effective capacity in the operations management, it is the capacity the Segment expects to achieve given current operating constraints [116]. Therefore, to compute the effective production rate, the run rate of the station is multiplied by the availability of that station, and the U of a station can be calculated using Equation 5-6.

$$U_i = \frac{WSPW \times N_i}{r_i \times A_i} \qquad \text{Equation 5-6}$$

Where;

N_i is the number of times each wafer visits the station,

r_i is the run rate of the station,

A_i is the availability of the station, and

i is the station number.

Fab Utilisation

In semiconductor manufacturing, the failure of equipment or processes is often not a hard failure in the sense that something breaks; but rather, a soft failure in which the equipment begins to produce out of the tolerance region. Due to the nature of the product and process, this may not be detected for some time. For this reason, the machines are not usually overloaded even if there is available capacity for production. Hence, based on management decisions, a maximum utilisation (U_{max}) is usually set for each machine depending on the nature of the process it performs.

This U_{max} relates to the utilisation of the expected availability of the Segment rather than the classic utilisation mentioned in the previous section. The fab Utilisation is a special measure of utilisation exclusively to the fab and it is denoted by (U^*), it includes U_{max} in its calculation as an operating constraint, thus, U^* is computed as given in Equation 5-7.

$$U^*{}_i = \frac{WSPW \times N_i}{r_i \times A_i \times U_{max_i}} \qquad \text{Equation 5-7}$$

Moreover, U^* is used to evaluate the theoretical throughput rate, in order to know the daily loading to the Segment. Different numbers of wafers per week are tested theoretically by the aid of Equation 5-7 to determine the number of lots that can be introduced to the Segment every day based on the capacity.

Based on these calculations, it is found that 3325 WSPW introduced to the Segment with 19 lots loading to the production line every day, is the maximum applied load given the maximum allowable capacity using the data presented in Table 5-6. It should be mentioned that an addition of an extra 25 wafers which is equal to one lot will need an additional machine at LPat station.

Table 5-6 presents the U calculated using Equation 5-6 and the U^* computed using Equation 5-7 of each station based on the production of 3325 wafers per week.

Table 5-6: Utilisation (U) and Fab Utilisation (U^*) of the stations.

Station		No. of Steps	Run Rate per Station (wafer/wk.)	Availability	U_{max}	Utilisation (U)	Fab Utilisation (U^*)
No.	Type						
1	MDep	3	21,840	0.76	0.85	0.601	0.707
2	TCheck	5	59,136	0.97	0.69	0.29	0.42
3	LPat	5	27,552	0.84	0.72	0.718	0.998
4	LAlign	5	33,600	0.97	0.67	0.51	0.761
5	LDim	10	70,560	0.96	0.65	0.491	0.755
6	MEtch	3	17,640	0.77	0.79	0.734	0.93
7	RWash	5	63,840	0.96	0.78	0.271	0.348
8	IDep	2	12,600	0.83	0.85	0.636	0.748
9	IPol	2	16,800	0.92	0.73	0.43	0.589
10	IEtch	2	12,600	0.75	0.72	0.704	0.977
11	VDep	2	12,600	0.82	0.77	0.644	0.836
12	VPol	2	16,800	0.79	0.82	0.501	0.611

Regarding U^* it is clear that LPat station has the highest utilisation; hence, it is the bottleneck station. However, with respect to U it is observable that the highest utilisation is MEtch station and this is due to removing the U_{max} from the utilisation calculation. Therefore, U^* is needed to identify the bottleneck station, based on management decisions LPat station is the bottleneck station and the value of U for this station should not exceed the U_{max}.

It should be noted that U_{max} is a soft constraint, meaning that stations may have U higher than U_{max} in some instances; however, it won't be consistently higher.

Finally, it should be mentioned that this highly classified data has been provided from a representative of the ICMR who has a great experience in the semiconductor manufacturing and is widely knowledgeable about such system behaviours.

After preparing the different input data for the model, simulation model development takes place, which is described in detail in the next chapter.

6 SIMULATION MODEL DEVELOPMENT

A simulation model of the Segment, presented in the previous chapter, has been developed in the ExtendSim™ Suite v8.0.2 simulation environment. This chapter presents in details the model development process.

Due to the complexity of the semiconductor wafer fabrication facilities, usually simpler models are used as a test bed for evaluating different manufacturing control strategies, where some of the work done in literature is referenced earlier in chapter 3.

In this chapter, the Segment is modelled to test different manufacturing control strategies. The model includes greater number of stations and machines with greater number of steps than most of the previously mentioned test beds. Moreover, it captures most of the challenges involved in a real wafer fab such as high re-entrancy, complex batching and sampling, variable breakdowns... etc.

6.1 MODELLING CHALLENGES DURING RESEARCH

A major challenge encountered during the modelling process is relative to the utilisation reported from the “Activity” blocks in ExtendSim™ as these blocks include downtime as part of the utilisation. However, in the Segment, there is another measure of utilisation which is the “Utilisation of Availability”, this measure is calculated using Equation 6-1.

$$Utilisation\ of\ Availability = \frac{Time\ In\ Use}{Total\ Time - Downtime} \qquad \text{Equation 6-1}$$

6.1.1 Utilisation of Availability

Utilisation of availability denoted by *UofA* is one of the performance measures in this work, which was not reported directly from any of the ExtendSim™ building blocks. Accordingly, a number of blocks have been added to each station so that it can report the *UofA*.

To calculate the *UofA* accurately based on Equation 6-1; an "Integrate" block is used that can integrate an input value over time. An "Integrate" block is added to the "Activity" block connected to the F (Full) connector that returns a value of one whenever a lot is being processed. This value is integrated over time resulting in the "Time in Use" (T_InUse). Another "Integrate" block is connected to the SD (ShutDown) connector that returns a value of one whenever a machine is down. Again, this value is integrated over time resulting in the "Downtime" (T_Down). T_InUse and T_Down reported from the "Integrate" blocks are input to an "Equation" block, which calculates the *UofA* based on Equation 6-1. This arrangement of blocks is shown in the simplified model in Figure 6-1.

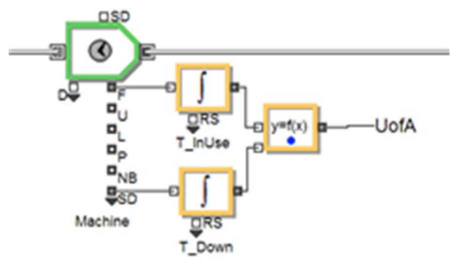

Figure 6-1: Reporting utilisation of availability.

6.1.2 Maximum Utilisation

Keeping the machines' utilisation below a pre-determined value of maximum utilisation (U_{max}) is the other challenge faced during modelling. Arrival of lots to stations or machines must be controlled, i.e. lots are prevented from entering the station or machine. Consequently, the *UofA* is prevented from exceeding U_{max}. The control logics for monitoring and controlling the *UofA* are provided in the following section.

6.1.3 Different Input Values and Models

Different input values are tested to control the flow of lots to stations or machines. First, introducing 18 lots per day which is the minimum loading that results in 3150 WSPW (126 lots per week) means there is still enough capacity in all stations for additional loading. Second, introducing 19 lots per day which is the maximum loading that results in 3325 WSPW (133 lots per week) means there is not enough capacity for additional loading in some stations. Finally, overloading some stations was tested by introducing 20 lots per day which results in 3500 WSPW (140 lots per day). It should be noted that these values are guided by the calculations mentioned in 0.

Three different versions of the model are developed to control the *UofA*, not to exceed the U_{max}. Different input values are tested (introducing 18, 19, and 20 lots per day) for the three versions shown in Figure 6-2, which are:

- Model A: Gated Control of the flow of lots based on station level utilization.
- Model B: Gated Control of the flow of lots based on machine level utilization.
- Model C: Machine shutdown based on keeping the *UofA* of each machine below Umax.

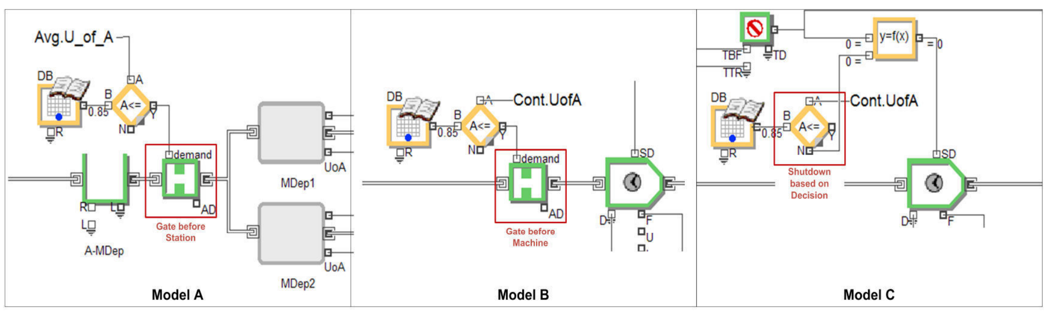

Figure 6-2: Three different versions of the model.

6.1.4 Performance Metrics

The performance metrics used in this work are:

- Maximum utilisation of availability (max *UofA*) for each station, which is reported from the model and should not exceed the maximum utilisation (U_{max}) of the fab for each station.
- Average utilisation of availability (avg. *UofA*) to each station, which is reported from the model and should be equal to the Utilisation (*U*), calculated using Equation 5-5, which includes the downtime as part of the utilisation and is calculated by multiplying the maximum utilisation (U_{max})

of the fab with the theoretically calculated fab utilisation (*U**) using Equation 5-7 for the same station.

- Average, minimum, and maximum throughput rate, this is the number of finished lots per week.

6.1.5 Experimentations, Results, and Analysis

The three different versions of the model are run when introducing different number of lots per day (18, 19, and 20 lots per day). Each simulation run covers one year (52 weeks); where, results are reported weekly. Analysis of results has shown the following; first, when comparing the maximum *UofA* to the U_{max} Model B and Model C performed better than Model A. Second, investigating the average *UofA* and how it should be compared to the standard utilisation; Model B showed the worst results with respect to Model A and Model C. Finally, when evaluating the throughput rate at different loading levels for all models; Model A and Model C were more capable of achieving the expected lots per week than Model B. In conclusion, model C is considered the more likely modelling version to be selected, this work has been published at [117].

6.2 REMODELLING

It is clear from the previously mentioned sections that preventing *UofA* from exceeding U_{max} results in extra modelling complexity. In addition, it is found that the model selected for controlling the *UofA* needs long computational time (around 40 minutes for one year simulation run time). Finally, this modelling approach leads to inducing a bottleneck that is not actually present in reality due to controlling the arrival of lots to the machines by shutting down the machines when the *UofA* reaches the U_{max}.

Therefore, several meetings with the ICMR representative were carried out discussing these issues. Finally, it was decided to rebuild the model without any of the earlier mentioned constraints, and just to monitor the utilisation reported from the model (*U* mentioned in chapter 3) not to exceed the U_{max}, also, ignoring the

UofA calculation and control to reflect what is really done at a real fab by just monitoring and not controlling.

This simplification results in considerable time savings where the new constructed model without any controls takes around 2 minutes computational time for a 1 year simulation run time. The following sections give a detailed description on the modelling processes under taken in this work.

6.3 MODEL CONSTRUCTION

The simulation model comprises 4 modules; a lot router, stations module with different hierarchal blocks to represent the stations, a shutdown module, and a module that collects and reports most of the results as shown in Figure 6-3.

The lot router ensures that the lots are sent to the stations in the exact sequence that is presented in the fab description. On the other hand the stations ensure processing of lots according to the numerical and operational characteristics of the stations.

The shutdown module gives signals to shutdown the machines based on the numerical and operational data of the machines breakdowns. Finally, the collecting and reporting results module gathers all of the results for further statistics and analysis.

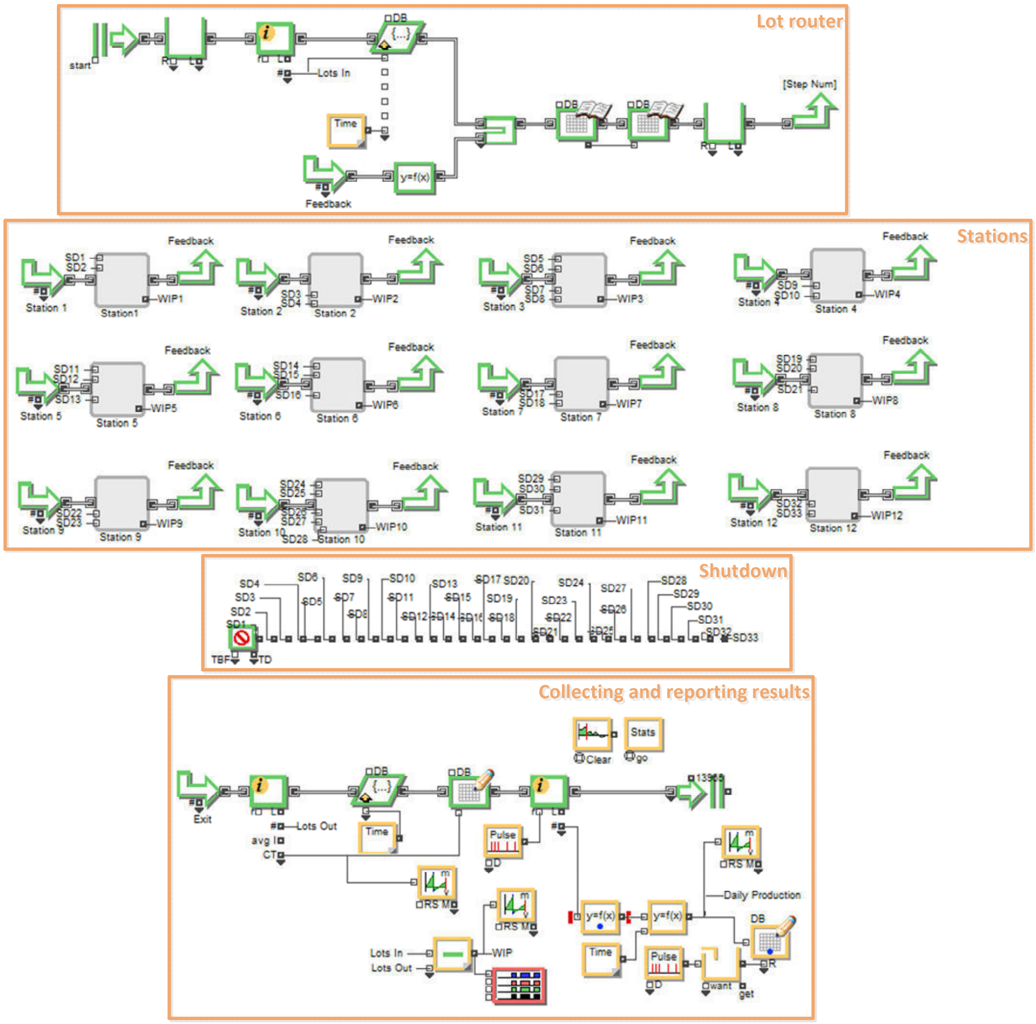

Figure 6-3: The constructed model.

6.3.1 Structure of Database

One of the main advantages in this simulation model building is the ExtendSim database, which is used to represent, manage, and track the status and properties of entities and resources. The database consists of tables, and each table has a group of fields that have relationships between each other.

Establishing a parent/child relationship is another powerful database feature, which limits a field's set of data to what is present in the parent. Instead of entering data directly into the child field, you select the data from a popup data selector that shows all the possible values from the parent field. Moreover, parent/child relationship helps in reducing data entry, keeping consistent data, preventing data duplication and reducing data entry errors as shown in Figure 6-4.

This database plays an important role, where it extracts the input data required for running the model from the specific tables using "Read" blocks, and then reports back results to the particular tables using "Write" blocks.

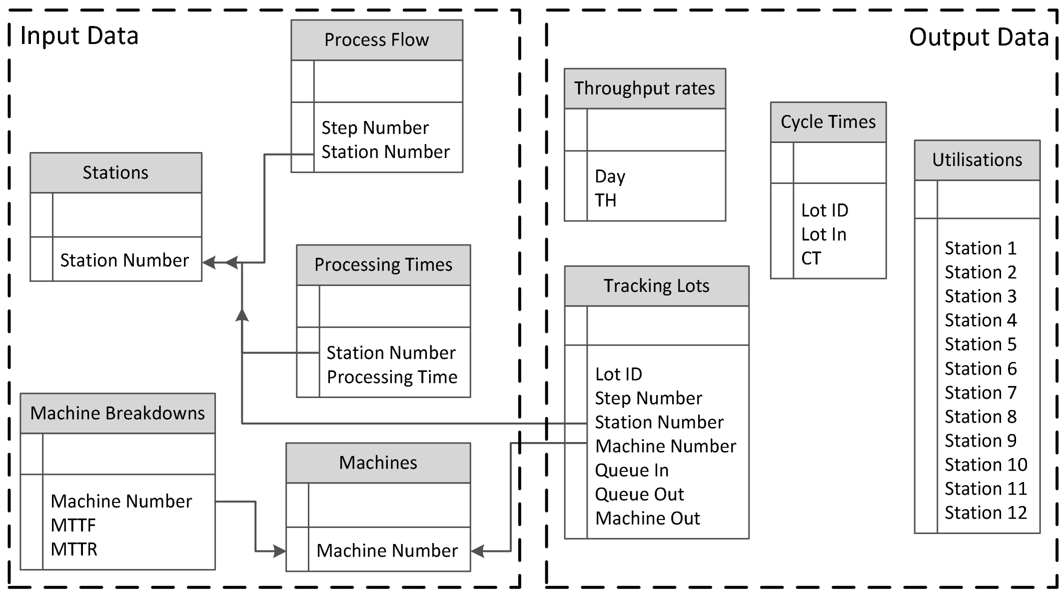

Figure 6-4: Constructed model database.

It is shown that the database has two main sections: the first section is responsible for the data entry that is related to the number of stations, the process flow of lots and the processing times of each station, along with the number of machines with their breakdowns. It consists of five tables, two of them are parent tables (Stations and Machines tables), that have parent/child relationships with the other three tables of the input data and another table from the second section. This output data section has four tables that report all the information and track the movement of every lot at the model in order to have a post processing full analysis that will help in verifying the model improving the Segment performance.

6.3.2 Attributes Definition

Lots flowing throughout the model are the main flow entities in the developed model. These entities are defined by a number of attributes, which are listed in Table 6-1.

Table 6-1: List of attributes used.

Attribute	Function
Lot ID	Defines each lot generated to the model.
Lot In	Defines the arrival time of the lot to the model.
Lot Out	Defines the departure time of the lot to the model.
Station Number	Defines the station number.
Step Number	Defines the step number of a lot.
Machine Number	Defines the machine number.
Processing Time	Defines the processing time needed to complete a specific operation by a machine.
Queue In	Defines the arrival time of the lot to a station queue.
Queue Out	Defines the departure time of the lot from a station queue.
Machine Out	Defines the departure time of the lot from a machine.
Sampled	States whether a lot should be sampled or not. The attribute value can be either Yes (sample lot) or No (don't sample lot, or skip operation) according to the sampling rate of the sampling stations.
None Sampled	States whether a lot was sampled or not at the sampling station with initial remains sampling condition. The attribute value can be either Yes (lot was not sampled) or No (lot was sampled).
LDim Sampled	Defines which machine at the sampling station with initial remains sampling condition sampled the lot. The attribute value can be either LDim _1 sampled, LDim _2 sampled, and LDim _3 sampled.

6.3.3 Modelling the Re-entrant Flow of Lots

The routing of lots based on the sequence of operations required for each job is modelled using the lot router shown in Figure 6-5. Part (A) of the lot router starts with introducing lots to the model according to the lot release control strategy.

Lots then flow to the "Set" block in order to set some attributes as: Lot ID, Step Number, Station Number (both are set as 1s), Lot In, and Sampled (No).

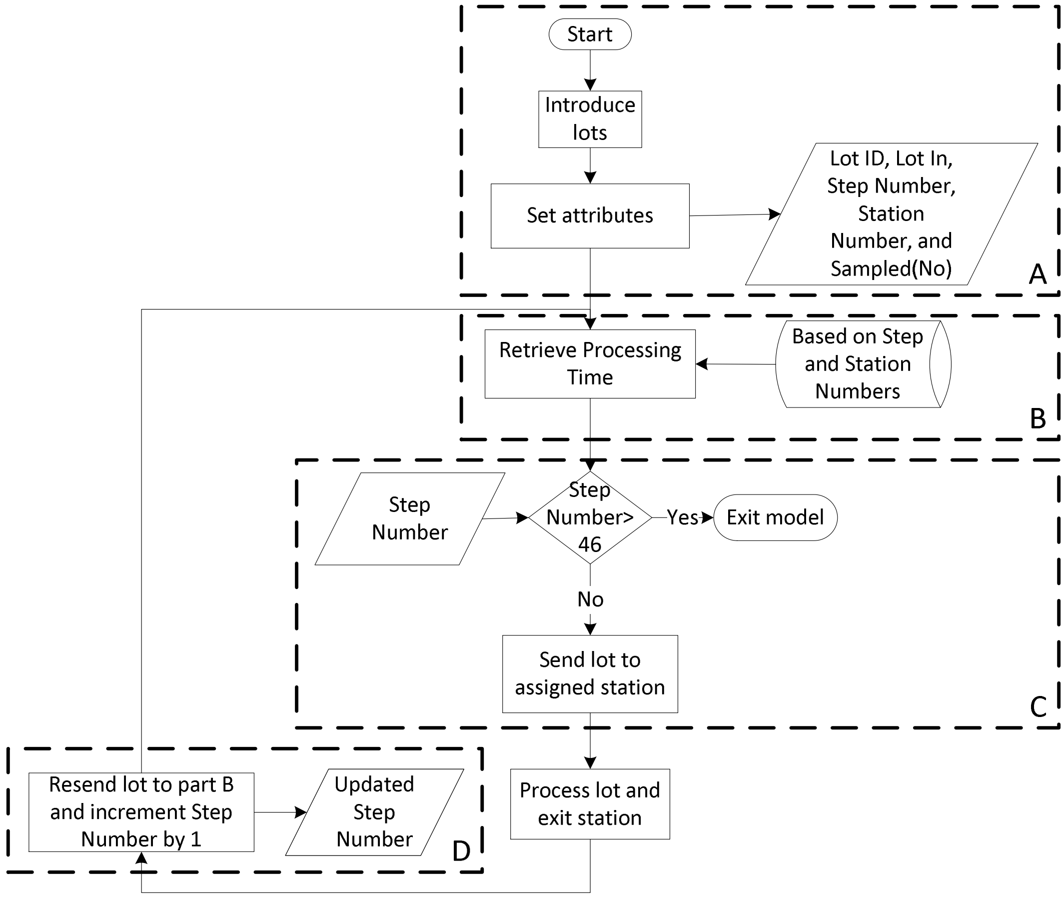

Figure 6-5: Routing of the lots.

As mentioned earlier, each lot requires 46 processing steps. For each step, the processing time of the lot needs to be defined before being sent to a station. In part (B) two "Read" blocks are used to retrieve the processing time from the database as presented in Figure 6-6.

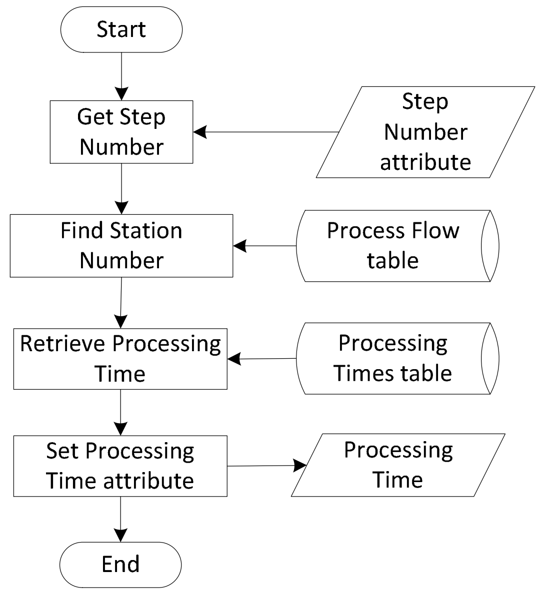

Figure 6-6: Retrieving processing times from database.

Since, the processing time for each station is fixed (as presented in Section 5.1.3); thus, based on the Step Number attribute, the next station that the lot will visit is determined using the first "Read" block. Next, based on the retrieved station number, the processing time at that station is retrieved using the second "Read" block. Finally, the processing time retrieved is stored in the entity as the Processing Time attribute.

Afterwards, the lots are sent to part (C) in Figure 6-5; where, a decision is made to determine whether or not the lots need further processing. If the Step Number is 46 or less, then it is sent to the station that serves this step, otherwise, it moves to the "Exit" block of the collecting and reporting results module (Figure 6-3). Lots are sent to the different stations using a "Throw" block that sends the lots to the stations depending on the Station Number and Step Number attributes as presented in Figure 6-7.

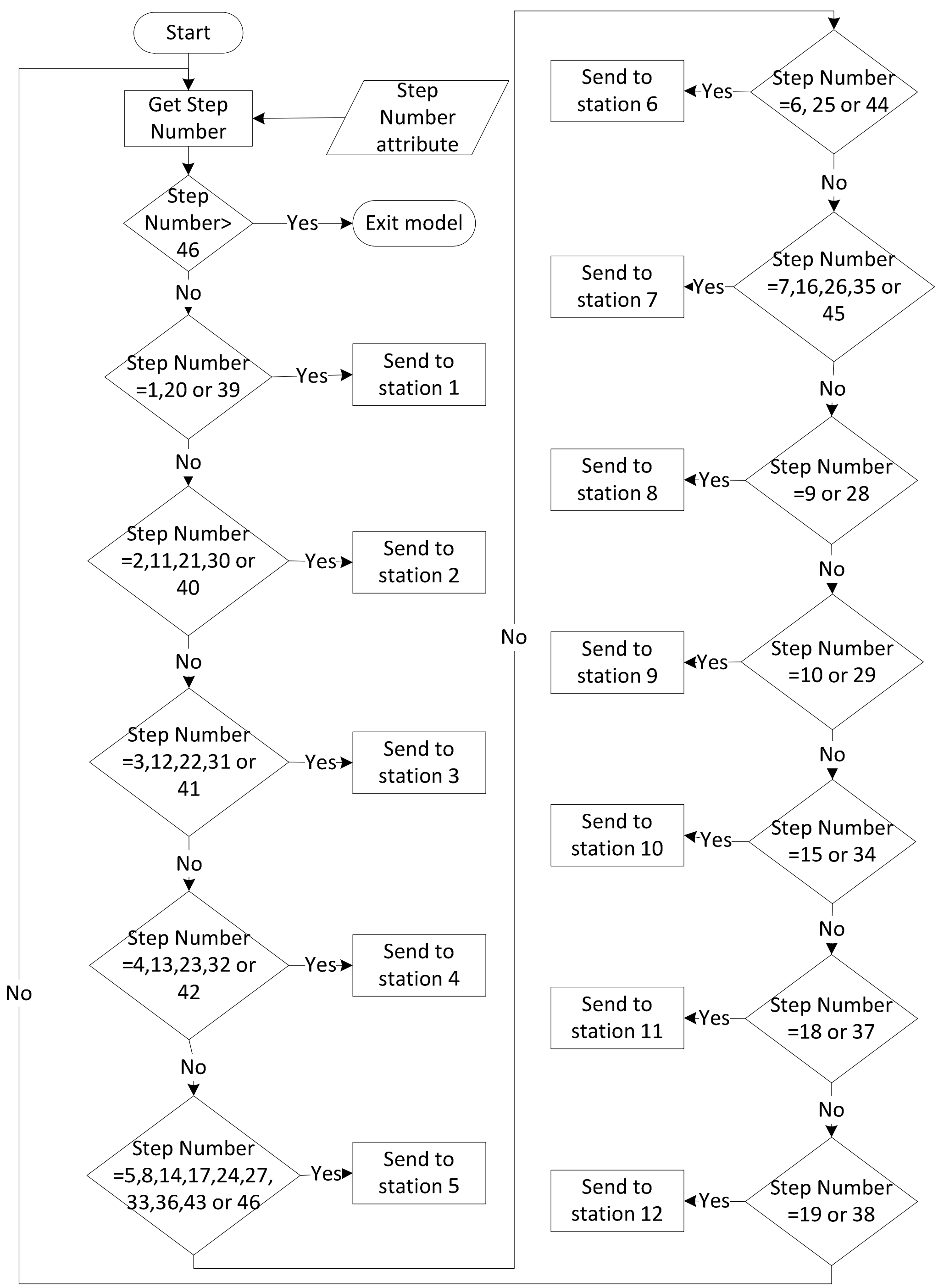

Figure 6-7: Sending lots to stations based on step number.

Finally, part (D) performs the feedback of lots that re-enter the model and join the flow of the other newly introduced lots to the model. This is achieved by receiving the unfinished lots from the 12 stations using a “Catch” block and incrementing the

Step Number by 1, indicating completion of the previous step. A "Select Item In" block is used to join the re-entering lots with the other ones.

6.3.4 Modelling Different Stations

Each station is modelled as a hierarchical block holding a number of parallel machines, with a "Catch" block before it and followed by a "Throw" block as shown in the stations module (Figure 6-3). The "Catch" block receives lots from part (C) in Figure 6-5 depending on the Step Number at the station responsible for serving that step. The "Throw" block sends lots to part (D) of the lot router described in the previous section indicating completion of the step at that station.

Stations Basic Structure

The hierarchical block representing the station get lots from the lot router, and then introduce them to the station. First, arrival times of lots to the station are set (Queue In attribute), then lots wait for the processing. At the end of each station there is an "Activity" block that represents the transport time to the next station.

It should be noted that the Processing Times attributes are retrieved from the database based on the Step Number and the Station Number attributes to the "Activity" block representing the machine. Moreover, the breakdowns of the machines are generated from the shutdown module through the database that stores the breakdown distributions of the machines.

Additionally, there are time stamps for each lot at every movement through the station before the queue, after the queue and after the processing on the machines, these time stamps are reported to the database through the "Write" block, the flow of lots through a station is presented in Figure 6-8.

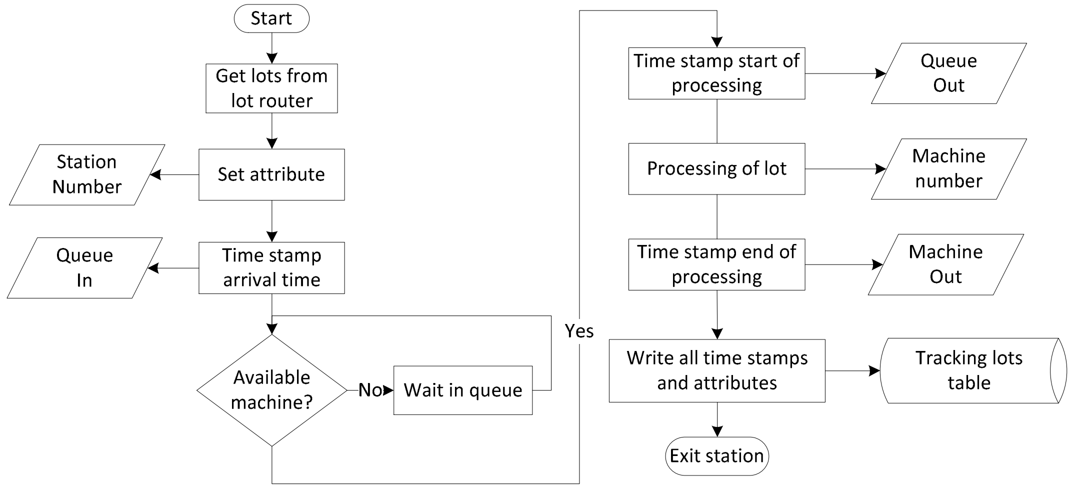

Figure 6-8: Modelling a station.

The 12 stations are modelled with the previously described modelling techniques and modifications are added to the measurement and batching stations.

Modelling Sampling at the Measurement Stations

There are three sampling stations at the Segment, TCheck, LAlign, and LDim. Each station has its rule for sampling as mentioned in the previous chapter. Two out of three lots and three out of four lots are sampled at TCheck and LAlign stations respectively; this is modelled by adding an "Information" block at the beginning of the station that counts the number of lots entering.

Based on the sampling rate the lots follow their route either to be sampled by entering the station or by skipping that processing step (None sampled lots) as shown in Figure 6-9.

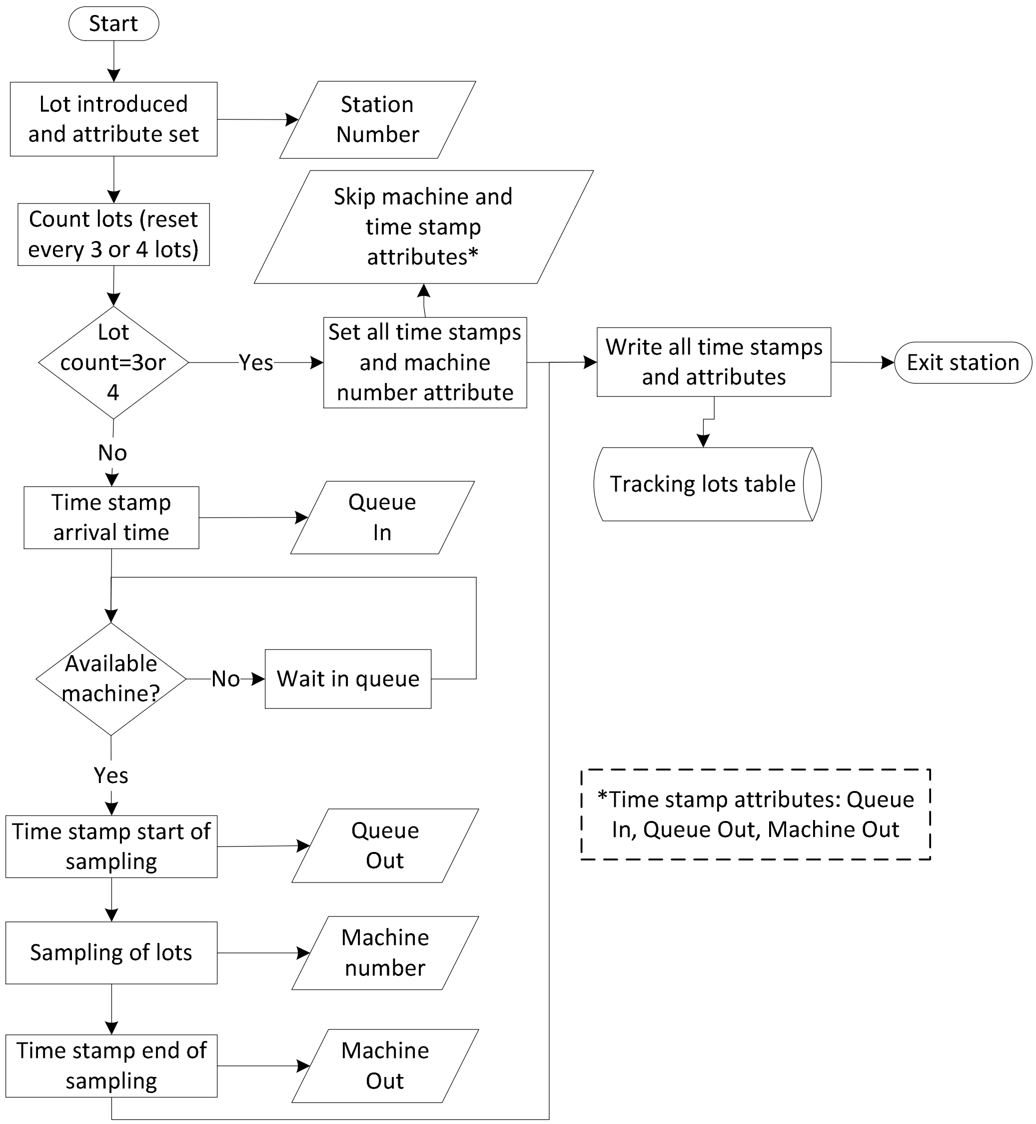

Figure 6-9: Modelling sampling stations 2 and 4.

On the other hand, LDim station which has a 2/3 sampling rate with initials remain sampling. This station is modelled in the same way mentioned earlier; however, an attribute is defined to confirm the sampling of lots and another one is set to identify the machine that was used for sampling the lot (Sampled lot and LDim Sampled attribute mentioned in Section 6.3.2). Thus, when that lot revisits the LDim station, it will be sampled on the same machine used before. Also, another attribute is set when a lot is not sampled (None Sampled attribute mentioned in Section 6.3.2); in order not to be sampled any other time it revisits the station as presented in Figure 6-10.

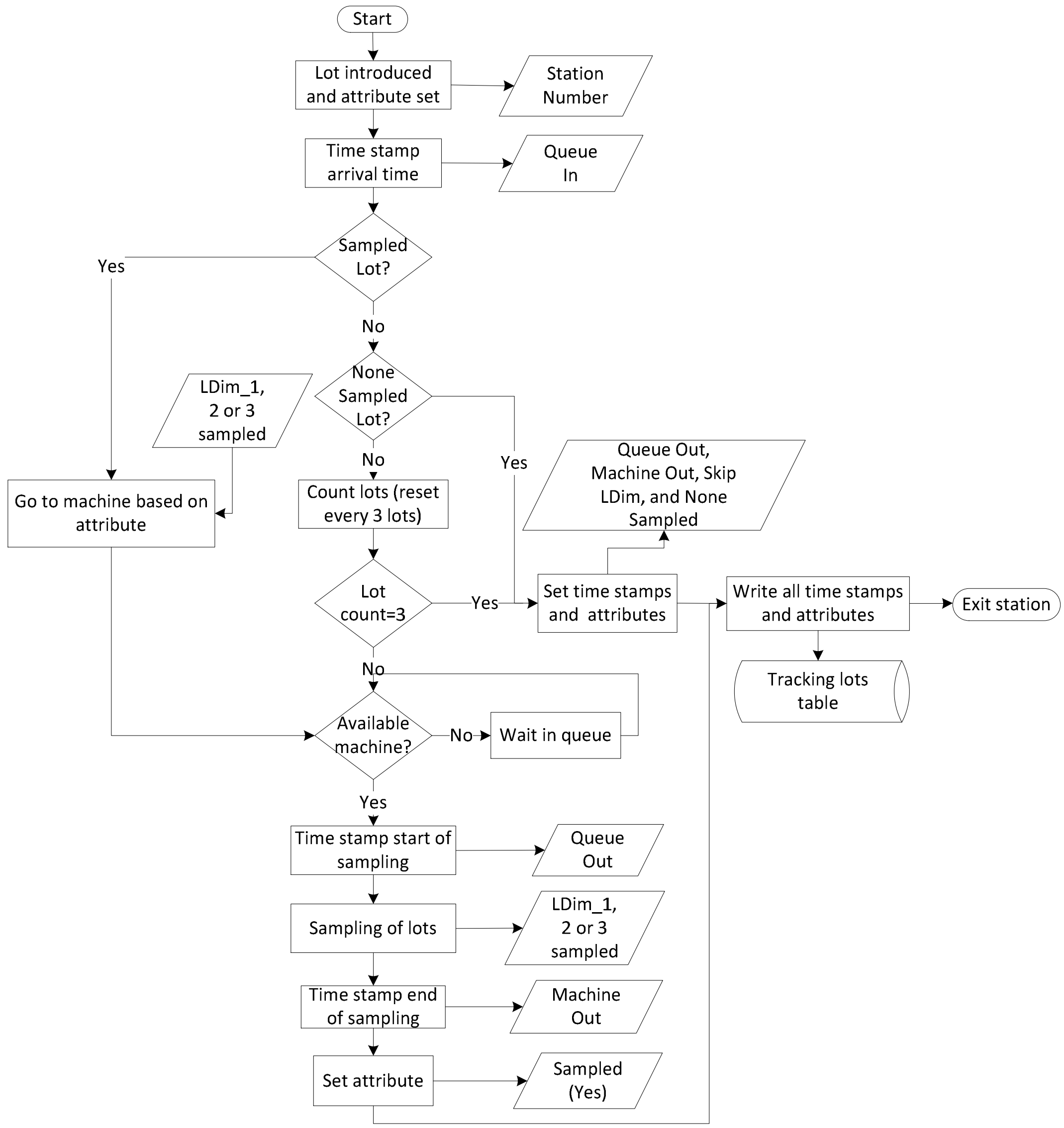

Figure 6-10: Modelling sampling station 5.

Modelling Batching Stations

At the Segment there are two batching stations: RWash and IEtch Stations, where, 2 lots of the same step are batched and then cascaded through the machine. This is applied by adding a "Queue Matching" block that matches 2 lots of the same Step Number attribute, followed by a "Batch" block and afterwards an "Un Batch" block, this is to ensure that the 2 batched lots enters the same machine and are processed at the same time as shown in Figure 6-11.

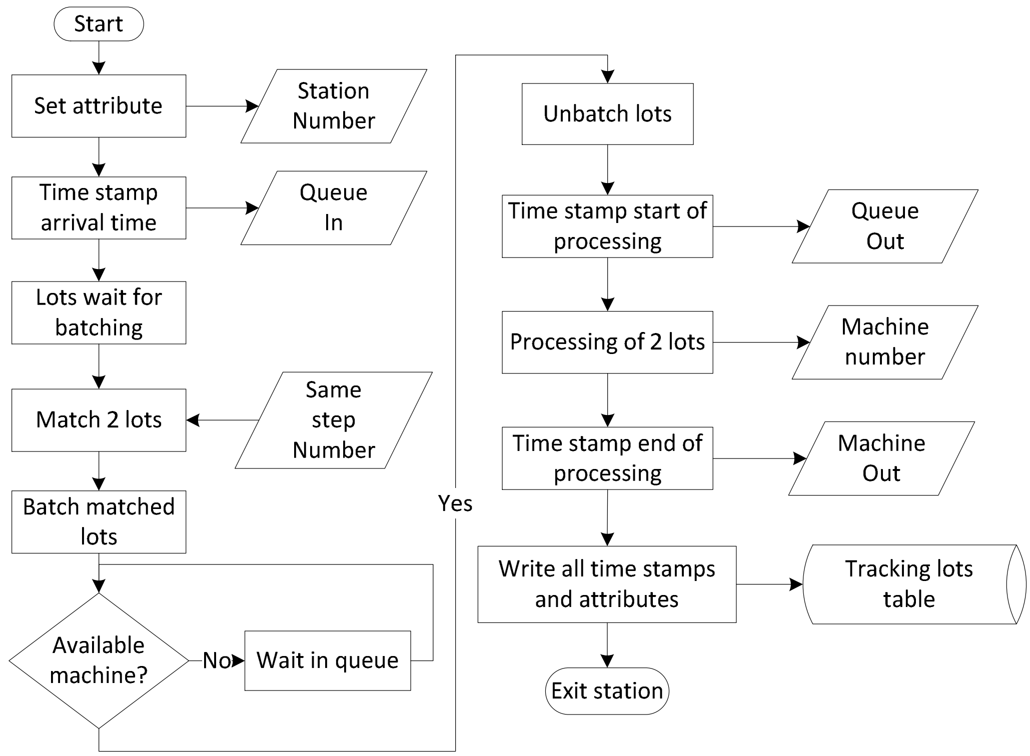

Figure 6-11: Modelling batching stations.

6.3.5 Reporting Results

As mentioned previously, after a lot completes the 46 processing steps, it is sent to the collecting and reporting results module (Figure 6-3). At that module, the recommended performance metrics for the Segment are calculated and reported. These measures are the mean and the variance of throughput rate, cycle time, and WIP, in addition to monitoring the mean utilisation (U) of each station to verify that it is below the U_{max}.

Throughput rate per day

Lots leaving the system pass through an "Information" block that counts the lots, the throughput rate is calculated on a daily basis; thus every day (1440 minutes) the value found at the "Information" block is written to the database through the "Write" block and a pulse is given to the "Information" block to reset its value to zero and restart counting as illustrated in Figure 6-12.

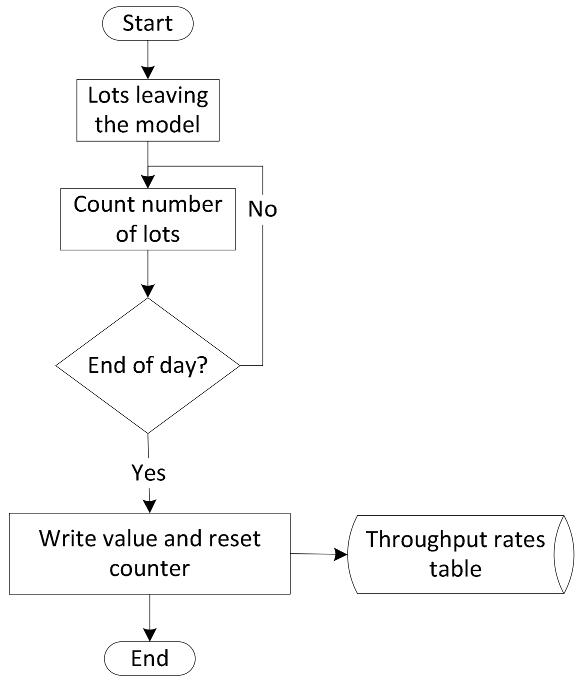

Figure 6-12: Reporting TH per day.

Values reported are fed into the "Mean and Variance" block to compute the mean of the daily throughput rate reported over the simulation run time and the variances of these values.

Cycle Time

The cycle time is reported using the fourth connector of the "Information" block located at the end of the model. This block uses the timing attribute "Lot In" which is the time when the lot entered the system that is set at part (A) of the lot router (mentioned earlier in Section 6.3.3, Figure 6-5).

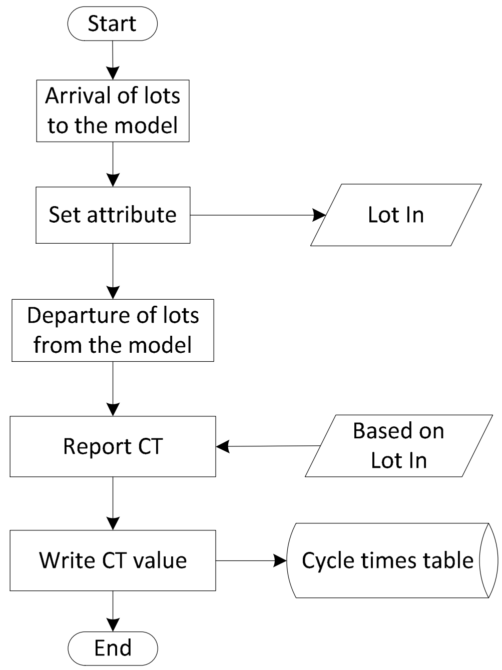

Figure 6-13: Reporting CT for every lot.

Also, upon leaving the system, the lot passes through a “Write” block that reports to the database its Lot ID, the time it entered the system (both are set at part (A) of the router), the time it left the system (the current time of passing through the “Set” block just before the “Write” block) and its cycle time which is the total elapsed time spent in the system.

This value is fed into the “Mean and Variance” block to calculate the mean cycle time reported over the simulation run time and the variances of these values.

Work In Process

Entering lots are counted at the lot router after immediately being created. Also lots that completed processing are counted just before leaving the model. The WIP is calculated by subtracting the lots leaving the system (lots out) from the lots that entered the system (lots in) as given in Figure 6-14.

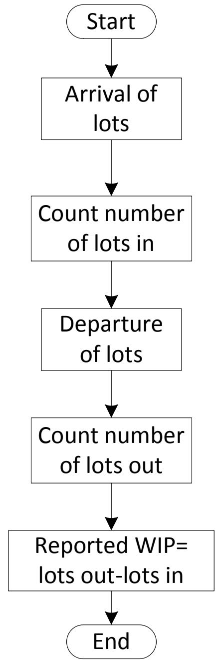

Figure 6-14: Calculating the WIP.

The calculated WIP values are fed into the “Mean and Variance” block to compute the mean WIP values calculated over the simulation run time and the variances of these values.

It should be noted that the WIP for every station is calculated by the same way as modelled for the whole Segment, but by counting the number of lots entering and leaving the station instead of counting the number of lots entering and leaving the Segment.

Utilisation

In order to monitor the utilisation of each station, the utilisations of all the machines within a station directly reported from the “Activity” blocks are instantaneously averaged every week to compute mean utilisation of that station. This value is transported every week to the utilisations table of the output data section at the database (see Figure 6-4) as shown in Figure 6-15.

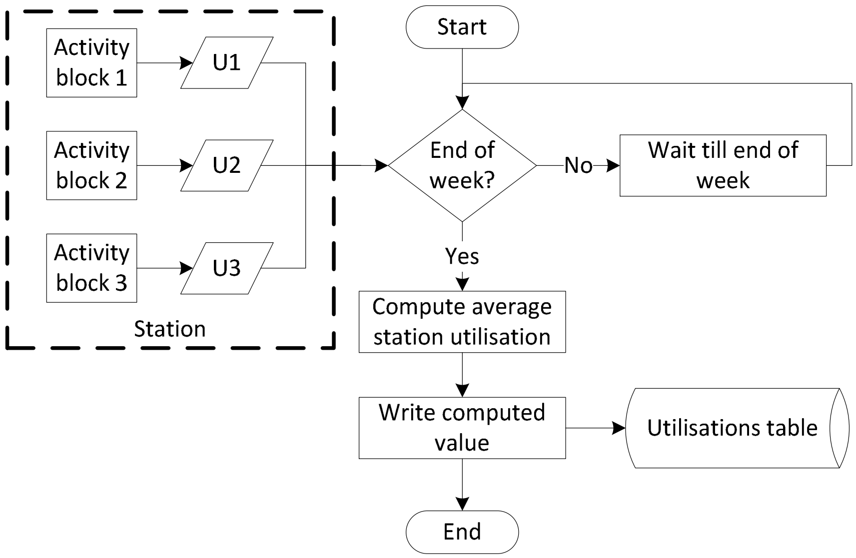

Figure 6-15: Reporting station utilisation.

Values reported for each station are fed into the "Mean and Variance" block to compute the mean of the station utilisation reported over the simulation run time.

6.3.6 Introducing Lot Release Strategies

Different lot release strategies are introduced to the model. These strategies aim at controlling the WIP either over the whole Segment or across different sections within the Segment.

This is achieved by applying a WIP cap using 3 blocks: "Queue" block with resource pool queue behaviour at beginning of the Segment/section, "Resource Pool" block with the desired WIP level, and "Resource Pool Release" block at the end of the Segment/section as presented in Figure 6-16.

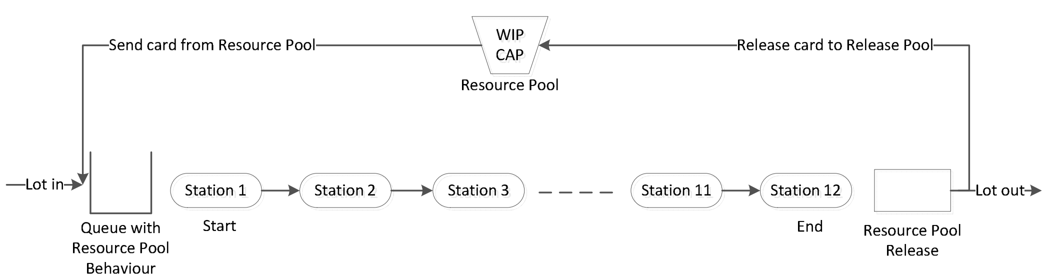

Figure 6-16: Controlling WIP over the Segment/section.

Whenever a lot enters the Segment/section through the “Queue” it seizes a card from the “Resource Pool” decreasing the number of cards available, and upon leaving the Segment/section through the “Resource Pool Release” that card is released back to the “Resource Pool” giving a signal to the beginning of the Segment/section that a new lot can be released to the Segment/section. The following sections discuss in detail the modelling of the different lot release control strategies used in this work.

CONWIP

To model CONWIP the WIP of the whole Segment is controlled. Therefore the “Queue” block with resource pool queue behaviour is placed at the beginning of the model, and the “Resource Pool Release” block that releases back the resource to the “Resource Pool” block of the model is located at the end of the model as shown in Figure 6-17. This is to ensure that the WIP of the whole model is controlled as intended.

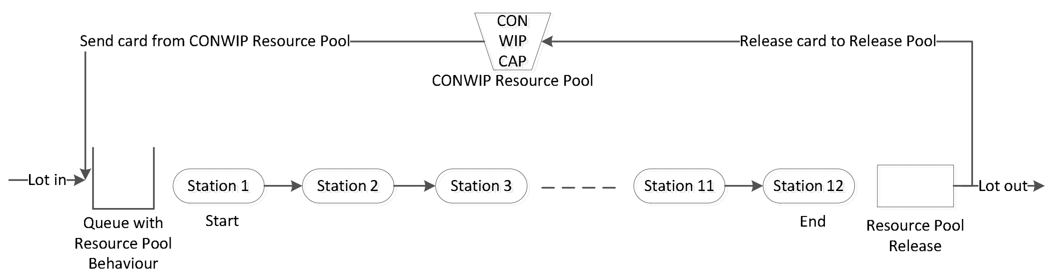

Figure 6-17: Modelling CONWIP lot release control strategy.

ICONWIP

The new ICONWIP is a variation of the CONWIP; where, there is a WIP cap on the whole Segment as in CONWIP. In addition to a “Gate” block that is closed to delay the release of lots based on a condition, and it is open when the condition is true as shown Figure 6-18.

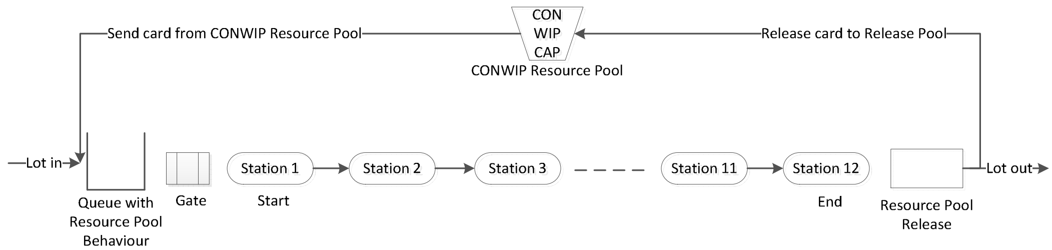

Figure 6-18: Modelling ICONWIP.

DBR

To apply DBR lot release control strategy, then the WIP of a section starting from the beginning of the Segment and ending with the bottleneck station of the Segment is controlled.

Here, the "Queue" block with resource pool queue behaviour is placed at the beginning of the model, whereas the "Resource Pool Release" block is located after the bottleneck station of the model. It should be noted that a card which is seized by a lot is not released back to the "Resource Pool" block unless that lot that will not revisit the bottleneck station any more as presented at Figure 6-19. This is done to make sure that the WIP of that section within the model is controlled as planned.

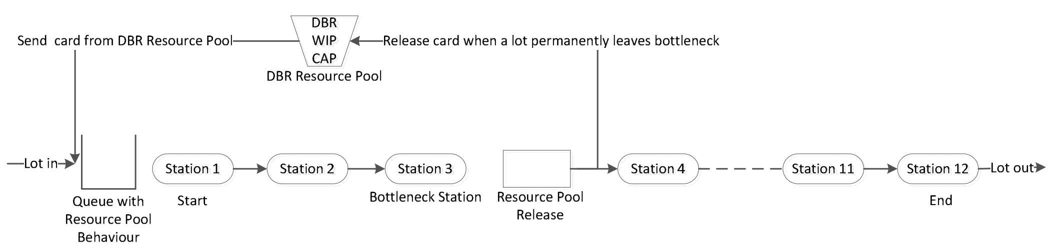

Figure 6-19: DBR lot release control strategy at the model.

Hybrid CONWIP/DBR

Combining the aforementioned lot release control strategies (CONWIP and DBR); results in a hybrid CONWIP/DBR that is also tested in this work. One "Queue" block with resource pool queue behaviour is placed at the beginning of the model. This block controls the release of lots to the whole model at CONWIP as well as it controls the release of lots to the section starting from the beginning of the model and ending with the bottleneck station at DBR as shown in Figure 6-20.

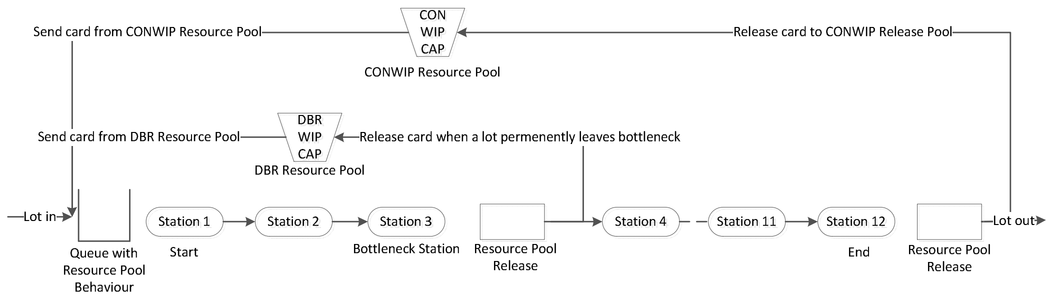

Figure 6-20: Controlling the release of lots at hybrid CONWIP/DBR.

Moreover, two "Resource Pool Release" blocks are needed to release back the cards to the two "Resource Pool" blocks. The one responsible for CONWIP is located at the end of the model and the other one responsible for DBR is located at the end of the bottleneck station. This is proposed to guarantee that the WIP of the whole model as well as the WIP of the selected section are controlled as intended.

LCONWIP

The proposed LCONWIP is a modification of the CONWIP; where, there is a WIP cap on the whole Segment as in CONWIP, in addition to loop WIP caps on selected stations requiring WIP control as shown in Figure 6-21.

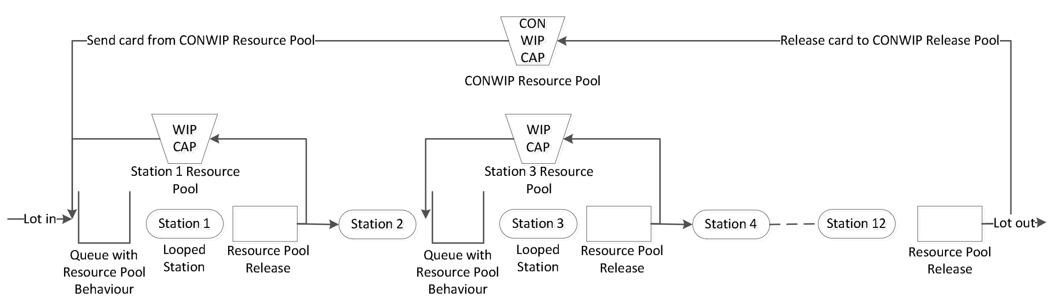

Figure 6-21: Modelling LCONWIP.

Accordingly, CONWIP is modelled in the same way mentioned earlier, and regarding the loop assigned to a station, the "Queue" block with resource pool queue behaviour is placed before the selected station to be controlled. Whereas the "Resource Pool Release" block that releases back the resource to the "Resource

Pool" block of that station is located after the selected station, to confirm that the WIP of the selected station is controlled as required.

6.4 MODEL VERIFICATION

This step was carried out by using animation capabilities of the model building software and by reporting the results of the different building blocks of the model to ensure that the model was working as it should be.

Moreover, it should be noted that the database played an important role at the verification process. The tracking lots table of the output data section (Figure 6-4) reports every movement of a lot within the model, and a sample of the results to a tracked lot (Lot ID 3740) is shown in Table 6-2 (in the next page).

Investigating the results in Table 6-2, it is shown that the process flow of lots matches the flow mentioned earlier (see Figure 5-1) and all steps are performed at the assigned stations as intended. Then to ensure that the processing times used in the model are equal to the input values.

A simple calculation is undertaken to compute the time a lot spends for processing. This is done by subtracting the time stamp of the queue out from the time stamp of the machine out, and the computed values are equal to the input values (refer back to Table 5-2), thus, the processing times are verified.

Considering the sampling stations (TCheck, LAlign, and LDim), it is obvious that when the lot skipped the sampling the time stamp of queue in, queue out and machine out are the same and there is no computed processing times, and this ensures that the lot is not sampled.

However, this lot is sampled on different machines when it revisits the same stations (TCheck and LAlign) because the sampling depends on the arrivals (For example step 2 is sampled on TCheck_2, step 11 is sampled on TCheck_1, and step 21 is not sampled). Also, it is noticed that the lot is sampled 10 times on the same machine of LDim station (LDim_3) and this verifies that initial remains sampling on same machines as planned.

Table 6-2: Tracking Lot ID 3740.

Results reported from tracking lots table at the database						Calculated Processing Time (minutes)
Step Number	Station Number	Machine Number	Queue In (minutes)	Queue Out (minutes)	Machine Out (minutes)	
1	Station 1	MDep_2	282,240.00	282,586.15	282,609.23	23.08
2	Station 2	TCheck_2	282,618.90	282,618.90	282,627.42	8.52
3	Station 3	LPat_4	282,635.52	282,635.52	282,672.10	36.59
4	Station 4	LAlign_1	282,682.30	282,682.30	282,697.30	15.00
5	Station 5	LDim_3	282,705.82	282,705.82	282,716.54	10.71
6	Station 6	MEtch_2	282,726.09	282,726.09	282,768.95	42.86
7	Station 7	RWash_1	282,775.55	282,775.55	282,791.34	15.79
8	Station 5	LDim_3	282,801.41	282,804.10	282,814.81	10.71
9	Station 8	IDep_2	282,824.05	282,848.88	282,908.88	60.00
10	Station 9	IPol_2	282,918.12	282,990.34	283,020.34	30.00
11	Station 2	TCheck_1	283,029.26	283,029.26	283,037.78	8.52
12	Station 3	LPat_3	283,046.93	283,046.93	283,083.52	36.59
13	Station 4	Skip LAlign	283,095.15	283,095.15	283,095.15	Skip
14	Station 5	LDim_3	283,104.36	283,111.61	283,122.32	10.71
15	Station 10	IEtch_4	283,129.58	283,221.43	283,421.43	200.00
16	Station 7	RWash_1	283,429.66	283,429.66	283,445.44	15.79
17	Station 5	LDim_3	283,455.49	283,455.49	283,466.20	10.71
18	Station 11	VDep_1	283,475.78	283,501.95	283,561.95	60.00
19	Station 12	VPol_1	283,570.62	283,808.15	283,838.15	30.00
20	Station 1	MDep_2	283,846.71	283,956.92	283,980.00	23.08
21	Station 2	Skip TCheck	283,990.28	283,990.28	283,990.28	Skip
22	Station 3	LPat_4	283,998.44	284,135.31	284,171.89	36.59
23	Station 4	LAlign_2	284,179.50	284,179.50	284,194.50	15.00
24	Station 5	LDim_3	284,203.61	284,203.61	284,214.32	10.71
25	Station 6	MEtch_1	284,222.32	284,324.55	284,367.41	42.86
26	Station 7	RWash_1	284,377.01	284,377.01	284,392.80	15.79
27	Station 5	LDim_3	284,402.14	284,402.14	284,412.86	10.71
28	Station 8	IDep_1	284,422.67	284,564.24	284,624.24	60.00
29	Station 9	IPol_1	284,632.87	284,632.87	284,662.87	30.00
30	Station 2	TCheck_1	284,670.16	284,670.16	284,678.68	8.52
31	Station 3	LPat_3	284,689.65	284,889.78	284,926.37	36.59
32	Station 4	LAlign_2	284,935.81	284,935.81	284,950.81	15.00
33	Station 5	LDim_3	284,961.12	284,961.12	284,971.83	10.71
34	Station 10	IEtch_2	284,979.64	285,438.49	285,638.49	200.00
35	Station 7	RWash_1	285,650.33	285,650.33	285,666.12	15.79
36	Station 5	LDim_3	285,673.50	285,696.14	285,706.85	10.71
37	Station 11	VDep_2	285,716.62	285,756.80	285,816.80	60.00
38	Station 12	VPol_2	285,828.05	285,828.05	285,858.05	30.00
39	Station 1	MDep_2	285,866.89	285,996.92	286,020.00	23.08
40	Station 2	Skip TCheck	286,029.81	286,029.81	286,029.81	Skip
41	Station 3	LPat_3	286,036.33	286,036.33	286,072.91	36.59
42	Station 4	LAlign_1	286,081.26	286,081.26	286,096.26	15.00
43	Station 5	LDim_3	286,104.20	286,112.53	286,123.24	10.71
44	Station 6	MEtch_1	286,132.31	286,138.54	286,181.39	42.86
45	Station 7	RWash_1	286,191.03	286,212.75	286,228.54	15.79
46	Station 5	LDim_3	286,238.22	286,238.22	286,248.94	10.71

Moreover to verify the sampling rates at TCheck and LAlign stations, a sample of lots visiting these stations with the queue in time stamps sorted ascendingly are shown in Table 6-3. It is clear that two out of three and three out of four lots are sampled in TCheck and LAlign stations as required, where sampling depends on the arrival of lots to the stations.

Table 6-3: Verification of sampling stations 2 and 4.

Station 2				Station 4			
Lot ID	Step Number	Machine Number	Queue In (minutes)	Lot ID	Step Number	Machine Number	Queue In (minutes)
1234	11	TCheck_1	93,813	1124	4	LAlign_1	85,747
1252	2	TCheck_2	93,825	1105	13	LAlign_2	85,757
1197	30	Skip TCheck	93,830	1125	4	LAlign_1	85,762
1253	2	TCheck_1	93,834	1126	4	Skip LAlign	85,779
1198	30	TCheck_2	93,844	1107	13	LAlign_2	85,784
1254	2	Skip TCheck	93,847	1128	4	LAlign_1	85,793
1185	40	TCheck_1	93,859	1127	4	LAlign_2	85,796
1180	40	TCheck_2	93,868	1108	13	Skip LAlign	85,816
1200	30	Skip TCheck	93,871	1129	4	LAlign_1	85,821
1188	40	TCheck_1	93,882	1130	4	LAlign_2	85,827
1203	30	TCheck_2	93,888	1110	13	LAlign_1	85,834
1182	40	Skip TCheck	93,895	1109	13	Skip LAlign	85,852
1191	40	TCheck_1	93,900	1131	4	LAlign_2	85,858
1199	30	TCheck_2	93,902	1132	4	LAlign_1	85,866
1187	40	Skip TCheck	93,916	1133	4	LAlign_2	85,872
1195	40	TCheck_1	93,926	1134	4	Skip LAlign	85,889
1201	30	TCheck_2	93,932	1112	13	LAlign_1	85,894
1186	40	Skip TCheck	93,939	1111	13	LAlign_2	85,900
1204	30	TCheck_1	93,946	1135	4	LAlign_1	85,923
1190	40	TCheck_2	93,951	1136	4	Skip LAlign	85,930

It should be noted that the same steps were carried out in LDim station, with deeper investigations to ensure that when a lot was sampled once it was sampled each time it visited the station on the same machine that was used for sampling the first time (check Table 6-2), and when a lot skipped sampling it was never sampled.

Finally, the verification process was held continually during model modification process to ensure that the model was working properly according to the pre-set logic after any modification added to the model and before moving to the next modification.

6.5 MODEL VALIDATION

Complete validation implies that the developed simulation model is behaving just like the real-world system. The Segment used in this work is designed to represent the reality of operations in a semiconductor and has been developed by a factory engineer with many years' experience in the field, so a full validation against data from a real fab is not possible. However, as mentioned in the literature review, three types of model validation can be applied, face validation, validation of model assumptions, and input/output transformation validation. Partial validation of the model based on the first two types was only possible in this work.

Face validation was the first goal of this simulation model, where, the constructed model appeared to be reasonable on its face. This was approved by consulting a representative of the ICMR who was knowledgeable about the system behaviour under study. This validation took place without deep investigation and was carried out using the animation capabilities of the simulation model, to confirm that the lots were being processed in the sequence mandated by the Segment, for example batching rules at RWash and IEtch stations, where, two lots were batched before processing, also sampling at the measurement stations (TCheck, LAlign, and LDim) is followed as intended, in addition to that machines were subjected to the different breakdowns as exposed.

Validation of model assumptions fall into two general classes: structural assumptions and data assumptions.

- The structural assumptions took place by validating the number of stations with their machines. For example, in MDep station there are 2 machines, in TCheck station there are 2 machines, and so on.

- The data assumptions were done by investigating the input model variables that were generated randomly in the model and made sure that they represent the actual variables, like the availability of the stations. The total down times of all the machines were reported from the model, then the average of each station was calculated, and finally the availability was computed using Equation 6-2, where, the total time is the simulation run time.

$$Availability = (1 - \frac{Down\ time}{Total\ time}) \times 100 \qquad \text{Equation 6-2}$$

As mentioned previously the model reports the total down time of each machine at the "Shutdown" block of the shutdown module (see Figure 6-3). Therefore, some calculations were carried out in order to calculate the availability of each station based on the reported values as shown in Table 6-4.

Table 6-4: Calculated availability based on down times reported.

Station		Average Station Down Time (minutes)	Computed Availability (%)	Target Availability (%)
No.	Type			
1	MDep	238,609	77.24	76
2	TCheck	29,669	97.17	97
3	LPat	157,575	84.97	84
4	LAlign	28,211	97.31	97
5	LDim	44,385	95.77	96
6	MEtch	223,636	78.67	77
7	RWash	44,116	95.79	96
8	IDep	179,722	82.86	83
9	IPol	86,399	91.76	92
10	IEtch	268,270	74.41	75
11	VDep	186,300	82.23	82
12	VPol	223,300	78.70	79

First the average down time of each station was computed as presented in the third column, then the availability was calculated using Equation 6-2, and the results were given in the fourth column to be compared to the last column which was the target availability. It was clear that the results of the computed availability are around the same values of the target availability.

Further data assumptions validation was achieved by comparing the provided data about stations utilisation "Target *U*" to that reported from the developed model "Reported *U*" as presented in Table 6-5.

Table 6-5: Target and reported *U*.

Station Type	Target *U*	Reported *U*	Station Type	Target *U*	Reported *U*
MDep	0.601	0.573	RWash	0.271	0.263
TCheck	0.290	0.191	IDep	0.636	0.618
LPat	0.718	0.708	IPol	0.430	0.411
LAlign	0.510	0.378	IEtch	0.704	0.671
LDim	0.491	0.325	VDep	0.644	0.626
MEtch	0.734	0.717	VPol	0.501	0.463

It was clear that the utilisations of all the stations reported from the model were around the values of the target utilisation calculated using Equation 5-6 to give the values presented in Table 5-6, except TCheck, LAlign, and LDim stations because these are sampling stations.

Also, adding the *non-sampling rate* of each station to the reported utilisation to match the target utilisation calculated using Equation 5-6 and give the values presented in Table 5-6 as shown in Table 6-6.

Table 6-6: Reported, calculated and target *U* of sampling stations.

Station Type	*Non-sampling rate*	Reported *U*	Calculated *U*	Target *U*
TCheck	1/3	0.191	0.255	0.636
LAlign	1/4	0.378	0.473	0.704
LDim	1/3	0.325	0.433	0.644

Finally, it should be noted that although the representative of the ICMR who provided all the needed data to develop the Segment and who was familiar with the system modelled and knowledgeable about its behaviour ensured a supportive collaboration during the model validation; yet, the developed model can only be claimed to be partially valid.

After the conceptual model has been translated, implemented in ExtendSim™ Suite v8.0.2, verified and validated to the extent possible; different experiments were carried out. This is discussed in details in the next chapter.

7 SEGMENT EXPERIMENTATION, RESULTS, AND ANALYSIS

So far, a full description of the Segment has been presented with all the important details in chapter 6. With the validation completed as far as possible, experiments to improve the performance of the Segment by applying different lot release control strategies can be undertaken. In this chapter the performance measures used in this work, along with the list of assumptions and the simulation parameters used for the simulation experiments are addressed. Then a preliminary analysis of the base model is presented followed by a number of scenarios that are classified in to two groups.

- Group I scenarios: These use the same methodologies applied earlier for the Minifab (discussed in Chapter 4), which starts with testing the effect of applying different Push behaviours, then evaluating the effect of the CONWIP application, and afterwards testing the impact of applying ICONWIP on the performance of the Segment that targets reducing the variability of arrivals that is induced by CONWIP as mentioned earlier.

- Group II scenarios: These aim to balance the distribution of WIP across the stations of the Segment, which is the second issue addressed in this work that appeared at further analysis of CONWIP results. It begins with evaluating the effect of applying DBR, then a combination CONWIP and DBR is tested that results in a hybrid CONWIP/DBR lot release control strategy , and finally a developed lot release control strategy named LCONWIP is proposed.

7.1 PERFORMANCE MEASURES

As mentioned earlier, the performance measures that are evaluated in this work include:

- *Throughput rate*, which is the number of finished lots per day. This is reported as the mean and variance of the daily throughput rate reported from the model averaged based on the outcomes of the number of replications ($\overline{\overline{TH}}, \bar{V}_{TH}$).

- *Cycle time,* which is the time spent to produce one lot starting from entering the fab to begin with step 1 (S_1) and ending with leaving the fab after finishing step 46 (S_{46}). This is reported as mean and variance of the cycle time reported for each lot over the run averaged based on the outcomes of the number of replications ($\overline{\overline{CT}}, \bar{V}_{CT}$).

- *Work in process*, this is the number of lots that entered the fab and still being processed. Which is reported as the mean and variance of the instantaneous WIP level reported throughout the run averaged based on the outcomes of the number of replications ($\overline{\overline{WIP}}, \bar{V}_{WIP}$).

- *Utilisation* of the resources (machines and stations), which is the percentage of time these resources are busy. This is reported as the mean of the weekly instantaneous monitored utilisation over the whole run averaged based on the outcomes of the number of replications ($\overline{\overline{U}}$).

The objective of this research is to achieve the target TH as well as to minimize the cycle time and work in process while keeping the utilisation of all stations below the U_{max} of each station. Moreover, the variances of these performance measures are to be minimized.

7.2 LIST OF ASSUMPTIONS

Some revisions and assumptions have been made to the fab, these include:

- Processing times are deterministic.

- Travel times are triangularly distributed.

- Random failure and random repair times are exponentially distributed.

- While the machines process wafer by wafer, WIP is delivered to each machine in lots of 25 wafers.

- Cascaded batching is not modelled explicitly for stations 7 and 10 (RWash and IEtch); however, it is factored in the processing times of those stations.
- The time units are minutes.
- Sampling is modelled; however, no rework is considered, as, it is too low to be considered.

7.3 SIMULATION PARAMETERS OF SEGMENT EXPERIMENTS

As mentioned earlier, the simulation parameters that must be defined for any simulation experiment are the simulation runtime, warmup period, and number of replications.

Setting the Length of the Simulation Run

Since the developed model in this work belongs to nonterminating simulations, then there is no definitive way of picking the simulation run time; however, it should be larger than the warmup period and needs to be determined by the model user. Thus, it is decided to set the simulation runtime with 2 years (1,048,320 minutes).

Determining the warmup period

Again to determine the warmup period (l) using Welch's method ten replications are carried out; each simulation run time covers a period of 2 years (728 days) resulting in 728 observations (m) for the daily throughput reported from each replication.

Different window sizes (w) are tried ($w = 5, w = 10, w = 15, w = 20, w = 30, w = 40, w = 50$ and $w = 60$) to calculate the moving average of the mean daily throughput until the plot of the moving average becomes reasonably smooth as shown in Figure 7-1. Based on that plot and using a window size of 60, it is clear that the plot becomes almost after a warmup period of 70 days.

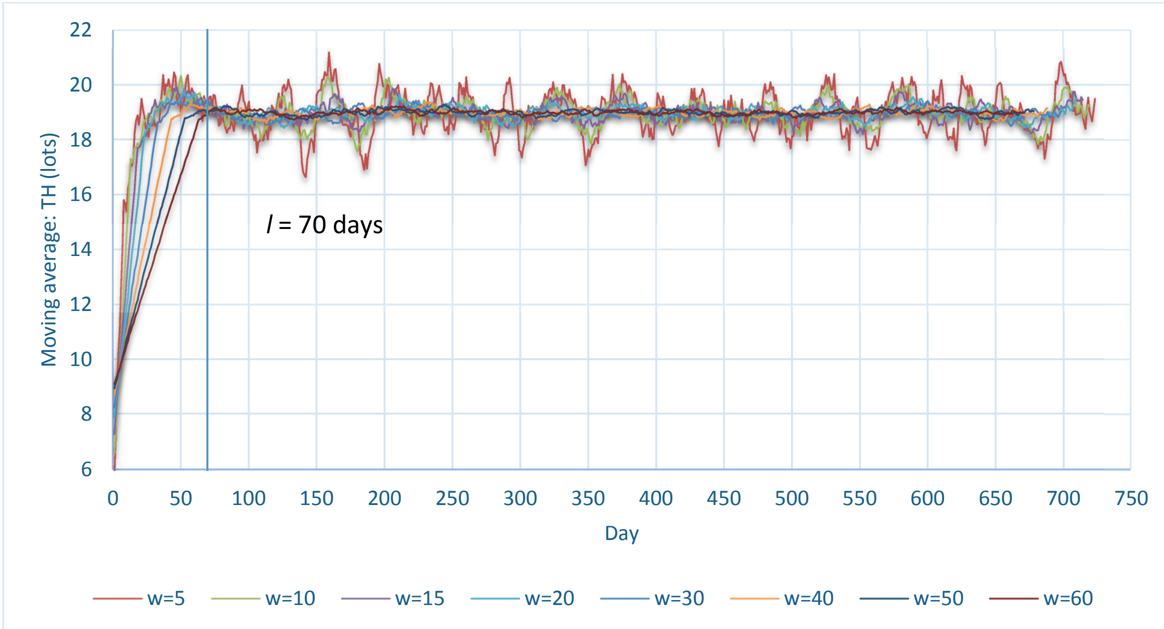

Figure 7-1: Moving average of daily TH at w=5, w=10, w=15, w=20, w=30, w=40, w=50, w=60.

Selecting the number of replications

To select the number of replications required for this study 40 replications are carried out; again, each of 2 years. The results for mean throughput per day and mean cycle time are reported.

In addition, the warmup period that is determined in the previous section is used in these runs and the results obtained from the first 70 days for throughput and cycle time are deleted.

Figure 7-2 shows a graph of the cumulative mean data. Based on the plot of cumulative points, it is clear that the line becomes almost flat after 25 replications for both measures of performance; hence, this will be the recommended number of replications for the experimentation work to follow.

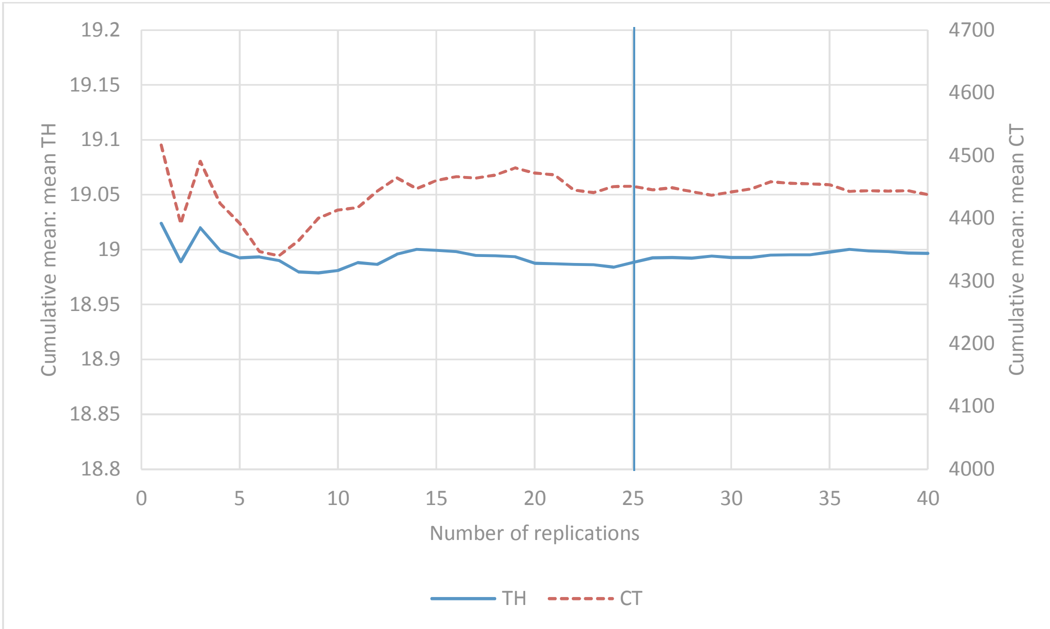

Figure 7-2: Cumulative mean of mean TH per day and mean CT.

In conclusion, it is decided that 25 replications are needed, each replication covers a simulation run time of 2 years, and with a warmup period of 70 days. Also, CRN is used; where, same random seeds are applied to all scenarios.

7.4 PRELIMINARY ANALYSIS

This preliminary analysis is undertaken to better comprehend the nature of the problem and gain familiarity with the phenomenon in the situation and understand what is occurring. The base (current) model is run with pushing 19 lots per day which is the original loading behaviour of the Segment. The utilisation of all stations (U) is monitored, and the mean of U averaged over the 25 replications and the U_{max} are presented in Figure 7-3 to show that the U of all the stations are kept below the U_{max} as intended.

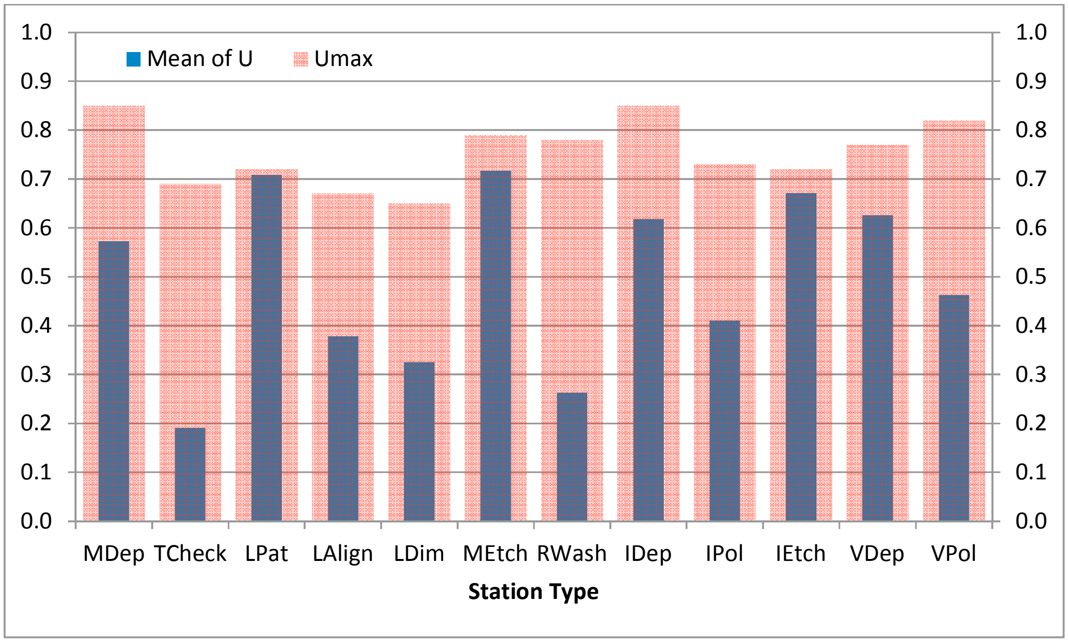

Figure 7-3: Averaged mean of *U* and U_{max} of all stations.

It is clear from the previously presented graph that the mean *U* values of each station are far away from the U_{max}, except LPat station, which is the closest. Therefore, the utilisation of this station only will be monitored in the experimentations presented in this chapter.

7.5 PUSH SCENARIOS

Two different Push models are tested based on different lots introduction behaviour; yet, both scenarios should still result in a mean TH of 19 lots per day which is the target TH in this study.

- First is introducing a batch of lots at the beginning of each day to the Segment (Push Batch).
- Second is pushing a lot with a deterministic input rate (Push Lot).

7.5.1 Push with Daily Loading (Push Batch)

As mentioned earlier, the Segment pushes 19 lots at the beginning of each day (Section 5.1.5). However, different loadings are introduced to the model at the same time interval to better understand the behaviour of the Segment, and the boundaries of the simulations are around the target TH.

Table 7-1 presents the mean TH, CT, WIP, and U_{LPat} averaged based on the outcomes of the 25 replication. The results show that whenever a number of lots are pushed, they are collected each day. Therefore, to confirm reaching the target TH at least 19 lots must be pushed daily. Moreover, not more than 19 lots can be pushed to avoid exceeding the U_{max} at LPat station.

Table 7-1: Summary of results-Push Batch.

Batch size (lots/day)	$\overline{\overline{TH}}$ (lots)	$\overline{\overline{CT}}$ (minutes)	$\overline{\overline{WIP}}$ (lots)	$\overline{\overline{U}}_{LPat}$
18	18	3,882	47.25	0.671
19	19	4,388	56.82	0.708
20	20	5,015	68.99	0.745
21	21	5,959	86.64	0.782

7.5.2 Push Lot

The other Push scenario tested is based on introducing a lot every constant time interval, to find this time interval, the number of minutes per day (1440 minutes) is divided by the number of lots produced daily (19 lots) resulting in 75.789 minutes. Therefore, a lot is introduced to the Segment every 75.789 (75.8) minutes.

A number of simulation experiments are tested with introducing a lot at different time intervals. The boundaries of these simulations are around the value calculated previously, and the results are presented in Table 7-2.

Table 7-2: Summary of results-Push Lot.

TBA (minutes)	$\overline{\overline{TH}}$ (lots)	$\overline{\overline{CT}}$ (minutes)	$\overline{\overline{WIP}}$ (lots)	$\overline{\overline{U}}_{LPat}$
69	20.87	5,201	75.38	0.777
72	20.00	4,426	61.47	0.745
75	19.20	3,905	52.06	0.716
75.789	19.00	3,792	50.03	0.708
78	18.46	3,537	45.34	0.688
81	17.78	3,278	40.48	0.663

It is noticed from the results that by increasing the TBA, TH decreases and falls below the target TH. As less lots are introduced to the Segment for a given time interval and there is an excess capacity for production. On the other side, by decreasing the TBA TH increases and may exceed the target TH. This is because more lots are pushed to the Segment for a given time interval, and there is not enough capacity for production causing an overloading to the bottleneck station (LPat station), this is justified by exceeding the U_{max} at LPat. Therefore, it is agreed that the target TH is the best TH that can be achieved with the Segment capacity by introducing a lot with the deterministic value calculated earlier in this section.

7.5.3 Comparing Push Scenarios

To better compare the performance of both scenarios, results of all experiments presented previously are plotted as shown in Figure 7-4. This figure presents the trade-off between TH and CT for both Push scenarios.

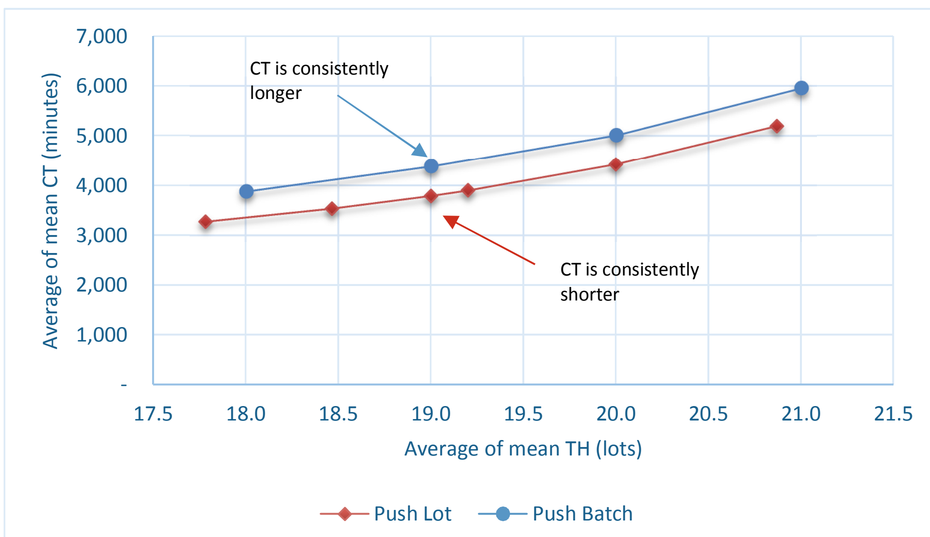

Figure 7-4: Comparing Push scenarios.

Although both models have deterministic nature in arrival of lots; by investigating the results, it is clear that Push Lot is performing better than Push Batch. This is related to the amount of lots pushed and the time interval between pushing them. In Push Batch a number of lots are pushed each day, whereas, in Push Lot the same number of lots are split all over the day, where a single lot is introduced to the Segment every time interval.

Figure 7-5 shows a sample of cycle times at Push Batch and Push Lot for the same lots. It is clear from the graph that the nineteenth lot at Push Batch always has the longest cycle time. This is because it is pushed to the Segment from the beginning of the day and spends too much time at the queue of the first station. Resulting in longer CT and also reflects on the WIP of the Segment, and this justifies the outperforming of Push Lot over Push Batch.

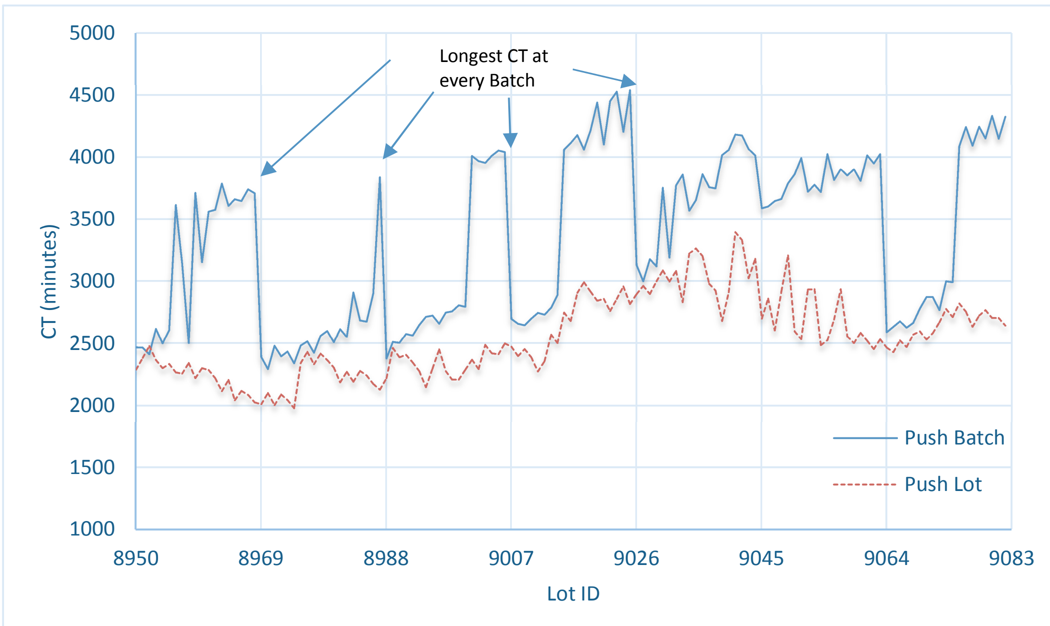

Figure 7-5: Cycle times of lot IDs from 8950 to 9083.

Therefore, it is concluded that pushing a lot every 75.8 minutes results in a better push performance, which achieved the target TH with CT 3,792 minutes and WIP 50 lots, it should be noted that these outcomes are taken as a reference to the upcoming scenarios.

7.6 CONWIP SCENARIOS

When applying CONWIP as a lot release control strategy the WIP level to use must first be set. This is achieved by referring back to the results of the best Push model

(Push Lot) that gives a mean WIP of 50 lots, which will be the first simulation experiment in this scenario and decreasing a lot for every WIP level trial.

Eight experiments are carried out starting with CONWIP level 50 lots and decrementing the CONWIP level by 1 lot for every simulation until reaching CONWIP level 43 lots. The results of these experiments are given in Table 7-3.

Table 7-3: Summary of results-CONWIP scenarios.

CONWIP (lots)	$\overline{\overline{TH}}$ (lots)	$\overline{\overline{CT}}$ (minutes)	$\overline{\overline{WIP}}$ (lots)	$\overline{\overline{U}}_{LPat}$
43	18.84	3,288	42.5	0.704
44	19.02	3,333	43.5	0.710
45	19.06	3,401	44.5	0.712
46	19.23	3,446	45.5	0.718
47	19.27	3,514	46.5	0.720
48	19.43	3,559	47.5	0.726
49	19.47	3,626	48.5	0.727
50	19.61	3,673	49.5	0.733

By investigating the previously shown results, it is clear that by decreasing the CONWIP level TH decreases until it falls below the target TH, thus, no further experiments are carried out, and the best CONWIP level selected is 44 lots.

7.6.1 Push and CONWIP

To compare Push Lot and CONWIP, a trade-off between TH and CT is very useful as presented in Figure 7-6. It is clear from this figure that both scenarios can produce the same TH; however, CONWIP is performing better than Push Lot, as same TH is produced with less CT at CONWIP than at Push Lot.

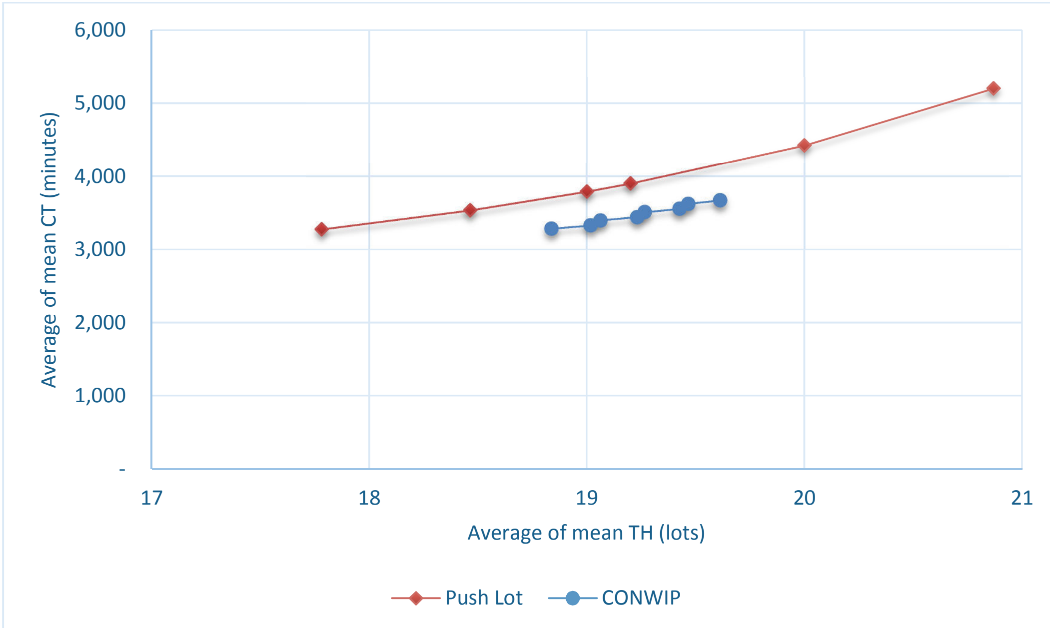

Figure 7-6: TH versus CT for Push Lot and CONWIP.

Unlike the results of Minifab, here CONWIP is better than Push. This is related to the nature of the stochasticity in the Segment under study and the Minifab. Although both models have deterministic inter-arrival times; yet, there is high variability at the Segment due to the variable breakdowns of all the stations, sampling at TCheck, LAlign and LDim stations and batching at RWash and IEtch stations, which was not the case in the Minifab.

To investigate the characteristic of lot arrivals at Push Lot and CONWIP, a sample of time between arrivals of lots is shown in Figure 7-7. At Push Lot the arrival of lots is regulated every 75.8 minutes since it is a deterministic input. However, at CONWIP there is variability of lot arrivals, this is due the fact that a lot is introduced to the Segment as soon as a lot departs.

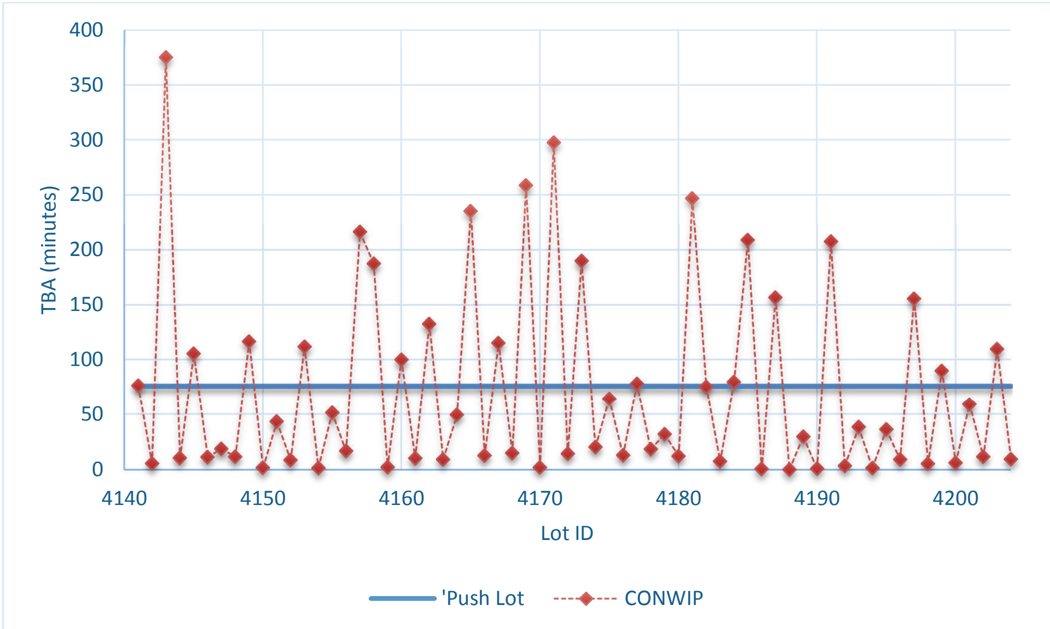

Figure 7-7: Time between arrivals of lots for Push Lot and CONWIP.

Regulating the arrival of lots is not the only factor of variability, and there are other sources of variability inherent at the Segment. However, CONWIP reduces this variability and hence, reduces the amount of waiting time in queues, reduction of waiting time in queues result in reduction of CT.

Therefore, CONWIP performs better than Push Lot, and it is recommended to test the effect of ICONWIP on the performance of the Segment. This is due to the benefit of ICONWIP that combines the effect of CONWIP as well as regulating the arrival of lots.

7.7 ICONWIP SCENARIOS

As mentioned earlier to apply ICONWIP two decision variables are required. The first is the CONWIP level, and referring back to the CONWIP results (Table 7-3), it is decided to test a minimum CONWIP level of 44 lots, which is the least CONWIP level that achieved the target TH, and a maximum CONWIP level of 47 lots, which is the CONWIP level that caused the U_{LPat} to reach the U_{max}.

The second decision variable is the min TBA that should pass between any 2 lots released to the Segment, and the limits of this decision variable is from 0 minute to 75 minutes for all CONWIP levels tested.

304 simulations are carried out starting from CONWIP level 44 to 47 lots, and for each CONWIP level a min TBA from 0 to 75 minutes. A sample of the results at CONWIP45 with min TBA 0 to 75 minutes is presented in Figure 7-8.

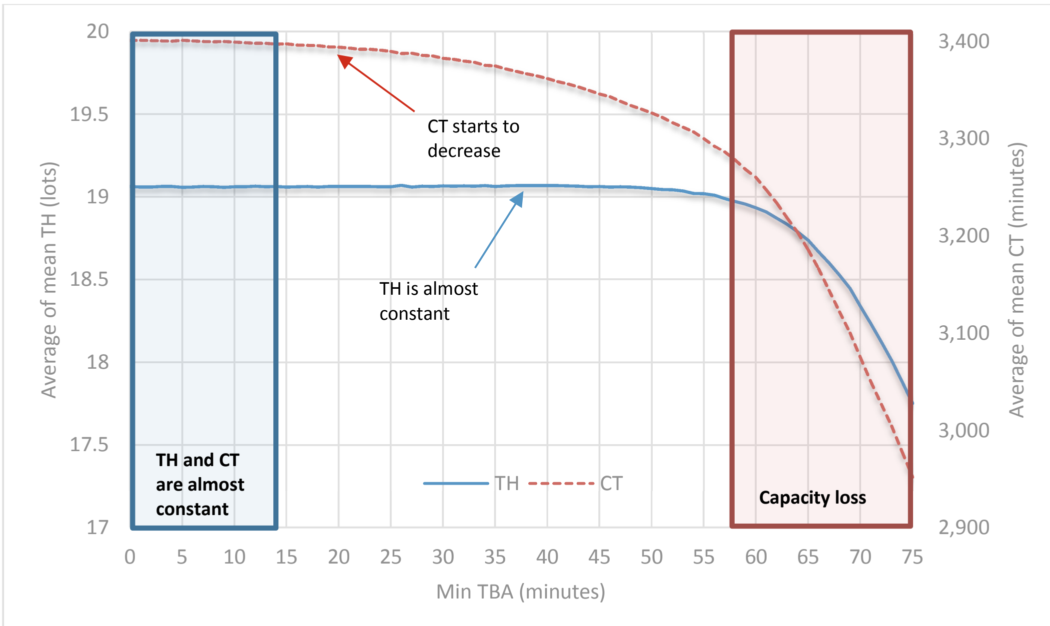

Figure 7-8: ICONWIP 45 results.

It is obvious that from min TBA 0 to 10 minutes TH and CT are almost constant, therefore CONWIP and ICONWIP have the same performance. Afterwards TH is almost steady and CT is slightly decreasing until min TBA 56 minutes, where TH falls below the Target TH, and then both measures are decreasing. Consequently, it is agreed that the best performance of ICONWIP45 is achieved with min TBA 56 minutes.

It should be noted that all the simulations tested have the same performance pattern for every CONWIP level, and the best ICONWIP simulation is selected when reaching the target TH, the summary of selected simulations results is given in Table 7-4.

Table 7-4: Summary of best ICONWIP strategy.

ICONWIP	Min TBA (minutes)	$\overline{\overline{TH}}$ (lots)	$\overline{\overline{CT}}$ (minutes)	$\overline{\overline{WIP}}$ (lots)	$\overline{\overline{U}}_{LPat}$
ICONWIP44	39	19	3,301	43.05	0.710
ICONWIP45	56	19	3,292	42.89	0.710
ICONWIP46	61	19	3,293	42.88	0.710
ICONWIP47	63	19	3,312	43.10	0.711

It is clear from the results that the target TH is attained with all ICONWIP levels; however, there are differences in CT and WIP. Also, it is noticed that with higher CONWIP levels the target TH is reached with more delay time before the release of lots (min TBA).

It should be noted that as the min TBA increases, the WIP level drops below the CONWIP level set for a period of time, resulting in lower WIP of the Segment, and referring to Little's law (Equation **2-1**) at constant TH with less WIP, CT is reduced.

7.7.1 CONWIP and ICONWIP

To compare CONWIP and ICONWIP, the results of the CONWIP level selected (CONWIP level 44 lots-Table 7-3), and the results of all ICONWIP simulations selected (Table 7-4) are presented in Figure 7-9.

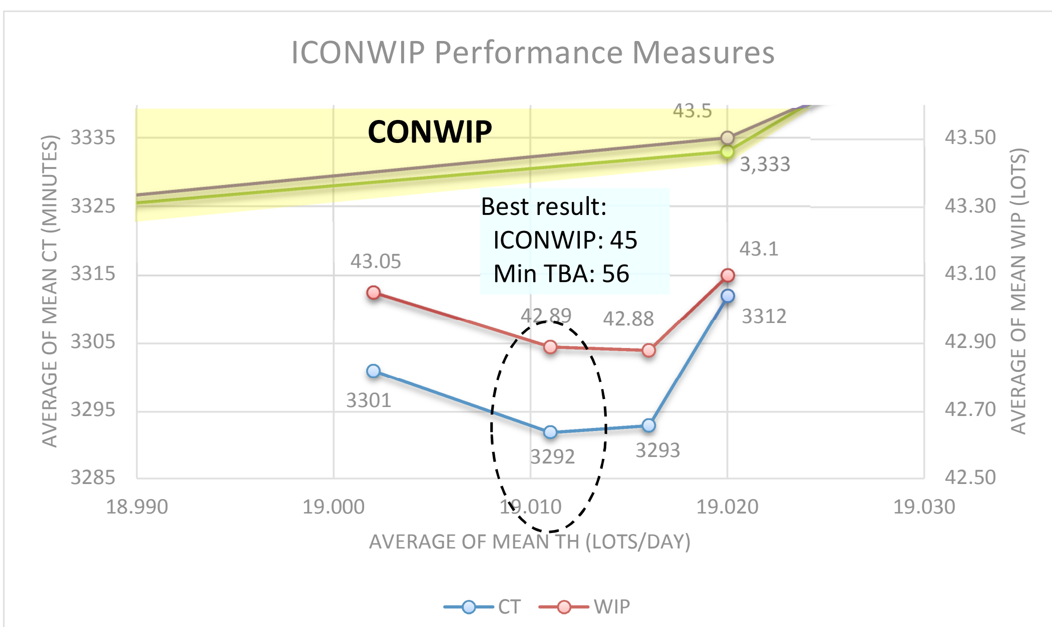

Figure 7-9: CONWIP and ICONWIP results.

It is clear that all the scenarios achieved the target TH, and CONWIP44 has the longest CT (3,333 minutes) and highest WIP levels (43.5 lots), therefore ICONWIP is outperforming CONWIP. Moreover, to select the best ICONWIP, it is noted that ICONWIP45 has the lowest CT (3,292 minutes). As a result it is concluded that ICONWIP45 is selected to be the best scenario tested.

This better performance is due to the rule of ICONWIP that avoids the release of new lots immediately after a departure happens. First, the arrival time of the last lot released to the Segment previously is checked, and if a predetermined time interval has passed, the new lot is released. Otherwise, the new lot is delayed for this time interval. At that time the WIP level drops below the WIP cap assigned causing a reduction to CT at a given TH (Equation 2-1).

Figure 7-10 presents a sample of time between arrivals at CONWIP and ICONWIP. It is obvious that ICONWIP has less variability when compared to CONWIP, and this is due to regulation of lots arriving to the Segment. For the sample shown, the minimum of the inter-arrival time is 56 minutes. Hence, none of the lots can have an inter arrival time less than 56 minutes; however, there is no limit on the maximum inter arrival time, because it is related to the departure of lots from the Segment.

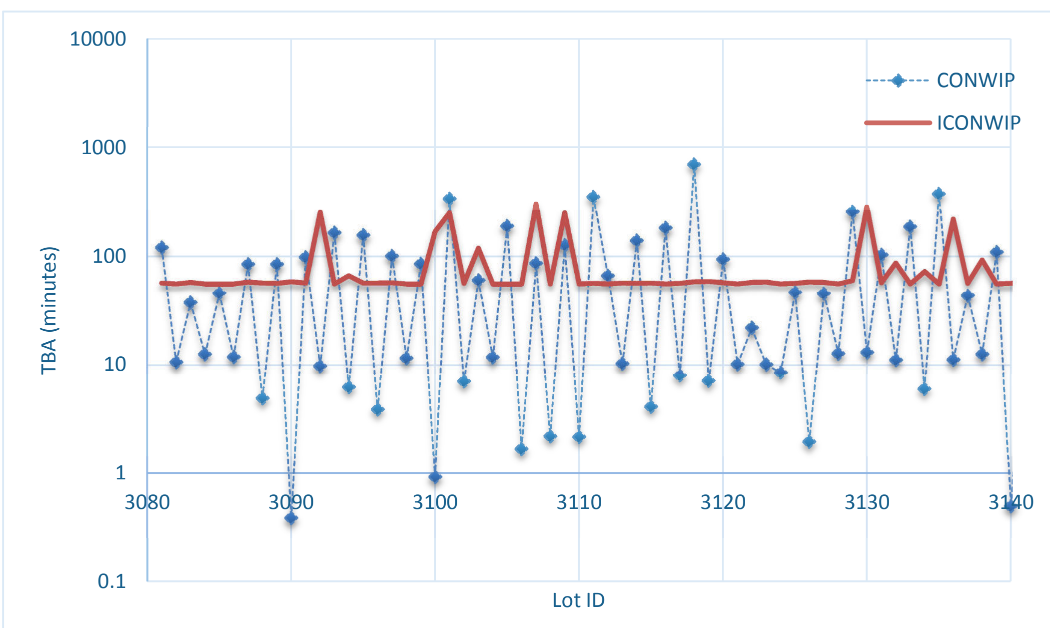

Figure 7-10: A sample of time between arrivals of lots for CONWIP and ICONWIP.

As mentioned earlier that this variability of arrivals affects the coefficient of variation of arrivals (c_a) to all the stations of the Segment, the mean c_a to all stations of both scenarios are given in Figure 7-11. It is observable from the results that ICONWIP has lower c_a at all the stations when compared to CONWIP, and this reduction of c_a results in lower CT (Equation 4-2), that leads to savings in WIP at constant TH (Equation 2-1).

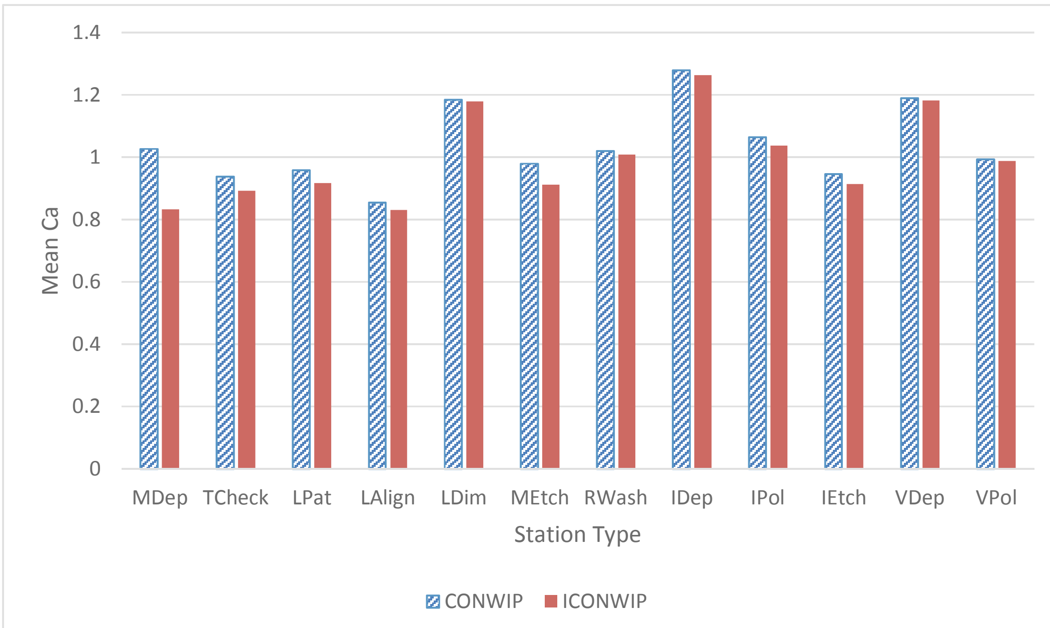

Figure 7-11: Mean c_a of all stations under CONWIP and ICONWIP.

7.8 SELECTION OF THE BEST SCENARIO IN GROUP I

Nelson's combined method discussed in Section 2.5.4 (Subsection Experimentation and Analysis) is applied here again to confirm the results obtained from the previous experiments and to select the best scenario in Group I scenarios. Table 7-5 shows the parameters and constants required for this application.

Table 7-5: Parameters and Constants for Nelson's method of Group I scenarios.

Parameter	Value	Constant	Value
$\propto$	0.05	t	2.875
k	4	h	3.158
n_o	25	ε	1

Table 7-6 shows the outcomes of the Nelson's combined method when applied on the Group I scenarios. It is clear that there is only one survivor, even with the indifference zone reduced to one minute over a cycle time of over 2 days, ICONWIP. Thus, this is the best scenario in Group I scenarios and the procedure is terminated.

Table 7-6: Results from Nelson's combined method- Group I scenarios.

Scenario	i	$\bar{Y}_i$	S_i^2	j	W_{ij}	$\bar{Y}_j + \max(0, W_{ij} - \varepsilon)$	Decision
Push Batch	1	4,388	66,653	2	9.36	3,800	Eliminate
				3	92.91	3,425	
				4	92.35	3,384	
Push Lot	2	3,792	63,613	1	9.36	4,397	Eliminate
				3	90.02	3,422	
				4	89.48	3,381	
CONWIP	3	3,333	1,987	1	92.91	4,480	Eliminate
				2	90.02	3,881	
				4	2.82	3,294	
ICONWIP	4	3,292	2,273	1	92.35	4,480	Keep
				2	89.48	3,880	
				3	2.82	3,335	

7.9 FURTHER CONWIP ANALYSIS

As mentioned previously, when applying CONWIP as a lot release control strategy to the Segment, an improvement is achieved when compared to Push. A deeper analysis to the Segment with CONWIP is undertaken in this chapter, and the results show that more lot release control strategies are applied to get better performance.

CONWIP improves the performance of the fab, specifically; it reduces the variability inherent in the fab and hence, reduces the amount of waiting time in queues. Reduction of waiting time in queues results in reduction of cycle time.

Furthermore, it should be mentioned that CONWIP doesn't only reduce the variability of WIP over the Segment by dropping the mean variances of the 25 independent runs from 416.2 to 0.25 (lots²), but it also reduces the variability of the WIP at each station.

Figure 7-12 presents the mean variances of WIP at each station of the Segment and confirms that CONWIP reduces the variability of WIP at each station. It is noticed that MDep, LPat, MEtch, IDep, IEtch, and VDep stations have higher WIP variability than TCheck, LAlign, LDim, RWash, IPol, and VPol stations, this is because the former stations have longer mean repair time than the latter ones.

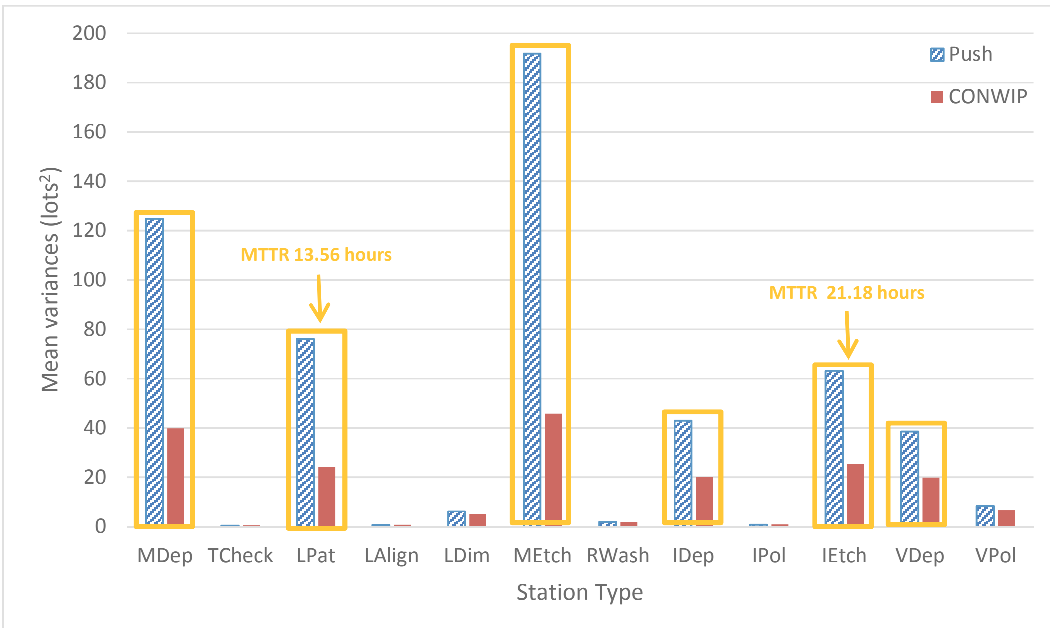

Figure 7-12: Mean variances of station WIP under Push and CONWIP.

Mean repair times for these stations (MDep, LPat, MEtch, IDep, IEtch, and VDep) varies from a maximum value of 21.18 hours at IEtch station to a minimum value of 13.56 hours at LPat station, which exceeds a time period that covers a shift.

Moreover, it should be noted that when one of the high mean time to repair stations has all its machines down, from 80% to 100% of the total WIP accumulates at that station waiting for the repair to end. Thus, in some instances all the WIP is stuck in one station while other stations are starved.

This particular situation is even worse than a Push system, Push systems have bottlenecks, where lots accumulate in front of certain stations, but the remaining stations would still have lots to operate on. However, here, the rest of the stations are ready for lot processing and are idle which results in an unbalanced loading of the Segment as presented in Figure 7-13.

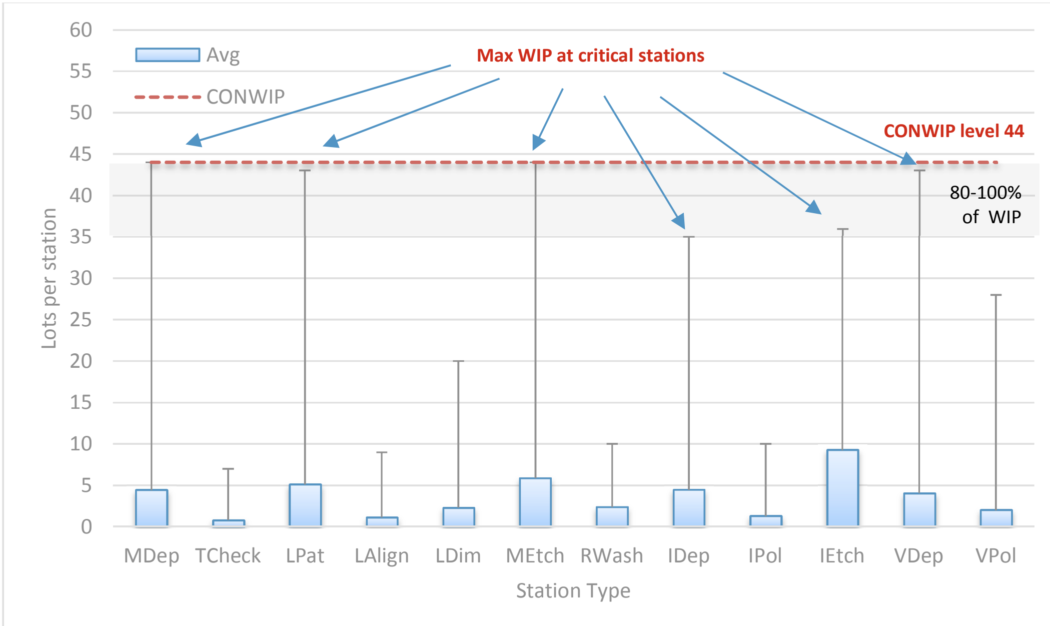

Figure 7-13: Average and maximum of WIP level through the stations under CONWIP.

This figure shows the average WIP of each station with the maximum number of lots that is achieved when the station is down. It is clear that MDep and MEtch stations reached the WIP level (44 lots) while stations LPat, IDep, IEtch, and VDep stations exceeded 80% of the total amount of WIP (35 lots).

After analysing the CONWIP results, it is evident that the CONWIP lot release control strategy drastically improved the Segment performance. However, the only drawback is the unbalancing the load of the Segment. This is because the WIP levels inside the CONWIP are not controlled individually by station, so if there is a bottleneck or a station down, high WIP levels can accumulate, just like a Push system. Though CONWIP significantly improved the Segment performance over Push, still, there is one problem found.

7.9.1 Additional Goal

After conducting CONWIP experiments and analysing the results, the objective of the work is updated to solve the problem appeared.

As mentioned earlier, this problem is created when a station is down for a long time while applying CONWIP. Since there is a limited number of lots at the Segment, and when all machines in a station are down at the same time, all the lots at the Segment will accumulate during the downtime and the rest of the stations are idle at that time.

Hence, the Segment is not balanced due to accumulating most of the lots and sometimes all of them at one station. Therefore, an additional objective to improve the distribution of WIP is considered.

7.10 DRUM BUFFER ROPE SCENARIOS

The first attempt to reduce the unbalancing effect of CONWIP is to use the Drum Buffer Rope (DBR) lot release control strategy. DBR controls the flow of lots to the bottleneck to ensure it can operate at maximum capacity; in addition, it should let the lots flow freely through the other section (after the bottleneck) behaving in a manner similar to the push system. Thus, it should combine the benefits of CONWIP and Push.

When applying DBR as a lot release control strategy the WIP level from the start of the fab to the bottleneck station must first be set. Whenever a lot leaves LPat station which is the bottleneck station, and will not revisit that station again, meaning that the lot has processed step 41, another lot should be released to the Segment.

To decide the WIP level in that section of the Segment, different experiments are conducted. Referring back to the results of the CONWIP model that gives a mean WIP of 44 lots, this provides the start value for the DBR WIP level. This value is reduced by 1 and the simulation repeated several times.

Five experiments are carried out starting with a DBR level of 44 lots, where $\overline{\overline{U}}$ exceeds the U_{max} of LPat station which is not acceptable. Hence it is decided to decrement the DBR WIP level by 1 lot, until the TH falls below the target TH at a DBR WIP level of 40 lots. Then the DBR WIP level is selected at 41 lots, at which the TH reaches the target TH as shown in Table 7-7.

Table 7-7: Summary of results-DBR scenarios.

DBR WIP level	$\overline{\overline{TH}}$ (lots)	$\overline{\overline{CT}}$ (minutes)	$\overline{\overline{WIP}}$ (lots)	$\overline{\overline{U}}_{LPat}$
44	19.39	3,603	49.13	0.724
43	19.25	3,544	47.98	0.719
42	19.17	3,477	46.90	0.716
41	19.02	3,419	45.75	0.711
40	18.94	3,352	44.69	0.708

Investigating the mean results accomplished using the DBR WIP level selected of 41 lots, and comparing them to the CONWIP results (refer to Table 7-3). It is obvious that both scenarios achieve the same TH; however, CONWIP is performing better as the same TH is achieved with less CT and WIP when compared to DBR.

Furthermore, when comparing the variability of the WIP at each station of the Segment at DBR and CONWIP, it is noticed that only MEtch station shows the highest variance than all the other stations that have around the same or a bit difference variance under DBR than CONWIP. Figure 7-14 presents the mean of variance of WIP at each station of the Segment for the 25 independent runs at CONWIP and DBR.

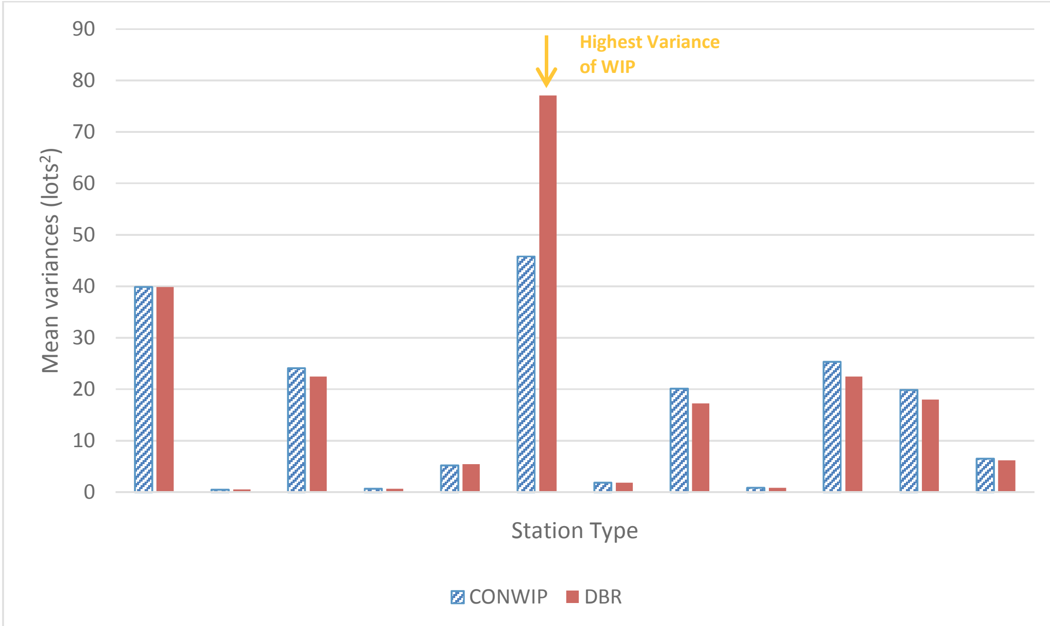

Figure 7-14: Mean variances of station WIP for CONWIP and DBR.

The previously shown figure confirms that MDep, LPat, MEtch, IDep, IEtch, and VDep stations still have higher WIP variability than TCheck, LAlign, LDim, RWash, IPol, VPol stations due to the longer repair times.

Figure 7-15 presents the WIP levels when applying the DBR lot release control strategy through all the stations of the Segment. By investigating MDep, LPat, MEtch, IDep, IEtch, and VDep stations that are considered as critical stations, it is clear that only MEtch reaches 66 lots, whereas none of the other stations exceed the DBR WIP level selected which is 41 lots.

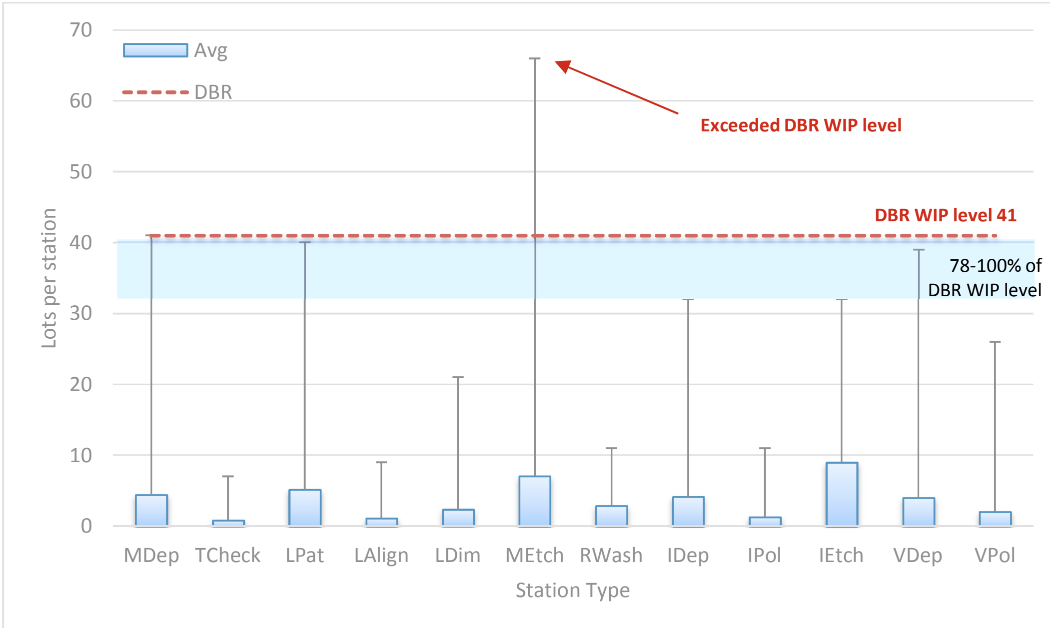

Figure 7-15: Average and maximum WIP level through the stations under DBR.

MDep station has reached the DBR WIP level of 41 lots and the other 4 stations reached WIP levels of higher than 78% of the DBR WIP level selected. Regarding MEtch station, it is a critical station that has a mean time to repair of 19.48 hours, and there is no WIP cap on the its last step (step 44), and this justifies the increase of variance of DBR at that station over CONWIP.

This is because the DBR controls the WIP of the fab from step 1 performed at MDep station up to step 41 performed at LPat the bottleneck station; however, step 44 performed at MEtch station flows freely in the uncontrolled section of the Segment.

As mentioned previously CONWIP behaves slightly better than DBR this is mainly attributed to the structure of the Segment; because the last step performed on the bottleneck station is step 41 out of total 46 steps required for completing a lot. Hence, most the line is controlled by a single WIP cap loop as in CONWIP.

As a result, CONWIP outperforms DBR that has potential for higher variability in sections without the WIP cap. Consequently, the next scenario considers a hybrid between CONWIP and DBR that addresses this drawback and aims to control the lots flowing freely after finishing step 41 at the bottleneck station.

7.11 HYBRID CONWIP/DBR SCENARIOS

When combining CONWIP and DBR lot release control strategies, it is intended to combine the benefits of both. First, the WIP level over the Segment and the WIP level from the start of the production line to the bottleneck station must be determined. In hybrid CONWIP/DBR lot release control strategy, a new lot is released to the production line if either a lot is departed from the Segment, or a lot permanently leaves the bottleneck station and will not revisit that station again.

Therefore, there are two decision variables: the first is the CONWIP level and the second is the DBR WIP level. The WIP level over the Segment is considered from the selected CONWIP level mentioned previously (Section 7.6), this CONWIP of 44 lots cannot be decreased to sustain the improved performance achieved by CONWIP; however, a higher CONWIP level of 45 lots is tested.

To decide the WIP level in the section from the start of the Segment to the bottleneck station, reference should be made to the selected DBR WIP level in the previous section of 41 lots. This value is the minimum DBR WIP level tested and the maximum is the CONWIP level. The results of all the simulations tested are given in Table 7-8.

Table 7-8: Summary of results-Hybrid CONWIP/DBR scenarios.

CONWIP/DBR WIP level	$\overline{\overline{TH}}$ (lots)	$\overline{\overline{CT}}$ (minutes)	$\overline{\overline{WIP}}$ (lots)	$\overline{\overline{U}}_{LPat}$
44/41	18.93	3,290	43.25	0.707
44/42	18.99	3,312	43.43	0.710
44/43	19.01	3,324	43.50	0.710
44/44	19.02	3,333	43.50	0.710
45/41	18.93	3,325	43.90	0.707
45/42	19.01	3,351	44.25	0.710
45/43	19.05	3,378	44.43	0.712
45/44	19.06	3,391	44.50	0.712
45/45	19.06	3,401	44.50	0.712

It is clear from the results shown that for every CONWIP level by increasing the DBR WIP level all the measures increase. This is attributed to the amount of WIP introduced to the Segment that affects all the measures. To select the CONWIP/DBR levels, the target TH should be achieved with the minimum CT and

WIP and this attained with CONWIP44/DBR43. Comparing the results of CONWIP44/DBR43 to the results of CONWIP44 (Table 7-3), it is evident that hybrid CONWIP/DBR is performing better than CONWIP, as same TH is produced but with slightly better CT.

Also, it is noticed that when both strategies have the same WIP levels (for example CONWIP44/DBR44) the results of this simulation is exactly the same as the results of CONWIP44 (see Table 7-3). This is because at this instance CONWIP is controlling the performance of the Segment and the DBR has the same WIP cap of CONWIP, so it does not have any effect on the performance of the Segment.

Additionally, it should be mentioned that CONWIP/DBR reduces the variability of the WIP at all the critical stations of the Segment when compared to CONWIP; however, all the other stations have the same variability at both strategies as presented in Figure 7-16.

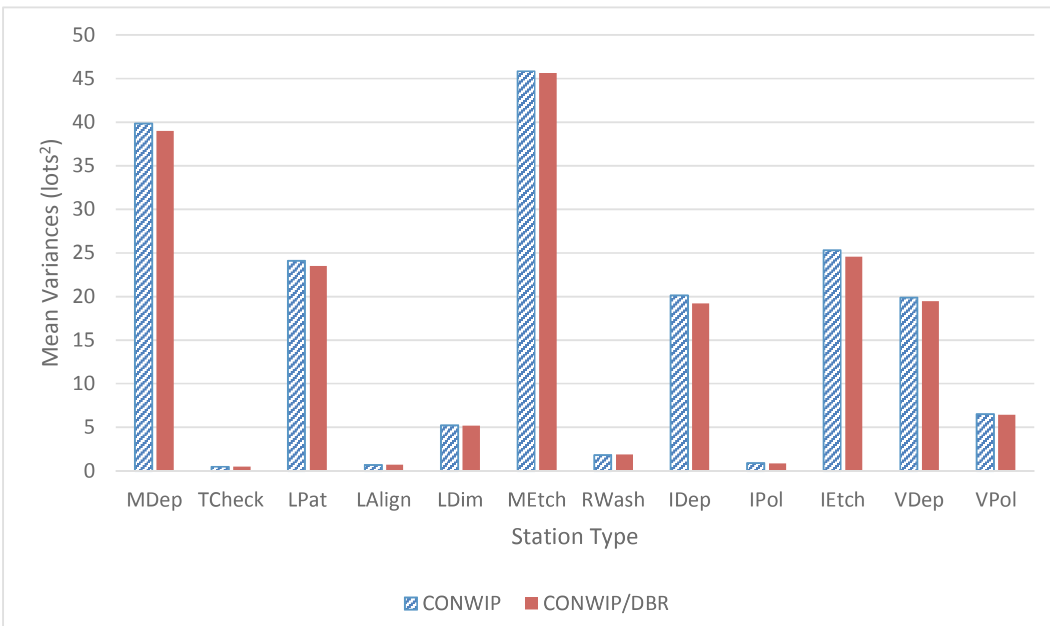

Figure 7-16: Mean variances of station WIP for CONWIP and CONWIP/DBR.

Figure 7-17 presents the WIP levels when applying the CONWIP/DBR lot release control strategy through all the stations of the Segment. It is clear that the maximum WIP at MEtch station now falls to the CONWIP level. Whereas, all the critical stations MDep, LPat, MEtch, IDep, IEtch, and VDep still accumulates at least 77% of the total WIP.

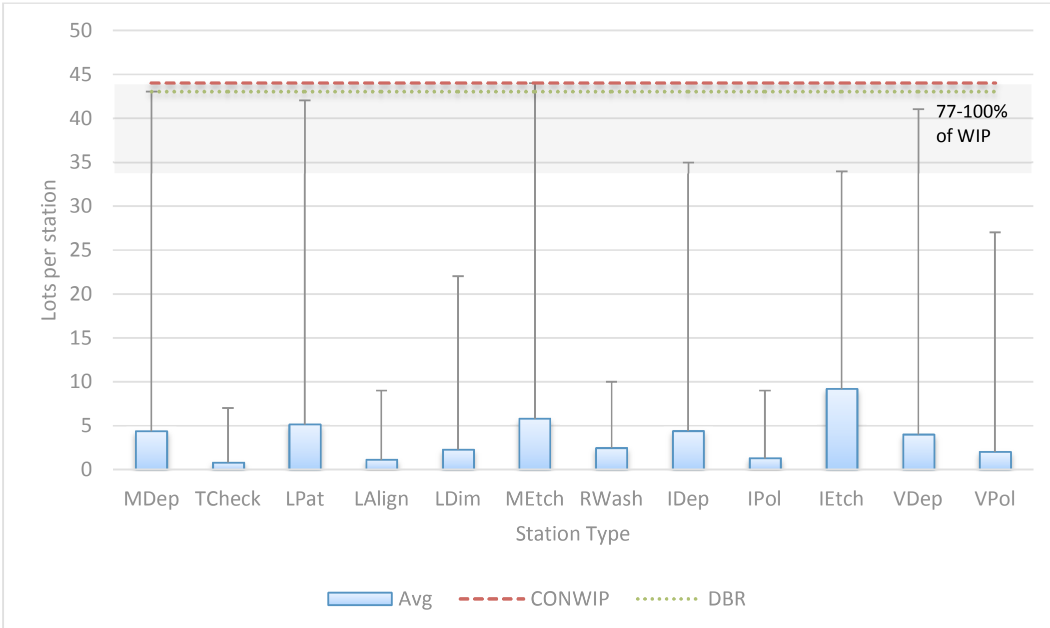

Figure 7-17: Average and maximum WIP level across the stations for CONWIP/DBR.

Finally, it is concluded that hybrid CONWIP/DBR performs slightly better than CONWIP; however, it doesn't balance the distribution of WIP across the Segment.

7.12 LCONWIP SCENARIOS

The current scenario investigates the effect of applying a new lot release control strategy on the performance measures. The proposed LCONWIP, where L stands for Looped, is a modification of CONWIP with a loop applied to the critical station that has a long repair time. The loop acts as a WIP cap that limits the number of lots entering that station to avoid accumulating the lots there. This will probably balance the lots distribution over the Segment, as well as will minimise the variability of the WIP flowing through the stations.

As mentioned earlier, at the Segment there are twelve stations, six of them have a mean time to repair more than a shift. These are MDep, LPat, MEtch, IDep, IEtch, and VDep stations and they are said to be critical stations. Table 7-9 shows the mean time to repair of all the stations in hours with the critical stations highlighted. Hence, it is clear that the critical stations are the stations that need a loop with WIP cap to limit the number of lots at these stations.

Table 7-9: Mean time to repair of all stations.

Station	MTTR (hours)	Station	MTTR (hours)
MDep	21.14	RWash	0.51
TCheck	1.50	IDep	14.97
LPat	13.56	IPol	1.47
LAlign	1.50	IEtch	21.18
LDim	4.31	VDep	15.86
MEtch	19.49	VPol	3.85

LCONWIP Experiments

In order to apply the developed LCONWIP lot release control strategy three steps are required:

- Apply CONWIP lot release control strategy to the Segment,
- Select the critical stations where the loops will be established, and
- Set the WIP cap for the loops developed.

Therefore, three decisions variables are necessary, first, the WIP level of the CONWIP, which is set at 44 lots as previously selected and also 45 lots is tested.

Second, the critical stations which are MDep, LPat, MEtch, IDep, IEtch, and VDep stations as explained previously.

Third, the WIP cap of the loops; where, it is known that in case of failures to all machines in a station at the same time, a queue is formed in front of that station, and due to re-entrancy each lot is expected to visit the same station more than once for performing different steps.

Therefore, the number of machines is multiplied by the number of steps at each critical station to find the estimated WIP cap per station, and the maximum value is taken as a base line to start a set of experiments, in order to decide the WIP cap of the loops as given in Table 7-10.

Table 7-10: Calculating the expected WIP cap at the critical stations.

Station	MDep	LPat	MEtch	IDep	IEtch	VDep
Number of Machines per station	2	4	3	3	5	3
Number of Steps per station	3	5	3	2	2	2
Expected WIP level per station (lots)	6	20	9	6	10	6

For each CONWIP level, different WIP levels at the critical stations are tested starting with 20 lots per loop, and then reducing the Loop WIP level by 1 until the TH falls below the target TH for each CONWIP level tested. The results of all the simulations tested are given in Table 7-11.

Table 7-11: Summary of results-LCONWIP scenarios.

CONWIP/Loop WIP level	$\overline{\overline{TH}}$ (lots)	$\overline{\overline{CT}}$ (minutes)	$\overline{\overline{WIP}}$ (lots)	$\overline{\overline{U}}_{LPat}$
44/20	19.00	3,324	43.39	0.710
44/19	19.00	3,322	43.37	0.710
44/18	18.99	3,320	43.33	0.710
45/20	19.05	3,390	44.38	0.712
45/19	19.05	3,389	44.35	0.712
45/18	19.04	3,386	44.32	0.712
45/17	19.04	3,384	44.27	0.711
45/16	19.03	3,381	44.21	0.711
45/15	19.03	3,375	44.13	0.711
45/14	19.02	3,371	44.04	0.711
45/13	19.00	3,366	43.93	0.710
45/12	18.99	3,360	43.81	0.710

It is obvious from the previous results that the target TH is achieved with most of the simulations tested. However, to select the combination of CONWIP and WIP cap of the loop, the target TH should be reached with the minimum CT and WIP. This is attained with CONWIP level of 44 lots, and a WIP cap of 19 lots at the loops of the critical stations.

Comparing the results of LCONWIP44/19 to the results of CONWIP44 (Table 7-3), it is shown that both strategies achieved the target TH; however, CT and WIP of

LCONWIP are lower than of CONWIP. Therefore, LCONWIP is outperforming CONWIP.

Moreover, it should be mentioned that LCONWIP reduces the variability of the WIP at all the looped stations of the Segment when compared to CONWIP. Whereas, the rest of the stations either have the same or slightly higher mean of variances as shown in Figure 7-18, which is not an issue because the variability of the latter stations is very low when compared to the former ones.

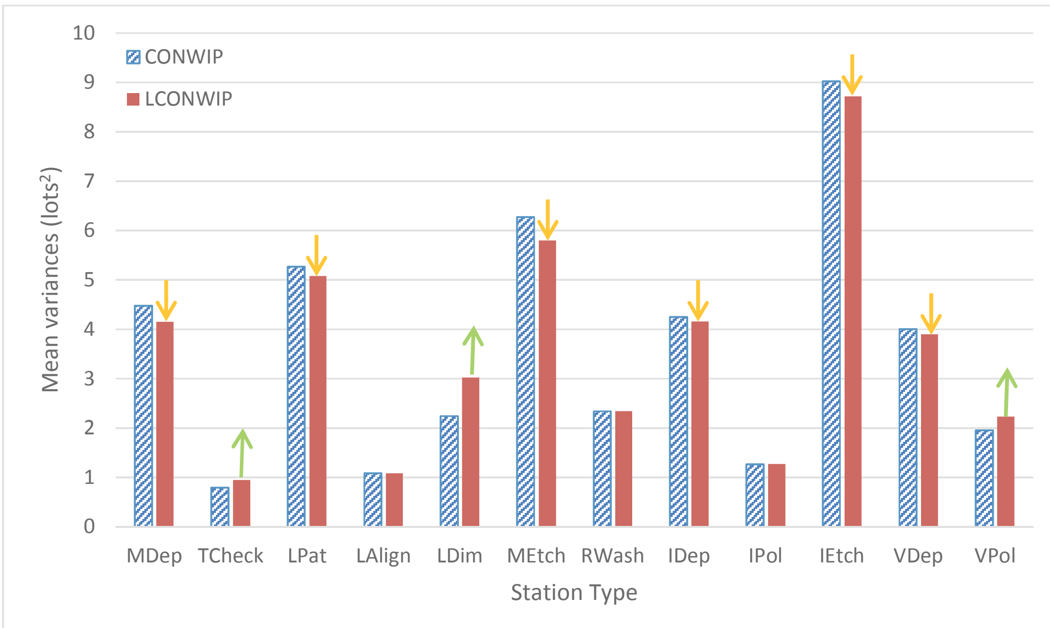

Figure 7-18: Mean variances of station WIP for CONWIP and LCONWIP.

It is observable that LAlign, RWash, and IPol stations have the same mean of variances of WIP at each station for both LCONWIP and CONWIP. On behalf of the stations with slightly higher mean of variances at LCONWIP than CONWIP they are TCheck, LDim, and VPol stations; this is because LPat, MEtch, and MDep stations follow these stations. Subsequently, lots may rest at these stations waiting for a signal from the critical station indicating that there is a vacancy for processing there.

Figure 7-19 presents the average and maximum values of the WIP level using the LCONWIP lot release control strategy at all stations of the Segment. By investigation, it is clear that none of the stations exceed the WIP cap assigned to the loops except VPol station that reached a maximum of 29 lots. Also, there is room between the WIP cap of the loops and the CONWIP which gives a space for lots to flow within the fab to complete processing in case of a station down, and thus avoid blocking which causes the Segment unbalanced behaviour.

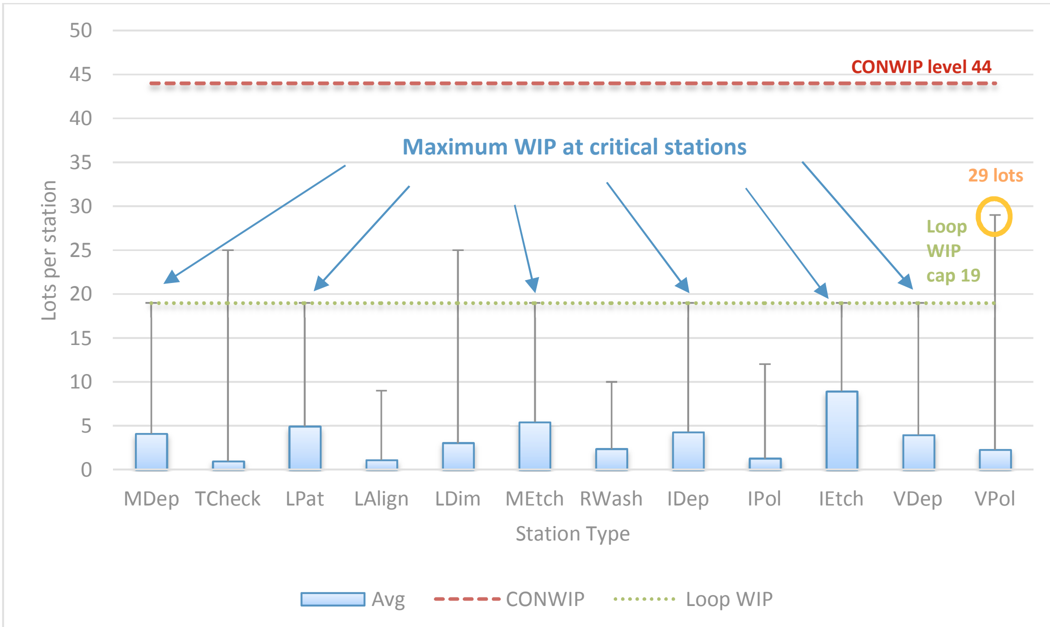

Figure 7-19: Average and maximum WIP level through stations under LCONWIP.

It should be noted that VPol station is not a critical station and it doesn't have a loop with a WIP cap. Exceeding the 19 lots at the station is because it is followed by MDep station, in the process routing, which is a critical station with a WIP cap. If MDep reached its WIP cap, lots finishing processing at station 12 will wait until there is room for that lot at MDep station.

As a result, it is concluded that the LCONWIP results in slightly better performance than CONWIP lot release control strategy; and also it improves the flow of WIP through the stations and results in better variability of WIP station at all the critical stations as well as balancing the load of the Segment.

7.13 SELECTION OF THE BEST SCENARIO IN GROUP II

To ensure the results accomplished from the previous section Nelson's combined method is applied here to select the best scenario in Group II scenarios. Table 7-12 shows the parameters and constants required for this application.

Table 7-12: Parameters and Constants for Nelson's method of Group II scenarios.

Parameter	Value	Constant	Value
$\propto$	0.05	t	2.875
k	4	h	3.158
n_o	25	ε	1

Table 7-13shows the outcomes of the Nelson's combined method when applied on the Group II scenarios. It is clear that there is only one survivor scenario which is the LCONWIP, thus this is the best scenario in Group II scenarios and the procedure is terminated.

Table 7-13: Results from Nelson's combined method- Group II scenarios.

Scenario	i	$\bar{Y}_i$	${S_i}^2$	j	W_{ij}	$\bar{Y}_j + \max(0, W_{ij} - \varepsilon)$	Decision
CONWIP	1	3,333	1,987	2	7.60	3,425	Eliminate
				3	1.46	3,325	
				4	1.94	3,323	
DBR	2	3,419	2,555	1	7.60	3,340	Eliminate
				3	7.08	3,330	
				4	6.53	3,328	
CONWIP/ DBR	3	3,324	1,968	1	1.46	3,334	Eliminate
				2	7.08	3,425	
				4	1.48	3,322	
LCONWIP	4	3,322	1,827	1	1.94	3,334	Keep
				2	6.53	3,424	
				3	1.48	3,325	

7.14 SELECTION OF THE BEST SEGMENT SCENARIO

For deeper confirmation of results, Nelson's combined method is applied and Table 7-14 shows the parameters and constants required for this application.

Table 7-14: Parameters and Constants for Nelson's method of all the Segment scenarios.

Parameter	Value	Constant	Value
$\propto$	0.05	t	3.166
k	7	h	3.746
n_o	25	ε	1

Table 7-15 shows the outcomes of the Nelson's combined method when applied on all the Segment scenarios. It is clear that there is only one survivor scenario which is the ICONWIP, thus this is the best scenario in all the Segment scenarios tested in this work and the procedure is terminated.

Table 7-15: Results from Nelson's combined method- All Segment scenarios.

Scenario	i	$\bar{Y}_i$	${S_i}^2$	j	W_{ij}	$\bar{Y}_j + \max(0, W_{ij} - \varepsilon)$	Decision
Push Batch	1	4,388	66,653	2	9.30	3,801	Eliminate
				3	101.32	3,434	
				4	100.71	3,393	
				5	101.21	3,520	
				6	102.01	3,426	
				7	102.35	3,424	
Push Lot	2	3,792	63,613	1	9.30	4,398	Eliminate
				3	98.14	3,431	
				4	97.55	3,390	
				5	98.11	3,517	
				6	98.78	3,423	
				7	99.20	3,421	
CONWIP	3	3,333	1,987	1	101.32	4,490	Eliminate
				2	98.14	3,890	
				4	2.11	3,295	
				5	7.37	3,426	
				6	0.61	3,325	
				7	1.14	3,323	
ICONWIP	4	3,292	2,273	1	100.71	4,489	Keep
				2	97.55	3,890	
				3	2.11	3,335	
				5	7.28	3,426	
				6	2.35	3,326	
				7	2.46	3,324	
DBR	5	3,418	2,555	1	101.21	4,490	Eliminate
				2	98.11	3,890	
				3	7.37	3,340	
				4	7.28	3,300	
				6	6.80	3,331	
				7	6.19	3,328	
CONWIP/ DBR	6	3,324	1,968	1	102.01	4,490	Eliminate
				2	98.78	3,891	
				3	0.61	3,334	
				4	2.35	3,295	
				5	6.80	3,425	
				7	0.63	3,323	
LCONWIP	7	3,322	1,827	1	102.35	4,491	Eliminate
				2	99.20	3,891	
				3	1.14	3,334	
				4	2.46	3,295	
				5	6.19	3,425	
				6	0.63	3,325	

7.15 CONCLUSIONS OF SEGMENT EXPERIMENTS

In this chapter a number of scenarios are applied to achieve a target TH of 19 lots per day with better CT and WIP, as well as minimizing the variances of these measures. Two groups of scenarios are conducted, Group I tests the effect of applying the same methodologies tested earlier on the Minifab. Group II evaluates the impact of applying other strategies that balances the distribution of WIP across the stations of the Segment. This section summarizes the results of all the scenarios conducted.

7.15.1 Conclusions of Group I Scenarios

Table 7-16 presents the mean and variance for the TH, CT and WIP averaged based on the outcomes of the 25 replications; ($\overline{\overline{TH}}$, $\bar{V}_{TH}$, $\overline{\overline{CT}}$, $\bar{V}_{CT}$, $\overline{\overline{WIP}}$ *and* $\bar{V}_{WIP}$) respectively of Group I scenarios. The results show that the target TH is achieved with all the models; however, there are major differences in the remaining performance measures.

Table 7-16: Results of Group I Scenarios.

Scenario	$\overline{\overline{TH}}$ (lots)	$\bar{V}_{TH}$ (lots^2)	$\overline{\overline{CT}}$ (minutes)	$\bar{V}_{CT}$ (minutes^2)	$\overline{\overline{WIP}}$ (lots)	$\bar{V}_{WIP}$ (lot^2)
Push Batch	19	80.94	4,388	2,615,000	56.8	489.4
Push Lot	19	46.55	3,792	2,426,000	50.0	416.2
CONWIP	19.02	42.09	3,333	490,281	43.50	0.25
ICONWIP	19.01	36.41	3,292	522,292	42.89	4.65

Comparing Push Batch and Push Lot, although both scenarios attained a $\overline{\overline{TH}}$ of 19 lots per day; for all the other measures of Push Lot are better than Push Batch as follows:

- $\bar{V}_{TH}$ is reduced from 80.94 to 46.55 lots^2, which is almost a 42% improvement. This reduction results in more consistency of production, which makes better confidence that demand is met, that leads to more customer satisfaction.

- $\overline{\overline{CT}}$ is decreased from 4,388 to 3,792 minutes per lot, gaining 14% better performance, and $\bar{V}_{CT}$ reduced from 2,615,000 to 2,426,000 minutes^2, giving 7% improvement.

- $\overline{\overline{WIP}}$ decreased from 56.8 to 50 lots and $\bar{V}_{WIP}$ dropped from 489.4 to 416.2 lots^2, resulting in 12% and 15% better performance.

Then, applying CONWIP improved the performance of the Segment when compared to Push Lot, although both scenarios achieved the target TH; however, all the other measures at CONWIP are better than at Push Lot as follows:

- $\bar{V}_{TH}$ is reduced from 46.55 to 42.09 lots^2, which is almost a 10 % improvement.

- $\overline{\overline{CT}}$ is decreased from 3,792 to 3,333 minutes per lot, gaining 12% better performance, and $\bar{V}_{CT}$ reduced from 2,615,000 to 490,281 minutes^2, and 80% improvement is achieved.

- $\overline{\overline{WIP}}$ decreased from 50 to 43.50 lots and $\bar{V}_{WIP}$ dropped from 416.2 to 0.25 lots^2, resulting in 13% and 99.99% better performance.

Finally, comparing ICONWIP and CONWIP, it is shown in Table 7-16 that $\overline{\overline{TH}}$ is the same at both scenarios, with less $\bar{V}_{TH}$ at ICONWIP. This decrease in $\bar{V}_{TH}$ gives a great confidence in consistent TH that affects positively meeting demand and results in more customer satisfaction as mentioned earlier. Moreover, ICONWIP results in lower $\overline{\overline{CT}}$ and $\overline{\overline{WIP}}$, resulting in 1.22% and 1.40% improvements in $\overline{\overline{CT}}$ and $\overline{\overline{WIP}}$ respectively, with minimal increase of $\bar{V}_{CT}$ and $\bar{V}_{WIP}$. This is due to the rule of ICONWIP that delays the release of new lots to the Segment after a departure happens. During this delay the WIP level drops below the WIP cap assigned, causing variability in the overall WIP of the Segment that impacts on the variability of CT as well; however, this variability is ensured to be lower than the WIP cap assigned. This results in lower WIP levels at some instances, thus, reduction of CT is achieved at constant TH (Equation 2-1), therefore, ICONWIP is selected to be the best scenario in Group I.

7.15.2 Conclusions of Group II Scenarios

It should be noted that although the purpose of these scenarios is to balance the WIP distribution across the stations; however, the improvement accomplished by CONWIP should at least be sustained or more improvement is achieved, therefore the results of these scenarios are presented in Table 7-17.

Table 7-17: Results of Group II Scenarios.

Scenario	$\overline{\overline{TH}}$ (lots)	$\bar{V}_{TH}$ (lots²)	$\overline{\overline{CT}}$ (minutes)	$\bar{V}_{CT}$ (minutes²)	$\overline{\overline{WIP}}$ (lots)	$\bar{V}_{WIP}$ (lot²)
CONWIP	19.02	42.09	3,333	490,281	43.50	0.25
DBR	19.02	43.20	3,419	543,428	45.75	11.39
CONWIP/DBR	19.01	41.44	3,324	483,866	43.50	0.25
LCONWIP	19.00	43.64	3,322	473,648	43.37	1.01

From the previously mentioned results, it is shown that all the scenarios attained the target TH; however, there are some variations at the rest of all the measures. Comparing CONWIP and DBR, it is shown that DBR has greater $\bar{V}_{TH}$, $\overline{\overline{CT}}$, $\bar{V}_{CT}$, $\overline{\overline{WIP}}$, and $\bar{V}_{WIP}$; therefore, it is ensured that CONWIP is better than DBR.

However combining CONWIP and DBR, results in less $\bar{V}_{TH}, \overline{\overline{CT}}\ and\ \bar{V}_{CT}$ with the same $\overline{\overline{WIP}}\ and\ \bar{V}_{WIP}$ when compared to CONWIP, as a results hybrid CONWIP/DBR is performing better than CONWIP, although it doesn't balance the WIP across all the stations of the Segment as intended (see Figure 7-17).

Investigating LCONWIP and CONWIP results, it is shown that LCONWIP has more $\bar{V}_{TH} and\ \bar{V}_{WIP}$ and less $\overline{\overline{CT}}$, $\bar{V}_{CT} and\ \overline{\overline{WIP}}$ when compared to CONWIP. Resulting in a better performance than CONWIP, as well as balancing the distribution of WIP across all the stations of the Segment (see Figure 7-19).

Considering hybrid CONWIP/DBR and LCONWIP results, it is given that LCONWIP has more $\bar{V}_{TH} and\ \bar{V}_{WIP}$ and less $\overline{\overline{CT}}$, $\bar{V}_{CT} and\ \overline{\overline{WIP}}$ when compared to hybrid CONWIP/DBR. Therefore, LCONWIP is outperforming hybrid CONWIP/DBR, as well as balancing the distribution of WIP across all the stations of the Segment (see Figure 7-19), as a result LCONWIP is considered to be the best scenario in Group II.

Finally, comparing all the scenarios; ICONWIP is selected to be the best scenario in all tested scenarios, if the Segment does not exhibit unbalanced distribution of WIP across the stations and the target is maximum CT and WIP reductions.

8 DISCUSSION

8.1 OVERVIEW

This work studied the effect of applying new lot release control strategies resulting from either combining or modifying lot release control strategies existing in literature. These strategies promises reduced cycle times, which is considered as a key performance criterion in semiconductor wafer fabs, since reduction of cycle time results in lower WIP levels for a given throughput rate [9]. This has motivated further investigations into methods of controlling and management of WIP in production lines in general and in wafer fabs specifically, which started by reviewing literature related to controlling manufacturing control systems. Most popular push and pull control strategies were firstly introduced to show the control mechanisms of each strategy. Stressing the fact that pull systems control WIP levels and push systems control throughput rates [22]; hence, pull strategies are more of interest to this work in terms of WIP management and control. This work was applied to the Minifab model and a representative segment of an existing wafer fabrication facility operating with the latest technologies used in the semiconductor manufacturing.

8.1.1 Findings of Literature

Several lot release control strategies were found in literature and a classification scheme was developed to identify the principal control mechanism applied for each class; namely, single station control, multi-station control, bottleneck station control, and variations and hybrid strategies were the four main classes used. Single station control is basically Kanban, which was one of the first pull strategies applied in production lines; however, Kanban was found to be not applicable to many manufacturing environments and was subject to several ad hoc modifications to improve its performance [25-31]. To that end CONWIP (multi-station control) was proposed as an alternative pull strategy to Kanban [26] and since that time, CONWIP is still regarded as one of the most popular pull strategies [34]. Again, this has led to more focus on reviewing the research work that studied

CONWIP specifically that concentrated on the applicability of CONWIP in different manufacturing environments, determining the optimum WIP level, and comparison of CONWIP to other manufacturing control systems.

CONWIP system for controlling a production line might be unsuitable in some manufacturing environments. That's essentially because CONWIP controls a production line using a single loop and doesn't control WIP distribution across the stations of the system, which leads to WIP build-up at bottleneck or critical stations. Therefore, modifications to CONWIP by combining it with other lot release strategies were recommended to overcome the unbalanced WIP distribution issue. Also, DBR as bottleneck station control strategy was suggested to solve that uneven distribution of WIP that can outperform CONWIP [34]; however this depends on the location of the bottleneck and whether the bottleneck is shifting or not [67]. In addition, CONWIP was compared to Push and applied to a simple production line under different variability of arrivals. Results showed that when high variability in arrivals exists, CONWIP is better than Push; however, Push can perform better than CONWIP when lots are released on a constant interval. In other words, CONWIP is better than Push given that arrivals are of high variability; Push can be better than CONWIP if lots are released deterministically [64].

Unbalanced WIP distribution was evident when applying CONWIP to the Segment. For that, DBR was first tested to improve the distribution of WIP and reduce the unbalancing effect induced by CONWIP. Then, a combination of CONWIP and DBR was tested to combine the advantages of both strategies. Finally, the developed LCOMWIP strategy was applied to balance the distribution of WIP across the stations of the Segment by adding WIP caps to control WIP levels at bottleneck or critical stations.

To determine the optimum WIP level in CONWIP, researchers selected different performance measures to either minimize cycle time or to maximise throughput rate. However, both measures are conflicting in nature; meaning, if cycle time is sought to be minimized, WIP levels will drop leading to loses in throughput rate; on the other hand, if the goal is to maximise the throughput rate, WIP level will increase leading to longer cycle times. Again, since this work is focusing on controlling and managing WIP levels in wafer fabs; accordingly, the single objective that was selected in this work was minimisation of WIP levels to achieve the same rate of throughput and preventing utilisation of bottleneck station to exceed a given threshold. At the same time, when achieving same throughput with lower WIP levels leads to reduction in cycle time, which matches previous research work that reduces cycle time by controlling WIP levels at same throughput rate [70].

8.1.2 Work Motivation

In this work two limitations of CONWIP were addressed, the first was related to the variability of Lot Arrivals to a system applying CONWIP. Since, the arrival of lots to a system depends on the departure of lots from the system; thus, highly variable inter-departure times will result in highly variable inter-arrival times as well. Consequently, highly variable inter-arrival times will induce variability throughout the production line, which degrades the performance of the line in terms of cycle times and WIP levels of the production line (as was discussed in details in Section 4.7). To overcome this drawback ICONWIP lot release control strategy was proposed that regulates the arrival of lots to the system and reduces the variability associated with it.

The second drawback was relevant to the distribution of WIP across the stations of a system. Queues in front of stations can repeatedly build-up at stations with low production rates (bottlenecks) or stations with repetitive failures. As a result, DBR lot release control strategy was applied to control the WIP forming at bottlenecks; moreover, a hybrid CONWIP/DBR lot release control strategy was tested also to combine the advantages of both CONWIP and DBR. Finally, to control the distribution of WIP over stations where queues were likely to accumulate (referred to as critical stations in this work), LCONWIP lot release control strategy was developed to reduce individual WIP levels at critical stations and improve the performance of the system.

8.1.3 Analysis Approach

It is noticed that since the application environment is highly complex, the only reasonable approach to demonstrating the effectiveness was to use modelling and simulation.

Simulation has been used in most of the literature reviewed to analyse complex production systems that are too complicated to tackle via analytic methods. However, conducting a successful simulation study is not quite a simple task. Simulation relies on huge amount of data that to be defined, formatted, and modelled in the right way. Data provided for the Segment was initially a spreadsheet showing the process flow needed to produce a single lot. This spreadsheet was further developed to include all the data presented in (Section 5.1); in addition, selecting the correct distribution for stochastic data can greatly affect the output of simulation; specifically, setting the statistical distribution for time to failure and time to repair was one of the challenges faced in this work. Exponential distributions for MTTF and MTTR were used to represent random failures and repair times affecting all stations in the Segment as it was repeatedly used in literature [48, 110, 113-115]. Then, to set the parameter values for the exponential distribution "Up and Down" times raw data provided by similar machines of semiconductor manufacturing were used (refer to Section 5.1.3 and Appendix B).

There were also several challenges faced when modelling the Segment using ExtendSim™ and although it is a powerful simulation environment; yet, its built-in blocks failed at some instances to accurately model the complexity of the Segment. The most important challenges faced in this work were presented in Section 6.1.

Finally, due to the stochastic nature of most of the input parameters used in the Segment, the simulation output reported exhibited high variability; the thing that necessitated several procedures to be undertaken to control that variability, such as:

- Using a warmup period of 70 days that was determined using the Welch's method.

- Long simulation runtime of 2 years (728 days), which was larger than the warmup period and was determined by the model user.

- The number of replications required for this study was set at 25 replications based on a graphical method that guarantees stability of both the mean throughput per day and mean cycle time.

These parameters, although resulted in higher confidence in values reported for the performance measures; yet, it required almost 100 minutes to execute a single scenario (an average of 4 minutes per replication).

In addition to simulation parameters, selecting the best scenario based on CRN were sought to be the most suitable method for analysing the Segment results and to make sure that there is a significant statistical difference between each pair of scenarios compared.

Finally, several researchers applied optimization using simulation to optimally set the WIP levels in all lot release control strategies [51, 62, 118]; however, due to the computational complexity associated with this approach, simple production lines were used to test their approach. In this work, optimisation using simulation to optimise the parameters of the proposed strategies like CONWIP/DBR, LCONWIP, and ICONWIP was tested. However, due to the excessive variability in the reported measures, long runtimes, and inability to use CRN in ExtendSim™; optimisation using simulation was deemed infeasible.

8.2 DISCUSSION OF CASE STUDIES

This work was applied to simpler models of wafer fabs that were used as a test bed for evaluating existing pull strategies and the developed ones. One of the most popular models used by researchers was the Minifab model, which was used in the early stage of this work, and led to the development of the ICONWIP.

Although the Minifab captures some of the challenges involved in a re-entrant fab; however, it has a limited number of stations, machines and steps. Thus, it was unable to address the limitation of the unbalanced WIP distribution across the stations and consequently, group II scenarios were not tested for the Minifab.

Also, Wein's model was found to be another popular model used by researchers that has larger number of stations including greater number of machines that are exposed to random breakdowns, and greater number of steps that are required to complete a production of a lot, resulting in higher re-entrancy when compared to Minifab; however, it does not include any of the complex batching and sampling processes found in real fabs.

Furthermore, both Minifab and Wein's models were developed during the 1980s and 1990s; therefore, a representative segment of an existing wafer fabrication facility operating with the latest technologies used in the semiconductor manufacturing was developed in collaboration with the ICMR.

Compared to the Minifab, this Segment included greater number of stations and machines with greater number of steps. Also, compared to Wein's model, the Segment addressed the significant challenges involved in operating current highly re-entrant wafer fabs such as high re-entrancy, complex batching processes (RWash and IEtch stations), sampling (TCheck, LAlign, and LDim stations), and stochastic variable breakdowns derived from actual data of similar machines (all the stations).

Table 8-1 compares the main differences between the Minifab and the Segment. It should be noted that due to the highly variable stochastic nature of the Segment when compared to that of the Minifab, the variances of TH, CT and WIP were added to the performance measures under study.

Table 8-1: Comparison of Minifab and Segment.

Point of Comparison	Mini-Fab	Segment
Year of development	1994	2011
Number of Products	2+Test Wafer	Single
Number of stations	3	12
Number of machines	5	33
Number of steps	6	46
Setup	At machine E (station 3)	None

Table 8-1: Comparison of Minifab and Segment.

Point of Comparison	Mini-Fab	Segment
Batching Operations	Batch 3 lots at station 1.	Batch 2 lots of the same step at stations 7 and 10.
Sampling Processes	None	Total count sampling at stations 2 and 4. Total count sampling with initials remain sampling and station 5.
Breakdowns	Preventive maintenance at all machines (deterministic). Unscheduled breakdowns at station 2 (MTTF/MTTR uniformly distributed).	Unscheduled breakdowns at all stations (MTTF/MTTR exponentially distributed).
Soft constraints	None	U should not exceed U_{max}.
Re-entrancy	2 layers per each station	Varies from 2 layers up to 10 layers for a station

8.3 DISCUSSION OF MINI-FAB EXPERIMENTS

The Minifab under study has two variability sources, the first is the inter-arrival times and the second is the unscheduled break downs of machines C and D at station 2 (refer to Section 4.2.3, Table 4-6). When the first source of variability was removed by switching from exponential input to deterministic input at the push model, the overall variability of the model was reduced, resulting in better performance; hence, the same TH was produced with shorter CT and lower WIP level (see Equation 2-1 and Equation 4-2).

Since the variability of the Minifab was minimal in the push-det. model, applying CONWIP induced extra variability component represented in the arrival of lots, which propagates to the other stations downstream (see Equation 4-1). Hence, same TH produced by Push with deterministic input was achieved with longer CT by CONWIP. This is related to the stochastic nature of the model as well as the deterministic input of the Push used in this study. Although, this deterministic nature doesn't exist in real life; yet, it was important to see the effect of removing it on the performance of the Minifab and to prove that reduction of the arrivals variability can actually result in better performance of CT. Therefore, ICONWIP lot release control strategy was developed in accordance to that conclusion and aimed at reducing the variability in arrivals by avoiding the release of new lots immediately after a departure happens as in CONWIP, which in turn reduces the propagation of variability downstream. ICONWIP reduces the variability of arrivals by setting a minimum value for TBA of lots that acts as a floor limiting the minimum TBA from varying greatly as in CONWIP. It starts by checking the arrival time of the last lot released to the line, and if a predetermined time interval has passed, a new lot is released; else, the lot is delayed until the minimum TBA passes. In addition to regulating the arrivals and reducing its variability; whenever a lot is delayed till the minimum TBA passes, WIP level drops below the WIP cap assigned; hence, the line is capable of achieving same TH in shorter CT.

8.4 DISCUSSION OF SEGMENT EXPERIMENTS

The same methodologies applied to the Minifab was tested on the Segment that included greater number of machines, more processing steps and exhibited more complexity and variability. Figure 8-1 summarizes all experiments conducted on the segment under study to evaluate its performance under Push Lot, Push Batch, CONWIP, ICONWIP, DBR, CONWIP/DBR, and LCONWIP. The dashed blocks signifies experiments to compare two strategies; where, the grey shaded block signifies an outperforming strategy. The figure also shows the sequence in which all experimentations on the Segment were carried out.

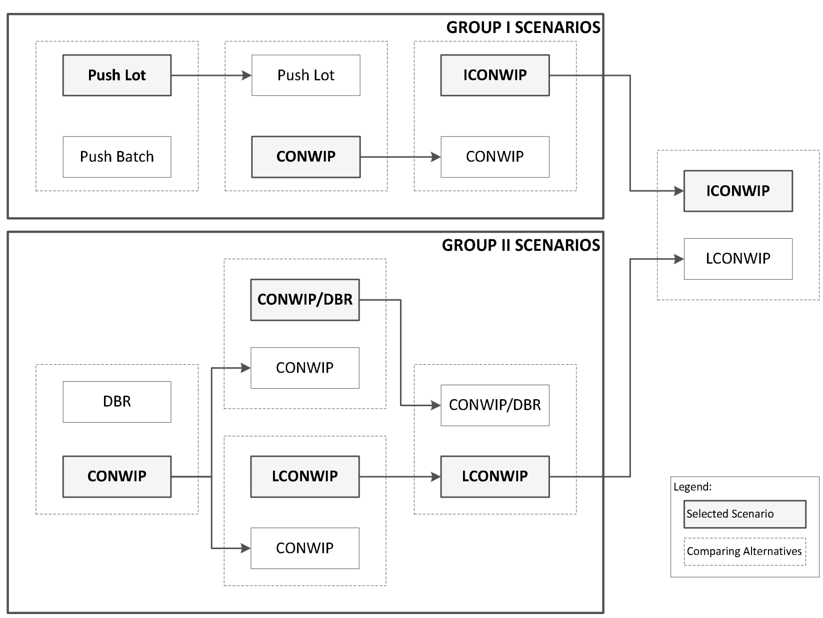

Figure 8-1: Summary of all scenarios tested.

Group I scenarios are the ones applied to the Minifab and were applied to the Segment to confirm the results achieved and to test the applicability of ICONWIP on larger models. Group I scenarios started with testing the effect of applying two Push behaviours, and then evaluating the impact of applying CONWIP application on the Segment was studied. Although CONWIP improved the performance of the Segment as intended; however, two issues were evident when analysing the results.

The first issue was the variability of arrivals to the first station that propagates to all the stations downstream and that was solved by applying the ICONWIP lot release control strategy resulting in a reduced c_a of all the stations (Equation 4-1). Reduced c_a resulted in shorter time in queues (Equation 4-2) and; hence, shorter CT. in addition, delayed introduction of lots resulted in lower WIP levels across the whole segment. This led to an overall improvement of performance; where target TH is attained with shorter CT and lower WIP (Equation 2-1).

The second issue was the unbalancing of WIP across the Segment due to the accumulation of WIP at the critical stations that have long repair times. Unbalanced WIP distribution was evident in the Segment due to its structure being longer and having more machines that exhibits long variable breakdowns. This issue was addressed by Group II scenarios; where, a number of scenarios recommended by literature were initially applied, starting with applying DBR lot release control strategy, then combining DBR and CONWIP in a hybrid lot release control strategy. In addition, applying the developed LCONWIP lot release control strategy sets a loop for every critical station. This loop prevents the release of lots to critical stations by placing an individual WIP caps for those stations that is lower than that of the CONWIP level; hence, the distribution of WIP across the Segment is achieved.

8.4.1 Group I Scenarios

The Segment under study is originally loaded with 19 lots per day; however; splitting these 19 lots across the day, resulted in introducing a single lot every 75.8 minutes that led to a better performance. Although, both models have deterministic inputs of lots; it was shown that Push Lot is performing better than Push Batch as presented in Table 7-16. This is because; with Push Batch, lots are loaded to the Segment at the beginning of the day as a batch that spends too much time waiting at the beginning of the line that varied from no waiting time for the first lot in the batch to maximum waiting time for the last lot in the batch. The accumulated lots at the beginning of the line resulted in more WIP and longer CT; on the other hand, Push Lot every fixed interval of time led to shorter queues at the beginning of the line and this justified why Push Lot outperformed Push Batch.

After that, the impact of applying CONWIP to the Segment was compared to that of applying Push Lot. The results confirmed that CONWIP outperformed Push Lot, as same TH was achieved with lower WIP and CT (see Table 7-16). Investigating the behaviour of lot arrivals under Push Lot and CONWIP showed that Push Lot regulated the arrival of lots to one every 75.8 minutes, which matches the deterministic input. However, at CONWIP there is variability of Lot Arrivals, this is due the fact that a lot is introduced to the Segment as soon as a lot is departed. It should be noted that unlike the results of Minifab, applying CONWIP to the Segment proved to be better than Push. This is due to the variability sources in the Segment that is greater compared to Minifab. Although both models have deterministic input; yet, there was still high variability observed at the Segment due to the variable breakdowns at all stations, sampling at TCheck, LAlign, and LDim stations, and complex batching operations at RWash and IEtch stations.

Next, the impact of applying ICONWIP was compared to CONWIP and results showed that the target TH was achieved for both scenarios; however, with lower variances noted with ICONWIP. This reduction in variance means a more consistent TH levels that affect positively meeting demand and result in more customer satisfaction (refer to Table 7-16). Moreover, ICONWIP resulted in lower averages of CT and WIP, with minimal increase in variances of CT and WIP. This is due to the mechanics of ICONWIP that delays the release of new lots to the Segment after a departure happens. During this delay the WIP level drops below the WIP cap assigned, and lots are produced in a shorter CT when compared to lots produced from the Segment when WIP level reaches the WIP cap. This caused greater variability in WIP and CT of the Segment; however, lowering the WIP and shortening CT often resulted in lower average CT and WIP and at the same time maintained a constant TH level. Finally, Nelson's combined method showed that ICONWIP was the best scenario in Group I scenarios.

8.4.2 Group II Scenarios

Group II scenarios were conducted specifically to address the second issue of WIP distribution across the Segment. First DBR was applied to the Segment and compared to CONWIP; however, it appeared that CONWIP behaved slightly better than DBR. DBR did not manage to balance the distribution of WIP across the stations of the Segment due to the nature of the Segment; where, the last step performed on the bottleneck station is Step 41 out of a total of 46 steps. Hence, most of the line was controlled by a single WIP cap loop as in CONWIP; confirming the outcome of the literature review that DBR performance relies mainly on the position of the bottleneck station.

Then, CONWIP was compared to hybrid CONWIP/DBR, which was again developed in this work as a variant to CONWIP by combining CONWIP and DBR. Results showed that hybrid CONWIP/DBR performed slightly better than CONWIP; however, it didn't balance the distribution of WIP across the Segment. Investigation of results showed that this was due to CONWIP was the dominating control factor of WIP and consequently of the Segment performance.

CONWIP was also compared to LCONWIP again to balance the distribution of WIP across the stations of the Segment. Critical stations were firstly defined and then the WIP levels for each loop controlling these stations were set. The performance of the Segment under LCONWIP was slightly better than CONWIP; also, it improved the distribution of WIP through the stations and resulted in better CT variances. It should be noted that the behaviour of LCONWIP resembles the behaviour of a queuing model with finite queue that limits buffer size in front of stations. This generally results in lower WIP levels, shorter CT; but also reduced TH levels [17]. Thus, improvements in WIP and CT meant sacrificing TH.

Furthermore, the performance of the segment running with LCONWIP was compared to CONWIP/DBR, it was shown that LCONWIP was slightly better than

CONWIP/DBR, and it balanced the distribution of WIP across the stations of the Segment and; hence, was the best scenario in Group II scenarios.

Finally, the best scenario selected from Group I (ICONWIP) was compared to that selected from Group II (LCONWIP) scenarios. Although both scenarios achieved the target TH; however, ICONWIP resulted in lower variances in TH than LCONWIP. This reduction in variances means more consistent TH levels, which increases confidence in meeting demand and leads to higher customer satisfaction (refer to Table 7-17). Also, averages of CT and WIP of ICONWIP are lower than those of LCONWIP; yet, variances of CT and WIP of ICONWIP is more than those of LCONWIP. This is due to the mechanism of ICONWIP as stated in Group I scenario discussion. Compared to LCONWIP, ICONWIP reduced CT by 0.9% and WIP by 1.11%; also, compared to CONWIP, ICONWIP reduced CT by 1.23% and WIP by 1.40%. It should be noted that the slightest improvement percentage in the semiconductor industry means savings of millions of dollars. Also, any improvements in this area of research is desirable as was evident from literature; where, application of Multi-CONWIP in semiconductor assembly lines showed that multi-CONWIP outperformed CONWIP and lowered CT by only 0.4% [70].

To conclude, ICONWIP was selected to be the best scenario in all tested scenarios, this was backed up by the results from Nelson's combined method. Given that the target is reducing the CT and WIP and not balancing the distribution of WIP across the stations of the Segment.

8.5 INDUSTRIAL IMPLICATIONS

LCONWIP should be easier to implement to wafer fabs as they are characterized in reality by the great number of stations and machines and hundreds of processing steps. Thus, monitoring smaller loops within the larger CONWIP loop can be more suitable especially in product mix environments. This was also confirmed by development of different CONWIP variations that addressed the same problem of controlling a large production lines with a single CONWIP loop [34].

On the other hand, ICONWIP implementation relies heavily on the lot arrivals and not on the structure of the production line in terms of location of bottleneck and critical stations as it is essentially a CONWIP strategy that controls the whole line using a single loop; yet, with a modified lot introduction mechanism. For that, ICONWIP can be applied to different manufacturing systems and can still improve the performance of these systems as confirmed by the improvement results obtained from both the Minifab and the Segment. Furthermore, ICONWIP is easier to implement as it does not require instantaneous introduction of lots when a lot leaves the line as in CONWIP and delayed introduction of lots (due to the minimum TBA) can be more suitable to real life wafer fabrication facilities.

9 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This work was undertaken to investigate the management of WIP and evaluate the effect of developing new lot release control strategies resulting from either combining or modifying lot release control strategies existing in literature. These strategies reduced cycle times, which results in lower WIP levels for a given throughput rate, improving the overall performance of wafer fabs.

This chapter reports the most important findings and conclusions of this work accompanied by recommendations and directions for future work.

9.1 CONCLUSIONS

The main conclusions drawn from this work are summarised as follows:

- ICONWIP lot release control strategy was developed; it reduces the variability of arrivals to the first station resulting in a reduced c_a for all the stations. This reduced c_a results in shorter time in queues and; hence, shorter CT for the lots. In addition, it delays the release of a new lot to the Segment after a departure happens, thus dropping the WIP below the WIP cap assigned for a short period of time causing lower average WIP levels. Thus, an overall improvement of performance is achieved; where the target throughput is attained with shorter cycle time and lower WIP level. This strategy had been developed first using the Minifab model and its effectiveness was confirmed on the Segment model.

- Also, the LCONWIP lot release control strategy was developed and applied to the Segment model only. It sets a loop for every critical station which prevents the release of lots to critical stations by placing individual WIP caps for those stations that is lower than that of the overall CONWIP level. LCONWIP improved the distribution of WIP across the Segment, while attaining slightly better CT and WIP to the ones achieved by CONWIP and hybrid CONWIP/DBR. However, ICONWIP was still found to be the best strategy among the different strategies tested in this work, if the Segment does not exhibit unbalanced distribution of WIP across the stations and the target is minimisation of CT and WIP.

- A combination of CONWIP and DBR lot release control strategies was tested resulting in the development of a hybrid CONWIP/DBR strategy that was applied to the Segment model. It performed slightly better than CONWIP; however, it didn't balance the distribution of WIP across the Segment. This was due to the location of the bottleneck station, after which the DBR could be applied, near the end of the Segment. CONWIP was the dominating control factor for WIP at the majority of operations and consequently DBR wasn't effective.

- Development of a new test bed that includes more of the challenges of real fabs that aren't found in the Minifab such as cascaded batching, sampling (with all the realistic constraints that apply to it), stochastic breakdowns and loading of machines up to specific utilisation levels (U_{max}). This enabled confirmation that the results of implementing some strategies that were developed based on the Minifab could be applied to larger systems and also allowed proving the effectiveness of the newly developed strategies. Detailed description of the Segment structural, numerical, and operational data is readily available to other researchers (Section 5.1).

- Preliminary tests applied to the Minifab showed that although it had several features of a real wafer fab it still didn't reflect the variability associated with the operations of a fab and was also limited in terms of number of machines and steps required to produce a lot. This meant that some of the strategies that were under study in this work were not applicable to the Minifab.

- Assessing the effect of applying different push strategies on the performance of the Minifab and the Segment. In the Minifab, switching from exponential input to deterministic input for Push models reduced the lot arrival variability, which consequently reduced the variability of arrivals to the other stations downstream. Furthermore, in the Segment, splitting a batch of lots and introducing a single lot every constant time interval resulted in reduced amount of variability in arrivals, which again led to a better performance of the Segment confirming the importance of reducing the arrivals' variability.

9.2 RECOMMENDATIONS FOR FUTURE WORK

It is recommended that further research be undertaken in the following areas:

- Selecting other industries that exhibit the re-entrant nature of semiconductor manufacturing such as dying process in textile industry and plating process in mirror manufacturing; and testing the impact of applying the developed lot release control strategies on them.
- Further modifying the ICONWIP to include a maximum, in addition to the minimum, time between arrivals. This might be able to further control the arrival variability.
- Applying effective optimisation techniques that would be able to determine the parameter values of the developed strategies that would further improve the WIP levels.

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[118] I. A. El-Khouly, "Multi-Objective Optimization Using Simulation for Scheduling Re-Entrant Flow Shop in Semiconductor Wafer Fabrication Facilities," Master of Science in Industrial and Management Engineering, Department of Industrial and Management Engineering, Arab Academy for Science, Technology and Maritime Transport (AASTMT), 2009.

Appendix A

A PUBLICATIONS RELATED TO THIS WORK

This Appendix lists the publications related to the topics discussed. The list is in sequential order with the most recent first.

I. A. El-Khouly, K. S. El-Kilany, and P.Young, "A Simulation Study of Lot Flow Control in Wafer Fabrication Facilities," International Conference on Industrial Engineering and Operations Management, 2012, pp. 2240-2249.

I. A. El-Khouly, K. S. El-Kilany, P.Young, and J. Geraghty, "A Comparison of Two Different Approaches to Multi-Criteria Optimisation of Semiconductor Fabrication," Industrial Simulation Conference, 2011, pp. 144-149.

I. A. El-Khouly, K. S. El-Kilany, and A. E. El-Sayed, "Effective Scheduling of Semiconductor Manufacturing using Simulation," World Academy of Science, Engineering and Technology, 2011, pp. 311-316.

I. A. El-Khouly, "Multi-Objective Optimization Using Simulation for Scheduling Re-Entrant Flow Shop in Semiconductor Wafer Fabrication Facilities," Master of Science in Industrial and Management Engineering, Department of Industrial and Management Engineering, Arab Academy for Science, Technology, and Maritime Transport (AASTMT), 2009.

I. A. El-Khouly, K. S. El-Kilany, and A. E. El-Sayed, "Modelling and Simulation of Re-Entrant Flow Shop Scheduling: An Application in Semiconductor Manufacturing," International Conference on Computers and Industrial Engineering, 2009, pp. 211-216.

Appendix B

B GENERATED BREAKDOWNS

This Appendix provides the "Up and Down" times raw data provided by similar machines of semiconductor manufacturing to establish the MTTF and MTTR of the Segment under study.

As mentioned in the thesis earlier, that the availability exhibited by the real machines is not used at the Segment, rather than Mean Time Between Failures (MTBF) is used to establish the mean frequency of the "failure-repair" cycle for the machine. The following steps show in details how the MTBF for every station is calculated.

B.1 MDEP, IDEP, AND VDEP STATIONS

This section presents raw data of time to failure and time to repair (TTF and TTR) in hours to machines similar to those found in MDep, IDep, and VDep stations. To calculate the MTBF of these data, the time between failures (TBF) are computed by adding TTF and TTR for every breakdown as shown in Table B-1. Then the computed values are averaged to get the MTBF used in the calculations presented in the thesis previously.

Table B-1: Calculating MTBF for MDep, IDep, and VDep stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1	24.79	14.72	39.52
2	92.14	0.96	93.10
3	42.91	3.68	46.58
4	74.23	0.85	75.09
5	70.73	0.24	70.97
6	35.40	14.66	50.06
7	68.82	10.88	79.69
8	48.09	6.42	54.50
9	30.70	15.36	46.06
10	22.43	3.38	25.80
11	68.25	4.28	72.53
12	87.74	3.34	91.08
13	21.85	31.54	53.39

Table B-1: Calculating MTBF for MDep, IDep, and VDep stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
14	149.48	1.16	150.63
15	78.53	1.61	80.14
16	72.91	0.14	73.05
17	40.58	7.77	48.35
18	24.87	7.90	32.77
19	81.16	0.03	81.19
20	191.82	0.63	192.44
21	25.27	0.02	25.29
22	132.46	17.45	149.91
23	1.39	0.04	1.43
24	4.13	0.03	4.17
25	0.25	0.08	0.33
26	3.46	1.21	4.67
27	1.55	0.13	1.68
28	2.50	0.13	2.62
29	50.24	9.81	60.05
30	71.98	0.04	72.02
31	75.66	4.49	80.15
32	66.00	8.52	74.52
33	74.15	5.93	80.09
34	73.01	7.71	80.72
35	56.05	10.35	66.40
36	63.15	9.18	72.33
37	6.24	0.24	6.48
38	18.37	0.00	18.38
39	3.71	0.05	3.76
40	36.93	0.09	37.02
41	3.19	0.14	3.33
42	2.03	1.06	3.09
43	24.95	17.69	42.64
44	51.66	0.22	51.88
45	3.47	0.07	3.55
46	68.27	10.92	79.20
47	138.26	2.70	140.97
48	75.69	3.29	78.98
49	34.17	4.18	38.35
50	30.04	13.20	43.24
51	151.56	3.36	154.92
52	65.98	0.01	65.99
53	144.38	2.20	146.58
54	159.06	2.88	161.94
55	135.69	1.37	137.06
56	101.65	3.52	105.16
57	41.03	2.34	43.38
58	43.72	9.78	53.50

Table B-1: Calculating MTBF for MDep, IDep, and VDep stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
59	96.92	0.02	96.94
60	0.15	0.02	0.16
61	26.41	1.86	28.27
62	48.95	0.31	49.26
63	61.25	0.19	61.44
64	77.60	0.03	77.63
65	113.84	4.59	118.43
66	6.14	33.84	39.98
67	87.07	2.03	89.09
68	81.23	1.24	82.47
69	10.99	5.87	16.86
70	16.69	1.32	18.01
71	100.48	0.01	100.49
72	116.47	2.39	118.86
73	54.67	10.00	64.66
74	20.88	1.55	22.43
75	243.87	5.61	249.48
76	14.83	44.25	59.07
77	150.76	5.44	156.20
78	185.10	12.92	198.02
79	171.51	1.27	172.78
80	162.56	38.66	201.22
81	309.08	0.91	309.99
82	108.29	7.55	115.84
83	339.08	25.45	364.52
84	46.02	0.40	46.42
85	50.08	0.00	50.08
86	52.63	4.07	56.70
87	118.68	1.11	119.79
88	5.83	0.04	5.87
89	67.74	8.85	76.60
90	167.52	1.27	168.78
91	50.81	4.18	54.99
92	30.14	98.45	128.58
93	61.22	48.91	110.13
94	72.68	0.91	73.59
95	91.34	7.44	98.78
96	89.91	2.74	92.66
97	19.72	0.58	20.29
98	18.55	9.90	28.45
99	62.10	4.13	66.23
100	103.87	16.57	120.44
101	31.44	4.75	36.19
102	100.56	0.93	101.50
103	51.00	1.42	52.42

Table B-1: Calculating MTBF for MDep, IDep, and VDep stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
104	21.33	0.16	21.49
105	4.79	8.43	13.22
106	46.62	0.81	47.42
107	199.27	11.01	210.29
108	49.51	8.51	58.02
109	42.92	0.12	43.04
110	191.85	0.38	192.23
111	90.85	6.74	97.59
112	10.03	4.52	14.55
113	12.36	0.04	12.40
114	46.58	30.56	77.14
115	52.61	1.01	53.61
116	46.79	0.34	47.13
117	126.86	2.37	129.23
118	7.47	6.87	14.34
119	19.00	2.82	21.82
120	359.49	8.98	368.47
121	203.59	32.20	235.79
122	16.48	1.30	17.78
123	358.18	13.49	371.66
124	97.71	0.16	97.86
125	95.32	0.12	95.44
126	207.13	48.21	255.34
127	4.69	1.30	5.99
128	398.91	0.08	398.99
129	10.82	6.59	17.41
130	52.19	0.00	52.19
131	128.80	0.19	128.98
132	87.25	0.89	88.14
133	41.37	30.44	71.80
134	9.62	0.43	10.05
135	3.79	0.01	3.81
136	175.77	4.18	179.94
137	159.03	0.01	159.05
138	116.68	11.65	128.33
139	95.47	18.42	113.90
140	285.15	3.02	288.17
141	43.75	0.26	44.00
142	0.79	0.02	0.80
143	8.58	17.14	25.72
144	116.03	4.00	120.03
145	193.77	27.90	221.67
146	1.52	0.04	1.57
147	4.10	0.01	4.11
148	276.59	10.17	286.76

Table B-1: Calculating MTBF for MDep, IDep, and VDep stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
149	134.19	0.32	134.51
150	2.16	0.31	2.46
151	109.87	4.07	113.94
152	46.90	0.97	47.87
153	47.53	0.33	47.87
154	29.29	0.09	29.38
155	19.17	8.93	28.10
156	23.56	6.13	29.69
157	28.62	0.66	29.29
158	44.36	28.36	72.72
159	103.14	10.91	114.04
160	178.88	0.02	178.90
161	50.08	8.65	58.72
162	288.71	0.16	288.87
163	14.29	18.96	33.25
164	13.13	0.00	13.14
165	9.14	0.01	9.15
166	12.36	3.47	15.83
167	99.35	1.47	100.81
168	29.43	0.15	29.58
169	19.87	1.01	20.88
170	53.24	42.73	95.97
171	315.68	3.34	319.02
172	153.02	14.07	167.10
173	53.69	4.03	57.73
174	98.22	1.28	99.50
175	49.52	1.32	50.84
176	23.68	11.33	35.01
177	37.39	0.00	37.39
178	0.33	0.02	0.35
179	147.06	0.41	147.47
180	21.11	33.54	54.65
181	205.08	2.81	207.90
182	52.11	1.44	53.54
183	14.64	4.18	18.82
184	41.71	26.59	68.30
185	11.34	0.01	11.35
186	39.81	0.98	40.79
187	17.54	0.70	18.24
188	143.65	0.96	144.61
189	161.13	23.18	184.31
190	271.25	0.22	271.47
191	96.06	1.38	97.44
192	22.50	1.43	23.94
193	13.78	0.05	13.83

Table B-1: Calculating MTBF for MDep, IDep, and VDep stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
194	13.68	13.99	27.67
195	117.40	0.35	117.75
196	7.77	0.03	7.80
197	2.54	3.47	6.01
198	57.23	12.25	69.47
199	22.87	0.12	22.99
200	157.28	16.52	173.80
201	27.24	2.90	30.15
202	165.40	0.56	165.96
203	44.08	6.48	50.55
204	127.16	7.29	134.45
205	213.98	13.83	227.81
206	120.14	4.02	124.17
207	143.19	25.05	168.24
208	108.44	5.33	113.77
209	95.97	9.85	105.83
210	330.52	11.34	341.86
211	33.95	3.09	37.04
212	211.13	2.16	213.29
213	63.20	5.73	68.92
214	129.29	0.98	130.27
215	49.35	39.20	88.55
216	120.47	7.34	127.82
217	85.63	2.44	88.06
218	211.73	2.71	214.44
219	7.80	5.61	13.40
220	61.61	0.03	61.64
221	197.04	0.50	197.53
222	66.75	9.84	76.59
223	39.68	2.15	41.82
224	46.48	34.93	81.41
225	11.26	2.42	13.68
226	1.76	0.27	2.03
227	33.27	0.55	33.82
228	31.63	4.18	35.81
229	32.20	0.42	32.62
230	81.85	6.38	88.23
231	187.20	6.47	193.68
232	222.99	1.08	224.06
233	34.04	0.01	34.05
234	6.61	1.13	7.75
235	63.75	18.89	82.63
236	195.99	0.55	196.54
237	47.42	12.18	59.59
238	27.62	1.53	29.15

Table B-1: Calculating MTBF for MDep, IDep, and VDep stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
239	148.57	0.66	149.23
240	24.94	8.99	33.93
241	24.88	1.36	26.24
242	121.67	0.11	121.78
243	180.62	23.54	204.16
244	154.50	1.30	155.79
MTBF (hours)			88.09

B.2 TCHECK AND LALIGN STATIONS

This section presents raw data of time to failure and time to repair (TTF and TTR) in hours to machines similar to those found in TCheck and LAlign stations. To calculate the MTBF of these data, the time between failures (TBF) are computed by adding TTF and TTR for every breakdown as shown in Table B-2. Then the computed values are averaged to get the MTBF used in the calculations presented in the thesis previously.

Table B-2: Calculating MTBF for TCheck and LAlign stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1	67.40	3.77	71.17
2	21.86	1.72	23.58
3	10.27	0.02	10.29
4	4.14	39.46	43.60
5	0.44	4.90	5.34
6	167.20	0.27	167.47
7	39.64	1.48	41.12
8	6.45	2.94	9.39
9	33.07	2.64	35.70
10	9.36	5.57	14.93
11	6.43	11.03	17.46
12	0.98	0.34	1.31
13	23.66	3.20	26.86
14	8.80	2.56	11.36
15	9.49	1.75	11.23
16	0.97	16.40	17.37
17	5.18	0.85	6.03
18	22.81	1.78	24.59
19	10.22	4.06	14.27
20	7.94	0.35	8.29
21	10.54	6.27	16.81
22	18.84	29.67	48.52

Table B-2: Calculating MTBF for TCheck and LAlign stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
23	6.32	2.36	8.68
24	9.64	11.35	20.99
25	96.65	4.22	100.88
26	13.26	1.26	14.52
27	8.09	28.49	36.57
28	0.92	8.91	9.83
29	102.86	1.65	104.50
30	10.35	36.69	47.04
31	17.95	12.66	30.61
32	4.70	86.49	91.19
33	9.51	3.85	13.35
34	8.16	14.24	22.39
35	9.76	0.09	9.85
36	11.91	25.30	37.21
37	10.70	51.37	62.07
38	32.63	0.48	33.11
39	57.24	0.18	57.43
40	98.09	7.71	105.80
41	4.29	10.28	14.57
42	13.72	7.97	21.69
43	124.03	13.87	137.89
44	10.13	71.09	81.22
45	12.91	8.61	21.52
46	51.39	15.17	66.56
47	8.83	10.73	19.56
48	13.27	24.47	37.73
49	23.54	1.18	24.72
50	75.79	0.01	75.80
51	12.00	52.25	64.25
52	110.77	11.01	121.78
53	12.99	2.43	15.42
54	21.58	0.63	22.21
55	11.36	9.20	20.56
56	86.80	4.87	91.68
57	7.12	13.15	20.27
58	10.85	16.11	26.96
59	31.89	0.37	32.26
60	11.63	6.88	18.51
61	5.11	2.27	7.39
62	9.73	2.80	12.52
63	9.20	5.22	14.42
64	6.78	2.68	9.46
65	33.32	19.28	52.60
66	4.72	0.54	5.26
67	11.47	6.52	17.99

Table B-2: Calculating MTBF for TCheck and LAlign stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
68	5.48	0.59	6.07
69	35.41	5.40	40.81
70	90.60	4.07	94.67
71	7.93	16.85	24.78
72	13.09	0.02	13.11
73	18.04	3.00	21.04
74	9.00	0.38	9.38
75	95.62	0.39	96.01
76	11.61	9.51	21.12
77	2.49	16.72	19.21
78	19.28	2.03	21.31
79	129.97	5.77	135.74
80	6.23	3.90	10.13
81	1.03	14.08	15.11
82	4.99	0.20	5.19
83	11.80	2.36	14.16
84	9.64	4.13	13.77
85	31.87	0.88	32.74
86	11.13	4.01	15.13
87	85.46	1.87	87.33
88	4.66	0.52	5.18
89	83.39	2.36	85.75
90	9.73	4.32	14.04
91	7.69	1.19	8.88
92	10.81	2.62	13.42
93	9.39	11.90	21.29
94	7.37	11.79	19.17
95	34.04	0.08	34.12
96	6.81	2.98	9.80
97	33.02	0.45	33.47
98	11.55	4.22	15.77
99	43.62	2.36	45.99
100	93.79	0.68	94.48
101	23.31	2.37	25.69
102	9.63	0.79	10.42
103	23.21	2.02	25.23
104	3.41	1.46	4.87
105	6.73	0.02	6.75
106	10.35	0.32	10.68
107	11.68	10.46	22.14
108	1.54	13.93	15.47
109	10.08	2.15	12.23
110	153.85	1.98	155.82
111	10.03	0.05	10.07
112	59.95	4.94	64.89

Table B-2: Calculating MTBF for TCheck and LAlign stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
113	45.22	0.02	45.24
114	117.81	0.71	118.52
115	86.19	6.17	92.36
116	1.46	3.78	5.24
117	81.70	4.38	86.07
118	43.62	4.31	47.94
119	7.68	7.22	14.90
120	4.78	2.50	7.28
121	25.29	1.05	26.33
122	27.47	5.59	33.06
123	30.39	0.51	30.90
124	11.49	8.46	19.94
125	111.54	2.82	114.36
126	9.18	6.23	15.41
127	126.87	0.45	127.32
128	10.47	0.42	10.89
129	11.56	0.38	11.94
130	307.16	3.10	310.26
131	37.37	32.62	69.98
132	15.38	0.36	15.73
133	11.65	3.09	14.74
134	20.91	2.62	23.53
135	69.38	1.88	71.26
136	46.13	5.28	51.41
137	18.71	7.01	25.72
138	16.99	5.30	22.29
139	18.70	19.75	38.45
140	16.27	8.80	25.07
141	3.20	1.90	5.10
142	10.08	7.24	17.32
143	4.76	2.44	7.20
144	282.67	2.96	285.64
145	23.93	14.16	38.08
146	9.84	0.90	10.75
147	11.10	10.90	22.00
148	1.11	43.07	44.18
149	4.95	16.06	21.01
150	199.93	0.53	200.46
151	11.45	2.69	14.13
152	5.02	1.24	6.26
153	15.07	1.72	16.78
154	94.28	1.75	96.03
155	118.26	0.08	118.34
156	11.92	1.59	13.51
157	10.39	37.32	47.71

Table B-2: Calculating MTBF for TCheck and LAlign stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
158	18.23	1.06	19.29
159	0.51	7.03	7.54
160	55.87	0.06	55.93
161	191.94	12.20	204.14
162	11.80	0.44	12.24
163	35.58	4.16	39.74
164	60.07	0.02	60.08
165	19.72	9.25	28.98
166	14.75	8.80	23.55
167	15.20	23.07	38.27
168	12.95	4.05	17.00
169	79.93	1.87	81.80
170	10.13	4.04	14.17
171	7.96	1.78	9.74
172	10.23	17.66	27.89
173	66.34	36.03	102.37
174	47.96	12.96	60.92
175	11.04	11.49	22.53
176	183.83	0.03	183.86
177	38.45	0.05	38.50
178	6.16	2.25	8.41
179	9.77	3.98	13.75
180	8.00	0.60	8.60
181	23.41	1.61	25.02
182	38.24	14.09	52.32
183	20.74	15.93	36.67
184	29.38	24.17	53.56
185	11.83	36.14	47.97
186	19.28	42.76	62.04
187	0.22	40.72	40.94
188	4.88	19.56	24.45
189	4.44	12.55	16.99
190	11.45	7.67	19.11
191	28.34	26.03	54.37
192	9.96	12.53	22.49
193	59.47	39.92	99.39
194	8.08	2.40	10.48
195	9.59	32.18	41.77
196	3.83	32.27	36.10
197	39.73	2.71	42.44
198	9.29	2.39	11.68
199	117.61	112.68	230.29
200	75.33	0.29	75.62
201	15.70	0.30	16.01
202	11.73	0.78	12.51

Table B-2: Calculating MTBF for TCheck and LAlign stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
203	23.19	63.79	86.97
204	15.18	94.68	109.85
205	55.42	0.85	56.28
206	6.15	2.52	8.67
207	33.72	0.01	33.73
208	1.56	0.32	1.88
209	67.57	0.14	67.71
210	262.57	0.93	263.50
211	4.48	0.70	5.18
212	11.28	1.44	12.73
213	79.93	0.01	79.94
214	287.61	0.18	287.79
215	110.84	0.77	111.61
216	228.16	0.06	228.22
217	1.19	0.05	1.24
218	105.76	0.76	106.52
219	11.24	2.28	13.52
220	9.73	7.83	17.56
221	4.16	0.09	4.25
222	168.49	0.13	168.62
223	11.28	1.54	12.82
224	10.47	0.20	10.67
225	263.79	0.07	263.86
226	72.77	0.30	73.07
227	106.86	0.92	107.78
228	11.07	1.38	12.44
229	10.64	1.50	12.13
230	203.12	0.24	203.36
231	11.14	0.38	11.52
232	11.61	0.28	11.89
233	283.49	1.00	284.49
234	19.19	0.01	19.20
235	176.05	4.93	180.98
236	19.05	0.07	19.12
237	97.21	0.01	97.22
238	10.71	0.51	11.22
239	31.08	0.62	31.70
240	111.80	0.34	112.13
241	11.66	0.33	11.99
242	11.68	1.11	12.79
243	22.88	1.30	24.19
244	118.71	0.78	119.48
245	323.21	2.15	325.36
246	63.05	0.01	63.07
247	51.43	2.67	54.11

Table B-2: Calculating MTBF for TCheck and LAlign stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
248	24.68	0.14	24.82
249	23.86	0.96	24.83
250	186.82	0.65	187.47
251	39.56	7.31	46.88
252	16.69	1.65	18.34
253	10.35	0.51	10.86
254	251.49	2.86	254.35
255	9.16	1.71	10.86
256	34.28	0.99	35.26
257	2.99	0.02	3.01
MTBF (hours)			50.08

B.3 LPAT, METCH, AND IETCH STATIONS

This section presents raw data of time to failure and time to repair (TTF and TTR) in hours to machines similar to those found in LPat, MEtch, and IEtch stations. To calculate the MTBF of these data, the time between failures (TBF) are computed by adding TTF and TTR for every breakdown as shown in Table B-3. Then the computed values are averaged to get the MTBF used in the calculations presented in the thesis previously.

Table B-3: Calculating MTBF for LPat, MEtch, and IEtch stations.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1	48.95	12.87	61.82
2	97.79	0.03	97.82
3	0.03	15.52	15.55
4	177.11	29.42	206.53
5	183.30	21.87	205.17
6	101.58	1.00	102.57
7	14.80	12.82	27.62
8	60.03	14.01	74.04
9	86.74	0.01	86.75
10	192.00	1.85	193.85
11	120.26	14.55	134.82
12	73.31	8.55	81.86
13	70.62	28.50	99.13
14	1.95	1.30	3.26
15	1.44	8.56	10.00
16	28.74	20.69	49.42
17	310.70	23.22	333.93
18	105.38	0.01	105.39

19	71.71	1.22	72.93
20	90.76	25.47	116.23
21	78.70	1.57	80.27
22	2.73	2.59	5.32
23	4.03	37.22	41.25
24	10.47	0.43	10.90
25	8.03	0.03	8.06
26	54.36	15.27	69.64
27	53.78	84.32	138.10
28	16.56	21.60	38.16
29	159.85	1.96	161.81
30	80.09	0.00	80.09
31	3.97	0.03	3.99
32	21.93	4.31	26.23
33	7.34	43.50	50.84
34	17.12	2.38	19.51
35	80.33	0.01	80.34
36	13.37	2.85	16.22
37	11.33	0.92	12.25
38	0.65	3.15	3.80
39	32.11	24.96	57.07
40	21.04	2.60	23.64
41	31.87	4.29	36.15
42	34.21	0.09	34.30
43	99.07	15.58	114.64
44	38.82	1.39	40.21
45	34.86	0.64	35.50
46	27.30	0.01	27.31
47	37.93	0.03	37.96
48	0.03	9.05	9.08
49	146.65	49.35	196.00
50	95.15	9.43	104.58
51	195.03	11.70	206.73
52	231.33	17.81	249.14
53	211.36	0.19	211.55
54	3.15	33.45	36.60
55	19.04	2.53	21.56
56	104.36	17.68	122.05
57	138.59	16.89	155.48
58	15.56	13.24	28.80
59	96.97	1.32	98.29
60	262.98	0.05	263.03
61	11.41	5.16	16.57
62	147.31	8.83	156.14
63	16.95	6.28	23.23
64	11.76	34.64	46.40
65	1.68	0.86	2.54
66	143.94	0.01	143.94
67	2.67	0.01	2.67

68	99.60	25.61	125.21
69	151.18	9.17	160.35
70	25.75	4.37	30.12
71	101.33	2.17	103.50
72	6.26	23.46	29.72
73	110.57	1.62	112.20
74	16.94	0.00	16.95
75	1.79	0.01	1.79
76	203.33	14.54	217.86
77	143.74	1.28	145.02
78	133.37	0.57	133.94
79	6.01	17.17	23.18
80	256.78	8.51	265.29
81	14.30	1.71	16.01
82	3.12	0.00	3.13
83	12.89	3.52	16.41
84	95.40	0.54	95.94
85	160.86	4.32	165.18
86	49.93	14.95	64.88
87	101.09	0.88	101.97
88	31.73	0.40	32.13
89	6.72	0.11	6.83
90	26.46	2.29	28.75
91	10.77	1.44	12.21
92	141.24	0.94	142.18
93	122.29	0.20	122.49
94	6.07	15.13	21.20
95	77.02	12.94	89.96
96	285.88	7.91	293.78
97	185.72	13.10	198.82
98	310.35	1.23	311.57
99	8.28	11.16	19.44
100	58.67	10.56	69.23
101	201.20	0.29	201.50
102	66.14	0.19	66.33
103	38.78	5.73	44.51
104	7.71	14.65	22.36
105	157.40	14.79	172.19
106	84.10	0.57	84.68
107	24.97	0.97	25.94
108	170.35	0.25	170.60
109	26.64	0.93	27.57
110	13.11	0.05	13.16
111	2.18	0.07	2.25
112	10.96	4.93	15.90
113	92.91	0.02	92.93
114	20.32	0.88	21.20
115	14.04	0.36	14.40
116	7.30	5.32	12.62

117	161.46	0.71	162.17
118	18.35	1.80	20.16
119	233.17	28.53	261.71
120	62.10	0.25	62.35
121	27.78	0.10	27.88
122	29.22	1.47	30.69
123	4.61	0.02	4.63
124	179.05	11.56	190.61
125	131.89	1.09	132.98
126	119.71	36.31	156.02
127	152.92	0.69	153.61
128	45.91	0.01	45.92
129	91.02	3.61	94.64
130	133.18	23.87	157.05
131	83.10	0.53	83.62
132	76.67	4.58	81.25
133	129.84	2.50	132.34
134	87.79	1.25	89.05
135	21.34	37.03	58.37
136	129.62	0.33	129.94
137	13.65	6.20	19.86
138	69.99	7.22	77.21
139	15.87	2.58	18.46
140	69.28	1.50	70.78
141	65.73	25.85	91.58
142	143.26	32.73	176.00
143	147.03	5.91	152.94
144	12.70	0.01	12.71
145	1.57	0.03	1.60
146	14.73	44.62	59.36
147	111.70	0.16	111.85
148	1.35	11.39	12.74
149	166.24	2.26	168.49
150	48.50	2.88	51.38
151	37.72	0.85	38.57
152	8.92	0.57	9.49
153	58.23	25.64	83.87
154	138.31	1.88	140.18
155	101.84	10.23	112.07
156	46.73	11.30	58.03
157	84.68	4.22	88.90
158	179.17	10.01	189.18
159	37.66	25.38	63.04
160	90.88	0.94	91.82
161	62.44	15.32	77.76
162	35.74	16.01	51.75
163	118.98	0.36	119.34
164	78.99	9.70	88.69
165	179.22	0.85	180.07

166	88.22	8.04	96.26
167	77.75	0.47	78.22
168	43.19	15.23	58.43
169	204.41	20.27	224.68
170	88.90	1.90	90.80
171	130.58	0.06	130.64
172	8.55	2.61	11.16
173	128.85	0.02	128.88
174	32.67	16.20	48.86
175	85.79	12.37	98.16
176	166.85	14.12	180.96
177	169.94	1.32	171.27
178	24.90	4.35	29.25
179	3.81	16.96	20.77
180	11.32	4.36	15.67
181	69.84	0.61	70.46
182	8.58	3.65	12.23
183	84.05	2.83	86.87
184	12.62	0.69	13.31
185	2.69	8.17	10.86
186	9.10	12.81	21.91
187	19.27	0.29	19.56
188	7.12	0.35	7.47
189	4.26	0.73	5.00
190	33.08	8.84	41.92
191	10.91	6.57	17.48
192	0.01	47.98	47.99
193	33.77	0.04	33.81
194	110.66	7.24	117.90
195	10.71	3.78	14.50
196	24.78	41.05	65.83
197	92.14	0.53	92.66
198	39.07	1.29	40.36
199	70.05	14.59	84.64
200	66.32	0.00	66.33
201	2.31	0.01	2.32
202	105.03	14.14	119.18
203	181.57	10.74	192.31
204	42.18	10.08	52.25
205	8.36	37.63	45.99
206	158.30	22.74	181.03
207	109.01	15.73	124.74
208	286.87	1.08	287.95
209	65.31	59.33	124.64
210	240.27	8.72	248.99
211	96.64	0.01	96.64
212	24.78	0.02	24.80
213	4.10	0.01	4.11
214	65.25	16.43	81.68

215	306.23	10.22	316.45
216	272.89	0.01	272.90
217	44.46	21.63	66.09
218	179.38	0.87	180.25
219	103.53	2.96	106.48
220	9.34	0.18	9.53
221	14.35	1.40	15.75
222	226.95	0.06	227.02
223	4.92	8.15	13.06
224	67.54	15.34	82.87
225	153.16	17.22	170.37
226	150.47	2.65	153.12
227	18.38	5.97	24.35
228	12.67	16.92	29.59
229	25.14	21.59	46.72
230	29.64	4.34	33.99
231	142.99	0.13	143.12
232	4.49	6.90	11.39
233	13.12	0.89	14.01
234	118.99	5.30	124.29
235	18.88	11.94	30.83
236	63.93	1.35	65.29
237	14.36	0.94	15.30
238	73.29	17.09	90.37
239	4.90	7.25	12.14
240	191.64	11.36	203.00
241	127.25	0.02	127.27
242	4.45	0.01	4.46
243	20.34	0.18	20.52
244	1.43	14.17	15.60
245	53.24	12.21	65.46
246	2.54	1.29	3.83
247	91.73	1.10	92.83
248	80.10	11.48	91.58
249	162.37	19.11	181.49
250	89.48	8.50	97.99
251	167.99	13.30	181.29
MTBF (hours)			84.73

B.4 LDIM STATION

This section presents raw data of time to failure and time to repair (TTF and TTR) in hours to machines similar to those found in LDim station. To calculate the MTBF of these data, the time between failures (TBF) are computed by adding TTF and TTR for every breakdown as shown in Table B-4. Then the computed values are averaged to get the MTBF used in the calculations presented in the thesis previously.

Table B-4: Calculating MTBF for LDim station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1	26.91	1.77	28.68
2	82.67	0.48	83.15
3	9.93	5.50	15.43
4	15.31	1.71	17.02
5	47.54	0.54	48.08
6	99.61	0.48	100.10
7	14.53	0.62	15.15
8	52.61	0.45	53.06
9	120.42	0.34	120.76
10	46.40	0.43	46.83
11	169.90	0.81	170.71
12	174.14	0.58	174.72
13	165.80	0.86	166.67
14	167.12	1.23	168.35
15	58.79	2.08	60.87
16	0.20	4.07	4.26
17	94.27	0.73	95.00
18	42.64	0.08	42.72
19	11.92	0.43	12.35
20	11.57	0.09	11.67
21	7.34	1.52	8.86
22	99.07	1.17	100.23
23	4.78	0.41	5.19
24	110.21	0.78	110.99
25	0.57	0.78	1.35
26	46.05	0.49	46.53
27	165.58	0.29	165.87
28	53.08	19.09	72.17
29	73.02	0.39	73.41
30	19.23	1.72	20.95
31	4.35	0.34	4.69
32	14.64	4.51	19.15
33	21.40	31.65	53.05
34	23.33	0.36	23.69
35	50.39	0.09	50.48
36	115.65	1.23	116.88
37	45.50	0.44	45.95
38	192.53	0.55	193.09
39	90.54	2.49	93.02
40	8.61	2.67	11.28
41	61.16	0.44	61.60
42	168.41	0.46	168.87

Table B-4: Calculating MTBF for LDim station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
43	311.14	0.48	311.61
44	53.83	1.51	55.34
45	138.33	0.71	139.04
46	18.64	0.01	18.65
47	125.13	0.36	125.49
48	193.75	0.22	193.97
49	164.57	0.39	164.96
50	332.46	0.43	332.90
51	0.96	1.14	2.10
52	144.58	0.41	144.99
53	55.72	0.58	56.30
54	251.12	0.75	251.87
55	79.05	0.49	79.53
56	164.12	0.51	164.62
57	171.62	0.54	172.16
58	170.80	1.46	172.27
59	3.43	0.91	4.34
60	42.20	1.45	43.65
61	10.55	1.58	12.14
62	10.41	0.37	10.77
63	67.00	1.31	68.31
64	26.85	0.03	26.88
65	161.61	0.60	162.21
66	42.26	6.35	48.61
67	121.80	0.01	121.81
68	333.42	0.36	333.77
69	168.88	0.44	169.31
70	172.75	0.32	173.08
71	163.01	0.43	163.44
72	165.29	0.51	165.80
73	167.36	0.01	167.37
74	56.86	1.82	58.68
75	93.33	0.52	93.85
76	186.04	0.89	186.94
77	92.44	3.10	95.54
78	47.57	0.45	48.02
79	167.55	0.46	168.01
80	28.85	1.52	30.36
81	161.28	0.63	161.91
82	143.74	0.39	144.13
83	20.12	3.20	23.31
84	164.91	0.29	165.20
85	4.15	0.46	4.61
86	166.71	0.43	167.14
87	308.72	0.40	309.12

Table B-4: Calculating MTBF for LDim station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
88	123.50	0.40	123.90
89	166.11	0.60	166.70
90	164.90	0.43	165.33
91	170.97	0.54	171.51
92	3.50	1.36	4.86
93	95.59	0.58	96.17
94	42.74	0.28	43.03
95	100.11	18.58	118.68
96	45.99	0.37	46.37
97	170.98	0.69	171.68
98	158.77	0.53	159.30
99	2.80	3.13	5.92
100	193.17	0.48	193.65
101	167.76	0.45	168.21
102	167.21	0.42	167.63
103	335.15	1.39	336.54
104	3.15	0.02	3.18
105	168.29	1.34	169.64
106	166.67	0.90	167.57
107	161.70	2.99	164.70
108	2.40	1.27	3.67
109	1.60	0.04	1.64
110	112.79	0.26	113.05
111	26.05	1.00	27.05
112	21.30	0.48	21.78
113	166.36	0.29	166.66
114	171.79	0.43	172.22
115	151.43	2.35	153.78
116	7.42	0.83	8.25
117	3.35	0.37	3.72
118	163.57	0.71	164.27
119	174.30	1.38	175.68
120	76.97	6.44	83.41
121	0.42	7.43	7.85
122	75.37	1.26	76.62
123	60.03	6.32	66.35
124	51.56	2.15	53.70
125	81.10	8.56	89.66
126	41.03	0.35	41.38
127	11.65	0.42	12.07
128	11.58	0.27	11.85
129	11.72	0.66	12.38
130	59.34	4.49	63.83
131	51.30	1.36	52.66
132	86.34	5.42	91.76

Table B-4: Calculating MTBF for LDim station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
133	0.69	2.71	3.40
134	3.69	0.06	3.76
135	1.05	0.48	1.54
136	16.24	1.92	18.16
137	120.07	0.56	120.63
138	168.63	0.49	169.12
139	165.27	0.46	165.73
140	168.88	2.10	170.98
141	168.30	0.45	168.74
142	167.31	0.20	167.51
143	160.23	101.74	261.96
144	73.72	0.47	74.19
145	36.34	4.20	40.54
146	119.04	0.18	119.22
147	179.53	11.65	191.18
148	4.73	0.49	5.23
149	108.10	0.44	108.54
150	18.46	120.89	139.35
151	164.41	0.13	164.54
152	71.04	3.83	74.87
153	329.29	0.92	330.21
154	167.41	0.62	168.03
155	40.95	630.03	670.99
156	167.95	0.68	168.63
157	173.96	0.91	174.87
158	89.64	7.08	96.72
159	67.73	0.36	68.08
160	335.23	0.44	335.67
161	166.17	0.35	166.52
MTBF (hours)			84.73

B.5 RWASH STATION

This section presents raw data of time to failure and time to repair (TTF and TTR) in hours to machines similar to those found in RWash station. To calculate the MTBF of these data, the time between failures (TBF) are computed by adding TTF and TTR for every breakdown as shown in Table B-5. Then the computed values are averaged to get the MTBF used in the calculations presented in the thesis previously.

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1	31.90	0.01	31.91
2	23.56	0.10	23.66
3	4.68	0.99	5.67
4	12.58	0.01	12.60
5	2.99	1.03	4.02
6	23.88	0.02	23.90
7	45.31	0.01	45.32
8	14.57	0.09	14.66
9	9.72	0.39	10.11
10	23.88	0.01	23.89
11	24.85	0.02	24.87
12	26.87	0.23	27.10
13	8.23	0.07	8.30
14	8.54	0.02	8.55
15	2.28	0.75	3.03
16	12.02	0.03	12.06
17	3.38	0.98	4.36
18	7.20	0.01	7.21
19	20.82	0.01	20.84
20	15.73	0.07	15.80
21	11.74	0.01	11.76
22	27.87	0.15	28.02
23	11.31	0.06	11.36
24	11.00	0.01	11.02
25	25.29	0.02	25.31
26	5.04	0.02	5.07
27	15.73	0.01	15.75
28	21.64	0.02	21.65
29	14.21	0.43	14.64
30	8.55	0.74	9.29
31	10.30	0.63	10.93
32	5.91	0.34	6.25
33	24.93	0.03	24.96
34	23.62	0.58	24.20
35	6.90	0.02	6.92
36	13.44	0.02	13.46
37	7.35	13.72	21.07
38	1.56	0.22	1.79
39	1.39	0.42	1.81
40	21.88	1.70	23.58
41	2.65	0.13	2.78
42	4.09	0.63	4.72
43	18.99	0.31	19.30
44	4.17	64.37	68.55
45	1.29	0.02	1.31

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
46	2.13	0.13	2.26
47	1.11	0.01	1.12
48	22.75	0.15	22.89
49	21.18	0.33	21.51
50	9.58	0.18	9.76
51	17.22	0.65	17.87
52	9.72	0.08	9.81
53	10.44	0.03	10.47
54	10.37	0.02	10.39
55	12.48	0.19	12.67
56	13.68	0.02	13.71
57	7.27	0.01	7.28
58	17.15	0.02	17.17
59	5.88	0.38	6.27
60	18.27	0.01	18.28
61	9.38	0.01	9.40
62	10.41	0.01	10.43
63	21.85	0.35	22.20
64	3.79	0.01	3.81
65	8.92	0.01	8.94
66	13.44	0.04	13.48
67	5.85	0.69	6.54
68	7.26	0.16	7.42
69	10.40	0.05	10.46
70	26.44	0.06	26.50
71	22.28	0.02	22.30
72	15.85	0.01	15.86
73	10.28	0.01	10.29
74	10.58	1.27	11.85
75	9.14	0.01	9.15
76	24.25	0.17	24.42
77	13.15	0.01	13.16
78	10.16	0.03	10.19
79	12.80	0.10	12.90
80	11.02	0.04	11.07
81	13.20	0.05	13.25
82	11.20	0.04	11.25
83	9.79	0.01	9.80
84	2.63	1.98	4.61
85	10.16	0.01	10.18
86	23.33	0.01	23.34
87	3.84	0.01	3.86
88	23.15	0.18	23.34
89	0.70	0.26	0.96
90	10.21	0.01	10.22

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
91	9.63	0.12	9.76
92	13.28	1.03	14.31
93	13.25	0.32	13.57
94	9.91	0.02	9.93
95	13.80	0.02	13.82
96	4.59	0.53	5.12
97	15.15	0.07	15.21
98	10.60	0.01	10.61
99	13.67	0.03	13.70
100	27.49	0.47	27.96
101	8.96	0.20	9.16
102	38.36	0.32	38.69
103	9.93	0.04	9.97
104	13.71	0.15	13.85
105	11.88	0.19	12.07
106	0.42	0.53	0.95
107	4.65	0.01	4.66
108	16.09	0.02	16.11
109	13.21	0.02	13.23
110	8.73	0.15	8.89
111	11.89	0.01	11.91
112	14.01	0.01	14.02
113	14.02	0.45	14.47
114	8.52	0.04	8.56
115	10.80	0.01	10.81
116	12.97	0.12	13.09
117	11.38	0.01	11.39
118	27.22	0.01	27.23
119	0.67	0.01	0.68
120	7.08	0.87	7.96
121	8.72	0.01	8.73
122	26.92	0.30	27.21
123	25.00	0.01	25.01
124	13.86	0.04	13.90
125	8.71	0.01	8.72
126	10.51	0.06	10.57
127	14.20	0.01	14.21
128	21.66	0.02	21.69
129	3.66	0.51	4.17
130	1.55	0.02	1.57
131	21.48	0.10	21.58
132	9.09	0.22	9.31
133	15.74	0.02	15.76
134	9.52	0.01	9.54
135	15.85	0.33	16.18

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
136	23.66	0.71	24.37
137	22.48	0.01	22.49
138	12.96	0.02	12.98
139	5.56	0.07	5.64
140	16.40	0.02	16.42
141	13.77	0.06	13.83
142	22.56	0.06	22.62
143	23.25	0.02	23.28
144	22.73	0.03	22.76
145	24.51	0.02	24.53
146	6.53	0.69	7.22
147	15.74	0.10	15.84
148	24.44	0.07	24.51
149	26.25	0.02	26.27
150	11.99	0.01	12.00
151	12.17	0.01	12.18
152	8.25	0.02	8.27
153	12.65	0.03	12.68
154	13.78	0.02	13.80
155	11.88	0.02	11.90
156	14.54	0.68	15.22
157	7.52	0.05	7.57
158	12.35	0.02	12.37
159	10.97	0.03	11.00
160	27.93	0.36	28.29
161	9.94	0.03	9.97
162	1.58	1.10	2.68
163	10.14	0.04	10.17
164	13.40	0.01	13.41
165	10.38	0.01	10.39
166	24.86	0.02	24.88
167	12.13	0.59	12.72
168	20.83	0.01	20.84
169	0.12	0.46	0.59
170	13.02	0.06	13.08
171	20.88	0.04	20.92
172	8.97	0.02	8.99
173	15.87	0.08	15.95
174	8.09	0.02	8.12
175	3.80	0.40	4.20
176	12.14	0.06	12.19
177	4.33	2.31	6.64
178	0.35	11.24	11.59
179	0.02	10.18	10.20
180	5.16	0.03	5.19

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
181	27.83	0.58	28.41
182	20.50	0.01	20.51
183	11.59	0.04	11.63
184	14.19	0.01	14.20
185	12.89	0.01	12.90
186	21.04	0.08	21.12
187	24.90	0.28	25.18
188	2.82	0.01	2.83
189	0.28	0.02	0.30
190	6.56	0.01	6.57
191	17.26	0.09	17.35
192	8.35	0.01	8.36
193	7.20	0.56	7.76
194	7.11	0.01	7.12
195	10.69	0.01	10.71
196	6.01	5.00	11.02
197	6.72	13.22	19.94
198	3.07	0.01	3.09
199	0.07	0.11	0.18
200	3.68	0.99	4.67
201	1.12	6.73	7.85
202	12.05	0.02	12.07
203	8.87	4.27	13.14
204	14.01	0.07	14.08
205	0.97	0.44	1.41
206	7.90	0.02	7.92
207	14.60	0.98	15.58
208	23.02	0.65	23.67
209	6.20	0.01	6.21
210	17.50	0.02	17.52
211	7.12	0.01	7.14
212	27.41	0.07	27.47
213	10.04	0.02	10.06
214	11.80	0.69	12.48
215	24.53	0.06	24.58
216	13.89	0.34	14.23
217	8.99	0.01	9.00
218	2.65	0.22	2.87
219	9.11	0.03	9.15
220	23.84	0.02	23.86
221	17.76	0.68	18.44
222	2.68	0.02	2.70
223	17.03	0.02	17.06
224	5.53	0.01	5.54
225	14.56	0.02	14.58

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
226	14.91	0.03	14.94
227	22.78	0.02	22.80
228	25.22	0.01	25.23
229	5.64	0.91	6.55
230	30.95	0.17	31.11
231	8.45	0.02	8.47
232	27.30	0.03	27.33
233	13.11	0.01	13.12
234	2.94	0.67	3.61
235	4.11	0.04	4.15
236	39.15	0.60	39.75
237	3.88	0.53	4.41
238	3.07	0.02	3.10
239	12.99	0.03	13.02
240	20.44	0.01	20.45
241	6.43	0.87	7.30
242	8.99	0.01	9.00
243	15.27	0.04	15.31
244	7.74	0.01	7.75
245	12.34	0.01	12.35
246	21.60	0.01	21.61
247	5.11	0.21	5.32
248	5.16	0.01	5.17
249	11.64	0.48	12.12
250	16.79	0.02	16.81
251	13.32	0.01	13.33
252	8.56	0.02	8.58
253	26.75	0.02	26.77
254	22.26	0.01	22.27
255	2.61	0.02	2.63
256	6.41	0.01	6.42
257	17.69	0.20	17.89
258	3.66	10.00	13.66
259	10.14	0.31	10.45
260	9.58	0.01	9.59
261	9.41	0.03	9.45
262	25.36	0.08	25.44
263	4.82	0.07	4.89
264	3.31	4.03	7.35
265	11.34	0.07	11.41
266	15.35	0.03	15.38
267	4.30	0.66	4.96
268	3.02	0.09	3.11
269	8.93	1.25	10.18
270	29.94	0.67	30.61

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
271	11.10	0.01	11.11
272	5.06	0.01	5.07
273	30.91	0.02	30.93
274	23.99	0.01	24.00
275	11.36	0.07	11.43
276	11.69	0.01	11.70
277	3.17	0.41	3.58
278	5.80	0.06	5.85
279	11.86	0.01	11.87
280	14.90	0.02	14.91
281	10.31	0.02	10.33
282	20.10	0.04	20.13
283	27.81	0.04	27.85
284	14.57	0.45	15.02
285	6.01	0.01	6.02
286	9.97	0.73	10.70
287	5.64	0.01	5.65
288	10.89	0.01	10.90
289	13.30	0.04	13.34
290	6.75	0.02	6.77
291	18.17	0.39	18.56
292	7.28	0.01	7.29
293	40.32	0.36	40.68
294	8.59	0.01	8.60
295	10.70	0.39	11.08
296	0.01	0.03	0.04
297	3.63	0.01	3.64
298	22.38	0.01	22.39
299	8.74	0.01	8.76
300	14.31	0.02	14.32
301	11.88	0.02	11.90
302	7.99	0.02	8.00
303	9.96	13.46	23.42
304	1.02	3.70	4.72
305	11.61	0.06	11.67
306	16.78	0.03	16.81
307	6.48	0.08	6.56
308	13.98	0.01	14.00
309	17.68	1.57	19.25
310	5.48	0.01	5.49
311	8.85	0.34	9.19
312	5.53	0.01	5.54
313	22.24	0.81	23.05
314	8.85	0.01	8.86
315	12.58	0.02	12.60

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
316	13.73	0.26	13.99
317	8.32	0.11	8.43
318	23.65	0.03	23.68
319	12.29	0.06	12.35
320	23.18	0.01	23.20
321	8.98	0.38	9.36
322	3.52	0.02	3.54
323	9.82	0.01	9.83
324	17.37	0.01	17.38
325	5.08	0.01	5.09
326	0.70	3.51	4.22
327	26.88	0.01	26.89
328	6.80	0.02	6.83
329	21.80	2.19	23.98
330	0.31	0.44	0.75
331	2.15	0.30	2.45
332	0.31	0.54	0.85
333	1.28	1.67	2.95
334	4.03	0.44	4.47
335	10.35	13.31	23.66
336	0.75	3.80	4.55
337	0.30	12.31	12.60
338	3.62	2.00	5.62
339	20.87	1.36	22.22
340	5.58	0.02	5.59
341	32.10	0.31	32.42
342	2.48	0.36	2.84
343	2.05	3.89	5.94
344	4.27	0.02	4.29
345	8.91	7.66	16.57
346	8.08	0.04	8.12
347	23.76	0.01	23.77
348	3.58	1.01	4.60
349	16.28	0.01	16.29
350	4.10	0.01	4.12
351	26.84	0.23	27.07
352	10.72	0.13	10.85
353	21.68	0.43	22.12
354	10.96	0.01	10.97
355	20.32	0.02	20.34
356	3.64	0.44	4.08
357	12.09	0.16	12.25
358	39.17	0.16	39.33
359	22.37	0.01	22.38
360	25.33	0.02	25.35

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
361	4.91	0.03	4.94
362	15.56	0.01	15.57
363	13.02	0.74	13.76
364	8.10	0.02	8.12
365	14.51	0.07	14.57
366	23.26	0.83	24.09
367	27.07	0.10	27.17
368	23.89	0.52	24.40
369	7.06	0.02	7.07
370	8.72	0.72	9.44
371	5.53	0.36	5.89
372	48.77	0.14	48.91
373	24.17	0.10	24.27
374	23.91	0.09	24.00
375	4.97	1.25	6.22
376	14.42	0.02	14.45
377	11.64	0.40	12.04
378	10.75	1.41	12.16
379	3.04	0.16	3.20
380	23.83	0.14	23.98
381	28.20	1.11	29.31
382	3.67	0.13	3.80
383	15.13	0.02	15.15
384	6.44	0.61	7.05
385	4.13	0.01	4.15
386	9.94	0.03	9.97
387	6.85	0.26	7.11
388	3.20	0.02	3.21
389	0.34	0.09	0.43
390	12.26	0.02	12.27
391	14.14	2.03	16.17
392	4.82	0.04	4.85
393	13.20	0.08	13.28
394	9.13	0.64	9.76
395	0.69	0.01	0.70
396	13.90	0.38	14.28
397	13.12	0.01	13.13
398	11.21	0.17	11.38
399	9.23	0.18	9.41
400	24.32	0.01	24.34
401	13.81	0.10	13.90
402	12.87	0.50	13.37
403	10.72	0.04	10.75
404	26.67	0.02	26.69
405	9.83	0.01	9.85

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
406	18.54	0.01	18.55
407	9.56	0.01	9.57
408	12.27	0.36	12.62
409	10.80	0.10	10.90
410	1.21	1.21	2.42
411	5.48	0.23	5.71
412	15.67	5.03	20.71
413	3.54	0.10	3.64
414	15.44	0.06	15.49
415	8.50	0.05	8.55
416	15.23	0.03	15.26
417	7.87	0.06	7.93
418	13.12	0.03	13.15
419	11.81	0.02	11.83
420	2.53	0.49	3.02
421	3.98	6.82	10.80
422	8.89	0.48	9.37
423	12.84	0.34	13.18
424	6.87	0.60	7.47
425	0.11	0.62	0.73
426	6.32	0.01	6.33
427	20.46	0.01	20.48
428	3.00	0.03	3.03
429	9.34	1.87	11.21
430	12.57	0.11	12.68
431	9.40	0.01	9.42
432	15.69	0.10	15.78
433	9.78	0.02	9.80
434	2.91	0.66	3.57
435	1.96	5.80	7.76
436	2.74	0.01	2.76
437	5.01	0.02	5.03
438	15.26	0.11	15.37
439	12.30	0.02	12.32
440	21.84	10.48	32.32
441	12.48	0.37	12.86
442	3.09	0.01	3.11
443	23.18	0.86	24.04
444	2.76	0.82	3.58
445	20.76	0.58	21.34
446	1.84	0.35	2.19
447	23.64	0.23	23.87
448	0.27	0.01	0.29
449	5.32	0.01	5.33
450	18.17	0.64	18.82

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
451	10.35	0.03	10.37
452	9.48	0.21	9.69
453	11.26	0.02	11.28
454	13.11	0.60	13.70
455	23.08	0.05	23.14
456	10.97	0.01	10.98
457	13.56	0.07	13.63
458	26.54	1.09	27.63
459	10.92	0.10	11.02
460	12.53	0.02	12.55
461	4.20	0.02	4.21
462	11.09	0.37	11.46
463	3.02	0.75	3.77
464	1.33	0.02	1.35
465	10.35	0.01	10.36
466	15.38	17.70	33.08
467	4.69	0.03	4.73
468	1.43	0.17	1.59
469	8.55	0.01	8.56
470	14.12	0.14	14.26
471	10.49	0.01	10.50
472	15.63	0.03	15.67
473	5.90	0.01	5.90
474	1.20	0.21	1.40
475	4.07	0.17	4.25
476	2.19	1.12	3.32
477	6.05	0.01	6.06
478	12.31	0.01	12.32
479	13.00	0.01	13.01
480	12.17	0.01	12.18
481	2.19	0.99	3.18
482	6.21	0.29	6.49
483	8.81	0.55	9.36
484	17.49	0.03	17.53
485	6.07	2.45	8.52
486	13.18	0.05	13.23
487	14.35	0.01	14.36
488	12.70	0.20	12.90
489	22.18	0.02	22.21
490	13.02	0.03	13.05
491	23.08	0.13	23.21
492	10.34	0.01	10.35
493	7.67	0.66	8.33
494	4.41	0.02	4.43
495	13.93	0.02	13.95

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
496	8.95	0.02	8.97
497	10.87	0.01	10.88
498	13.84	0.02	13.86
499	9.79	5.38	15.18
500	1.18	0.65	1.84
501	19.15	1.05	20.20
502	9.70	0.07	9.77
503	27.59	1.24	28.83
504	9.82	0.01	9.83
505	7.70	0.02	7.72
506	10.45	0.36	10.81
507	13.50	0.01	13.51
508	7.56	3.89	11.44
509	3.48	0.04	3.51
510	12.09	0.03	12.12
511	17.37	8.90	26.28
512	9.74	0.05	9.80
513	19.54	1.01	20.55
514	0.48	1.86	2.35
515	1.52	0.02	1.53
516	23.62	0.06	23.68
517	8.07	0.42	8.49
518	17.14	0.50	17.63
519	0.08	0.01	0.10
520	31.91	0.02	31.93
521	3.49	0.12	3.61
522	30.41	0.75	31.16
523	2.17	0.02	2.19
524	13.58	0.02	13.60
525	18.17	0.27	18.44
526	2.51	0.80	3.32
527	8.17	0.02	8.19
528	6.01	0.43	6.44
529	7.62	1.15	8.77
530	15.76	0.09	15.85
531	7.39	0.03	7.41
532	12.34	0.03	12.37
533	23.20	0.01	23.21
534	12.79	0.01	12.80
535	8.87	0.59	9.46
536	18.91	0.80	19.71
537	7.30	0.01	7.31
538	10.91	0.02	10.93
539	14.59	0.01	14.60
540	12.84	0.01	12.86

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
541	4.32	2.10	6.42
542	4.89	0.11	5.00
543	2.37	0.21	2.58
544	7.21	0.06	7.27
545	13.82	0.02	13.83
546	8.42	2.74	11.16
547	3.21	0.01	3.23
548	6.55	0.01	6.56
549	18.59	0.57	19.15
550	7.35	0.03	7.39
551	24.70	0.02	24.72
552	15.56	0.04	15.60
553	10.70	0.09	10.79
554	20.79	0.03	20.82
555	7.48	0.05	7.53
556	0.47	0.13	0.60
557	3.58	0.01	3.59
558	8.72	4.32	13.04
559	1.97	0.10	2.07
560	22.10	0.02	22.12
561	25.78	0.19	25.97
562	0.12	0.02	0.14
563	12.67	0.02	12.69
564	10.98	0.07	11.05
565	12.32	0.01	12.33
566	11.14	1.99	13.13
567	2.36	0.64	3.00
568	7.48	0.30	7.78
569	10.58	0.03	10.61
570	10.11	0.01	10.12
571	12.51	0.05	12.56
572	24.29	0.07	24.35
573	23.54	0.49	24.03
574	2.02	0.20	2.22
575	0.39	4.55	4.94
576	4.56	0.01	4.57
577	14.29	0.35	14.64
578	8.81	0.01	8.83
579	13.83	0.01	13.85
580	7.35	0.01	7.36
581	9.63	12.91	22.54
582	14.23	0.03	14.25
583	15.39	0.01	15.40
584	13.20	0.03	13.23
585	9.46	0.01	9.47

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
586	14.72	0.23	14.96
587	10.27	0.01	10.28
588	6.35	0.10	6.45
589	21.37	0.24	21.61
590	8.73	0.01	8.74
591	10.09	0.03	10.11
592	15.09	0.01	15.11
593	12.51	0.01	12.52
594	11.74	2.70	14.44
595	5.36	0.09	5.45
596	10.94	0.02	10.96
597	28.11	0.59	28.70
598	4.41	0.64	5.05
599	2.46	0.01	2.47
600	13.01	0.13	13.14
601	23.46	0.02	23.47
602	3.29	0.54	3.82
603	9.37	0.01	9.38
604	23.01	0.02	23.03
605	22.20	0.03	22.23
606	16.82	0.45	17.28
607	4.64	0.35	4.99
608	29.07	0.02	29.09
609	11.91	0.01	11.92
610	9.91	0.02	9.94
611	13.56	0.02	13.58
612	13.10	0.01	13.11
613	12.92	0.09	13.02
614	9.16	0.01	9.17
615	8.84	0.03	8.87
616	6.95	0.69	7.64
617	17.09	0.28	17.38
618	12.60	0.02	12.62
619	14.14	0.01	14.15
620	2.32	0.02	2.34
621	10.06	0.06	10.12
622	13.35	0.01	13.36
623	32.92	0.05	32.96
624	14.80	0.46	15.26
625	8.08	0.05	8.14
626	39.91	0.68	40.59
627	16.19	0.02	16.21
628	38.95	0.02	38.97
629	4.64	0.67	5.31
630	10.61	0.01	10.62

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
631	5.31	0.04	5.35
632	17.82	0.01	17.83
633	12.63	0.06	12.69
634	8.63	0.01	8.64
635	14.96	0.01	14.97
636	4.90	0.84	5.74
637	4.43	0.01	4.44
638	10.33	0.03	10.36
639	9.82	0.02	9.84
640	3.85	0.79	4.64
641	2.18	1.16	3.34
642	5.12	0.01	5.13
643	15.58	0.01	15.59
644	9.32	0.03	9.35
645	10.77	0.01	10.77
646	27.21	0.02	27.23
647	13.58	0.10	13.68
648	6.46	0.03	6.49
649	18.62	0.71	19.33
650	5.60	0.34	5.95
651	1.00	0.01	1.01
652	26.16	0.02	26.17
653	14.38	0.01	14.40
654	8.23	0.01	8.24
655	11.08	0.01	11.09
656	15.95	1.47	17.41
657	8.44	0.01	8.46
658	8.94	0.01	8.95
659	13.41	0.01	13.42
660	12.91	0.04	12.95
661	2.69	0.66	3.35
662	23.42	0.22	23.64
663	8.70	0.01	8.71
664	12.13	0.04	12.16
665	23.62	0.08	23.70
666	13.42	0.01	13.43
667	24.78	0.03	24.80
668	17.42	0.02	17.44
669	8.61	0.61	9.22
670	11.10	0.01	11.10
671	22.75	0.02	22.76
672	0.44	0.91	1.35
673	22.33	0.08	22.42
674	9.31	0.01	9.33
675	14.10	0.12	14.22

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
676	36.79	0.22	37.01
677	18.75	0.01	18.76
678	17.35	0.71	18.06
679	15.30	0.87	16.17
680	5.36	10.26	15.62
681	10.66	0.03	10.69
682	13.78	0.56	14.35
683	6.53	0.03	6.56
684	0.42	0.01	0.43
685	23.55	0.14	23.70
686	15.95	1.83	17.78
687	28.29	0.02	28.31
688	47.35	0.02	47.36
689	12.67	0.08	12.75
690	1.92	0.84	2.77
691	7.52	0.04	7.56
692	23.46	0.01	23.47
693	25.03	0.02	25.05
694	26.81	0.30	27.11
695	11.18	0.07	11.25
696	5.44	0.05	5.49
697	15.92	0.05	15.97
698	10.89	0.01	10.90
699	20.58	0.01	20.59
700	15.94	0.04	15.99
701	32.81	3.37	36.18
702	3.34	0.19	3.53
703	22.35	0.01	22.36
704	25.35	0.01	25.36
705	4.98	0.02	5.00
706	15.62	0.01	15.63
707	26.96	0.57	27.53
708	8.94	0.24	9.18
709	26.46	0.06	26.52
710	23.49	0.70	24.19
711	12.56	2.97	15.53
712	2.47	9.19	11.66
713	1.01	0.02	1.03
714	3.41	0.01	3.42
715	13.29	0.02	13.30
716	23.84	0.17	24.02
717	26.48	0.12	26.60
718	6.38	0.24	6.62
719	17.84	0.31	18.15
720	14.79	0.19	14.98

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
721	4.87	0.75	5.62
722	5.19	0.38	5.57
723	18.32	0.04	18.36
724	24.28	0.82	25.10
725	26.06	0.17	26.23
726	23.83	1.11	24.94
727	7.76	0.11	7.87
728	15.44	0.01	15.46
729	11.18	0.01	11.20
730	9.95	0.04	9.99
731	7.60	0.73	8.33
732	2.39	0.01	2.41
733	12.26	0.02	12.28
734	3.17	1.09	4.26
735	1.94	1.28	3.22
736	11.71	1.54	13.25
737	0.23	0.01	0.24
738	13.31	0.18	13.50
739	1.64	1.94	3.57
740	6.69	0.01	6.70
741	13.91	0.80	14.71
742	0.23	0.29	0.52
743	15.24	0.01	15.26
744	8.42	0.05	8.47
745	3.09	0.48	3.57
746	2.57	0.26	2.84
747	1.38	0.02	1.39
748	7.86	0.53	8.38
749	2.34	0.38	2.72
750	14.75	0.01	14.76
751	13.83	0.13	13.96
752	11.32	1.20	12.53
753	0.73	0.05	0.77
754	10.79	0.06	10.85
755	26.41	0.02	26.44
756	9.94	0.01	9.95
757	4.69	0.11	4.80
758	9.54	0.80	10.35
759	3.40	0.01	3.41
760	9.45	0.01	9.46
761	12.26	0.06	12.32
762	11.17	0.14	11.30
763	32.28	0.25	32.53
764	12.84	0.01	12.85
765	11.20	0.21	11.41

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
766	2.74	1.04	3.78
767	2.70	0.13	2.83
768	16.29	0.33	16.62
769	0.37	0.01	0.38
770	4.85	4.34	9.20
771	3.23	0.03	3.26
772	11.81	0.01	11.82
773	9.17	0.01	9.18
774	29.98	0.12	30.10
775	11.60	0.24	11.84
776	10.77	0.53	11.30
777	0.75	0.20	0.95
778	11.09	0.41	11.50
779	10.70	0.01	10.72
780	10.10	0.22	10.33
781	12.81	0.01	12.82
782	14.54	0.08	14.62
783	9.43	0.03	9.45
784	14.57	0.03	14.60
785	5.03	0.02	5.05
786	15.83	0.15	15.98
787	11.40	0.79	12.20
788	10.97	0.09	11.07
789	15.46	0.26	15.72
790	20.97	0.02	20.99
791	2.75	1.69	4.44
792	22.31	0.86	23.17
793	21.28	0.02	21.29
794	7.53	1.47	9.00
795	16.85	0.26	17.10
796	0.24	0.01	0.25
797	0.62	0.27	0.89
798	4.42	0.01	4.43
799	18.19	0.60	18.79
800	10.85	0.03	10.88
801	8.85	0.05	8.90
802	11.65	0.03	11.67
803	13.92	0.03	13.95
804	11.50	0.01	11.51
805	12.69	0.01	12.70
806	9.63	0.01	9.64
807	13.67	6.49	20.16
808	1.32	10.73	12.04
809	0.46	9.90	10.36
810	1.18	0.10	1.28

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
811	8.53	0.01	8.54
812	9.25	0.15	9.40
813	7.23	0.01	7.25
814	16.57	0.01	16.59
815	10.35	0.01	10.36
816	39.40	0.21	39.61
817	0.58	1.78	2.36
818	6.00	0.02	6.02
819	13.69	1.11	14.80
820	9.92	0.01	9.94
821	4.37	0.07	4.43
822	11.22	0.53	11.76
823	0.54	0.01	0.55
824	4.83	0.02	4.84
825	15.02	0.01	15.03
826	12.31	0.01	12.32
827	12.97	0.03	13.00
828	1.52	0.21	1.73
829	10.37	0.01	10.38
830	13.04	0.01	13.05
831	6.33	0.03	6.35
832	9.89	1.59	11.47
833	5.86	0.04	5.90
834	21.60	0.04	21.63
835	14.20	0.01	14.21
836	12.79	0.22	13.02
837	22.02	0.02	22.04
838	13.17	0.04	13.21
839	4.39	0.01	4.40
840	7.28	2.44	9.72
841	9.03	0.08	9.10
842	10.31	0.03	10.34
843	10.76	1.92	12.69
844	0.11	0.01	0.12
845	13.87	0.01	13.88
846	8.99	0.01	9.00
847	11.65	0.01	11.66
848	12.89	0.02	12.91
849	17.39	0.52	17.91
850	5.41	0.07	5.49
851	15.32	3.59	18.91
852	4.82	0.03	4.85
853	10.14	1.01	11.15
854	6.28	0.01	6.29
855	21.19	0.01	21.20

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
856	7.30	0.20	7.50
857	12.95	0.03	12.97
858	11.52	0.02	11.53
859	15.00	0.03	15.02
860	4.20	0.96	5.16
861	6.81	0.05	6.86
862	25.24	0.26	25.50
863	10.30	0.02	10.33
864	0.31	0.01	0.32
865	23.14	0.02	23.16
866	24.90	0.04	24.94
867	1.51	0.46	1.97
868	2.61	0.58	3.19
869	20.45	0.04	20.50
870	0.57	0.01	0.58
871	65.93	1.27	67.20
872	0.57	0.59	1.15
873	0.43	0.02	0.45
874	9.98	0.80	10.79
875	2.89	0.31	3.20
876	20.67	0.06	20.73
877	8.96	0.02	8.98
878	16.34	0.06	16.40
879	9.13	0.01	9.14
880	25.94	1.37	27.32
881	21.12	0.02	21.15
882	19.38	0.01	19.39
883	9.49	0.12	9.61
884	19.88	0.01	19.89
885	11.12	0.75	11.87
886	14.01	0.05	14.06
887	12.84	0.01	12.85
888	21.11	0.05	21.16
889	7.98	9.31	17.29
890	20.48	0.01	20.49
891	16.23	0.02	16.25
892	7.35	0.02	7.37
893	17.27	0.35	17.62
894	7.12	0.01	7.13
895	15.95	0.12	16.07
896	1.82	1.77	3.59
897	2.23	0.01	2.24
898	20.51	0.38	20.89
899	4.86	0.03	4.89
900	1.34	1.30	2.64

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
901	8.41	0.01	8.42
902	8.86	4.33	13.19
903	14.54	0.29	14.82
904	2.20	0.29	2.49
905	6.10	0.06	6.16
906	12.66	0.41	13.07
907	13.42	0.23	13.64
908	0.06	0.01	0.07
909	12.78	0.01	12.79
910	22.92	0.41	23.33
911	7.16	0.02	7.18
912	8.10	0.50	8.60
913	18.66	0.01	18.68
914	10.11	0.01	10.12
915	2.57	1.75	4.31
916	0.67	0.58	1.25
917	1.67	0.94	2.61
918	0.39	0.66	1.05
919	3.41	0.04	3.44
920	24.32	0.04	24.36
921	23.36	0.01	23.38
922	2.60	0.17	2.77
923	9.23	0.02	9.25
924	14.58	0.35	14.93
925	4.27	0.53	4.80
926	17.87	0.01	17.88
927	7.38	0.01	7.39
928	16.57	0.03	16.60
929	4.07	0.48	4.55
930	1.49	0.01	1.51
931	14.42	0.03	14.44
932	15.08	0.01	15.10
933	9.44	0.91	10.35
934	2.86	0.02	2.89
935	9.42	0.01	9.43
936	22.17	0.01	22.19
937	3.08	0.01	3.09
938	11.02	0.03	11.05
939	25.67	0.73	26.39
940	0.18	0.01	0.19
941	9.25	0.01	9.26
942	7.10	0.89	7.98
943	5.95	0.02	5.97
944	13.65	0.02	13.67
945	19.75	0.12	19.87

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
946	11.00	0.03	11.03
947	28.02	0.65	28.67
948	4.92	0.32	5.24
949	2.22	0.01	2.23
950	12.76	0.19	12.95
951	19.10	0.70	19.80
952	0.50	0.01	0.51
953	6.62	0.48	7.10
954	9.45	0.01	9.46
955	23.02	0.02	23.04
956	14.67	0.52	15.19
957	6.91	0.99	7.89
958	21.31	0.02	21.33
959	28.92	0.02	28.94
960	9.99	1.63	11.62
961	0.76	0.01	0.77
962	0.35	0.46	0.82
963	0.93	0.27	1.20
964	7.50	0.02	7.52
965	13.72	0.01	13.73
966	5.87	1.01	6.88
967	19.13	0.08	19.21
968	11.79	0.01	11.81
969	6.14	0.01	6.15
970	25.12	0.03	25.14
971	12.62	0.01	12.63
972	12.70	0.13	12.83
973	10.82	0.05	10.87
974	16.22	0.02	16.24
975	32.69	0.05	32.73
976	23.63	0.06	23.69
977	4.17	1.34	5.51
978	11.92	4.04	15.96
979	19.04	0.02	19.06
980	16.24	0.02	16.26
981	17.38	5.32	22.70
982	8.04	1.20	9.24
983	6.89	0.02	6.91
984	13.47	0.47	13.93
985	2.06	0.01	2.07
986	11.13	0.03	11.16
987	11.96	0.01	11.97
988	9.55	0.02	9.57
989	7.87	0.21	8.07
990	3.68	0.01	3.70

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
991	14.86	0.01	14.87
992	9.58	0.82	10.40
993	9.93	0.02	9.95
994	7.68	0.40	8.08
995	2.54	0.02	2.56
996	12.64	0.01	12.65
997	14.70	0.04	14.74
998	10.18	0.03	10.21
999	10.73	0.01	10.74
1000	27.29	0.02	27.30
1001	13.37	0.11	13.48
1002	4.72	0.52	5.25
1003	1.27	0.02	1.29
1004	26.37	0.02	26.39
1005	27.82	0.19	28.02
1006	12.55	0.01	12.56
1007	8.21	0.01	8.22
1008	11.60	0.01	11.61
1009	2.00	0.18	2.18
1010	13.22	1.49	14.71
1011	8.46	0.01	8.47
1012	15.57	0.01	15.58
1013	6.66	0.01	6.67
1014	12.90	0.03	12.93
1015	13.08	0.55	13.63
1016	21.98	0.01	22.00
1017	0.19	0.01	0.20
1018	3.20	0.37	3.56
1019	0.03	0.02	0.05
1020	8.32	0.07	8.39
1021	23.30	0.30	23.60
1022	13.64	0.01	13.65
1023	13.78	0.96	14.74
1024	0.47	1.98	2.44
1025	0.47	0.05	0.51
1026	7.12	0.03	7.15
1027	17.42	0.03	17.45
1028	19.47	1.22	20.69
1029	22.30	0.05	22.35
1030	17.54	0.94	18.48
1031	5.28	0.03	5.30
1032	10.31	0.01	10.33
1033	11.47	0.99	12.47
1034	46.06	0.01	46.07
1035	10.54	0.01	10.55

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1036	17.22	0.74	17.97
1037	4.76	0.01	4.77
1038	15.15	0.58	15.73
1039	2.75	1.76	4.51
1040	17.40	0.03	17.43
1041	21.10	1.01	22.11
1042	12.26	0.76	13.02
1043	28.13	0.08	28.22
1044	4.77	1.36	6.12
1045	13.11	0.01	13.12
1046	28.66	0.26	28.92
1047	11.73	0.19	11.92
1048	8.74	0.59	9.33
1049	24.08	0.02	24.10
1050	22.71	0.02	22.73
1051	15.62	4.56	20.18
1052	2.89	0.66	3.54
1053	24.37	0.75	25.12
1054	26.80	0.37	27.17
1055	11.17	0.12	11.29
1056	20.55	0.03	20.59
1057	11.86	0.01	11.88
1058	20.29	0.01	20.30
1059	15.93	0.05	15.98
1060	2.59	0.91	3.51
1061	10.28	0.02	10.30
1062	25.79	0.14	25.93
1063	22.39	0.01	22.40
1064	25.47	0.12	25.60
1065	20.25	0.01	20.26
1066	17.63	0.95	18.58
1067	9.02	0.05	9.07
1068	5.72	0.73	6.44
1069	2.05	0.06	2.11
1070	27.16	7.47	34.63
1071	17.20	0.04	17.24
1072	23.52	0.47	23.99
1073	7.14	0.01	7.16
1074	14.96	0.03	14.99
1075	5.53	2.47	8.00
1076	17.29	0.15	17.44
1077	23.48	0.12	23.61
1078	48.36	0.13	48.50
1079	7.69	1.15	8.84
1080	11.85	0.01	11.87

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1081	27.16	0.14	27.31
1082	23.85	0.16	24.01
1083	6.21	0.69	6.91
1084	5.19	0.03	5.21
1085	15.12	1.45	16.57
1086	4.11	0.12	4.23
1087	10.49	0.04	10.53
1088	4.81	0.03	4.83
1089	32.10	0.06	32.15
1090	12.03	0.02	12.06
1091	20.96	0.01	20.98
1092	13.46	0.08	13.54
1093	5.55	2.47	8.02
1094	2.19	0.01	2.20
1095	3.98	0.99	4.97
1096	9.94	0.25	10.19
1097	12.37	0.01	12.38
1098	11.11	0.01	11.12
1099	13.96	0.54	14.50
1100	1.43	0.45	1.88
1101	4.81	0.02	4.83
1102	11.07	0.61	11.69
1103	0.95	0.02	0.96
1104	7.44	0.39	7.83
1105	6.02	0.11	6.13
1106	8.50	9.71	18.21
1107	0.54	3.15	3.69
1108	2.03	0.05	2.08
1109	7.90	12.20	20.10
1110	2.19	3.81	6.00
1111	0.60	0.03	0.62
1112	9.53	0.01	9.54
1113	22.01	0.02	22.03
1114	29.85	0.14	29.98
1115	7.27	0.27	7.54
1116	4.68	0.13	4.82
1117	1.22	0.03	1.25
1118	7.84	0.51	8.35
1119	10.49	0.17	10.66
1120	12.80	0.01	12.81
1121	10.13	0.29	10.42
1122	15.89	0.03	15.92
1123	9.05	0.04	9.09
1124	12.00	0.03	12.03
1125	11.78	0.02	11.80

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1126	2.49	0.48	2.97
1127	6.21	0.01	6.21
1128	13.49	1.12	14.61
1129	5.05	0.37	5.42
1130	9.95	0.08	10.03
1131	11.64	0.05	11.69
1132	12.26	0.10	12.36
1133	10.71	0.20	10.90
1134	0.67	0.01	0.68
1135	10.76	0.02	10.78
1136	12.37	0.10	12.48
1137	10.46	0.01	10.47
1138	14.58	0.06	14.64
1139	10.10	0.01	10.11
1140	13.96	0.02	13.99
1141	5.04	0.37	5.41
1142	14.81	0.08	14.90
1143	15.54	0.98	16.53
1144	23.00	0.24	23.24
1145	21.00	0.01	21.02
1146	26.74	0.88	27.62
1147	21.17	0.04	21.21
1148	5.72	0.58	6.30
1149	19.60	0.43	20.03
1150	23.60	0.62	24.22
1151	10.31	0.02	10.33
1152	9.40	0.11	9.51
1153	11.70	0.02	11.72
1154	13.77	0.03	13.80
1155	11.42	0.02	11.43
1156	11.72	0.10	11.82
1157	10.55	0.02	10.57
1158	12.22	1.31	13.54
1159	26.64	1.02	27.66
1160	11.10	0.02	11.12
1161	9.36	0.13	9.49
1162	7.26	0.01	7.27
1163	16.49	0.07	16.57
1164	10.58	0.02	10.60
1165	25.72	4.74	30.45
1166	7.11	0.01	7.12
1167	10.28	0.02	10.30
1168	13.89	0.05	13.94
1169	10.77	0.01	10.79
1170	14.92	0.16	15.09

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1171	0.42	0.03	0.45
1172	11.69	0.03	11.72
1173	9.22	0.02	9.23
1174	12.35	0.02	12.36
1175	12.93	0.01	12.94
1176	12.15	0.01	12.16
1177	0.53	0.36	0.89
1178	3.98	0.01	4.00
1179	8.10	0.03	8.14
1180	6.40	0.03	6.43
1181	17.14	0.04	17.18
1182	21.91	0.06	21.97
1183	14.03	0.01	14.05
1184	12.76	0.21	12.96
1185	22.12	0.03	22.15
1186	0.51	0.02	0.52
1187	3.76	8.85	12.61
1188	12.51	0.29	12.79
1189	10.28	0.01	10.30
1190	10.39	0.05	10.43
1191	12.93	0.02	12.94
1192	13.74	0.01	13.75
1193	8.99	0.02	9.01
1194	10.89	0.01	10.90
1195	13.73	0.03	13.76
1196	17.00	0.27	17.27
1197	12.55	0.35	12.90
1198	16.89	0.10	16.99
1199	23.77	7.26	31.02
1200	8.21	0.01	8.22
1201	6.93	0.02	6.95
1202	12.86	0.04	12.89
1203	26.53	0.01	26.55
1204	11.95	0.03	11.98
1205	21.76	0.59	22.35
1206	2.63	0.01	2.64
1207	0.80	0.26	1.06
1208	8.82	0.02	8.84
1209	1.22	0.01	1.23
1210	15.02	0.16	15.18
1211	2.54	0.50	3.04
1212	4.13	0.30	4.43
1213	0.48	0.01	0.49
1214	24.86	0.04	24.91
1215	9.12	1.11	10.23

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1216	15.45	0.07	15.52
1217	0.57	0.02	0.59
1218	47.33	0.39	47.72
1219	6.57	0.73	7.30
1220	13.84	0.02	13.86
1221	13.53	0.04	13.58
1222	20.94	0.05	20.99
1223	9.00	0.01	9.01
1224	16.37	0.12	16.49
1225	8.98	0.01	8.99
1226	13.21	0.02	13.24
1227	5.39	0.60	5.99
1228	5.86	0.03	5.89
1229	10.28	13.12	23.40
1230	19.40	0.05	19.44
1231	9.43	0.11	9.54
1232	20.10	0.02	20.12
1233	11.02	0.03	11.05
1234	14.50	0.02	14.52
1235	5.30	0.35	5.65
1236	7.32	0.02	7.34
1237	21.22	0.45	21.66
1238	13.22	0.02	13.24
1239	14.91	0.02	14.93
1240	9.11	0.01	9.12
1241	16.15	0.02	16.17
1242	3.13	0.98	4.11
1243	28.01	0.02	28.03
1244	15.58	0.04	15.63
1245	10.31	0.78	11.09
1246	20.53	0.03	20.55
1247	5.46	0.88	6.35
1248	5.29	0.02	5.30
1249	8.71	4.34	13.04
1250	24.12	0.02	24.14
1251	5.41	0.88	6.28
1252	19.54	0.32	19.86
1253	13.04	0.03	13.06
1254	10.62	0.07	10.69
1255	12.36	0.01	12.37
1256	20.18	0.36	20.54
1257	3.03	0.30	3.33
1258	10.51	0.05	10.55
1259	9.75	0.01	9.76
1260	13.03	0.04	13.07

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1261	22.63	0.37	23.00
1262	1.18	0.06	1.24
1263	22.61	0.47	23.08
1264	0.82	0.03	0.85
1265	2.14	0.15	2.29
1266	9.12	0.01	9.14
1267	14.72	0.33	15.05
1268	9.00	0.03	9.03
1269	2.98	14.48	17.46
1270	3.61	0.02	3.62
1271	16.56	0.01	16.57
1272	6.01	0.02	6.03
1273	14.10	0.02	14.12
1274	15.44	0.02	15.45
1275	13.20	0.02	13.22
1276	9.35	0.02	9.37
1277	14.79	0.26	15.05
1278	3.62	5.60	9.21
1279	1.99	0.74	2.72
1280	9.41	0.02	9.43
1281	17.30	1.99	19.29
1282	6.37	0.80	7.17
1283	11.95	1.89	13.84
1284	10.09	0.48	10.56
1285	12.54	0.02	12.56
1286	6.95	4.15	11.10
1287	6.73	1.71	8.43
1288	0.22	0.01	0.23
1289	0.16	0.01	0.17
1290	1.93	0.56	2.49
1291	8.51	0.02	8.54
1292	11.33	1.90	13.23
1293	10.88	0.92	11.80
1294	2.98	0.64	3.61
1295	7.46	0.02	7.48
1296	9.76	0.22	9.99
1297	3.15	0.03	3.17
1298	1.85	3.23	5.08
1299	8.02	1.10	9.11
1300	5.90	0.02	5.92
1301	6.61	0.47	7.09
1302	9.51	0.02	9.52
1303	14.01	0.17	14.18
1304	8.85	0.02	8.87
1305	22.19	0.02	22.21

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1306	7.09	0.71	7.80
1307	8.95	0.17	9.12
1308	5.24	0.01	5.25
1309	29.01	0.05	29.05
1310	11.97	0.01	11.98
1311	9.85	0.04	9.89
1312	13.63	0.01	13.63
1313	11.61	1.23	12.84
1314	4.40	0.02	4.42
1315	8.77	0.06	8.82
1316	9.12	0.09	9.21
1317	9.24	0.03	9.27
1318	24.63	0.02	24.65
1319	12.56	0.02	12.58
1320	14.19	0.03	14.21
1321	12.10	0.06	12.16
1322	13.58	0.01	13.59
1323	9.12	0.04	9.16
1324	6.33	1.57	7.90
1325	15.67	0.14	15.81
1326	15.13	0.02	15.16
1327	8.13	0.11	8.24
1328	40.69	0.02	40.71
1329	16.64	0.38	17.02
1330	19.29	2.77	22.06
1331	3.86	1.05	4.91
1332	11.13	0.02	11.15
1333	4.13	0.05	4.18
1334	11.95	0.07	12.02
1335	5.07	0.11	5.18
1336	17.68	0.01	17.69
1337	12.72	0.07	12.79
1338	8.39	0.01	8.40
1339	6.81	0.53	7.35
1340	7.72	0.02	7.74
1341	10.21	0.01	10.22
1342	10.20	0.04	10.23
1343	14.76	0.04	14.80
1344	8.27	0.02	8.30
1345	17.24	1.29	18.53
1346	6.44	0.03	6.47
1347	10.74	0.01	10.75
1348	22.82	0.99	23.81
1349	17.05	0.07	17.13
1350	6.39	0.02	6.41

Table B-5: Calculating MTBF for RWash station.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1351	20.56	7.67	28.22
1352	0.59	6.34	6.93
1353	7.00	0.09	7.09
1354	11.93	0.55	12.49
1355	12.13	0.02	12.15
1356	8.26	0.01	8.27
1357	11.54	0.02	11.56
1358	7.69	0.72	8.41
1359	7.03	1.47	8.51
1360	8.51	0.02	8.53
1361	10.92	0.02	10.94
1362	11.14	0.02	11.17
1363	13.07	0.01	13.08
1364	35.57	0.19	35.75
1365	8.48	3.63	12.11
1366	23.55	0.08	23.64
1367	7.74	0.98	8.72
1368	29.69	0.03	29.72
1369	12.87	0.30	13.17
1370	4.22	0.02	4.24
1371	7.27	22.06	29.33
1372	13.92	1.09	15.01
1373	22.46	0.04	22.50
1374	10.29	0.02	10.31
1375	12.65	0.03	12.68
1376	10.32	0.01	10.34
1377	3.37	29.17	32.54
1378	3.07	0.04	3.11
1379	10.40	0.01	10.41
MTBF (hours)			12.67

B.6 IPOL AND VPOL STATIONS

This section presents raw data of time to failure and time to repair (TTF and TTR) in hours to machines similar to those found in IPol and VPol stations. To calculate the MTBF of these data, the time between failures (TBF) are computed by adding TTF and TTR for every breakdown as shown in Table B-6. Then the computed values are averaged to get the MTBF used in the calculations presented in the thesis previously.

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1	11.05	3.57	14.63
2	11.58	0.72	12.30
3	24.13	1.21	25.34
4	19.18	1.15	20.33
5	20.27	5.67	25.94
6	18.42	0.34	18.76
7	10.50	0.78	11.28
8	9.37	1.26	10.63
9	24.18	0.50	24.68
10	25.24	0.53	25.77
11	19.87	0.48	20.35
12	21.48	1.47	22.96
13	29.20	0.20	29.39
14	15.82	0.53	16.34
15	8.96	0.03	8.99
16	25.43	1.37	26.80
17	29.04	0.48	29.53
18	19.16	0.18	19.34
19	4.72	1.76	6.48
20	21.79	12.26	34.04
21	23.47	0.43	23.90
22	15.46	0.25	15.72
23	14.26	0.37	14.63
24	31.58	0.53	32.11
25	6.55	0.47	7.01
26	20.75	0.25	21.00
27	20.04	1.18	21.22
28	31.97	0.42	32.39
29	22.91	0.36	23.27
30	29.20	1.62	30.82
31	26.93	0.70	27.63
32	25.31	0.43	25.74
33	7.90	0.74	8.65
34	12.18	0.01	12.19
35	9.77	4.18	13.94
36	15.65	2.05	17.69
37	22.56	1.03	23.58
38	21.31	0.68	22.00
39	23.94	1.48	25.42
40	23.77	0.53	24.30
41	24.82	0.33	25.16
42	0.21	0.31	0.52
43	23.92	0.02	23.94
44	20.19	0.62	20.81
45	20.90	1.50	22.40

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
46	24.96	0.21	25.17
47	23.25	0.99	24.24
48	2.70	0.45	3.15
49	9.14	0.32	9.46
50	13.47	0.46	13.93
51	3.88	1.53	5.40
52	7.12	0.50	7.61
53	24.76	0.54	25.30
54	7.22	1.85	9.07
55	18.30	0.30	18.60
56	9.51	0.18	9.69
57	12.32	1.61	13.93
58	11.96	1.27	13.24
59	9.28	0.64	9.92
60	17.78	0.76	18.55
61	25.40	0.29	25.68
62	24.24	0.31	24.55
63	1.93	0.01	1.94
64	5.29	2.94	8.23
65	12.26	0.01	12.28
66	11.14	1.05	12.19
67	29.21	0.94	30.16
68	3.03	0.35	3.38
69	26.57	3.43	29.99
70	27.60	0.23	27.83
71	28.42	0.52	28.94
72	19.30	5.45	24.75
73	22.16	0.50	22.67
74	15.94	1.23	17.16
75	11.51	0.49	12.00
76	30.01	0.87	30.87
77	31.06	0.28	31.34
78	21.35	0.59	21.94
79	17.81	5.65	23.46
80	18.30	1.01	19.30
81	20.89	0.39	21.28
82	31.57	0.88	32.45
83	46.71	0.61	47.32
84	28.87	0.14	29.01
85	13.75	0.01	13.75
86	8.31	0.31	8.61
87	21.97	1.20	23.17
88	28.41	2.59	31.00
89	29.01	0.94	29.95
90	22.59	0.49	23.08

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
91	25.51	0.08	25.58
92	26.05	0.51	26.56
93	19.01	4.34	23.35
94	24.09	0.50	24.59
95	23.18	0.33	23.51
96	4.38	1.10	5.47
97	18.52	0.36	18.88
98	1.44	0.30	1.73
99	23.19	0.60	23.79
100	13.78	6.53	20.31
101	0.88	10.19	11.07
102	6.16	0.01	6.17
103	13.77	0.17	13.94
104	20.88	0.40	21.28
105	10.30	0.86	11.16
106	6.29	0.02	6.31
107	2.13	0.47	2.59
108	19.38	0.28	19.66
109	19.82	0.82	20.65
110	25.28	1.81	27.09
111	5.00	4.75	9.75
112	3.90	1.64	5.54
113	28.84	1.59	30.43
114	16.92	0.86	17.77
115	7.74	4.91	12.66
116	25.91	3.04	28.95
117	17.76	0.77	18.54
118	13.72	0.55	14.26
119	21.10	1.23	22.32
120	14.02	0.04	14.06
121	17.64	1.25	18.89
122	18.84	0.56	19.41
123	31.39	1.38	32.77
124	22.72	0.42	23.13
125	17.69	0.36	18.05
126	10.10	0.54	10.64
127	17.54	0.02	17.56
128	11.04	1.30	12.34
129	19.54	0.93	20.47
130	15.43	0.07	15.50
131	1.61	1.49	3.10
132	20.95	1.26	22.21
133	29.71	1.12	30.84
134	11.74	1.13	12.87
135	5.40	0.40	5.79

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
136	18.97	0.15	19.12
137	26.22	1.18	27.40
138	30.09	0.39	30.48
139	11.82	0.78	12.61
140	11.32	1.08	12.40
141	28.12	0.42	28.54
142	22.40	1.65	24.04
143	20.82	0.54	21.36
144	6.83	0.02	6.85
145	13.88	0.54	14.42
146	31.13	0.98	32.10
147	20.07	0.29	20.35
148	22.41	4.14	26.55
149	22.12	0.34	22.46
150	10.18	1.53	11.71
151	23.13	0.60	23.73
152	18.91	0.31	19.22
153	24.06	0.14	24.20
154	26.04	0.55	26.59
155	13.56	0.03	13.59
156	7.35	0.81	8.16
157	22.57	0.24	22.81
158	24.11	1.99	26.10
159	26.30	0.56	26.87
160	29.52	0.27	29.79
161	20.35	2.24	22.60
162	21.46	6.36	27.81
163	11.47	0.70	12.17
164	46.99	1.12	48.11
165	1.88	28.48	30.35
166	29.49	0.25	29.75
167	10.17	0.01	10.18
168	15.39	0.43	15.81
169	22.80	0.15	22.96
170	24.94	0.71	25.65
171	20.22	1.77	21.99
172	18.44	0.92	19.36
173	21.88	0.64	22.52
174	16.82	8.80	25.61
175	28.22	0.44	28.65
176	15.85	0.85	16.70
177	16.38	4.22	20.59
178	15.14	0.28	15.42
179	17.50	0.48	17.98
180	17.01	0.46	17.46

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
181	23.34	0.73	24.07
182	19.20	0.01	19.22
183	5.89	0.28	6.17
184	16.12	0.63	16.76
185	19.61	0.23	19.84
186	9.78	0.65	10.43
187	1.12	1.42	2.54
188	6.43	1.33	7.76
189	5.49	1.29	6.78
190	14.32	0.43	14.75
191	8.32	1.97	10.29
192	0.06	0.53	0.58
193	8.43	0.42	8.85
194	13.96	4.84	18.80
195	2.43	0.44	2.86
196	8.31	0.48	8.79
197	15.10	2.36	17.46
198	5.87	0.87	6.74
199	14.58	0.14	14.72
200	14.64	0.37	15.01
201	24.32	0.79	25.11
202	16.49	0.37	16.85
203	2.91	0.31	3.22
204	11.67	0.06	11.73
205	10.79	0.45	11.25
206	16.39	0.48	16.87
207	11.93	0.01	11.94
208	3.31	0.79	4.10
209	13.59	0.41	14.00
210	2.38	0.31	2.69
211	11.32	0.07	11.39
212	9.28	0.35	9.63
213	23.18	0.19	23.37
214	23.81	0.76	24.57
215	19.34	0.02	19.36
216	21.21	9.28	30.49
217	17.90	0.99	18.89
218	20.40	0.49	20.89
219	10.85	1.07	11.92
220	13.18	0.71	13.89
221	23.10	0.98	24.08
222	23.20	0.40	23.60
223	8.11	0.45	8.57
224	13.74	0.18	13.92
225	2.24	0.47	2.72

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
226	22.94	1.91	24.85
227	1.49	0.38	1.87
228	22.19	0.25	22.45
229	1.92	0.17	2.09
230	20.37	1.17	21.55
231	21.44	0.85	22.29
232	10.85	3.20	14.04
233	16.60	0.49	17.09
234	20.18	4.14	24.32
235	24.41	0.43	24.85
236	20.37	0.44	20.81
237	23.83	0.52	24.35
238	27.23	0.92	28.15
239	25.91	0.29	26.19
240	4.40	0.24	4.64
241	14.69	3.48	18.17
242	5.00	0.01	5.01
243	14.30	0.25	14.55
244	30.17	0.49	30.66
245	29.29	0.49	29.78
246	16.36	0.94	17.30
247	29.32	0.47	29.80
248	5.09	21.86	26.95
249	20.24	0.75	20.99
250	8.55	1.08	9.63
251	0.85	8.40	9.25
252	18.02	0.63	18.65
253	27.88	0.46	28.34
254	17.90	0.26	18.15
255	20.93	0.17	21.10
256	28.43	1.24	29.67
257	26.99	0.49	27.48
258	24.09	0.66	24.75
259	20.09	1.04	21.13
260	18.54	0.73	19.27
261	19.33	0.32	19.65
262	16.77	2.13	18.90
263	6.76	1.44	8.21
264	18.73	0.26	18.99
265	23.98	0.42	24.41
266	24.41	0.44	24.85
267	18.69	0.56	19.25
268	15.35	1.05	16.40
269	19.35	2.64	21.98
270	34.44	1.17	35.61

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
271	3.27	0.26	3.53
272	28.27	0.28	28.55
273	17.56	1.57	19.13
274	31.06	0.22	31.28
275	7.36	0.65	8.01
276	2.90	0.87	3.77
277	12.76	0.26	13.02
278	22.40	0.42	22.83
279	11.16	3.27	14.44
280	5.80	0.05	5.85
281	4.70	0.17	4.87
282	3.17	1.46	4.63
283	22.80	0.13	22.93
284	9.84	5.44	15.28
285	19.23	1.46	20.69
286	28.95	0.03	28.98
287	9.41	1.97	11.38
288	12.08	0.51	12.59
289	16.74	3.31	20.05
290	7.06	0.62	7.68
291	16.63	0.01	16.63
292	6.41	0.47	6.88
293	19.26	0.22	19.47
294	5.06	0.27	5.33
295	12.17	1.76	13.93
296	29.00	2.85	31.84
297	21.26	0.53	21.78
298	22.79	0.33	23.13
299	4.10	0.41	4.51
300	22.44	0.24	22.68
301	24.04	1.28	25.32
302	24.07	4.16	28.23
303	12.80	0.60	13.40
304	24.57	1.29	25.86
305	24.25	0.36	24.61
306	32.93	0.24	33.17
307	26.40	0.38	26.78
308	23.45	0.44	23.89
309	4.94	0.56	5.50
310	0.10	3.52	3.61
311	23.65	0.02	23.67
312	23.45	0.37	23.82
313	28.21	0.37	28.58
314	22.42	0.54	22.97
315	21.24	0.35	21.59

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
316	22.91	0.45	23.37
317	11.96	2.26	14.22
318	15.60	0.89	16.49
319	17.73	0.37	18.11
320	22.70	1.10	23.80
321	5.23	0.50	5.73
322	20.81	0.61	21.42
323	27.75	0.61	28.35
324	7.05	0.23	7.28
325	21.49	5.06	26.55
326	0.31	0.98	1.29
327	17.00	0.01	17.01
328	22.24	0.70	22.94
329	0.57	0.01	0.58
330	23.71	0.15	23.85
331	22.93	0.97	23.90
332	20.18	0.48	20.67
333	23.28	1.01	24.29
334	23.37	0.55	23.92
335	22.22	0.20	22.42
336	21.45	0.25	21.70
337	1.25	1.72	2.97
338	27.47	2.72	30.19
339	17.40	0.64	18.04
340	11.19	12.05	23.24
341	10.72	0.11	10.83
342	12.24	0.94	13.17
343	10.13	1.09	11.22
344	14.65	0.43	15.08
345	9.45	0.26	9.71
346	7.73	0.21	7.94
347	24.38	1.27	25.65
348	19.75	2.02	21.77
349	4.29	0.73	5.02
350	29.03	6.57	35.60
351	12.44	0.52	12.96
352	0.00	2.94	2.94
353	1.19	3.22	4.41
354	27.86	4.11	31.97
355	20.74	0.05	20.79
356	17.62	0.46	18.08
357	34.83	1.41	36.24
358	15.09	0.26	15.34
359	8.52	0.03	8.54
360	25.48	0.44	25.93

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
361	1.73	1.07	2.80
362	2.58	0.34	2.93
363	7.93	0.57	8.49
364	14.17	10.41	24.58
365	12.46	0.91	13.38
366	8.00	0.50	8.50
367	15.60	1.93	17.53
368	11.82	0.76	12.58
369	14.74	1.86	16.60
370	29.20	0.63	29.83
371	27.93	2.82	30.75
372	21.15	0.46	21.62
373	28.17	2.44	30.61
374	22.01	0.55	22.56
375	30.42	0.98	31.39
376	32.80	0.75	33.54
377	26.85	0.10	26.95
378	27.87	0.73	28.60
379	22.27	0.59	22.86
380	21.49	0.72	22.21
381	23.11	0.29	23.40
382	3.51	0.01	3.52
383	16.63	0.51	17.14
384	5.82	0.62	6.44
385	16.77	0.15	16.92
386	6.53	0.55	7.08
387	21.97	0.70	22.67
388	21.37	0.53	21.89
389	26.16	0.29	26.45
390	12.17	0.81	12.98
391	11.25	0.06	11.31
392	5.91	0.47	6.38
393	15.09	5.10	20.19
394	10.07	0.01	10.08
395	24.73	1.85	26.58
396	26.74	0.62	27.36
397	19.35	0.48	19.83
398	19.88	0.23	20.11
399	18.87	0.82	19.69
400	9.44	0.25	9.69
401	3.71	0.25	3.96
402	27.69	1.55	29.24
403	31.87	1.06	32.93
404	22.89	0.00	22.90
405	3.83	0.33	4.16

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
406	16.85	0.52	17.37
407	25.42	0.51	25.93
408	19.79	0.47	20.26
409	0.01	0.03	0.04
410	2.67	0.01	2.68
411	17.50	0.43	17.93
412	18.11	0.44	18.55
413	16.16	0.53	16.69
414	20.88	0.70	21.58
415	22.74	0.48	23.22
416	15.07	0.86	15.93
417	6.02	6.02	12.04
418	24.39	0.43	24.82
419	10.12	0.42	10.54
420	10.82	0.39	11.21
421	12.53	0.26	12.79
422	6.62	0.15	6.77
423	14.60	1.29	15.89
424	18.05	0.43	18.49
425	16.11	0.23	16.34
426	17.41	0.43	17.84
427	20.18	0.65	20.84
428	15.91	3.11	19.02
429	13.06	0.36	13.43
430	13.10	0.42	13.52
431	16.24	0.36	16.59
432	15.40	0.21	15.61
433	10.50	0.48	10.98
434	11.73	0.01	11.74
435	21.98	0.95	22.93
436	17.85	0.65	18.50
437	18.92	0.25	19.17
438	14.12	0.24	14.35
439	18.14	0.43	18.56
440	12.43	0.67	13.09
441	14.65	1.98	16.63
442	15.06	0.65	15.71
443	3.99	0.80	4.80
444	24.69	5.17	29.86
445	21.24	0.54	21.78
446	24.94	0.78	25.72
447	17.18	0.82	18.00
448	2.56	0.05	2.61
449	15.40	0.26	15.66
450	21.40	0.42	21.82

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
451	1.13	0.47	1.60
452	13.34	0.07	13.41
453	13.37	0.43	13.80
454	13.56	0.36	13.93
455	7.22	0.43	7.65
456	22.89	2.48	25.37
457	1.64	0.26	1.90
458	18.20	0.37	18.58
459	17.85	0.76	18.61
460	8.38	0.54	8.91
461	14.47	0.46	14.94
462	20.56	0.50	21.06
463	13.50	0.60	14.10
464	16.44	0.56	17.00
465	9.85	0.28	10.13
466	15.95	8.42	24.38
467	18.67	0.48	19.15
468	19.13	0.66	19.79
469	20.83	3.55	24.38
470	17.48	0.37	17.85
471	17.16	0.33	17.49
472	3.36	0.37	3.73
473	17.18	0.46	17.64
474	17.78	0.59	18.37
475	1.12	0.40	1.53
476	19.76	1.11	20.87
477	16.89	0.95	17.84
478	23.84	0.38	24.22
479	19.35	0.37	19.72
480	6.69	0.01	6.70
481	11.08	0.42	11.50
482	23.82	0.72	24.54
483	17.37	0.87	18.24
484	23.55	2.07	25.62
485	21.66	0.40	22.06
486	8.36	0.47	8.83
487	12.38	0.45	12.83
488	14.35	0.71	15.07
489	16.22	0.35	16.57
490	16.38	1.15	17.53
491	20.69	2.47	23.16
492	12.72	0.45	13.17
493	6.38	0.58	6.97
494	17.17	0.48	17.65
495	11.00	0.38	11.39

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
496	1.93	0.05	1.98
497	5.05	0.55	5.61
498	23.42	0.46	23.88
499	19.52	1.61	21.13
500	20.73	4.03	24.76
501	18.63	0.23	18.86
502	24.14	1.12	25.26
503	24.17	0.31	24.49
504	15.40	0.43	15.83
505	13.67	0.70	14.37
506	2.21	0.01	2.23
507	17.83	0.68	18.51
508	20.25	0.30	20.55
509	20.92	0.23	21.15
510	17.82	0.38	18.20
511	20.83	0.16	20.99
512	9.82	0.38	10.20
513	4.97	3.59	8.56
514	16.07	1.96	18.02
515	16.95	0.41	17.36
516	3.27	0.78	4.05
517	18.95	0.22	19.17
518	19.54	0.79	20.33
519	12.62	0.52	13.14
520	22.44	0.76	23.20
521	25.12	0.65	25.77
522	22.39	0.75	23.14
523	19.89	0.26	20.15
524	23.76	0.43	24.19
525	19.69	0.21	19.90
526	33.98	0.33	34.31
527	28.43	8.43	36.86
528	28.14	0.88	29.02
529	22.34	0.36	22.69
530	23.05	0.49	23.54
531	24.87	0.55	25.42
532	21.18	0.78	21.96
533	25.92	1.03	26.94
534	21.25	0.81	22.06
535	23.11	1.03	24.13
536	4.25	0.07	4.32
537	16.11	1.23	17.35
538	2.47	0.01	2.48
539	23.13	0.74	23.87
540	2.50	0.17	2.67

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
541	26.79	0.48	27.27
542	26.00	0.18	26.18
543	21.34	0.47	21.81
544	10.40	0.76	11.16
545	23.68	0.41	24.10
546	16.87	0.74	17.61
547	1.36	0.16	1.52
548	22.55	3.72	26.27
549	18.64	0.22	18.86
550	29.20	0.00	29.20
551	22.84	0.50	23.34
552	26.05	0.53	26.58
553	22.83	0.39	23.22
554	3.59	0.03	3.62
555	24.25	0.55	24.80
556	28.83	0.73	29.55
557	21.41	1.01	22.42
558	19.75	0.67	20.42
559	12.86	0.38	13.24
560	12.59	0.06	12.65
561	12.78	0.46	13.24
562	2.19	3.80	5.99
563	25.33	0.42	25.75
564	28.11	0.49	28.61
565	19.58	0.36	19.93
566	29.84	0.45	30.29
567	17.04	0.58	17.62
568	1.43	2.02	3.45
569	22.91	0.36	23.27
570	1.45	0.36	1.81
571	20.02	0.01	20.03
572	24.34	0.23	24.57
573	2.20	1.75	3.95
574	20.42	4.10	24.51
575	10.49	0.24	10.73
576	8.67	0.01	8.67
577	21.66	0.46	22.12
578	25.84	0.24	26.08
579	5.30	0.43	5.73
580	9.85	0.04	9.89
581	3.09	20.23	23.31
582	16.84	0.80	17.63
583	20.85	0.41	21.25
584	21.49	0.64	22.13
585	20.13	0.51	20.63

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
586	10.11	0.67	10.77
587	12.67	1.14	13.81
588	10.21	0.16	10.38
589	11.64	3.22	14.86
590	11.53	0.25	11.78
591	14.62	0.32	14.93
592	4.35	0.13	4.48
593	16.10	1.61	17.72
594	18.73	2.08	20.81
595	13.30	1.64	14.94
596	4.21	0.32	4.53
597	16.28	0.31	16.59
598	23.31	0.31	23.62
599	9.16	0.34	9.49
600	6.29	11.91	18.20
601	17.40	0.14	17.55
602	24.44	0.30	24.74
603	23.52	0.46	23.98
604	16.59	0.74	17.33
605	28.55	0.42	28.98
606	1.06	0.43	1.49
607	1.45	1.41	2.86
608	14.56	2.90	17.47
609	23.99	1.18	25.17
610	28.82	0.94	29.76
611	21.34	0.74	22.08
612	21.21	0.48	21.69
613	5.83	0.42	6.26
614	22.59	0.19	22.78
615	4.66	1.99	6.65
616	24.43	6.14	30.57
617	10.16	0.20	10.36
618	17.14	0.44	17.58
619	26.33	11.51	37.84
620	24.44	0.80	25.25
621	4.86	5.55	10.41
622	29.40	0.25	29.66
623	25.01	2.53	27.54
624	40.00	0.85	40.84
625	32.55	0.24	32.79
626	27.60	0.58	28.18
627	29.61	0.31	29.92
628	28.98	0.39	29.37
629	20.46	0.54	21.00
630	14.61	1.55	16.16

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
631	5.20	0.01	5.21
632	2.87	0.13	3.00
633	20.33	10.73	31.06
634	4.18	0.55	4.73
635	13.05	0.68	13.73
636	17.34	1.10	18.44
637	20.55	0.54	21.09
638	20.74	0.49	21.23
639	14.47	0.70	15.17
640	1.58	0.32	1.90
641	21.99	0.02	22.02
642	20.53	0.32	20.84
643	14.01	0.48	14.49
644	14.82	0.55	15.37
645	10.83	1.86	12.69
646	24.80	1.69	26.49
647	26.14	0.57	26.71
648	18.70	3.58	22.28
649	16.55	0.69	17.24
650	25.25	0.57	25.82
651	27.80	0.60	28.40
652	21.45	1.26	22.70
653	24.55	1.92	26.47
654	24.56	0.29	24.85
655	21.18	0.45	21.62
656	15.95	0.49	16.43
657	21.70	0.42	22.12
658	19.88	2.28	22.16
659	15.73	0.75	16.48
660	7.92	0.58	8.49
661	12.59	1.91	14.50
662	14.57	0.62	15.18
663	18.81	0.20	19.01
664	23.60	0.00	23.60
665	18.48	0.49	18.97
666	18.38	0.50	18.88
667	14.92	0.49	15.40
668	5.03	0.54	5.57
669	15.12	3.62	18.74
670	20.08	0.13	20.21
671	13.89	0.41	14.31
672	0.72	5.79	6.52
673	1.16	5.37	6.52
674	3.91	1.25	5.16
675	12.39	3.30	15.69

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
676	13.53	0.54	14.07
677	13.14	0.45	13.60
678	19.13	0.39	19.52
679	17.00	0.41	17.41
680	14.92	0.82	15.74
681	4.75	0.02	4.77
682	0.14	0.20	0.33
683	20.74	0.01	20.75
684	19.49	0.56	20.04
685	16.97	0.69	17.66
686	12.86	0.23	13.08
687	13.56	0.46	14.02
688	5.42	0.24	5.66
689	16.06	8.39	24.45
690	6.68	0.52	7.20
691	11.90	0.62	12.52
692	3.32	0.46	3.77
693	14.04	4.94	18.98
694	4.85	0.03	4.88
695	15.46	0.76	16.22
696	19.12	0.36	19.48
697	22.93	0.56	23.49
698	18.61	1.25	19.86
699	18.86	0.26	19.13
700	18.80	0.51	19.32
701	13.46	0.41	13.86
702	13.32	0.46	13.78
703	9.70	0.37	10.08
704	19.02	2.18	21.20
705	25.19	0.01	25.20
706	19.08	0.39	19.47
707	22.07	0.17	22.24
708	20.89	0.21	21.10
709	11.61	1.38	12.99
710	2.22	0.01	2.24
711	2.77	0.56	3.33
712	0.56	0.39	0.95
713	10.63	0.08	10.71
714	14.79	0.37	15.15
715	2.12	0.44	2.55
716	15.51	8.49	24.00
717	2.12	0.51	2.63
718	19.92	1.57	21.49
719	0.57	0.68	1.24
720	22.19	2.30	24.48

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
721	13.16	0.05	13.21
722	19.21	3.58	22.79
723	15.50	0.57	16.07
724	20.41	0.59	21.00
725	22.50	0.43	22.92
726	17.24	0.46	17.70
727	21.56	0.19	21.75
728	18.21	0.61	18.81
729	19.51	0.53	20.04
730	19.60	0.66	20.26
731	23.90	0.33	24.23
732	17.20	0.66	17.87
733	24.30	0.41	24.71
734	22.66	2.09	24.75
735	20.91	0.39	21.31
736	14.62	0.31	14.93
737	14.37	1.14	15.51
738	9.25	0.01	9.26
739	1.20	0.75	1.95
740	13.16	0.73	13.89
741	23.44	0.38	23.82
742	2.13	0.01	2.14
743	21.41	0.37	21.78
744	14.35	0.80	15.15
745	17.80	0.44	18.24
746	17.70	0.47	18.17
747	18.07	0.37	18.44
748	16.38	0.41	16.79
749	19.10	3.02	22.12
750	18.23	0.10	18.33
751	18.81	0.50	19.31
752	17.78	0.42	18.20
753	1.32	0.43	1.75
754	14.30	2.15	16.45
755	16.07	0.38	16.45
756	2.88	0.01	2.89
757	21.24	0.39	21.62
758	21.77	0.01	21.78
759	18.21	0.50	18.71
760	26.46	0.52	26.98
761	22.50	0.59	23.09
762	15.33	0.46	15.79
763	22.42	2.69	25.11
764	22.96	0.48	23.43
765	18.59	0.22	18.81

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
766	6.11	0.38	6.49
767	29.23	0.87	30.09
768	19.74	0.26	20.00
769	17.46	0.56	18.02
770	21.35	1.85	23.20
771	23.64	0.33	23.97
772	23.54	0.20	23.73
773	31.24	0.33	31.56
774	25.90	0.23	26.13
775	22.01	0.62	22.63
776	31.65	1.04	32.69
777	2.86	0.50	3.36
778	19.53	0.59	20.12
779	19.89	3.59	23.48
780	26.85	1.04	27.89
781	28.08	0.45	28.54
782	14.27	0.59	14.86
783	26.07	3.05	29.12
784	22.65	0.61	23.26
785	16.17	3.34	19.51
786	7.55	0.43	7.98
787	11.36	0.01	11.37
788	26.74	0.31	27.05
789	21.81	0.38	22.19
790	30.68	0.77	31.45
791	16.15	0.82	16.97
792	18.32	3.49	21.81
793	26.60	2.83	29.43
794	18.80	0.67	19.46
795	18.05	1.08	19.13
796	30.86	0.19	31.05
797	22.29	0.41	22.70
798	26.07	0.42	26.50
799	18.61	1.21	19.82
800	9.79	0.08	9.87
801	15.08	0.52	15.60
802	23.73	25.33	49.06
803	22.54	0.45	23.00
804	14.48	0.41	14.88
805	9.87	0.02	9.89
806	25.37	1.87	27.24
807	26.63	0.48	27.11
808	22.96	0.50	23.46
809	20.66	0.42	21.09
810	21.66	0.40	22.06

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
811	22.26	0.35	22.60
812	5.61	0.65	6.26
813	21.36	0.03	21.39
814	19.70	0.75	20.45
815	3.53	0.37	3.91
816	26.42	0.71	27.13
817	28.29	0.84	29.13
818	6.90	0.85	7.75
819	11.75	0.01	11.76
820	22.81	0.35	23.17
821	23.09	3.62	26.71
822	22.72	1.47	24.19
823	25.05	0.83	25.87
824	22.41	0.40	22.80
825	26.40	0.17	26.58
826	19.89	0.34	20.23
827	26.59	0.07	26.66
828	23.62	1.35	24.97
829	22.55	0.85	23.40
830	22.80	1.31	24.11
831	21.46	0.99	22.46
832	15.26	1.17	16.43
833	8.92	0.17	9.10
834	20.55	3.57	24.12
835	17.38	0.68	18.06
836	18.97	0.75	19.72
837	9.57	0.61	10.17
838	16.29	5.33	21.61
839	9.13	0.55	9.68
840	18.94	0.62	19.57
841	24.22	0.39	24.60
842	24.66	0.66	25.32
843	6.69	0.02	6.71
844	7.24	1.73	8.97
845	24.38	4.60	28.98
846	24.61	3.12	27.73
847	20.70	1.27	21.97
848	24.52	1.04	25.56
849	13.75	0.75	14.50
850	11.92	0.10	12.02
851	2.47	0.87	3.34
852	25.79	0.86	26.65
853	23.33	0.41	23.74
854	27.37	4.11	31.49
855	28.84	0.39	29.23

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
856	21.40	2.16	23.56
857	31.94	0.19	32.12
858	24.69	0.39	25.08
859	30.43	2.85	33.28
860	25.45	0.26	25.71
861	13.61	1.12	14.73
862	13.14	0.01	13.15
863	23.35	0.30	23.65
864	19.11	1.10	20.22
865	28.90	0.84	29.74
866	21.17	0.77	21.93
867	14.31	0.94	15.25
868	15.07	0.01	15.08
869	17.73	0.44	18.17
870	28.89	1.19	30.08
871	13.88	4.65	18.53
872	20.07	7.48	27.54
873	20.48	1.06	21.54
874	22.65	0.51	23.16
875	19.62	1.27	20.89
876	16.96	2.12	19.08
877	17.78	0.47	18.25
878	4.50	0.61	5.11
879	21.69	0.38	22.07
880	0.47	0.02	0.49
881	18.21	0.90	19.11
882	9.08	0.71	9.79
883	13.57	3.29	16.86
884	19.91	0.49	20.40
885	28.03	0.48	28.52
886	23.29	0.99	24.27
887	27.81	0.17	27.98
888	22.84	0.33	23.17
889	24.25	6.82	31.07
890	3.91	6.42	10.33
891	19.88	0.01	19.89
892	17.38	0.45	17.83
893	19.33	0.40	19.74
894	19.45	0.35	19.80
895	2.08	0.12	2.20
896	19.78	0.15	19.93
897	1.31	0.37	1.68
898	21.00	0.10	21.10
899	17.20	1.10	18.30
900	22.13	0.49	22.62

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
901	0.33	0.31	0.64
902	25.08	0.71	25.79
903	18.99	0.28	19.28
904	23.56	0.59	24.16
905	15.67	0.53	16.20
906	3.56	0.05	3.61
907	14.26	8.52	22.78
908	5.67	5.59	11.26
909	11.81	1.17	12.98
910	14.46	0.51	14.97
911	7.34	5.34	12.69
912	11.89	24.30	36.19
913	16.74	2.64	19.38
914	20.74	0.39	21.13
915	17.44	0.34	17.79
916	21.14	0.96	22.10
917	15.90	0.57	16.47
918	10.19	0.31	10.50
919	8.38	2.48	10.86
920	15.71	1.16	16.87
921	13.99	0.66	14.65
922	14.50	0.55	15.04
923	11.58	0.36	11.94
924	13.75	4.87	18.62
925	18.43	0.26	18.69
926	22.63	0.64	23.26
927	5.96	0.72	6.68
928	12.65	0.27	12.92
929	18.43	1.29	19.72
930	14.64	0.63	15.27
931	10.19	1.89	12.08
932	14.00	0.08	14.08
933	14.09	0.43	14.52
934	15.62	0.33	15.95
935	14.14	0.47	14.60
936	30.50	0.35	30.85
937	21.80	0.62	22.42
938	22.46	0.25	22.72
939	26.66	0.98	27.64
940	15.38	0.47	15.85
941	12.32	0.39	12.71
942	20.76	3.34	24.10
943	17.82	1.02	18.84
944	17.86	0.59	18.45
945	19.73	0.42	20.15

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
946	19.07	0.97	20.04
947	14.35	0.79	15.14
948	8.42	1.19	9.61
949	7.73	0.79	8.51
950	9.53	0.01	9.54
951	13.28	0.43	13.71
952	13.27	0.30	13.56
953	5.97	0.50	6.46
954	19.18	0.26	19.44
955	18.67	0.30	18.97
956	23.14	0.01	23.15
957	22.26	0.92	23.17
958	21.43	7.03	28.46
959	1.64	0.94	2.58
960	20.33	0.41	20.74
961	16.92	0.61	17.53
962	20.85	0.43	21.28
963	22.56	0.80	23.36
964	21.79	0.41	22.20
965	20.04	3.72	23.75
966	6.77	0.07	6.83
967	13.57	0.01	13.58
968	15.09	0.01	15.10
969	25.99	0.49	26.48
970	20.27	0.43	20.70
971	10.98	0.49	11.47
972	23.92	4.42	28.35
973	19.59	0.67	20.26
974	20.23	0.29	20.52
975	21.64	0.46	22.09
976	17.17	0.40	17.57
977	20.24	0.43	20.67
978	0.82	0.01	0.83
979	22.51	0.39	22.90
980	14.14	0.47	14.60
981	18.38	0.48	18.86
982	19.75	0.36	20.12
983	21.93	0.19	22.13
984	19.08	0.25	19.33
985	24.10	5.84	29.94
986	16.76	0.51	17.26
987	17.39	0.46	17.85
988	14.40	0.30	14.70
989	8.89	0.37	9.26
990	21.54	0.41	21.95

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
991	13.71	0.43	14.14
992	2.58	0.02	2.59
993	21.44	0.27	21.70
994	28.98	0.38	29.36
995	25.34	0.52	25.86
996	19.22	0.26	19.48
997	20.16	0.45	20.61
998	13.69	0.35	14.04
999	6.48	6.64	13.12
1000	32.27	1.26	33.53
1001	21.06	0.38	21.43
1002	25.91	0.40	26.31
1003	23.04	0.35	23.39
1004	25.73	0.38	26.11
1005	16.99	0.82	17.81
1006	1.31	0.01	1.33
1007	22.10	0.41	22.50
1008	29.38	0.57	29.95
1009	13.66	0.34	14.00
1010	10.81	1.88	12.69
1011	26.09	1.01	27.09
1012	22.77	0.46	23.23
1013	13.31	0.38	13.69
1014	12.38	0.01	12.38
1015	6.83	0.31	7.14
1016	26.20	0.59	26.79
1017	24.84	0.44	25.28
1018	9.70	0.04	9.74
1019	17.09	10.75	27.83
1020	17.53	0.82	18.35
1021	21.68	0.51	22.19
1022	19.47	0.02	19.49
1023	6.29	0.95	7.24
1024	17.51	0.94	18.45
1025	11.56	0.28	11.84
1026	2.51	0.53	3.04
1027	6.32	1.46	7.78
1028	24.16	0.36	24.52
1029	2.86	0.03	2.89
1030	19.17	0.84	20.02
1031	28.47	0.45	28.92
1032	26.95	0.56	27.51
1033	21.74	1.49	23.23
1034	26.12	0.88	27.00
1035	25.27	0.24	25.51

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1036	7.33	8.74	16.07
1037	25.98	0.60	26.58
1038	25.22	0.45	25.67
1039	22.61	0.51	23.12
1040	28.65	0.54	29.19
1041	14.80	0.77	15.57
1042	31.62	0.47	32.09
1043	7.48	0.85	8.33
1044	10.03	0.54	10.57
1045	23.97	0.55	24.52
1046	25.24	1.12	26.36
1047	23.35	0.52	23.87
1048	21.82	0.15	21.97
1049	12.05	0.01	12.05
1050	9.42	0.87	10.28
1051	6.22	3.23	9.45
1052	21.95	0.68	22.62
1053	23.35	0.58	23.93
1054	28.10	0.95	29.05
1055	18.68	3.48	22.16
1056	21.81	1.52	23.33
1057	19.91	0.55	20.46
1058	19.09	0.28	19.37
1059	28.56	2.84	31.40
1060	23.11	0.75	23.86
1061	21.59	0.39	21.98
1062	17.97	0.70	18.67
1063	28.00	4.36	32.36
1064	16.59	0.21	16.80
1065	17.88	1.16	19.03
1066	21.54	0.19	21.73
1067	14.55	0.49	15.04
1068	19.49	0.41	19.90
1069	22.28	0.01	22.29
1070	2.81	1.04	3.84
1071	21.22	0.78	22.00
1072	17.61	0.43	18.03
1073	29.97	1.14	31.11
1074	19.32	0.33	19.65
1075	24.53	0.21	24.74
1076	28.86	7.78	36.64
1077	22.36	1.15	23.51
1078	20.49	0.08	20.56
1079	12.43	0.54	12.97
1080	10.96	0.94	11.90

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1081	11.51	0.62	12.13
1082	29.14	0.76	29.90
1083	25.60	0.63	26.23
1084	23.10	1.40	24.50
1085	29.14	0.00	29.15
1086	20.74	1.12	21.86
1087	28.18	0.47	28.65
1088	23.72	0.34	24.06
1089	30.99	0.33	31.32
1090	33.86	3.94	37.80
1091	25.27	1.11	26.38
1092	30.17	0.81	30.99
1093	24.12	0.00	24.12
1094	0.37	0.02	0.39
1095	24.10	1.67	25.77
1096	18.76	0.01	18.77
1097	13.49	1.02	14.51
1098	15.36	0.36	15.72
1099	19.15	0.46	19.61
1100	27.26	0.21	27.48
1101	21.14	0.35	21.49
1102	27.42	0.39	27.81
1103	25.31	1.13	26.44
1104	22.71	2.83	25.54
1105	6.40	29.80	36.19
1106	12.34	0.38	12.73
1107	14.20	2.42	16.63
1108	19.99	1.03	21.02
1109	20.81	0.56	21.37
1110	24.51	0.41	24.93
1111	42.43	0.63	43.06
1112	4.17	10.24	14.41
1113	2.49	0.94	3.44
1114	5.92	0.01	5.93
1115	13.76	1.47	15.22
1116	20.12	0.27	20.39
1117	0.78	2.95	3.73
1118	31.77	0.49	32.25
1119	20.71	0.51	21.22
1120	19.08	0.69	19.76
1121	21.54	0.93	22.47
1122	21.81	1.05	22.86
1123	31.52	0.71	32.23
1124	6.47	0.59	7.06
1125	11.29	1.26	12.55

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1126	11.22	0.52	11.74
1127	2.53	1.56	4.09
1128	9.90	0.52	10.43
1129	0.18	0.02	0.20
1130	23.99	1.00	24.99
1131	17.87	1.58	19.45
1132	0.75	0.53	1.28
1133	6.53	4.59	11.12
1134	13.02	0.53	13.55
1135	19.28	10.24	29.52
1136	15.36	0.28	15.64
1137	1.50	0.61	2.12
1138	16.76	0.14	16.90
1139	14.23	1.00	15.23
1140	3.89	0.53	4.42
1141	3.19	1.88	5.07
1142	11.70	0.74	12.44
1143	5.04	4.99	10.03
1144	19.91	0.68	20.59
1145	19.32	0.48	19.79
1146	20.50	0.46	20.96
1147	18.95	0.41	19.36
1148	22.31	0.56	22.87
1149	7.25	18.07	25.32
1150	18.65	1.34	19.99
1151	14.64	0.77	15.41
1152	10.86	1.74	12.61
1153	6.71	0.45	7.16
1154	11.46	4.88	16.34
1155	14.35	0.02	14.38
1156	5.04	0.85	5.89
1157	19.17	3.04	22.22
1158	16.94	3.60	20.54
1159	28.21	0.45	28.65
1160	6.68	0.15	6.83
1161	10.81	1.08	11.89
1162	16.88	0.64	17.53
1163	6.46	0.63	7.10
1164	8.84	1.06	9.90
1165	7.60	0.37	7.97
1166	13.96	0.58	14.54
1167	14.65	0.52	15.17
1168	5.01	6.30	11.31
1169	28.70	4.59	33.29
1170	20.57	0.49	21.05

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1171	21.43	1.86	23.29
1172	15.42	13.44	28.86
1173	3.93	6.95	10.87
1174	1.12	1.70	2.82
1175	4.41	1.97	6.38
1176	14.27	0.58	14.85
1177	16.66	0.58	17.25
1178	22.68	1.51	24.19
1179	20.64	0.44	21.07
1180	1.02	0.32	1.33
1181	24.14	0.02	24.16
1182	20.39	0.09	20.48
1183	21.86	0.36	22.22
1184	19.71	0.38	20.09
1185	4.94	0.60	5.54
1186	19.06	0.69	19.76
1187	17.18	1.46	18.64
1188	21.91	0.58	22.49
1189	12.56	0.26	12.82
1190	15.08	0.50	15.58
1191	20.72	1.14	21.86
1192	23.22	0.43	23.66
1193	14.86	0.44	15.29
1194	19.02	0.36	19.38
1195	20.83	0.70	21.53
1196	10.23	0.12	10.35
1197	21.16	2.44	23.61
1198	6.40	5.23	11.63
1199	15.05	0.01	15.06
1200	12.95	0.07	13.03
1201	14.95	0.47	15.43
1202	25.59	1.94	27.53
1203	6.18	1.02	7.21
1204	10.75	0.58	11.33
1205	15.26	0.51	15.77
1206	16.92	0.77	17.68
1207	25.86	0.33	26.18
1208	19.61	0.37	19.98
1209	6.96	2.76	9.72
1210	14.71	0.39	15.10
1211	20.27	0.10	20.37
1212	24.56	0.42	24.99
1213	19.71	0.57	20.28
1214	15.67	1.38	17.04
1215	21.21	0.40	21.60

Table B-6: Calculating MTBF for stations 9 and 12.

Breakdown	TTF (hours)	TTR (hours)	TBF (hours)
1216	20.53	3.54	24.07
1217	25.58	0.59	26.17
1218	13.64	1.38	15.02
1219	23.32	0.72	24.04
1220	18.70	0.67	19.36
1221	20.81	0.84	21.65
1222	27.20	1.63	28.83
1223	0.63	1.98	2.61
1224	3.24	0.49	3.73
1225	2.50	17.66	20.16
1226	11.63	1.91	13.53
1227	15.41	0.86	16.27
1228	29.79	0.50	30.28
1229	6.66	0.48	7.15
1230	14.94	1.30	16.24
1231	5.24	0.57	5.81
1232	10.04	0.58	10.62
1233	10.60	1.14	11.74
1234	23.51	0.43	23.94
1235	31.90	3.67	35.58
1236	21.55	1.26	22.81
1237	28.84	0.28	29.12
1238	8.41	5.19	13.61
1239	26.18	0.39	26.56
1240	23.52	0.59	24.11
1241	24.35	0.24	24.60
1242	18.29	1.13	19.42
1243	27.61	0.57	28.19
1244	24.49	0.29	24.78
1245	33.56	0.51	34.07
MTBF (hours)			18.35

A p p e n d i x   C

C REPORTED UTILISATIONS

This Appendix presents the average utilisation of stations monitored at the end of every week. The values given in Table C-1 shows the reported results of the Push-daily loading (representing the original loading of the segment) to a single run that covers two years (104 weeks) including the first 10 weeks of the warm up period. It is clear from the results that the U of all stations are below the U_{max}.

Table C-1: Reported utilisations of Batch.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.49	0.15	0.55	0.29	0.25	0.50	0.20	0.48	0.32	0.44	0.44	0.29
2	0.57	0.17	0.63	0.34	0.29	0.55	0.23	0.55	0.37	0.58	0.54	0.38
3	0.56	0.17	0.61	0.34	0.29	0.61	0.23	0.51	0.36	0.57	0.54	0.40
4	0.58	0.19	0.66	0.37	0.32	0.69	0.25	0.56	0.40	0.63	0.59	0.44
5	0.59	0.19	0.67	0.37	0.32	0.69	0.25	0.60	0.41	0.65	0.58	0.44
6	0.59	0.19	0.69	0.37	0.32	0.72	0.26	0.59	0.41	0.64	0.59	0.44
7	0.57	0.19	0.68	0.37	0.32	0.72	0.26	0.59	0.41	0.65	0.60	0.44
8	0.56	0.19	0.68	0.37	0.32	0.71	0.26	0.59	0.41	0.66	0.61	0.44
9	0.57	0.19	0.67	0.37	0.32	0.68	0.26	0.58	0.40	0.65	0.60	0.43
10	0.58	0.19	0.69	0.37	0.32	0.71	0.26	0.59	0.41	0.66	0.60	0.44
11	0.57	0.19	0.69	0.37	0.32	0.70	0.26	0.59	0.41	0.66	0.60	0.44
12	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.59	0.40	0.65	0.60	0.44
13	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.41	0.66	0.60	0.44
14	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.41	0.66	0.60	0.44
15	0.58	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.45
16	0.57	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.45
17	0.58	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.41	0.65	0.61	0.45
18	0.59	0.19	0.67	0.37	0.32	0.69	0.26	0.59	0.40	0.65	0.61	0.44
19	0.59	0.19	0.68	0.37	0.32	0.70	0.26	0.59	0.41	0.66	0.61	0.45
20	0.58	0.19	0.68	0.38	0.32	0.70	0.26	0.60	0.41	0.67	0.62	0.45
21	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.45
22	0.59	0.19	0.69	0.38	0.33	0.70	0.26	0.60	0.41	0.67	0.61	0.45
23	0.58	0.19	0.69	0.38	0.33	0.70	0.26	0.61	0.41	0.67	0.62	0.45
24	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.60	0.41	0.67	0.61	0.45
25	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.61	0.41	0.67	0.61	0.45
26	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.61	0.41	0.67	0.61	0.45
27	0.57	0.19	0.69	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.61	0.45
28	0.58	0.19	0.69	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.61	0.46
29	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.61	0.46
30	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.61	0.41	0.67	0.61	0.46
31	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.61	0.46

Table C-1: Reported utilisations of Batch.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
32	0.58	0.19	0.69	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.61	0.46
33	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.62	0.46
34	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.62	0.46
35	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.61	0.46
36	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.61	0.41	0.67	0.61	0.46
37	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.61	0.41	0.68	0.61	0.46
38	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.61	0.41	0.68	0.61	0.46
39	0.58	0.19	0.70	0.38	0.33	0.69	0.26	0.61	0.41	0.68	0.61	0.46
40	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.61	0.41	0.68	0.61	0.46
41	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.61	0.46
42	0.58	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.68	0.61	0.46
43	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.61	0.46
44	0.58	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.68	0.61	0.46
45	0.58	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.68	0.61	0.46
46	0.58	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.68	0.61	0.46
47	0.58	0.19	0.69	0.38	0.33	0.69	0.26	0.62	0.41	0.67	0.61	0.46
48	0.58	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.68	0.61	0.46
49	0.57	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.68	0.61	0.46
50	0.57	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.68	0.61	0.46
51	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.61	0.46
52	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.61	0.46
53	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.61	0.46
54	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.61	0.46
55	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.61	0.46
56	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.61	0.46
57	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
58	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.62	0.46
59	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
60	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.68	0.62	0.46
61	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.68	0.62	0.46
62	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.68	0.62	0.46
63	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.68	0.62	0.46
64	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.68	0.62	0.46
65	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
66	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.68	0.62	0.46
67	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
68	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
69	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
70	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.68	0.62	0.46
71	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
72	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
73	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
74	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
75	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
76	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46

Table C-1: Reported utilisations of Batch.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
77	0.57	0.19	0.71	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
78	0.57	0.19	0.71	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
79	0.57	0.19	0.71	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
80	0.57	0.19	0.71	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
81	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
82	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
83	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
84	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
85	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
86	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
87	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
88	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
89	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
90	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
91	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
92	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
93	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
94	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
95	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
96	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
97	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.62	0.47
98	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.63	0.47
99	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.63	0.47
100	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.63	0.47
101	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.63	0.47
102	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.63	0.47
103	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.63	0.47
104	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.63	0.47

It should be noted that the reported results of the Push-det., CONWIP, ICONWIP, DBR, Hybrid CONWIP/DBR, and LCONWIP presented and selected in the thesis earlier are shown in Table C-2, Table C-3, Table C-4, Table C-5, Table C-6, and Table C-7 respectively. Every table shows the results of a single run that covers a simulation run time of two years (104 weeks) including the first 10 weeks of the warm up period. It is clear from the results shown that for all the lot release control strategies tested the U of all the stations are ensured to be below the U_{max}. However, only when DBR and Hybrid CONWIP/DBR are applied, the U of station 3 rarely reached the U_{max} (10 out of 104 weeks at DBR and 3 out of 104 weeks at Hybrid CONWIP/DBR).

Table C-2: Reported utilisation of Push Lot.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.48	0.14	0.51	0.28	0.24	0.47	0.18	0.45	0.31	0.42	0.41	0.27
2	0.56	0.17	0.61	0.34	0.28	0.54	0.22	0.53	0.37	0.55	0.52	0.37
3	0.55	0.17	0.60	0.33	0.28	0.60	0.22	0.51	0.36	0.55	0.52	0.39
4	0.58	0.18	0.65	0.37	0.31	0.69	0.25	0.56	0.40	0.62	0.58	0.44
5	0.59	0.18	0.66	0.37	0.31	0.69	0.25	0.60	0.40	0.64	0.57	0.44
6	0.59	0.19	0.68	0.37	0.32	0.71	0.26	0.60	0.41	0.64	0.58	0.44
7	0.57	0.19	0.67	0.37	0.32	0.72	0.26	0.60	0.41	0.64	0.59	0.44
8	0.56	0.19	0.67	0.37	0.32	0.71	0.26	0.59	0.41	0.66	0.60	0.44
9	0.58	0.19	0.67	0.37	0.32	0.68	0.25	0.59	0.40	0.65	0.59	0.43
10	0.57	0.19	0.69	0.37	0.32	0.71	0.26	0.60	0.41	0.66	0.60	0.44
11	0.57	0.19	0.69	0.37	0.32	0.69	0.26	0.60	0.41	0.65	0.60	0.44
12	0.57	0.19	0.68	0.37	0.32	0.68	0.26	0.59	0.40	0.64	0.59	0.44
13	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.41	0.66	0.60	0.44
14	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.41	0.65	0.60	0.44
15	0.58	0.19	0.68	0.37	0.32	0.70	0.26	0.61	0.41	0.65	0.61	0.45
16	0.57	0.19	0.68	0.37	0.32	0.70	0.26	0.61	0.41	0.66	0.61	0.45
17	0.58	0.19	0.67	0.37	0.32	0.69	0.26	0.60	0.41	0.65	0.60	0.45
18	0.59	0.19	0.67	0.37	0.32	0.69	0.26	0.59	0.40	0.65	0.61	0.44
19	0.59	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.45
20	0.58	0.19	0.68	0.38	0.32	0.70	0.26	0.61	0.41	0.66	0.62	0.45
21	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.45
22	0.59	0.19	0.69	0.38	0.33	0.70	0.26	0.61	0.41	0.67	0.61	0.45
23	0.58	0.19	0.69	0.38	0.33	0.70	0.26	0.61	0.41	0.67	0.61	0.45
24	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.61	0.41	0.66	0.61	0.45
25	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.61	0.41	0.67	0.61	0.45
26	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.61	0.41	0.67	0.61	0.45
27	0.58	0.19	0.69	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.61	0.46
28	0.58	0.19	0.69	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.61	0.46
29	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.61	0.46
30	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.61	0.41	0.67	0.61	0.46
31	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.61	0.46
32	0.58	0.19	0.69	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.61	0.46
33	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.62	0.46
34	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.62	0.46
35	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.61	0.46
36	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.61	0.46
37	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.61	0.46
38	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.61	0.46
39	0.58	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.68	0.61	0.46
40	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.61	0.47
41	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.61	0.47
42	0.58	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.68	0.61	0.46
43	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.61	0.46

Table C-2: Reported utilisation of Push Lot.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
44	0.58	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.68	0.61	0.46
45	0.58	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.68	0.61	0.46
46	0.58	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.68	0.61	0.47
47	0.58	0.19	0.69	0.38	0.33	0.69	0.26	0.62	0.41	0.67	0.61	0.46
48	0.58	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.67	0.61	0.46
49	0.58	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.68	0.61	0.46
50	0.57	0.19	0.70	0.38	0.33	0.69	0.26	0.62	0.41	0.67	0.61	0.46
51	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.61	0.46
52	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.61	0.46
53	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.61	0.46
54	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.61	0.46
55	0.57	0.19	0.69	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.61	0.46
56	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.61	0.46
57	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.62	0.46
58	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.62	0.47
59	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
60	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.62	0.47
61	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.62	0.47
62	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
63	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
64	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
65	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
66	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
67	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
68	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
69	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
70	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
71	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
72	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
73	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.62	0.47
74	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
75	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
76	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
77	0.57	0.19	0.71	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
78	0.57	0.19	0.71	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
79	0.57	0.19	0.71	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.62	0.47
80	0.57	0.19	0.71	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
81	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
82	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
83	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
84	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
85	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
86	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
87	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
88	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47

Table C-2: Reported utilisation of Push Lot.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
89	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
90	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
91	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
92	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
93	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
94	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
95	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
96	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
97	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.63	0.47
98	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.63	0.47
99	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.63	0.47
100	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.63	0.47
101	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.63	0.47
102	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.63	0.47
103	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.63	0.47
104	0.57	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.63	0.47

Table C-3: Reported utilisations of CONWIP.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.59	0.18	0.66	0.35	0.30	0.58	0.24	0.57	0.40	0.58	0.55	0.36
2	0.59	0.18	0.64	0.35	0.30	0.59	0.24	0.56	0.39	0.60	0.57	0.39
3	0.56	0.17	0.61	0.34	0.29	0.62	0.23	0.51	0.36	0.56	0.53	0.39
4	0.57	0.18	0.64	0.36	0.31	0.67	0.25	0.55	0.39	0.61	0.57	0.43
5	0.57	0.18	0.65	0.36	0.31	0.67	0.25	0.58	0.39	0.63	0.56	0.43
6	0.57	0.18	0.66	0.36	0.31	0.69	0.25	0.58	0.40	0.62	0.57	0.43
7	0.57	0.19	0.67	0.37	0.32	0.72	0.26	0.59	0.41	0.64	0.59	0.43
8	0.57	0.19	0.68	0.38	0.32	0.72	0.26	0.60	0.41	0.66	0.61	0.44
9	0.57	0.18	0.67	0.36	0.31	0.68	0.25	0.58	0.40	0.64	0.59	0.43
10	0.57	0.19	0.68	0.37	0.32	0.70	0.26	0.59	0.40	0.65	0.59	0.43
11	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.41	0.66	0.60	0.44
12	0.57	0.19	0.68	0.37	0.32	0.68	0.26	0.59	0.40	0.64	0.59	0.43
13	0.57	0.19	0.68	0.37	0.32	0.68	0.26	0.59	0.40	0.66	0.60	0.44
14	0.57	0.19	0.67	0.37	0.32	0.68	0.26	0.60	0.40	0.65	0.60	0.44
15	0.57	0.19	0.67	0.37	0.32	0.69	0.26	0.60	0.40	0.65	0.60	0.44
16	0.57	0.19	0.67	0.37	0.32	0.70	0.26	0.60	0.40	0.65	0.60	0.44
17	0.57	0.19	0.67	0.37	0.32	0.68	0.26	0.59	0.40	0.65	0.60	0.44
18	0.57	0.18	0.66	0.36	0.31	0.68	0.25	0.58	0.40	0.64	0.60	0.43
19	0.58	0.19	0.66	0.37	0.32	0.69	0.26	0.59	0.40	0.65	0.60	0.44
20	0.57	0.19	0.67	0.37	0.32	0.69	0.26	0.60	0.40	0.65	0.61	0.44
21	0.57	0.19	0.68	0.37	0.32	0.68	0.26	0.59	0.40	0.65	0.60	0.44
22	0.58	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.40	0.65	0.60	0.44

Table C-3: Reported utilisations of CONWIP.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
23	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.45
24	0.58	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.45
25	0.58	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.40	0.66	0.60	0.45
26	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.60	0.40	0.66	0.60	0.45
27	0.57	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.40	0.66	0.61	0.45
28	0.57	0.19	0.69	0.37	0.32	0.70	0.26	0.61	0.41	0.67	0.61	0.45
29	0.58	0.19	0.69	0.38	0.33	0.70	0.26	0.61	0.41	0.67	0.61	0.46
30	0.58	0.19	0.70	0.38	0.32	0.70	0.26	0.61	0.41	0.67	0.61	0.46
31	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.61	0.46
32	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.62	0.46
33	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.62	0.46
34	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.62	0.46
35	0.59	0.19	0.70	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
36	0.59	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
37	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
38	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.61	0.47
39	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.61	0.47
40	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.62	0.47
41	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.62	0.47
42	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
43	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
44	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
45	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
46	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
47	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
48	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
49	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
50	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
51	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
52	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
53	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
54	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
55	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
56	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
57	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.41	0.68	0.62	0.47
58	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
59	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.62	0.41	0.68	0.62	0.47
60	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
61	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
62	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
63	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
64	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
65	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
66	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
67	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47

Table C-3: Reported utilisations of CONWIP.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
68	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.41	0.68	0.62	0.47
69	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.41	0.68	0.62	0.47
70	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
71	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.62	0.47
72	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
73	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
74	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.63	0.47
75	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.63	0.47
76	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.63	0.47
77	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
78	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
79	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.63	0.47
80	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
81	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
82	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.63	0.47
83	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
84	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
85	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
86	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
87	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
88	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
89	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
90	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
91	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
92	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
93	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
94	0.57	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.63	0.47
95	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.63	0.47
96	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.48
97	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.48
98	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
99	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
100	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
101	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
102	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
103	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
104	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.64	0.48

Table C-4: Reported utilisations of ICONWIP.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.58	0.17	0.64	0.34	0.29	0.58	0.23	0.56	0.38	0.56	0.54	0.35

Table C-4: Reported utilisations of ICONWIP.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
2	0.59	0.18	0.64	0.35	0.30	0.58	0.24	0.56	0.39	0.60	0.56	0.39
3	0.55	0.17	0.60	0.33	0.28	0.62	0.23	0.51	0.36	0.56	0.53	0.39
4	0.56	0.18	0.63	0.35	0.30	0.67	0.24	0.55	0.39	0.61	0.57	0.42
5	0.57	0.18	0.64	0.36	0.30	0.67	0.25	0.58	0.39	0.63	0.56	0.42
6	0.57	0.18	0.66	0.36	0.31	0.69	0.25	0.58	0.39	0.62	0.57	0.43
7	0.57	0.19	0.67	0.37	0.32	0.71	0.26	0.59	0.40	0.64	0.59	0.43
8	0.57	0.19	0.68	0.37	0.32	0.72	0.26	0.60	0.41	0.66	0.61	0.44
9	0.57	0.18	0.66	0.36	0.31	0.68	0.25	0.58	0.40	0.64	0.59	0.43
10	0.57	0.19	0.67	0.37	0.32	0.70	0.26	0.59	0.40	0.65	0.59	0.43
11	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.41	0.65	0.60	0.44
12	0.57	0.19	0.67	0.37	0.32	0.68	0.26	0.59	0.40	0.64	0.59	0.43
13	0.57	0.19	0.67	0.37	0.32	0.68	0.26	0.59	0.40	0.66	0.60	0.44
14	0.57	0.19	0.67	0.37	0.32	0.68	0.26	0.60	0.40	0.65	0.60	0.44
15	0.57	0.19	0.67	0.37	0.32	0.69	0.26	0.60	0.40	0.65	0.60	0.44
16	0.57	0.19	0.67	0.37	0.32	0.70	0.26	0.60	0.41	0.65	0.60	0.44
17	0.57	0.19	0.67	0.37	0.32	0.68	0.26	0.59	0.40	0.64	0.60	0.44
18	0.58	0.18	0.66	0.36	0.31	0.68	0.25	0.58	0.40	0.64	0.60	0.43
19	0.58	0.19	0.66	0.37	0.32	0.69	0.25	0.59	0.40	0.65	0.60	0.44
20	0.57	0.19	0.67	0.37	0.32	0.69	0.26	0.59	0.40	0.65	0.60	0.44
21	0.57	0.19	0.67	0.37	0.32	0.68	0.25	0.59	0.40	0.65	0.60	0.44
22	0.58	0.19	0.68	0.37	0.32	0.69	0.26	0.59	0.40	0.65	0.60	0.44
23	0.58	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.45
24	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.41	0.66	0.61	0.45
25	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.40	0.66	0.60	0.44
26	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.40	0.66	0.60	0.44
27	0.57	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.40	0.66	0.60	0.45
28	0.57	0.19	0.69	0.37	0.32	0.70	0.26	0.61	0.41	0.67	0.61	0.45
29	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.61	0.41	0.67	0.61	0.45
30	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.61	0.41	0.67	0.61	0.45
31	0.58	0.19	0.70	0.38	0.32	0.70	0.26	0.61	0.41	0.67	0.61	0.46
32	0.58	0.19	0.69	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.61	0.46
33	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.61	0.46
34	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.61	0.46
35	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.42	0.68	0.62	0.47
36	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.62	0.47
37	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.61	0.47
38	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.42	0.68	0.61	0.47
39	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.42	0.68	0.61	0.47
40	0.59	0.19	0.71	0.38	0.33	0.70	0.26	0.62	0.42	0.68	0.61	0.47
41	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.61	0.47
42	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
43	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.69	0.62	0.47
44	0.59	0.19	0.70	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
45	0.59	0.19	0.70	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
46	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47

Table C-4: Reported utilisations of ICONWIP.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
47	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
48	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
49	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
50	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.62	0.47
51	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
52	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
53	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
54	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
55	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
56	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
57	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
58	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
59	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
60	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
61	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
62	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
63	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
64	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
65	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
66	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
67	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
68	0.58	0.19	0.71	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
69	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
70	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
71	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.62	0.47
72	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.62	0.47
73	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
74	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
75	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
76	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
77	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
78	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
79	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.63	0.47
80	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
81	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
82	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
83	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
84	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
85	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
86	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
87	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
88	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
89	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
90	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
91	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47

Table C-4: Reported utilisations of ICONWIP.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
92	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
93	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
94	0.57	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.63	0.47
95	0.57	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.63	0.47
96	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
97	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.48
98	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
99	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
100	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
101	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
102	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
103	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
104	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.64	0.48

Table C-5: Reported utilisations of DBR.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.61	0.18	0.66	0.35	0.30	0.60	0.24	0.58	0.39	0.57	0.56	0.36
2	0.61	0.18	0.66	0.36	0.31	0.59	0.24	0.56	0.39	0.60	0.57	0.39
3	0.56	0.17	0.61	0.34	0.29	0.63	0.23	0.52	0.36	0.56	0.54	0.39
4	0.57	0.18	0.64	0.36	0.31	0.68	0.25	0.55	0.39	0.61	0.57	0.43
5	0.58	0.18	0.65	0.36	0.31	0.68	0.25	0.59	0.39	0.63	0.57	0.43
6	0.57	0.18	0.67	0.36	0.31	0.70	0.25	0.59	0.40	0.62	0.57	0.43
7	0.57	0.19	0.67	0.37	0.32	0.72	0.26	0.60	0.41	0.64	0.59	0.44
8	0.57	0.19	0.68	0.38	0.33	0.72	0.26	0.60	0.42	0.66	0.61	0.44
9	0.57	0.19	0.67	0.37	0.32	0.69	0.25	0.59	0.40	0.64	0.59	0.43
10	0.57	0.19	0.68	0.37	0.32	0.70	0.26	0.59	0.41	0.65	0.60	0.44
11	0.57	0.19	0.69	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.44
12	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.59	0.40	0.65	0.60	0.44
13	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.41	0.66	0.60	0.44
14	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.41	0.66	0.60	0.44
15	0.57	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.41	0.65	0.61	0.44
16	0.57	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.44
17	0.57	0.19	0.67	0.37	0.32	0.69	0.26	0.59	0.40	0.65	0.60	0.44
18	0.58	0.19	0.66	0.37	0.32	0.69	0.26	0.59	0.40	0.64	0.60	0.44
19	0.58	0.19	0.67	0.37	0.32	0.70	0.26	0.59	0.40	0.65	0.60	0.44
20	0.58	0.19	0.67	0.37	0.32	0.69	0.26	0.60	0.40	0.65	0.61	0.44
21	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.40	0.65	0.60	0.44
22	0.58	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.41	0.66	0.61	0.45
23	0.58	0.19	0.69	0.38	0.32	0.70	0.26	0.61	0.41	0.66	0.61	0.45
24	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.61	0.41	0.66	0.61	0.45
25	0.58	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.45

Table C-5: Reported utilisations of DBR.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
26	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.45
27	0.57	0.19	0.69	0.37	0.32	0.70	0.26	0.61	0.41	0.67	0.61	0.45
28	0.58	0.19	0.69	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.61	0.45
29	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.61	0.41	0.67	0.61	0.46
30	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.61	0.41	0.67	0.61	0.46
31	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.62	0.46
32	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.62	0.46
33	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
34	0.59	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
35	0.59	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
36	0.59	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
37	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.62	0.47
38	0.59	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.62	0.47
39	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.69	0.62	0.47
40	0.59	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
41	0.59	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.62	0.47
42	0.59	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.62	0.47
43	0.59	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.62	0.47
44	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
45	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
46	0.59	0.20	0.71	0.39	0.33	0.71	0.27	0.64	0.42	0.69	0.62	0.47
47	0.59	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.62	0.47
48	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
49	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
50	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
51	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
52	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.62	0.47
53	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.62	0.47
54	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.62	0.47
55	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.62	0.47
56	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
57	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
58	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
59	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
60	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
61	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
62	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.62	0.41	0.68	0.62	0.47
63	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
64	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
65	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
66	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
67	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
68	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.62	0.47
69	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
70	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47

Table C-5: Reported utilisations of DBR.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
71	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
72	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
73	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
74	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
75	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
76	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
77	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
78	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
79	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
80	0.58	0.19	0.72	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
81	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
82	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
83	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
84	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
85	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
86	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
87	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
88	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
89	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
90	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.48
91	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.48
92	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.48
93	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.48
94	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.48
95	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.48
96	0.58	0.19	0.72	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
97	0.58	0.20	0.72	0.39	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
98	0.58	0.20	0.72	0.39	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
99	0.58	0.20	0.72	0.39	0.33	0.72	0.27	0.64	0.42	0.69	0.64	0.48
100	0.58	0.20	0.72	0.39	0.33	0.72	0.27	0.64	0.42	0.69	0.64	0.48
101	0.58	0.20	0.72	0.39	0.33	0.72	0.27	0.64	0.42	0.69	0.64	0.48
102	0.58	0.20	0.72	0.39	0.33	0.72	0.27	0.64	0.42	0.69	0.64	0.48
103	0.58	0.20	0.72	0.39	0.33	0.72	0.27	0.64	0.42	0.69	0.64	0.48
104	0.58	0.20	0.72	0.39	0.33	0.72	0.27	0.64	0.42	0.69	0.64	0.48

Table C-6: Reported utilisations of Hybrid CONWIP/DBR.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.59	0.17	0.65	0.35	0.30	0.58	0.23	0.57	0.39	0.57	0.54	0.36
2	0.59	0.18	0.64	0.35	0.30	0.59	0.24	0.56	0.38	0.61	0.56	0.39
3	0.56	0.17	0.60	0.34	0.29	0.62	0.23	0.51	0.36	0.57	0.53	0.39
4	0.57	0.18	0.63	0.36	0.30	0.67	0.25	0.55	0.39	0.61	0.57	0.42

Table C-6: Reported utilisations of Hybrid CONWIP/DBR.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
5	0.57	0.18	0.65	0.36	0.30	0.67	0.25	0.58	0.39	0.63	0.56	0.42
6	0.57	0.18	0.66	0.36	0.31	0.69	0.25	0.58	0.40	0.62	0.56	0.42
7	0.57	0.19	0.67	0.37	0.32	0.71	0.26	0.59	0.40	0.64	0.58	0.43
8	0.57	0.19	0.68	0.38	0.32	0.72	0.26	0.60	0.41	0.67	0.61	0.44
9	0.57	0.18	0.67	0.36	0.31	0.68	0.25	0.58	0.40	0.65	0.59	0.43
10	0.57	0.19	0.68	0.37	0.32	0.70	0.26	0.59	0.40	0.66	0.59	0.43
11	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.41	0.66	0.60	0.44
12	0.57	0.19	0.68	0.37	0.32	0.68	0.26	0.59	0.40	0.65	0.59	0.43
13	0.57	0.19	0.68	0.37	0.32	0.68	0.26	0.59	0.40	0.66	0.60	0.44
14	0.57	0.19	0.67	0.37	0.32	0.68	0.26	0.60	0.40	0.65	0.60	0.44
15	0.57	0.19	0.67	0.37	0.32	0.69	0.26	0.60	0.40	0.65	0.60	0.44
16	0.57	0.19	0.67	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.60	0.44
17	0.57	0.19	0.67	0.37	0.32	0.68	0.26	0.59	0.40	0.65	0.60	0.44
18	0.57	0.18	0.66	0.36	0.31	0.68	0.25	0.58	0.40	0.64	0.59	0.43
19	0.58	0.19	0.66	0.37	0.32	0.69	0.26	0.59	0.40	0.65	0.60	0.44
20	0.57	0.19	0.67	0.37	0.32	0.69	0.26	0.59	0.40	0.65	0.60	0.44
21	0.57	0.19	0.67	0.37	0.32	0.68	0.26	0.59	0.40	0.65	0.60	0.44
22	0.58	0.19	0.68	0.37	0.32	0.69	0.26	0.59	0.40	0.66	0.60	0.44
23	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.45
24	0.57	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.45
25	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.40	0.66	0.60	0.44
26	0.57	0.19	0.69	0.37	0.32	0.69	0.26	0.60	0.40	0.66	0.60	0.44
27	0.57	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.40	0.66	0.60	0.45
28	0.57	0.19	0.69	0.37	0.32	0.70	0.26	0.61	0.41	0.67	0.61	0.45
29	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.61	0.41	0.67	0.61	0.46
30	0.58	0.19	0.70	0.37	0.32	0.70	0.26	0.61	0.41	0.67	0.61	0.46
31	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.61	0.41	0.67	0.61	0.46
32	0.58	0.19	0.69	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.61	0.46
33	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.61	0.46
34	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.68	0.62	0.46
35	0.59	0.19	0.70	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.62	0.47
36	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
37	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
38	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.69	0.61	0.47
39	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.69	0.61	0.47
40	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.61	0.47
41	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.69	0.62	0.47
42	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
43	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
44	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
45	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
46	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
47	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
48	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
49	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47

Table C-6: Reported utilisations of Hybrid CONWIP/DBR.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
50	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.62	0.47
51	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
52	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
53	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
54	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
55	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
56	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
57	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.42	0.68	0.62	0.47
58	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
59	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.42	0.68	0.62	0.47
60	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
61	0.57	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
62	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
63	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
64	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
65	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
66	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
67	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
68	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
69	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
70	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
71	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.62	0.47
72	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
73	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
74	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
75	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
76	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
77	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
78	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
79	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.63	0.47
80	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
81	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
82	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
83	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
84	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
85	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
86	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
87	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
88	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
89	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
90	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
91	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
92	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
93	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
94	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47

Table C-6: Reported utilisations of Hybrid CONWIP/DBR.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
95	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.48
96	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.48
97	0.58	0.19	0.72	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
98	0.58	0.20	0.71	0.39	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
99	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
100	0.58	0.20	0.71	0.39	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
101	0.58	0.19	0.72	0.39	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
102	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
103	0.58	0.19	0.72	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
104	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48

Table C-7: Reported utilisations of LCONWIP.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.60	0.18	0.66	0.35	0.30	0.59	0.24	0.57	0.40	0.57	0.56	0.36
2	0.59	0.17	0.64	0.35	0.30	0.58	0.24	0.56	0.38	0.60	0.56	0.38
3	0.55	0.17	0.60	0.33	0.29	0.62	0.23	0.51	0.36	0.55	0.53	0.38
4	0.56	0.18	0.63	0.35	0.30	0.67	0.25	0.55	0.39	0.60	0.56	0.42
5	0.57	0.18	0.64	0.35	0.30	0.67	0.25	0.58	0.39	0.62	0.56	0.42
6	0.57	0.18	0.66	0.36	0.31	0.69	0.25	0.58	0.39	0.61	0.56	0.42
7	0.57	0.19	0.66	0.37	0.31	0.71	0.26	0.59	0.40	0.63	0.58	0.43
8	0.57	0.19	0.68	0.37	0.32	0.72	0.26	0.60	0.41	0.65	0.61	0.44
9	0.57	0.18	0.66	0.36	0.31	0.68	0.25	0.58	0.40	0.63	0.59	0.42
10	0.57	0.19	0.67	0.37	0.32	0.70	0.26	0.59	0.40	0.64	0.59	0.43
11	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.59	0.41	0.65	0.60	0.43
12	0.57	0.19	0.67	0.37	0.32	0.68	0.26	0.59	0.40	0.64	0.59	0.43
13	0.57	0.19	0.67	0.37	0.32	0.68	0.26	0.59	0.40	0.65	0.60	0.43
14	0.57	0.19	0.67	0.37	0.32	0.68	0.26	0.59	0.40	0.65	0.60	0.44
15	0.57	0.19	0.67	0.37	0.32	0.69	0.26	0.60	0.40	0.64	0.60	0.44
16	0.56	0.19	0.67	0.37	0.32	0.69	0.26	0.60	0.40	0.65	0.60	0.44
17	0.57	0.19	0.66	0.37	0.32	0.68	0.26	0.59	0.40	0.64	0.60	0.44
18	0.57	0.18	0.66	0.36	0.31	0.68	0.25	0.58	0.40	0.63	0.59	0.43
19	0.58	0.19	0.66	0.37	0.32	0.69	0.26	0.58	0.40	0.64	0.60	0.44
20	0.57	0.19	0.67	0.37	0.32	0.69	0.26	0.59	0.40	0.65	0.60	0.44
21	0.57	0.19	0.67	0.37	0.32	0.68	0.26	0.59	0.40	0.64	0.60	0.44
22	0.58	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.40	0.65	0.60	0.44
23	0.58	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.45
24	0.57	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.41	0.66	0.61	0.45
25	0.57	0.19	0.68	0.37	0.32	0.69	0.26	0.60	0.40	0.66	0.60	0.44
26	0.57	0.19	0.69	0.37	0.32	0.69	0.26	0.60	0.40	0.66	0.60	0.44
27	0.57	0.19	0.68	0.37	0.32	0.70	0.26	0.60	0.40	0.66	0.60	0.45
28	0.57	0.19	0.69	0.37	0.32	0.70	0.26	0.61	0.41	0.66	0.61	0.45

Table C-7: Reported utilisations of LCONWIP.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
29	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.61	0.41	0.66	0.61	0.45
30	0.58	0.19	0.69	0.37	0.32	0.70	0.26	0.61	0.41	0.66	0.61	0.45
31	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.61	0.41	0.67	0.61	0.46
32	0.58	0.19	0.69	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.61	0.46
33	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.62	0.46
34	0.58	0.19	0.70	0.38	0.33	0.70	0.26	0.62	0.41	0.67	0.62	0.46
35	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.62	0.47
36	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.62	0.47
37	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.62	0.47
38	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.61	0.47
39	0.59	0.19	0.70	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.61	0.47
40	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.61	0.47
41	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.62	0.47
42	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.69	0.62	0.47
43	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.62	0.42	0.69	0.62	0.47
44	0.59	0.19	0.70	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
45	0.59	0.19	0.70	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
46	0.59	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
47	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
48	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
49	0.58	0.19	0.71	0.38	0.33	0.70	0.27	0.63	0.42	0.68	0.62	0.47
50	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.62	0.47
51	0.58	0.19	0.70	0.38	0.33	0.70	0.27	0.62	0.42	0.68	0.62	0.47
52	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
53	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
54	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
55	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.62	0.47
56	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
57	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.42	0.68	0.62	0.47
58	0.58	0.19	0.70	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
59	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
60	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.62	0.47
61	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.67	0.62	0.46
62	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
63	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.46
64	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
65	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
66	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
67	0.58	0.19	0.70	0.38	0.33	0.71	0.26	0.62	0.41	0.68	0.62	0.47
68	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.41	0.68	0.62	0.47
69	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
70	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.62	0.42	0.68	0.62	0.47
71	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.62	0.47
72	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
73	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47

Table C-7: Reported utilisations of LCONWIP.

Week	Station number											
	1	2	3	4	5	6	7	8	9	10	11	12
74	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
75	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
76	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
77	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
78	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
79	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.68	0.63	0.47
80	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
81	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
82	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.62	0.42	0.68	0.63	0.47
83	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
84	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
85	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.68	0.63	0.47
86	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
87	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
88	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
89	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
90	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
91	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
92	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
93	0.57	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
94	0.57	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.63	0.47
95	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.63	0.47
96	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.47
97	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.63	0.48
98	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
99	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
100	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
101	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
102	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
103	0.58	0.19	0.71	0.38	0.33	0.72	0.27	0.63	0.42	0.69	0.64	0.48
104	0.58	0.19	0.71	0.38	0.33	0.71	0.27	0.63	0.42	0.69	0.64	0.47