System Improvements in Valve Manufacturing Cell at Waters Corporation

by

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ABSTRACT

This thesis addresses the challenge of improving on-time delivery performance of stators in the high mix valve manufacturing cell at the Milford facility of Waters Corporation with a focus on efficient line design without exceeding the average WIP levels observed in the current system. A detailed study of the current process was done and it was concluded that the poor on-time delivery performance of stators to the assembly department could be attributed to the unacceptably long fabrication lead times—due to the long waiting induced by the fabrication of a high mix of 28 different types of stators—and the lack of an efficient inventory management policy that makes the system susceptible to extreme situations of either stock-outs or inventory explosion. Therefore, a pull-type production system with a responsive fabrication line establishing WIP control and an end of line standardized finished goods inventory management was designed and implemented.

An efficient line design was developed by dedicating lines for high volume and high mix parts and by placing in-process buffers to implement a Kanban based pull-type production process that in turn limits the amount of WIP as well. An overall lead time reduction from 21 days to 3 days was achieved through the implementation of this line design and a 40% reduction in WIP levels was observed simultaneously. For standardizing the finished goods inventory management in order to maintain high service levels while eliminating the possibility of WIP explosion, a mixed inventory review policy or the (s,S) policy—that uses a re-order point to trigger production at appropriate times and a base stock level that maintains an upper control limit on the inventory levels—is suggested for implementation. With this policy, a calculated service level of at least 96% is expected even for high demand periods alongside a 50% reduction in average finished goods inventory levels.

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1. Introduction

1.1 Motivation
Waters Corporation is a manufacturer of high performance liquid chromatography (HPLC) Systems, Mass Spectroscopy and associated products such as chromatography columns, valves sample extraction instruments and chemical reagents. The Waters facility at Milford, Massachusetts is the headquarters of the company and houses an in-house production system for various components and sub-assemblies of the HPLC systems. The current manufacturing for valves—a critical sub-assembly of HPLC systems—is carried out in a separate manufacturing cell, the valve cell, a high mix cell that manufactures 28 different types of stators for valve assembly in batches.

The main problem associated with the valve cell is the poor on-time delivery performance of stators to the assembly department. The poor on-time delivery performance can be attributed to the presence of such a high mix of parts that leads to long waiting times for part types resulting in unacceptably long production lead times and inefficient finished goods inventory planning and control making it susceptible to extreme situations of stock-outs or inventory explosion. With higher expected demand in future, these problems are likely to result in much longer average lead time on all parts, backlog and excessive work in process (WIP) inventory.
1.2 Process Overview
The processing of stators utilizes the valve cell and the milling machine from the NC milling department. The valve cell consists of two turning machines, 4 robo-drill machines and 2 wire-EDM machines. The 4 robo-drill machines are called Robo-drill machine 2, Robo-drill machine 3, Robo-drill machine 4 and Robo-drill machine 5. The shop floor layout is shown in Fig. 1. After being machined through the valve cell, the stators are processed through a series of cleaning and inspection processes. These processes include de-burring, lapping, passivation, VCN cleaning and critical cleaning. For instance, the entire fabrication process for 212 stators, the highest volume part type in the valve cell, involves 10 steps. These 10 steps in order of operation are turning, milling, robo-drilling, wire EDM, de-burring, lapping, passivation, vacuum cycling nucleation (VCN) cleaning, critical clean and packaging. A more detailed process description will be given in Chapter 3.

Fig. 1 Valve cell layout
1.3 Objectives
The primary objective of this project is to implement manufacturing systems and process improvements in the valve cell of Waters Corporation at their Milford, MA facility. More specifically this translates to three main objectives:

1. Develop a responsive fabrication system for stators through lead time reduction
2. Establish an efficient finished goods inventory review policy to achieve high service levels.
3. Determine the optimum operating conditions and tool material for throughput improvement of the bottleneck process for additional responsiveness.

1.4 Scope and Thesis Organization
The 212 stators account for approximately 52% of the total valve cell production making it the highest volume and most critical stator. This serves as the rationale behind selecting 212 stators for studying the process flow in depth and carrying out major analyses for problem identification and improvement. Therefore, this project focuses on the lead time reduction for 212 stator fabrication, standardization of 212 stator finished goods inventory management and improvement of the robo-drilling process which is the bottleneck in the 212 stator process flow. While the proposed solutions are associated with 212 stator fabrication, the respective solutions seek to leverage the production of other stator types as well.

Inferences based on the study of the current process are described in detail in Chapter 3 while Chapter 4 to Chapter 7 discuss the proposed improvements and related implementation results.
1.5 Task Division
As mentioned above the project is divided into three main areas: lead time reduction, efficient inventory management and bottleneck process improvement. Each team member is in charge of one area and delegates responsibility to other team members in his/her area based on expertise. Yan Zhuang is responsible for carrying out detailed statistical and machine capability analysis for bottleneck process improvement in 212 stator manufacturing. Bingxin Yao and this author are responsible for the achievement of an efficient production system through a responsive fabrication line and standardized finished goods inventory management. This thesis in particular focuses on the modeling of a responsive fabrication line.
2. Literature Review

Basic factory physics principles relating cycle time, throughput and inventory levels are discussed by Hopp and Spearman [1]. In addition to this, a discussion on batching laws, influence of variability, push-pull production systems and implementing a pull planning framework is also provided by Hopp and Spearman. These concepts are summarized below.

2.1 Basic Principles of Factory Physics

If the utilization $U$ of a workstation is defined as the fraction of time the workstation is not idle due to lack of parts, $U$ can be calculated as [1]

$$U = \frac{r_{arrival}}{P_{effective}}$$

(2.1)

where $r_{arrival}$ is the rate of arrival of parts and $P_{effective}$ is the effective production rate. $P_{effective}$ is the maximum average processing rate of the work-station taking into account failure rates, set-ups and other non-productive factors. It is important to note that increasing $U$ of a station without making any other changes causes a highly non-linear increase in the average WIP and cycle time.

The bottleneck rate or $r_{bottleneck}$, that can be defined as the throughput/production rate of the workstation having the highest long term utilization in a line, the raw process time or $T_o$, which is the average time it takes one job to traverse the entire line without waiting at any station, and
the critical WIP level or $WIP_{critical}$, which is the WIP level that is required to support the achievement of maximum throughput or $rate_{bottleneck}$ assuming no variability in the system are related in the following way [1]

$$WIP_{critical} = rate_{bottleneck} \times T_0$$

(2.2)

The $rate_{bottleneck}$ in the above equation of course represents the capacity of the system that sets the control limit on the number of parts that can be released into the system or line. In other words the rate at which parts are released into the system should be less than or equal to $rate_{bottleneck}$ for stability. However, in the practical world, even if efforts are made to release parts into the system at $rate_{bottleneck}$, once a system reaches steady state, it will release work at an average rate that is lesser than the average capacity. This is an important factory law and helps better management decisions regarding capacity planning.

Investigating further into the relationship between WIP, process time and throughput, Little’s Law [2] provides the following fundamental factory relationship, assuming no variability,

$$WIP = TH \times CT$$

(2.3)

where WIP, TH, CT represent the work in process, throughput and cycle time of the line respectively. This law states that WIP is always equal to the product of throughput and cycle time at any WIP level. The Little’s Law can be applied to one station, a line or an entire plant and can even be applied to lines with non-zero variability. The law provides insights such as how cycle time can be reduced by reducing the WIP for a given throughput, calculation of
expected queue lengths at each workstation through the line by using the cycle time of the station.

U of a given station can also be deduced by knowing the queue length and number of machines at that station.

From the above, we realize that larger batch sizes result in more waiting and hence longer cycle times for a given throughput rate. Batching also has a significant impact on variability pooling and variability reduction. Therefore, batching laws are important in analyzing trade-offs regarding larger/smaller batch sizes. There are two kinds of batches—process batches and transfer batches [2].

A process batch size consists of a number of jobs of a part family that are processed on a workstation before it undergoes a set-up to process another part family. The process batch size is determined by how long it takes to change over to another part family. The rule therefore is in order to achieve a given capacity, the longer the set-up time the larger the batch size used. Also, as process batch sizes get large, cycle time increases proportionally with batch size. Other process batching laws state that the minimum process batch size to achieve a stable system maybe greater than one and that the cycle time at the station maybe minimized for some process batch size which may be greater than one.

A transfer batch size is the number of parts that are accumulated before transferring to the next station. The smaller the transfer batch size, the shorter the cycle time achieved since the wait to
batch time is significantly reduced. Lot splitting is the technique of employing a large process batch to minimize utilization but a small transfer batch to reduce the cycle time. Smaller transfer batches however may result in more material handling resulting in a trade-off versus shorter cycle time. In fact, cellular manufacturing facilitates shorter cycle times through lot splitting owing to the physical compactness of the cell.

Therefore batching decisions can impact WIP, cycle time and throughput. If reducing cycle time is the main focus then using a batch size just greater than the size that gives 100% utilization in order to maintain a stable system is favorable.

Another aspect of batching is variability pooling and variability reduction. Batching helps reduce variability [1]. Let $t_o$ and $\sigma_o$ be the mean and standard deviation of a random variable that describes the process time of a single part. The process time Co-efficient of Variation (CV) or $c_o$ for this part is given as:

$$c_o = \frac{\sigma_o}{t_o} \quad (2.4)$$

On the other hand, for a batch of $n$ such parts the CV for a batch or $c_o(batch)$ is given by:

$$c_o(batch) = \frac{\sigma_o(batch)}{t_o(batch)} = \frac{\sigma_o \sqrt{n}}{t_o n} = \frac{c_o}{\sqrt{n}} \quad (2.5)$$
Therefore batching helps in variability reduction and is especially important in sampling for quality control albeit its negative effects on cycle time and WIP levels.

Batching can help reduce variability but since variability is inherent in every manufacturing system, buffering to mitigate variability is required. Variability can in fact be buffered by some combination of inventory, capacity and time.

2.2 Inventory Review Policies
Two basic inventory review policies – the continuous review policy and the periodic review policy are described in detail by Simchi-Levi et al [3]. The major concepts involved in these policies are discussed in the following sections.

2.2.1 Continuous Review Policy
In a continuous review policy, inventory is monitored continuously and an order is placed whenever the inventory position reaches a particular point referred to as the reorder point [3]. In general, such a review policy leads to a highly responsive inventory management system.

In order to characterize this policy, it is important to understand the concept of inventory position. Inventory position is defined as the summed total of the actual inventory on hand plus the number of units ordered which have not arrived.

To implement the continuous review model in practice, we employ a typical approach known as the \((Q, R)\) policy, in which an order of \(Q\) units would be placed whenever the inventory level drops to the reorder point \(R\). This concept is illustrated in Fig. 2.
The reorder point $R$ here consists of two components, which covers the average inventory consumption during lead time and a safety stock to account for demand variabilities, i.e

$$R = \text{Average demand over lead time} + \text{safety stock} \tag{2.6}$$

The order quantity $Q$, on the other hand, needs to be optimized according to the nature of the distributor’s operation. Two typical optimization models – the Economic Order Quantity (EOQ) Model and the Newsvendor Model are illustrated as follows.

2.2.1.1 Economic Order Quantity (EOQ) Model

The EOQ model determines the optimal order quantity based on cost minimization. It takes into consideration the tradeoff between inventory holding cost and ordering cost [5]. A small order quantity will result in a large ordering frequency, which leads to larger ordering cost, but at the
same time reduces the average inventory level kept in the warehouse which, on the other hand, deceases the total inventory holding cost. In contrast, a large order quantity would require lower ordering frequency at the price of higher inventory holding cost.

Therefore, the economic order quantity or $Q^*$ is mathematically expressed as:

$$Q^* = \sqrt{\frac{2k \times D}{h}}$$  \hspace{1cm} (2.7)

where $h$ is the holding cost per unit, $k$ is the ordering cost and $D$ is the demand rate.

2.2.1.2 Newsvendor Model

The newsvendor model aims to determine the optimal order quantity which maximizes the expected profit in a single planning period under stochastic demand [6]. The model defines an overage cost which is the difference between the original cost of an item and the salvage value of unsold inventory, as well as an underage cost expressed as lost profit due to unmet demand.

The optimal order quantity is hence established as a function of the overage and underage costs under certain demand scenario, given as:

$$F(Q^*) = \frac{C_u}{C_u + C_o}$$  \hspace{1cm} (2.8)

where $F(x)$ represents the cumulative distribution function of demand, and $C_u$ and $C_o$ are the underage and overage costs respectively.
2.2.2 Periodic Review Policy
In contrast to the continuous review policy discussed so far, in a period review policy, the inventory level is reviewed at fixed intervals on a regular basis and an order of appropriate quantity is placed after each review [3]. This policy is suitable to implement in systems where continuous review of inventory levels and frequent orders are inconvenient or costly.

The working mechanism of the periodic review policy is demonstrated in Fig. 3. As can be observed, this review policy is characterized by a single factor – the base stock level $B$. The target base stock level, along with a specific review period is determined by the warehouse, the inventory position is then reviewed at these intervals and orders are placed to replenish the inventory back to the target level.

![Graph](image)

Fig. 3: Illustration for base stock inventory review policy. $L$ represents the lead time for an order and $r$ is the review period. An order is place after each review to raise the inventory position back to the base stock level $B$.[4]

The base stock level or $B$ in a periodic review system is set up in a way that it would be enough to protect the warehouse from shortages until the next order reaches. Since orders arrive at
intervals of \( r + L \) days, the base stock level should be able to cover the average demand during this period of time with a certain safety factor, taking into consideration the uncertainties in demand forecast. This is given by:

\[
B = \text{Average demand over}(r + L)\text{days} + \text{Safety stock} \tag{2.9}
\]

2.2.3 Vendor Managed Inventory
The two basic inventory review policies discussed previously effectively help to ensure a predetermined customer service level while at the same time keep the inventory level under control and prevent inventory explosion caused by inappropriate planning and anxiety. To further improve the coordination between the supplier and the customer and reduce overall inventory costs, strategic partnerships are usually employed.

Vendor managed inventory or VMI is a typical example of such partnerships in which information on demand is shared between the supplier and the customer [3]. The supplier is then given the authority to manage the inventory at the customer outlet and makes decisions on how much inventory should be kept on hand and when an order should be shipped [7]. This inventory management strategy integrates the operations at both sides and entirely eliminates the influence of variation inflation in a traditional supply chain system. The inventory cost incurred by the customer is reduced and the same would be true for the supplier in a long run due to better coordination of production and distribution.
2.3 Push-Pull Production System
A push system releases jobs for production based on a schedule which is in turn based on demand. A pull system on the other hand releases a job on the floor triggered by a signal signifying a change in the status of the line, for instance, the signaling of production upstream as parts when the process downstream requires parts as a result of a change in the downstream process [3].

Another way to look at a push system is as a make-to-order system as production is order based and not based on any signaling. However, a pull system can be seen as a make-to-stock model as production upstream is signaled by some void in the stock level downstream. In fact, the base stock model tends well to a pull system as orders can be triggered whenever the stock falls below the base stock level.

Most real world systems are however hybrid push-pull systems. For instance, if a job release is authorized by a Kanban card, a feature of a pull-type system, but production is delayed due to anticipated lack of demand dictated by the master production schedule, a feature of a push-type system, then this results in a hybrid push-pull system [8-10].

2.4 Features and Benefits of a Pull Production System
The key feature of a pull production system is that it establishes a WIP cap and therefore avoids the production of extra WIP that do not contribute to increasing the throughput [1]. The WIP cap is established for instance using a Kanban system where the amount of WIP on the floor is limited by the number of Kanban cards used for triggering production. Also since a pull system is make-to-stock it automatically allows for the establishment of a WIP cap/level as any void in
the stock level signals production to only fill up stock to the specified/base stock level. Since a pull production system helps in reducing WIP and keeping an upper bound on WIP, it helps in reducing average cycle times as well without compromising on throughput.

Therefore, the above features of a pull system result in a number of benefits like reduction of manufacturing costs since WIP will never grow beyond a pre-specified level, reduction of cycle time variability as the WIP cap also prevents any cycle time explosion since it eliminates the danger of WIP explosion, pressure for quality improvements due to decreased WIP that facilitates defect detection and increased flexibility through delayed release of parts that makes engineering and priority or scheduling changes easy and ensures production of parts is authorized close to when the actual demand is realized to the maximum extent. Thus the pull system helps in developing a highly responsive customer service.

2.4.1 CONWIP and Kanban System
The easiest way to establish a WIP cap for the Pull system is through CONWIP or constant work-in-process. The WIP level is controlled by coordinating the release of a job with the departure of another job in the line, that is, a synchronized release and departure of jobs to maintain constant WIP in line[1].

Benefits of a CONWIP system over a pure push system include the ability to observe the WIP levels directly as opposed to the possibility of WIP levels going up and down in a push system depending on the release rate determined by available capacity. Moreover, CONWIP helps achieve the same throughput with lesser WIP on average than a push system. An important
factory law regarding the robustness of CONWIP states that, "CONWIP is more robust to errors in WIP level than the push system is to errors in release rates."

Also, CONWIP can help in completing work ahead of schedule if circumstances permit.

Kanban system differs from CONWIP system in that it is more complex and usually involves the setting of more parameters than CONWIP. For instance, CONWIP requires a single card count unlike Kanban that requires a card count for each station. However, a pure Kanban system results in a lead time of zero (part is available at outbound stock whenever required) whereas the lead time in a CONWIP system is always small but never zero.

The Kanban system is more suited to a repetitive manufacturing environment i.e. a manufacturing environment where parts flow along a fixed sequence and at steady rates. CONWIP on the other hand shows more robustness to product mix due to generation of work backlogs and as a result of line-specific cards. CONWIP can also adjust to a changing bottle-neck because the WIP naturally accumulates in front of the bottle-neck. CONWIP also induces less operator stress as compared to the Kanban system where operators have to often wait for production signals even if they have raw materials to produce the required parts. Thus, CONWIP is more flexible than a Kanban system but unlike a pure Kanban system can never have a lead time of zero.
2.5 ARENA Simulation Software

ARENA simulation software is used for modeling dynamic processes and is a discrete event simulation software owned by Rockwell Automation [11]. Discrete-event simulation models systems as a sequence of discrete processes, each of which occurs at a particular instant of time resulting in a change in the state of the system.

ARENA simulation follows an entity based flowchart methodology and this makes it useful for documenting processes as compared to other simulation software that are either not visually compatible that is purely code based or focus more on process animation than process documentation.

Entities in ARENA (for example part types) flow through various processes that are depicted by modules that are connected to obtain a process flowchart for the system, and seize control of resource capacity as these entities are processed. This flowchart model of ARENA helps in accurately modeling and analyzing a process or system as the flowchart methodology facilitates documentation of each module or process. This results in highly detailed documentation and model development for the processes being analyzed.

Key advantages of ARENA simulation software that leverages the flowchart methodology are that it is easier to learn than other simulation tools, it is easier to validate, verify and debug, and it is easier to communicate details of complex systems or processes to others.

ARENA Academic Lab Package which is one of the ARENA academic software editions and is the academic and non-commercial version of the commercially available Enterprise Suite
OptQuest for optimization, packaging, etc. The enterprise suite also does away with any system boundaries to analyze, model and solve.
3. Description & Characterization of Current System

In this chapter an attempt at understanding the current system and characterizing the same is made. Stators that both contribute to a significant percentage of the valve cell production and are critical to the bottom line of the company are identified. The stator that weighs highest on the combination of these factors is chosen as representative of the system operations and major analyses are carried out for this stator. The system is investigated and analyzed in detail and areas of improvement are identified. A brief description of the process flow for all other major stators is also given to have a holistic view of the system.

3.1 Percentage Production of Stators in Valve Cell

Although the valve cell is a high mix manufacturing cell and produces twenty eight different types of stators, the major and most frequently produced stators and their percentage production is shown in Table 1.

<table>
<thead>
<tr>
<th>Part no.</th>
<th>Annual Production (number of parts)</th>
<th>Percentage Production (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>212</td>
<td>16355</td>
<td>52.2</td>
</tr>
<tr>
<td>213</td>
<td>3674</td>
<td>11.7</td>
</tr>
<tr>
<td>237</td>
<td>2300</td>
<td>7.3</td>
</tr>
<tr>
<td>230</td>
<td>1999</td>
<td>6.4</td>
</tr>
<tr>
<td>215</td>
<td>650</td>
<td>2.1</td>
</tr>
<tr>
<td>251</td>
<td>1533</td>
<td>4.9</td>
</tr>
<tr>
<td>250</td>
<td>968</td>
<td>3.1</td>
</tr>
<tr>
<td>236</td>
<td>809</td>
<td>2.6</td>
</tr>
</tbody>
</table>
As can be seen from Table 1 the 212 stator accounts for more than 50% of the total production of the valve cell. Also each unit stator irrespective of the type has the same unit profit making 212 the most critical given the units of 212 produced annually. Therefore, Part 212 is chosen as an example to study the process and for analysis.

3.2 Process Flow
Process flow for different stator types is studied. The process flow for 212 stators is discussed in detail. The process flow for all other major part types is explained briefly in Section 3.2.2.

3.2.1 Process Flow for 212 stators
All stator types more or less follow a similar manufacturing sequence. However, the exact sequence of process steps for 212 stators is depicted in Fig. 4

The 212 stators in the current system are produced as a factory order of 100 parts or as a batch of 100 parts. Factory orders have codes that can be entered into the SAP system to track the status of the factory order through the line. Therefore, all stator production is attached to factory orders and every 212 stator factory order moves as a batch of 100 parts. Four trays, each having a capacity of 28 parts, are used to hold 100 parts that form one factory order.
As can be seen from Fig. 4, the process for fabricating 212 stators starts from the turning machine which has a cycle time of 3.72 minutes per part. 100 blanks of 212 stators are turned and batched as part of the factory order they are being processed under before the batch is sent for milling.

Milling for the 212 stators takes place in a separate department called the NC Milling department since the machines in the valve cell do not have the capability to mill the special slot characteristic to 212 stators. In addition to the slot, vertical hole drilling of the 212 stators takes place in the milling machines. These vertical holes are used for locating the stators for subsequent processes. The slot milling and vertical hole drilling operations on the milling machine account for a total cycle time of 7.2 minutes per part.
After the 212 factory order is finished in the NC milling department, the entire factory order is sent to Robo-drill machine 4 or Robo-drill machine 5 based on either availability. Conical holes are then drilled into each part for a cycle time of 16.5 minutes per part for both Robo-drill machine 4 and Robo-drill machine 5.

This process is followed by the wire-EDM process to drill the bottom holes of the stator and the wire-EDM machine takes 4.2 minutes per part to finish. Parts are usually fed into the wire-EDM process as a batch of 28 parts. Due to the proximity of Robo-drill machines 4 and 5 and the wire-EDM machine, sometimes lot-splitting is observed from the robo-drilling process to the wire-EDM process. This however is not part of any standardized rule and is done at operators’ will.

The wire-EDM process marks the end of machining processes on the stators and after this the 212 stators are made to go through a series of cleaning and inspection processes. The factory order is first sent to the lapping room for cleaning and is then sent for de-burring. After de-burring the order comes back to the lapping room to get lapped. This is followed by passivation in the passivation room before the order is moved back to the lapping room for VCN/solvent cleaning followed by critical clean for the 100 part order in the passivation room again. Finally the order moves to the critical clean room where each stator is packaged/bagged before being sent to the uncoated parts inventory. As described in the introduction section, the parts are then sent for DLC coating after which they are stored in the finished goods inventory ready for assembly.
A summary of the process times per part for all processes involved in 212 stator fabrication is given in Table 2-

Table 2 Process times for all processes from Turning to Critical Cleaning for 212 stators

<table>
<thead>
<tr>
<th>Cycle time at each workstation (minutes per part)</th>
<th>$t_{\text{turn}}$</th>
<th>$t_{\text{mill}}$</th>
<th>$t_{\text{robo}}$</th>
<th>$t_{\text{EDM}}$</th>
<th>$t_{\text{de-burr}}$</th>
<th>$t_{\text{lap}}$</th>
<th>$t_{\text{pass}}$</th>
<th>$t_{\text{VCN}}$</th>
<th>$t_{\text{CC}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3.72$</td>
<td>$7.2$</td>
<td>$16.5$</td>
<td>$4.2$</td>
<td>$2.1$</td>
<td>$3$</td>
<td>$0.6$</td>
<td>$0.06$</td>
<td>$0.18$</td>
<td>$0.18$</td>
</tr>
</tbody>
</table>

where $t_{\text{turn}}$, $t_{\text{mill}}$, $t_{\text{robo}}$, $t_{\text{EDM}}$, $t_{\text{de-burr}}$, $t_{\text{lap}}$, $t_{\text{pass}}$, $t_{\text{VCN}}$ and $t_{\text{CC}}$ are the cycle times per part for turning, milling, robo-drilling, wire-EDM, de-burring, lapping, passivation, VCN and critical cleaning respectively.

3.2.2 Process Flow for Other Major Stator Types

As described in the section above, the flow of all stators through the system is attached to factory orders. However, not all factory orders indicate a batch size of 100 as in the case for the 212 stators. The batch sizes related to factory orders for different part types are shown in Table 3.

Table 3 Size of factory orders for each stator type

<table>
<thead>
<tr>
<th>Size of factory order for each stator type (number of stators)</th>
<th>$S_{212}$</th>
<th>$S_{213}$</th>
<th>$S_{215}$</th>
<th>$S_{230}$</th>
<th>$S_{236}$</th>
<th>$S_{237}$</th>
<th>$S_{250}$</th>
<th>$S_{251}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$100$</td>
<td>$100$</td>
<td>$100$</td>
<td>$80$</td>
<td>$100$</td>
<td>$96$</td>
<td>$16$</td>
<td>$30$</td>
<td></td>
</tr>
</tbody>
</table>

where $S_{212}$, $S_{213}$, $S_{215}$, $S_{230}$, $S_{236}$, $S_{237}$, $S_{250}$, $S_{251}$ are the factory order sizes for 212 stators, 213 stators, 215 stators, 230 stators, 236 stators, 237 stators, 250 stators and 251 stators respectively.

Unlike the 212 stators, where after the turning operation is completed on a factory order, the order is sent to the milling machine, the factory orders of all other part types are sent to Robo-drill machine 2 for vertical hole drilling that aids location in subsequent processes.
After Robo-drill machine 2, all stator types go to Robo-drill machine 4 or Robo-drill machine 5, based on availability of either, for conical hole drilling, except for Part 215 which goes to Robo-drill machine 3 after Robo-drill machine 2. Part 215 requires central hole drilling in addition to conical hole drilling unlike other parts and hence is sent to Robo-drill machine 3 that has the capability to do the same being a five-axis machine.

The process flow after robo-drilling is the same for all parts where they go to the wire-EDM machine before being sent for all cleaning and inspection processes in the exact same sequence as that described for 212 stators. The EDM process times might differ according to part type though. The process flow of part types through the valve cell and process times for different part types for all production steps till the wire-EDM process is summarized in Table 4. The process flow and process times per part after the wire-EDM for all other part types is the same as that listed in Table 2.

It can be seen from the process times per part in Table 4 that Robo-drill machines 3, 4 and 5 are the bottlenecks in the process flow for stators with the highest process time per part of 16.5 minutes.
3.2.3 Efficiency of Machines Supporting Stator Fabrication

Historical data for each machine type is used to arrive at approximate figures of the mean time to fail and mean time to repair for respective machines. The mean time to repair and mean time to fail are then used to calculate machine efficiency or Efficiency using the relationship given in Equation (3.1):

\[
Efficiency = \frac{MTTF}{MTTF + MTTR}
\]

where \( MTTF \) is the mean time to fail and \( MTTR \) is the mean time to repair for a machine. The results are summarized in Table 5. Efficiency is calculated for machine types because the valve cell consists of an identical pair of lathe machines, and wire-EDM machines. All robo-drill machines are also seen to have the same efficiencies.
It can be seen from Table 5 that the machines that account for longer cycle times per part like the milling and robo-drilling machines have relatively higher efficiencies. On the other hand faster processes like turning and EDM have a lower efficiency.

### Table 5 MTTR, MTTF and Efficiency calculations for Machine types

<table>
<thead>
<tr>
<th>Machine</th>
<th>MTTR (Days)</th>
<th>MTTF (Days)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lathe</td>
<td>2.0</td>
<td>33.00</td>
<td>0.94</td>
</tr>
<tr>
<td>Milling</td>
<td>0.5</td>
<td>87.00</td>
<td>0.99</td>
</tr>
<tr>
<td>Robo-Drill machine 2,3,4 &amp; 5</td>
<td>1.0</td>
<td>49.00</td>
<td>0.98</td>
</tr>
<tr>
<td>Wire EDM</td>
<td>1.0</td>
<td>22.33</td>
<td>0.96</td>
</tr>
</tbody>
</table>

3.3 Current System Characterization

Having acquired a detailed understanding of part flow through the valve cell and the processes involved for different part types, an attempt at characterizing the system is made. Owing to the complexity involved in analyzing a high part mix production system, the system is characterized by tracking the flow of 212 orders alone. Since the 212 stators account for more than 50% of valve cell production, they are the most critical and frequently found part type on the shop floor and hence a simplified definition of the system can be obtained by tracking 212 orders without compromising on the true picture.

Three metrics are chosen for describing the current system-

1. Average inventory volume before each process step
2. Average inventory waiting time before each process step
3. Total lead time of in-house production for 212 stators
A general understanding of WIP accumulation and the overall impact of batching and wait-to-batch time on overall queue time and lead time can be obtained by the three metrics listed above and discussed in detail in the following sub-sections.

3.3.1 Average Inventory Volume before Stations
The average inventory volume at stations before each process step is calculated by manually counting the number of trays waiting to get processed by the next respective machine. As mentioned earlier all orders are passed along as a set of trays that are the part of a factory order. The total number of 212 trays, irrespective of the factory order they are part of, before all stations/process steps from the turning process to the critical clean process is counted once a day for seven days. The average WIP inventory observed before all stations of 212 fabrication along with their standard deviations or Std dev is summarized in Table 6.

As can be seen from Table 6, WIP accumulation is significantly higher in front of the milling and robo-drilling stations as compared to all other stations with the highest WIP accumulation in front of the robo-drilling station at approximately 11 trays where one tray can hold 28 parts. This is in direct relation to the cycle times per part for milling which is 7.2 minutes per part and for robo-drilling which is 16.5 minutes per part. It is also observed that the standard deviation of inventory volume in front of the robo-drill station which is 2.7 trays is significantly lower than 11.3 trays which is the mean number of trays waiting in front of the robo-drill station indicating a fairly constant and high WIP accumulation in front of robo-drilling as it is the slowest process in the line.
In this experiment raw material waiting for turning is ignored as the primary focus of the experiment was to observe WIP accumulation once the part is in process, i.e. after raw material has been turned.

### Table 6 Average WIP inventory observed before each process step

<table>
<thead>
<tr>
<th>WIP waiting for Milling</th>
<th>WIP waiting for Robo-drill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of trays</td>
</tr>
<tr>
<td>Mean: 4.3 trays Std dev: 3.7 trays</td>
<td>Mean: 11.3 trays Std dev: 2.7 trays</td>
</tr>
<tr>
<td>Mean: 0.4 trays Std dev: 0.5 trays</td>
<td>Mean: 0.6 trays Std dev: 1.5 trays</td>
</tr>
<tr>
<td>Mean: 0.6 trays Std dev: 1.5 trays</td>
<td>Mean: 1.1 trays Std dev: 2 trays</td>
</tr>
<tr>
<td>Mean: 2.1 trays Std dev: 3.1 trays</td>
<td>Mean: 0 trays Std dev: 0 trays</td>
</tr>
</tbody>
</table>

No inventory observed
3.3.2 Average Inventory Waiting Time before Stations

The average amount of time that one factory order waits before each station is arrived at by tracking 30 different 212 stator factory orders from the SAP system. The wait time before each station for every factory order is recorded and an average waiting time before each station is deduced from the waiting times before the respective station for all factory orders considered. The average time that a 212 stator factory order has to wait for all processes is summarized in Table 6.

From Table 6, it can be seen that the maximum amount of time a factory order has to wait before any process is approximately 7 days and this is in front of the robo-drilling station. This is again due to the longer cycle time per part of robo-drilling which is accentuated further by the wait-to-batch time of 100 parts.

The second highest waiting time is in front of the milling station. This can again be attributed to the relatively higher cycle time per part for milling, the very short cycle time per part, almost half of that of milling, of the process preceding milling, i.e. turning and wait-to-batch time.

Despite the imbalance of the line and planned release of orders, some amount of randomness is observed in the data due to the large sample size of 30 factory orders taken into consideration for this experiment. This randomness could be attributed to productivity of operator, tool break and other random but insignificant disruptions.
Table 7: Average waiting time for an entire factory order before process steps

<table>
<thead>
<tr>
<th>Process Step</th>
<th>WIP Waiting Time</th>
<th>Inventory Waiting Time (Days)</th>
<th>Mean</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIP waiting time for Milling</td>
<td>10</td>
<td>-</td>
<td>5.2</td>
<td>2.8</td>
</tr>
<tr>
<td>Mean: 5.2 days Std dev: 2.8 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WIP waiting time for Robo-drill</td>
<td>5</td>
<td>-</td>
<td>6.8</td>
<td>3.7</td>
</tr>
<tr>
<td>Mean: 6.8 days Std dev: 3.7 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WIP waiting time for EDM</td>
<td>1</td>
<td>-</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Mean: 1.2 days Std dev: 1.3 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WIP waiting time for De-burring</td>
<td>2</td>
<td>-</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Mean: 1.4 days Std dev: 1.3 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WIP waiting time for Lapping</td>
<td>10</td>
<td>-</td>
<td>2.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Mean: 2.6 days Std dev: 1.7 trays</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WIP waiting time for Passivation</td>
<td>5</td>
<td>-</td>
<td>0.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Mean: 0.6 days Std dev: 1 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WIP waiting time for Solvent clean</td>
<td>8</td>
<td>-</td>
<td>2.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Mean: 2.1 trays Std dev: 3.1 trays</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WIP waiting time for Critical clean</td>
<td>16</td>
<td>-</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Mean: 0.7 days Std dev: 0.9 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.3.3 Total Lead time of In-house Production for 212 Factory Orders

The average total lead time of a factory order from the start of turning to the end of critical cleaning is estimated by tracking thirty 212 stator factory orders on the SAP system. The factory orders are tracked from the day they are processed through turning to the day they are finished at critical cleaning. The results of this analysis are plotted and shown in Fig. 5.

![Lead time for a factory order of 212 stators](image)

**Fig. 5: Average lead time for a factory order of 212 stators**

It is seen that an average lead time of approximately 21 days is observed with a standard deviation of 6.2 days indicating a fairly long lead time for a factory order of 212 stators. In fact, the results indicate that the total lead time is between approximately 19 days and 23 days with 95% confidence. Also, the maximum lead time observed for a 212 factory order is 46 days.

Again, some randomness is observed due to the large sample size considered for this analysis and due to many random but insignificant disruptions/events associated with the data for such a large sample size.

3.3.4 Conclusion of System Characterization

If one 212 stator factory order is run on the line from turning to critical cleaning assuming that machines are always available once the order is batched up from the preceding process ready to
be moved to the subsequent process (as a batch), then the total lead time from turning to critical cleaning can be calculated using Equations (3.2) and (3.3):

\[
LT = S_{212} \times \frac{(t_{\text{turn}} + t_{\text{mill}} + t_{\text{robo}} + t_{\text{EDM}} + t_{\text{de-burr}} + t_{\text{lap}} + t_{\text{pass}} + t_{\text{VCN}} + t_{\text{CC}})}{60} + \text{time}_{\text{clean}}
\] (3.2)

where \(LT\) is the lead time in hours and \(\text{time}_{\text{clean}}\) is the additional time in hours to clean a factory order after lapping.

Therefore,

\[
\text{number}_{\text{days}} = \frac{LT}{\text{valve}_{\text{daily}}}
\] (3.3)

where the \(\text{number}_{\text{days}}\) is the theoretical lead time for a 212 stator factory order in days assuming no waiting or queuing and \(\text{valve}_{\text{daily}}\) is the number of hours of operation of the valve cell per day.

Using the process times per part from Table 2 in Equations (3.2) and (3.3), the theoretical lead time for a 212 stator factory order is given in Table 8.

<table>
<thead>
<tr>
<th>(\text{time}_{\text{clean}}) (hours)</th>
<th>(LT) (hours)</th>
<th>(\text{valve}_{\text{daily}}) (hours)</th>
<th>(\text{number}_{\text{days}}) (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>63.9</td>
<td>16.5</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Table 8 Theoretical lead time for a 212 stator factory order assuming no waiting and queuing
Therefore, it is calculated that the system can produce one factory order of 212 stators in approximately four days. But the average lead time based on analysis carried out in Section 3.3.3 is approximately 21 days.

This indicates that there is a huge impact on the raw lead time of not only 212 orders but also orders of other part types due to a large amount of queuing induced by the presence of such a high mix of parts in the valve cell.

In addition to queuing due to a very high mix of parts in the line, the wait to batch time for the factory orders under process results in significantly long cycle times per batch at each station. This also further increases the inventory waiting time for other factory orders of different part types that are not being processed.

Again, longer waiting in front of a station leads to higher WIP accumulation especially before stations that as such have a long cycle time per part.

3.4 Current Finished Goods Inventory
After the critical cleaning process is finished, factory orders are shipped to a coating vendor. The lead time for the coating process is approximately 18 days. The coated factory orders that are shipped back are then stored in the finished goods inventory from where parts are withdrawn by the Assembly department.
Planned finished goods inventory levels for every week of the third quarter of the year are obtained from SAP and shown under the ‘Avail. quantity’ column in Fig. 6.

<table>
<thead>
<tr>
<th>A...</th>
<th>Period/segment</th>
<th>Pind ind. reqmts</th>
<th>Requirements</th>
<th>Receipts</th>
<th>Avail. quantity</th>
<th>ATP quantity</th>
<th>Actual coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock</td>
<td>28/2013</td>
<td>0</td>
<td>136</td>
<td>0</td>
<td>1,603</td>
<td>0</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>29/2013</td>
<td>0</td>
<td>348</td>
<td>0</td>
<td>1,119</td>
<td>0</td>
<td>14.9</td>
</tr>
<tr>
<td></td>
<td>30/2013</td>
<td>0</td>
<td>290</td>
<td>0</td>
<td>829</td>
<td>0</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>31/2013</td>
<td>0</td>
<td>333</td>
<td>0</td>
<td>491</td>
<td>0</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>32/2013</td>
<td>0</td>
<td>510</td>
<td>116</td>
<td>97</td>
<td>0</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>33/2013</td>
<td>0</td>
<td>456</td>
<td>443</td>
<td>84</td>
<td>0</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>34/2013</td>
<td>0</td>
<td>184</td>
<td>186</td>
<td>86</td>
<td>0</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>35/2013</td>
<td>0</td>
<td>106</td>
<td>106</td>
<td>86</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>36/2013</td>
<td>0</td>
<td>270</td>
<td>369</td>
<td>185</td>
<td>0</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>37/2013</td>
<td>0</td>
<td>379</td>
<td>380</td>
<td>186</td>
<td>0</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>38/2013</td>
<td>0</td>
<td>362</td>
<td>380</td>
<td>204</td>
<td>0</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>39/2013</td>
<td>0</td>
<td>355</td>
<td>331</td>
<td>180</td>
<td>0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Fig. 6: Weekly planned inventory levels for the third quarter as obtained from SAP

As can be seen from Fig. 6, there is fluctuation in the number of finished 212 stators available at the finished goods inventory for assembly. In fact, the available quantity ranges from a very high quantity of 1603 parts to very low quantity of just 84 parts.

Further investigation is carried out and it is observed that there is no finished goods inventory review policy and estimated finished goods inventory levels to be maintained each week are based on long term planning. Long term planning of inventory levels to maintain is risky because a sudden surge in demand that is not predicted by planners will result in shortage. On the other hand, a lower demand than that expected by planners will result in finished goods inventory explosion leading to high average inventory levels and high associated costs.
More real time finished goods inventory level planning and monitoring can be obtained by standardizing finished goods inventory management through the use of an inventory review policy and maintaining a safety stock calculated based on the variability in demand observed. Standardization of inventory management implies triggering of orders based on a periodic review period or based on reaching a pre-determined re-order inventory level which is revised with updated demand data. The safety stock together with an inventory review policy helps protect finished goods inventory levels from variability in demand that results in high on time delivery performance and service level to the customer, the assembly department in this case, with more steady average inventory levels, that is no WIP explosion, through more real-time and updated planning.

3.5 On Time Delivery Performance
Although system inefficiencies are observed in both the valve cell fabrication and current finished goods inventory planning, they can be ignored as long as the assembly department does not face shortages, i.e. the on time delivery performance of 212 stators to the assembly department is high. It is required that fabrication maintains at least a 90% on time delivery performance to the assembly department. Current on time delivery performance for 212 stators is shown in Fig. 7.
Fig. 7: On time delivery performance for 212 stators to the assembly department for the second quarter of 2013.

The on time delivery performance for 212 stators for each individual week in the second quarter is used and the average on time delivery performance for the second quarter of 2013 is calculated as 53.61%. This is far below the targeted on time delivery performance of at least 90%.

The poor on time delivery performance is as expected given the excessively long lead times and waiting times during 212 stator fabrication as discussed in Section 3.3 in detail and due to a lack of proper finished goods inventory management as discussed in Section 3.4.

An inappropriate finished goods inventory planning gives way to a higher probability of stock outs and the lead time for sourcing parts taking 212 stators as an example, in case of finished goods inventory stock outs is very long—approximately 39 days taking into account the long in-house fabrication lead time of approximately 21 days for a 212 factory order and 18 days for coating of 212 stators.

Furthermore, on time delivery performance for other major part types is expected to be similar to that of 212 stators as they are expected to be equally impacted by the long lead times and wait
times during their fabrication due to high mix of parts in the valve cell and due to the poor planning of finished goods inventory.

3.6 Concluding Thoughts on Current Operations and Problem Statement
It is seen that the main problem associated with stator production is the poor on time delivery of stators to the assembly department. This is in part due to long in-house production lead times and in part due to poor finished goods inventory management. The number of parts planned in the finished goods stock room is either too high or too low which makes the finished stock inflexible to sudden changes in demand from assembly. The responsiveness of the system to sudden changes in demand is as such low owing to the long lead time of approximately 40 days it takes to source parts.

Higher product availability is therefore a requisite for better on time delivery performance.
Therefore, the main goal of this project is to improve the stator to assembly on time delivery performance to meet the targeted on time delivery performance of at least 90%.

The on time delivery performance will be improved by establishing a more responsive fabrication system that reduces the overall lead time and standardizing finished goods inventory management.

Also, Waters Corporation has an emphasis on lean manufacturing as a corporate policy. Therefore, though not the primary objective, an attempt at obtaining a leaner system with reduced overall WIP levels and a standardized finished goods inventory that avoids WIP
explosion will be made by eliminating extra inventory that does not contribute to improving system throughput and responsiveness.
4. Proposed Design of System

In this chapter, a solution to the problems identified in Chapter 3 is proposed. An idea for a new system is presented, the rationale behind the idea is discussed and the feasibility of the idea is examined. Revisions of both the fabrication system and the finished goods inventory management are addressed by the proposed idea.

4.1 Overview of the Proposed System
An overview of the proposed production system is shown in Fig. 8. A detailed explanation of Fig. 8 will be explained throughout the chapter. Since the main problem identified in the valve production system is that of the poor on time delivery of stators to the assembly department, the most critical area to improve is responsiveness to the customer to ensure there are no shortages of parts that shuts down assembly.

From literature review and as discussed in Section 2.4, a pull system helps develop a highly responsive customer service. This is because unlike a push system which plans the release of orders months ahead, a pull system maintains stock levels and triggers production upstream whenever there is a void in the end of line stock levels caused by the withdrawal of some stock by the customer which in this case is the assembly department.

Therefore, the pull system works on replenishing depleted stocks throughout the production line. Stock levels to be maintained throughout the production system are calculated real time using the
Fig. 8: Over-view of the proposed system
most updated demand data that helps in calculating how much needs to be held in stock over the
time it takes to replenish depleted stock or the lead time in addition to the safety stock that
accounts for demand variability over the lead time. Thus, a pull system ensures delayed
production of parts close to when the demand is actually realized as it works on triggering
production from the end of line that is the finished goods inventory.

Therefore, to solve the problem of poor on time delivery performance in the current system, it is
necessary to establish a pull system for the high volume parts like 212 stators that account for
approximately 52% of total stator production and 213 stators that account for approximately 12%
of total stator production. Since the remaining 26 stator types account for only 36% of total valve
cell production indicating very low volumes of such parts produced annually, the scope of
changing the production policy from push to pull is limited to only the 212 and 213 stators. This
is because of the complexity involved in the form of documentation changes, personnel training
and co-ordination & monitoring issues that would be required for such a high mix of parts.

In any case, the pull system designed for 212 and 213 stators seeks to eliminate traditional
queuing and WIP/final inventory explosion problems associated with push production and results
in the automatic leverage of the push production for all other low volume parts by reducing
overall lead times.

Apart from improving responsiveness, a pull system also helps in establishing an upper control
limit on WIP and final inventory levels. This is achieved as the system works only on
replenishing a void in stock levels, caused by customer withdrawal of finished goods, and eliminates WIP/inventory accumulation.

In conclusion, a successful pull system establishment entails both a responsive fabrication line that can achieve fast replenishment of depleted goods as well as a standardized finished goods inventory review policy that is able to generate triggers for replenishment at the right time to ensure high service level to the customer in the long run. The establishment of a pull based fabrication line and the importance of a suitable inventory review policy are both discussed in detail in Sections 4.2 and 4.3.

4.2 Fabrication System for Responsiveness
The fabrication system consists of all processing steps from the start of turning to the end of critical cleaning. As mentioned in Section 3.2.1, the uncoated finished parts are sent for coating after critical cleaning. The minimum number of parts that must be sent to the coating vendor to achieve economies is two hundred and fifty parts. Features of the proposed fabrication system are discussed in detail in the following sub-sections.

4.2.1 Line Dedication
As can be seen in Fig. 8, the new fabrication system consists of two separate lines that merge into one after the Wire-EDM process. The idea behind the two separate but almost identical lines is to have one line that is a high volume line to keep parts flowing as and when they are required to without any obstacles such as set-ups and waiting for batching of different part types. Since the only very high volume part type of the valve cell is the 212 stator this line is dedicated to the
production of 212 stators alone. The line on the left of Fig. 8 represents the high volume line. The other line on the right in Fig. 8 is a high mix line that takes care of the production of the remaining stator types.

Through this segregation, the high volume line will be carrying approximately 52% of the production load through the fabrication of 212 stators and the high mix line will be carrying a production load of 48% with set-ups and change-overs between the production of various part types. The most significant parts out of this mix account for 38% of total stator production while the remaining 10% consist of part types that have very low annual sales.

Each line consists of one turning machine and one wire-EDM machine. Since the robo-drill process is the identified bottleneck in the manufacture of 212 stators, two robo-drill machines will be placed in the high volume line as opposed to the current system where usually only one robo-drill machine is available for 212 stator fabrication. With this although robo-drilling will still remain the bottle-neck of the entire process but the bottle-neck cycle time per part will be cut down in half. Since with the new robo-drill machine, the total number of robo-drill machines on the floor is four, the remaining two robo-drill machines will be added to the high mix line.

The allocation of machines as shown in Fig. 8 for the respective lines is done based on the machines that are used for the production of 212 stators and for the remaining part types. For instance, the valve cell currently has two identical turning machines and one is allocated to each line.
After turning, as discussed in Section 3.2, the 212 stators go over to the NC milling department for slot milling and vertical hole drilling while all other part types go to Robo-drill machine 2 for vertical hole drilling alone since other part types do not require slot milling. Accordingly, the NC milling machine is allocated to the high volume line and Robo-drill machine 2 to the high mix line.

Moreover, most part types use Robo-drill machines 4 and 5 except Part 215 that uses Robo-drill machine 3 for central hole and conical hole drilling. Also since the new Robo-drill machine is identical to Robo-drill 4 and 5 and since Robo-drill machine 3 is capable of conical hole drilling similar to Robo-drill machine 4 and 5, albeit slower than its counterparts, the allocation of the robo-drill machines are done so that the high volume line has the new Robo-drill machine and Robo-drill machine 4 while the high mix line has Robo-drill machine 3 and Robo-drill machine 5. The two lines will merge after the wire-EDM process and will go through the exact same sequence of processes till critical cleaning.

Before proceeding further, a capacity analysis is done to verify if the existing capacity of the system can support the proposed fabrication system based on line dedication.

4.2.1.1 Capacity Analysis for High Volume Line
Referring to Table 1, we see that the annual production of 212 stators is 16355 parts. Since the valve cell operates for five days a week, therefore the daily required production of 212 stators on average in the valve cell is 63 parts.
The daily available hours to machines in the valve cell are 16.5 hours. However, since the line uses two robo-drill machines, the daily number of hours available to the robo-drill workstation is twice of 16.5 hours, that is, 33 hours. Milling happens in the NC milling department and this department operates for 22.5 hours per day instead of 16.5 hours like the valve cell.

The number of hours of operation for each workstation on the high volume line to satisfy the daily production requirement of 63 parts can be calculated using Equation (4.1):

\[
\text{hours}_{\text{req, workstation}} = \frac{t_{\text{workstation}}}{60} \times 63
\]  

(4.1)

where \( \text{hours}_{\text{req, workstation}} \) is the number of hours required per day for each workstation and \( t_{\text{workstation}} \) is the cycle time per part for each workstation in minutes.

Also, using the efficiencies of the machines from Table 5 the downtime per day for each workstation can be calculated by multiplying the number of hours available per day to each workstation times \((1 - \text{Efficiency})\) for the respective workstation. For instance, since 16.5 hours are available to the turning workstation per day, the downtime per day for the workstation is obtained by multiplying 16.5 hours by \((1-0.94)\) which gives a total downtime of 0.99 hours per day for the turning workstation on average.

Since there are no set-ups in the high volume line, utilization, \( u_{\text{workstation}} \) of the machine can then be calculated as the number of hours of operation required per day to satisfy the daily 212 stator production requirement divided by the total uptime per day as shown in Equation (4.2).
where $hours_{av.workstation}$ is the number of hours available for each workstation per day that could either be 16.5 hours for instance if the workstation is part of the valve cell or 22.5 hours if the workstation being considered is the milling machine. The $downtime_{workstation}$ is the number of hours of downtime for a workstation per day.

Table 9 provides the results of workstation utilization calculated for all machines in the high volume line by using information in Table 4 & Table 5 and substituting the respective workstation in Equations (4.1) and Equations (4.2).

<table>
<thead>
<tr>
<th>Workstation</th>
<th>$hours_{av.workstation}$ (hours)</th>
<th>$downtime_{workstation}$ (hours)</th>
<th>Daily demand for 212 stators (#parts)</th>
<th>$hours_{req.workstation}$ (hours)</th>
<th>$u_{workstation}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning</td>
<td>16.5</td>
<td>1</td>
<td>63</td>
<td>3.9</td>
<td>25.2</td>
</tr>
<tr>
<td>Milling</td>
<td>22.5</td>
<td>0.2</td>
<td>63</td>
<td>7.5</td>
<td>33.9</td>
</tr>
<tr>
<td>Robo-drilling</td>
<td>33</td>
<td>0.7</td>
<td>63</td>
<td>17.3</td>
<td>53.5</td>
</tr>
<tr>
<td>Wire-EDM</td>
<td>16.5</td>
<td>0.7</td>
<td>63</td>
<td>4.4</td>
<td>27.9</td>
</tr>
</tbody>
</table>

Also, information from the NC milling department suggests that it devotes 50% of the available time on milling for other parts and the remaining 50% of the available time on 212 stator milling. From Table 9, we can see that the milling machine utilization for stators alone is 33.89% which is less than the reserved capacity of 50%. Putting even 213 stators on the high volume line was considered but was not carried further due to limitations on the milling capacity.
Moreover, Table 9 shows the utilization values for all machines is fairly low. This implies that there is ample capacity in the high volume line to support the fabrication of 212 stators alone.

4.2.1.2 Capacity Analysis for High Mix Line
The total annual requirement of all stators other than the 212 stators is 15045 parts. Similar to how daily production requirement is deduced in the high volume line, the daily production requirement for the high mix line is 58 parts. The minimum order size used on the shop floor is 25 parts. Using conservative assumptions like all the high mix part types are pushed in order sizes of 25 parts and that the maximum number of set-ups on a given day based on daily production quantity on the high mix line will be 3 set-ups, since maximum number of set-ups = 58/25 +1, the number of hours required per day at each workstation is therefore given by Equation (4.3):

$$\text{hours}_{\text{req.workstation}} = \frac{t_{\text{workstation}}}{60} \times 58 + 3 \times t_{\text{set-up.workstation}}$$

(4.3)

where $t_{\text{set-up.workstation}}$ is the set-up time for the respective workstation in hours.

Table 10 shows the set-up times at various workstations which are uniform irrespective of the parts that the set-up is being performed between.
Table 10 Set-up times required at each machine

<table>
<thead>
<tr>
<th>Workstation</th>
<th>( t_{\text{set-up, workstation}} ) (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning</td>
<td>1</td>
</tr>
<tr>
<td>Robo-drill 2</td>
<td>1</td>
</tr>
<tr>
<td>Robo-drill 3 or 5</td>
<td>0.5</td>
</tr>
<tr>
<td>EDM</td>
<td>0</td>
</tr>
</tbody>
</table>

Moreover, \( u_{\text{workstation}} \) can be calculated using Equation (4.2) for the workstations in the high mix line. Table 4, Table 5 and Equations (4.2) and (4.3) are used for carrying out the capacity analysis and the results are presented in Table 11.

Table 11 Capacity Analysis for High Mix line consisting of all stators

<table>
<thead>
<tr>
<th>Workstation</th>
<th>( \text{hours}_{\text{av, workstation}} ) (hours)</th>
<th>( \text{downtime}_{\text{workstation}} ) (hours)</th>
<th>Daily demand for high mix stators (#parts)</th>
<th>( \text{hours}_{\text{req, workstation}} ) (hours)</th>
<th>( u_{\text{workstation}} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning</td>
<td>16.5</td>
<td>1</td>
<td>58</td>
<td>6.6</td>
<td>42.6</td>
</tr>
<tr>
<td>Robo-drill 2</td>
<td>16.5</td>
<td>0.3</td>
<td>58</td>
<td>12.7</td>
<td>78.3</td>
</tr>
<tr>
<td>Robo-drill 3 &amp; 5</td>
<td>33</td>
<td>0.7</td>
<td>58</td>
<td>17.5</td>
<td>54.1</td>
</tr>
<tr>
<td>Wire-EDM</td>
<td>16.5</td>
<td>0.7</td>
<td>58</td>
<td>11.5</td>
<td>73</td>
</tr>
</tbody>
</table>

4.2.1.3 Capacity Analysis of the Line from Lapping to Critical Clean
To verify there is enough capacity in the line from lapping to critical cleaning to support all 28 different part types, capacity analysis is done for the line from lapping to critical cleaning. There
are no set-ups involved in the line except for the Lapping process step where set-up time is equal to 1.5 hours. Also there are two lapping machines in the lapping room dedicated for all stators.

Since the total daily production requirement from lapping to critical clean is a total of 121 parts per day (63+58 parts/day=121 parts/day) and again making conservative assumptions of all part types being processed in the minimum lot size implying a maximum of 6 set-ups per day, a capacity analysis can be done for this part of the line. Note that there are no down-times in this part of the line since they are all cleaning and inspection processes that are mainly manual. Table 12 summarizes the result of the capacity analysis for the lapping to critical clean line.

Table 12 Capacity analysis of line from lapping to critical clean

<table>
<thead>
<tr>
<th>Workstation</th>
<th>$hours_{avg,workstation}$ (hours)</th>
<th>Daily demand for all stators (#parts)</th>
<th>$hours_{req,workstation}$ (hours)</th>
<th>$U_{workstation}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>De-burring</td>
<td>16.5</td>
<td>121</td>
<td>4.2</td>
<td>25.7</td>
</tr>
<tr>
<td>Lapping</td>
<td>16.5</td>
<td>121</td>
<td>15.1</td>
<td>45.6</td>
</tr>
<tr>
<td>Passivation</td>
<td>33</td>
<td>121</td>
<td>1.2</td>
<td>7.3</td>
</tr>
<tr>
<td>VCN cleaning</td>
<td>16.5</td>
<td>121</td>
<td>1.8</td>
<td>10.8</td>
</tr>
<tr>
<td>Critical Clean</td>
<td>16.5</td>
<td>121</td>
<td>0.4</td>
<td>2.2</td>
</tr>
</tbody>
</table>
4.2.2 In-Process Buffers
In addition to dedicating lines for the flow of high volume parts and high mix parts, responsiveness can be achieved by establishing in-process buffers. As shown in Fig. 8, the proposed fabrication line has in-process buffers between turning and milling, milling and robodrilling, and between robodrilling and the wire-EDM process. There is also a buffer established at the end of the line after critical cleaning before the parts are sent for coating.

The basic rationale behind incorporating in-process buffers is to cut the processing lead time by having required parts available in the buffer, for instance the buffer after robodrilling, for the downstream process like EDM and then triggering production upstream to replenish the quantity withdrawn from the buffer. In fact, in process buffers are a means to achieve a pull system. From Fig. 8 we can imagine when final finished goods inventory triggers orders for coated stators assuming a lead time of 18 days for the coating process for sourcing coated stators, the quantity corresponding to that ordered by finished goods inventory will be withdrawn from the uncoated finished parts buffer and sent for coating. In order to replenish the uncoated finished parts inventory, same quantity of parts will be withdrawn from the robo-drill buffer and processed through EDM and subsequent processes till critical clean. Again, to replenish the robo-drill buffer, parts will be withdrawn from the milling buffer and robo-drilled. The milling buffer will then be replenished by milling parts drawn from the turning buffer which will then be replenished by turning raw material.

Thus each in-process buffer behaves like a super-market for the subsequent process. For instance, the in-process buffer after turning is a super-market for the milling process as the parts to be
milled are withdrawn from the turning super-market and turning then works on re-building the
stock level for its super-market.

This system is in fact fairly simple to implement especially in the high volume line that only has
one part type as any depletion or void in stock levels of a super-market can be immediately
replenished owing to no set-ups.

Implementing a pull system through in-process buffers also helps in realizing constant WIP in
the process and also helps in eliminating extra WIP that is not required to realize the throughput
of the system. By having just sufficient WIP required to keep the utilization of the system
bottleneck, in our case the robo-drill machines, high and busy, the system automatically operates
at the system bottleneck throughput rate which is the maximum throughput rate a system can
achieve. Any extra WIP in the system leads to increase in waiting and cycle times and hence
overall lead time. Calculation of appropriate stock levels using a type of base stock policy for
different in-process buffers is discussed in detail in Chapter 5.

Referring to Fig. 8, the proposed fabrication system is expected to be more responsive than the
current system as through the use of in-process buffers the push process has been delayed till
after robo-drilling as compared to the current system that pushes right from turning which
therefore involves production through robo-drilling as well which is the bottle-neck inflating lead
time. In the proposed system, from an in-house production point of view, parts can be pulled
from the robo-drill super-market and pushed from EDM to critical clean. Thus, the in-house
production push-pull boundary lies in between robo-drilling and wire EDM.
The reason for establishing the in-house production push pull boundary as such is that firstly it is essential that a robo-drilling super-market exists because robo-drilling is the bottle-neck process and secondly the processes from EDM onwards are very fast with negligible amount of waiting observed through these processes in the current system as well, and processed as batches, i.e., a fixed batch of parts are loaded onto the EDM machine and into the cleaning tanks during part processing from EDM to critical cleaning. Since these processes are not time consuming and batch based, there is no need for in-process buffers to cut the lead time.

Thus when parts are ordered from the finished goods inventory the lead time should most probably, with a probability associated with the service level wished to be maintained, be the time from when parts are processed at EDM to when they arrive at the finished goods inventory after coating. Even if there are stock outs, say in the robo-drill super-market, the use of in-process buffers along the line till after the robo-drill process significantly reduces the lead time.

In conclusion, in-process buffers help in establishing a replenishment based pull system. The use of in-process buffers facilitates immediate withdrawal of parts and hence reduces the overall lead time thereby providing good responsiveness and high service levels. Moreover, in-process buffers help control WIP levels by working to replenish only that much that is depleted.

4.2.3 Other Ideas and Features of the Proposed Fabrication System
The proposed line design as shown in Fig. 8 involves ideas that are different from the current system operations and practices. Firstly, the pull based system helps in the cognitive elimination order based processing. Order based batching is characteristic to a push system that results in
problems like high WIP waiting times, long queue lengths, WIP accumulation, etc., as each work-station waits to complete an order before passing the entire order to the next station. The proposed fabrication system that works on replenishment of the amount withdrawn does away with order based processing as instead of releasing orders on the shop floor, WIP and inventory depletion signals trigger production upstream that then replenishes depleted quantities.

Other ideas for improving efficiencies include the use of lot splitting. For instance, if a process is waiting for parts to fabricate, the process upstream can fabricate and send the overall quantity required by the former process in smaller lots so that the parts are kept moving and there is something for the process that is waiting to work on. This helps in reducing wait to batch time besides keeping the process downstream from starving. The policy of lot splitting in the proposed system can be used in the push part of the line where for instance if two trays enter into the lapping room, then instead of waiting for both trays to get lapped, one tray could be sent for the passivation process while the other tray is still being worked on. Using the same example, in the current system an entire order of four trays is first entirely lapped before sending the entire order to passivation.

Another insight into the system is that since the robo-drill cycle time per part is longer than the wire-EDM cycle time per part, there is a possibility of the robo-drilling super-market to stock out if EDM continuously withdraws parts from the super-market. However, because the cycle time per part for the robo-drill station for the proposed system is 8.25 minutes as opposed to the 16.5 minutes in the current system, the rate at which the system can replenish the super-market has doubled, assuming the robo-drill machine is fully busy. Therefore, a policy of permitting EDM
withdrawal only till daily demand is satisfied can be implemented after which EDM production can stop as the robo-drill workstation re-builds the super-market stock. As discussed in detail in chapter 5 and chapter 6, using this policy, the proposed system has the capacity to meet even the highest monthly demand observed in a year which is not possible to implement if only one robo-drill machine is used to replenish the super-market.

Another key aspect of the system is to establish an optimal batch size or Kanban size for a Kanban based pull system implementation so that the batch size must be large enough to not significantly change current utilization but small enough to aid significant reduction in cycle times per machine thereby reducing overall lead times. This will be discussed in detail in Chapter 5.

Also, an important feature of the proposed fabrication system is the use of a standardized inventory management policy for the uncoated finished parts inventory at the end of critical clean as it is essential that there are always uncoated parts available in this inventory to protect against any variability encountered during the coating process and to ensure on time delivery of coated stators to assembly. An inventory management policy like the base stock policy can be implemented so that whenever stock falls below the base stock level an order for uncoated finished parts is placed on the fabrication line upstream. This again facilitates keeping an upper control on the amount of inventory without compromising on responsive part fulfillment.
4.3 Finished Goods Inventory
Since a successful pull system implementation requires both a responsive fabrication line discussed above and efficient finished goods inventory management to generate triggers upstream at the right time, in this section various inventory review policies to achieve standardized inventory management are discussed. Another idea of merging fabrication and assembly inventories to reduce overall inventory levels without compromising on the service level is briefly presented.

4.3.1 Comparison of Various Inventory Review Policies
The first policy that is discussed is a continuous review policy. A continuous review policy for finished goods inventory in a pull system is ideal as the key feature of a continuous review policy is the generation of triggers whenever the inventory position reaches a pre-determined re-order level, enabled by continuous monitoring of the inventory position (refer to chapter 2 for discussion on inventory position). The re-order level is calculated as the average demand over the lead time it takes for the ordered quantity to arrive to replenish inventory in addition to some safety stock that accounts for demand variability over the lead time.

\[ Re - order\ level = Demand\ rate \times Lead\ time + z\sigma\sqrt{Lead\ time} \]  \hspace{1cm} (4.4)

where \( Re - order\ level \) is expressed in parts, \( z \) is the service level wished to be maintained and \( \sigma\sqrt{Lead\ time} \), the standard deviation in demand over lead time.

Whenever the inventory position reaches the re-order level, a fixed quantity is ordered. The fixed order quantity is mostly an economic order quantity (EOQ) that is calculated based on annual
demand, annual holding costs and annual ordering costs. The EOQ is that quantity that minimizes the annual total cost of handling inventory and ordering parts. Refer to Section 2.2.1.1 for EOQ calculation.

Referring to Fig. 6, where order quantities planned do not seem standardized, we see that the continuous inventory review policy is not only an ideal trigger policy for pull system but also helps in standardizing inventory management by the use of a fixed EOQ whenever it places an order. This is particularly suited to the system at Waters since a quantity of a minimum of 250 parts must be ordered by the finished goods inventory owing to the constraint of sending at least 250 parts to the coating vendor. Therefore, the EOQ model helps achieve high service levels.

Another method of calculating the fixed order quantity for the continuous review policy is derived through the Newsvendor model. This fixed order quantity can be updated based on most current demand as if the costs of underage and overage per unit inventory remains the same, then the newsvendor model calculates order quantity as:

\[ F(Q^*) = \frac{C_U}{C_U + C_o} \]  \hspace{1cm} (4.5)

where \( F(x) \) is the cumulative distribution function of the demand. This will result in more real-time updating of the fixed order quantity. However, this model calculates the order-quantity based on the risk of underage/overage whichever is higher and hence allows for shortages.

Major advantages of the continuous review policy include high customer responsiveness due to continuous monitoring of inventory position and achievement of high service levels with lesser average inventory as compared to other inventory review policies. A major disadvantage of the
continuous review policy is that though it is ideal for generating triggers for orders it is difficult and expensive to set-up as it requires continuous monitoring.

The periodic/base stock review policy, unlike the continuous review policy does not monitor stock levels continuously but at fixed intervals. An order of the appropriate quantity to replenish the stock to the base stock level is then made at each review. Thus instead of instantaneous triggering of fixed quantities, the base stock policy results in delayed triggering of variable quantities. Though not as ideal for a pull system as a continuous review policy, the base stock policy is more frequently used as a review policy because of its easier set up. If the review period is denoted by \( r \) time units, then the base stock level of the finished goods inventory so that there is enough in the inventory till the next order arrives, which is one review period plus the lead time for the order to arrive, will be calculated as:

\[
B = \text{Average demand rate} \times (r + \text{Lead time}) + z\sigma \sqrt{r + \text{Lead time}}
\] (4.6)

Major advantages of implementing a base stock policy are easier set-ups and less overall transaction costs. Also, the base stock level, in parts, helps establish a maximum level of inventory that can be held in the system. On the other hand, the major disadvantages include a possibility of stock out due to non-continuous monitoring and hence compromised service level. Therefore, a pure base stock policy is not suitable for the finished goods inventory of the proposed system since the main goal of the proposed system is to maintain high service levels. However, a pure continuous review policy though best suited to the project objective of
improving customer responsiveness, is also not feasible to implement given the capability of real
time monitoring required.

Therefore, a mixed review policy that can combine both the advantages of quasi continuous
monitoring for efficient triggering from the continuous review policy and the easier set up and
upper inventory control limit of the base stock policy seems ideal for the proposed system at
Waters.

A mixed review policy, also called an (s,S) policy establishes a re-order level, s that is the same
as the re-order level of the continuous review policy. The base stock level S is calculated as the
sum of re-order level and fixed order quantity determined by the EOQ model. If a policy of daily
review is therefore established and it is observed that the inventory position has gone below s,
albeit not by much since a review would have happened a day before when the re-order level s
would not have been touched, enough is ordered to raise the inventory position to S. This order
quantity should not be very different from the EOQ as the maximum difference between the
EOQ and this order quantity will be a day’s demand.

In conclusion, a mixed review policy is adopted for the proposed system as it provides quick
responsiveness, is more practical to implement and establishes an upper inventory control limit.

4.3.2 Merging Fabrication and Assembly Inventories
In the current system, the fabrication department and the assembly department hold separate
inventories of coated stators. However, a policy of merging these inventories is proposed. By
having a centralized control and visibility of total coated stator inventory, the fabrication
department can make last minute adjustments in the actual quantity to be produced thereby
saving a few hours of capacity which could also be used to do other work [12].

Moreover, merging inventories also leads to reduced overall inventory levels. This is so because
in a system like the current one at Waters where the fabrication department and assembly
department both hold separate inventories, both parties tend to keep some amount of extra
inventory for safety to protect themselves. While this is understandable such a practice leads to
unnecessary and redundant inventory that does not contribute to improving service levels and
this becomes visible only by merging the two inventories.

Thus by merging the two inventories, lesser inventory levels can be achieved without impacting
high service levels.

4.4 Conclusion on Design of System
A new system based on pull production is proposed. The pull system consists of two aspects, i.e.
a more responsive fabrication line and a suitable finished goods inventory review policy for
generating triggers in a pull system.

An attempt at making the fabrication line more responsive by having dedicated lines for the high
volume 212 stators and high mix parts is discussed and a capacity analysis to validate the design
is made. Placement of in-process buffers to facilitate pull from the bottleneck super-market is
discussed and is expected to reduce lead times drastically by starting production from after the process bottleneck.

Moreover, the advantages and disadvantages of various inventory review policies for finished goods inventory is discussed and the adoption of a mixed review policy or (s,S) policy is decided due to its feasibility in implementation and its feature of having an inventory control limit that therefore avoids the possibility of WIP explosion.

Finally, the idea of merging fabrication and assembly inventories to obtain a high service level with lesser inventory is presented.
5. Line Modeling

In this chapter mathematical models for the in-process buffers for the proposed line are developed. These models are used to compare the lead time and average inventory levels of the proposed system and the current system to verify the adoption of the proposed system. Various scenarios will be tested on these models and the parameters of the scenario that result in maximum lead time and WIP reduction are chosen for implementation on the floor.

5.1 Establishment of WIP Cap (CONWIP) and Base Stock Policy
As discussed earlier, the proposed system shown in Fig. 8 emulates a pull production system. The key feature of a pull production system is the establishment of an upper control limit on the WIP, i.e., a WIP cap to eliminate extra WIP that does not increase throughput.
Also in chapter 2, it is understood that CONWIP and Kanban system are two methods of establishing pull production and that the Kanban system is more suited to repetitive manufacturing conditions.

Since the dedicated line for 212 stators represents repetitive manufacturing processes and conditions (since the line will only be producing 212 stators with no set-ups or disruptions associated with product mix), the Kanban system is used as an example for modeling the line. For a Kanban system, the WIP cap is established by the use of Kanban cards. The amount of WIP on the floor is limited by the number of Kanban cards used for signaling production. The implementation of a Kanban system is discussed in detail in the next chapter.
The establishment of a Kanban based pull system is through the use of in-process buffers that are make-to-stock and trigger production upstream whenever there is a void in the stock levels to replenish the void. Therefore, as discussed in Chapter 2, the base stock model tends well to a pull system as orders can be triggered whenever the stock falls below the base stock level.

The base stock model is therefore adopted for analysis of in-process buffers. The model is discussed in detail in the Section 5.2.

5.2 A Model for In-process Buffers
The Strategic Inventory Placement model that uses a base stock model to set the base stock equal to the maximum demand over the net replenishment lead time is shown in Fig. 9. The rectangular box in the figure with a circle and triangle depicts a production stage that holds inventory. The circle represents a process or production and the triangle represents inventory.

![Base stock model considering inbound and outbound service times](image)

**Fig. 9: Base stock model considering inbound and outbound service times [4]**

Considering the isolated production stage shown in Fig. 9, let \( s_{i-1} \) days be the inbound service time to this stage from a previous stage where service time implies the delivery time that a stage quotes to its customer and \( s_i \) days be the outbound service time that this stage quotes to its
customer. Let \( L_i \) days be the lead time associated with the stage. \( L_i \) accounts for both the production lead time \( PLT_i \) days and the review period \( r \) days, so that:

\[
L_i = (PLT_i + r) \quad (5.1)
\]

The replenishment time or \( RT_i \) i.e. the time it takes to replenish an order once a production request is made is equal to the inbound service time from the previous stage plus the lead time at the present stage. Thus,

\[
RT_i = (s_{i-1} + L_i) \quad (5.2)
\]

where \( RT_i \) is in days.

The net replenishment time or \( \tau_i \) on the other hand is the number of days of stock/inventory a stage should hold to be able to quote a service time of \( s_i \) to the next stage. Therefore,

\[
\tau_i = (s_{i-1} + L_i - s_i) \quad (5.3)
\]

where \( \tau_i \) is expressed in days.
This implies that the base stock for stage $i$ or $Base\ stock_i$ should be equal to the maximum demand over $\tau_i$ days. Hence if $\mu$ parts is the daily demand and if $\sigma$ parts is the standard deviation in daily demand,

$$Base\ stock_i = \mu \tau_i + z\sigma \sqrt{\tau_i}$$ (5.4)

where $Base\ stock_i$ is expressed in number of parts.

And safety stock for stage $i$ or $SS_i$ which is the base stock minus the average demand over $\tau_i$ days is given by equation (5.5):

$$SS_i = z\sigma \sqrt{\tau_i} = z\sigma \sqrt{s_{i-1} + L - s_i}$$ (5.5)

where $SS_i$ is expressed in number of parts.
The proposed system design shown in Fig. 8 can be modeled using the above model. Fig. 10 shows a schematic representation of the proposed system to model the system as per the base stock model.

![Fig. 10: Schematic representation of the proposed line design for 212 stators](image)

As can be seen from Fig. 10, the first block represents the turning process and the buffer of turned blanks associated with that. Similarly, the second and third blocks represent the milling and robo-drilling process with their associated in-process buffers. The fourth block represents all processes from the wire-EDM process to critical cleaning and the buffer associated with these processes is the uncoated finished stator inventory. This thesis models all these in-process buffers using the model discussed above. The next block i.e. the coating block is just a process and is not modeled as it has no buffers but is taken into consideration as needed. The last block is the finished goods inventory block. Please refer to Bingxin Yao's thesis [13] for finished goods inventory modeling.
5.3 Application of Model for In-process Buffers in High Volume Line
Since a Kanban based pull system is being considered for implementation, the in-process buffers are modeled for different Kanban sizes. Since one tray as mentioned in Chapter 3 holds 28 parts, Kanban sizes that are multiples of 28 and less than 100, since the current factory order for 212 stators is of 100 parts and leads to long waiting, are considered. Therefore, in process buffer modeling is done for Kanban sizes of 28, 56 and 84 parts.

Based on finished goods inventory management calculations [13], the EOQ for 212 stators is calculated as 330 parts. Since the in house production produces only in multiples of 28 parts, the closest multiple to 330 parts is 336 parts and hence whenever an order is dispatched from uncoated finished parts inventory, a production signal is triggered upstream to the EDM station for a quantity of 336 parts of 212 stators to fill the void of 330 parts.

Moreover, in order to model a pull process where the subsequent stage can pull parts immediately from the previous stage, the service time quoted by each stage to the next stage is set to zero.

The application of the model discussed in Section 5.2 for lead time calculation and base stock level calculation will be discussed in Section 5.3.1.
5.3.1 Lead time and Base Stock Levels

Let the Kanban size chosen be $K$ parts and let $K$ be a multiple of 28 parts as discussed in the earlier part of Section 5.3. Let the review period, $r$ be 0.5 days to ensure checking of depletion at least twice a day. Refer to Table 13 for process times per part in minutes for 212 stators. In addition to the process times per part, the stators are cleaned after lapping where each tray of stators goes through two stages of cleaning that are 15 minutes long each.

<table>
<thead>
<tr>
<th>Cycle time at each workstation (minutes per part) for high volume line</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{\text{turn,hv}}$</td>
</tr>
<tr>
<td>3.72</td>
</tr>
</tbody>
</table>

where $t_{\text{turn,hv}}, t_{\text{mill,hv}}, t_{\text{robo,hv}}, t_{\text{EDM,hv}}, t_{\text{de-burr,hv}}, t_{\text{lap,hv}}, t_{\text{pass,hv}}, t_{\text{VCN,hv}}, t_{\text{CC,hv}}$ are the cycle times per part in minutes for turning, milling, robo-drilling, wire-EDM, de-burring, lapping, passivation, VCN and critical cleaning respectively for the high volume line.

Since there are two 15 minute cleaning stages, the cycle time for cleaning one tray is 30 minutes, but the cycle time for cleaning 2 trays simultaneously will be 45 minutes. Since, the number of trays that will go through cleaning simultaneously for a Kanban size of $K$ parts is $\left(\frac{K}{28}\right)$ trays.

Therefore,

$$time_{\text{clean,pull}} = 15 \times \left(\frac{K}{28} + 1\right)$$ (5.6)

where $time_{\text{clean,pull}}$ is the additional cleaning time in minutes for the proposed pull-type system.
Also all the operations listed in Table 13 are done in the valve cell except the milling operation which is done in the NC milling department. Table 14 gives the hours of operation of the Valve cell and the NC milling department per day.

Let $milling_{daily}$ represent the number of hours of operation of the NC milling department. Table 14 summarizes the hours of operation of the valve cell and the NC milling department per day.

**Table 14 Hours of operation per day for the Valve cell and the NC Milling Department**

<table>
<thead>
<tr>
<th></th>
<th>$valve_{daily}$ (hours)</th>
<th>$milling_{daily}$ (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16.5</td>
<td>22.5</td>
</tr>
</tbody>
</table>

With this information, the equations for production lead time for each stage are derived. Since the system emulates a pull process, the service time quoted by the robo-drilling stage to the EDM-CC stage, that quoted by the milling stage to the robo-drilling stage and the service time quoted by the turning stage to the milling stage are all zero.

Fig. 11: Loops indicating difference in production lead time

Production lead time for this stage is the time it takes to produce 336 parts.

Production lead time for these stages is the time it takes to produce the Kanban size.
Moreover, it is important to note that since the uncoated finished inventory places an order of 336 parts, the production lead time for the EDM-CC stage is the time it will take to produce 336 parts.

However, since Wire-EDM only pulls one Kanban size of parts from the robo-drill buffer at a time, the production lead time for replenishing the void will be equal to the time the robo-drill workstation takes to produce one Kanban size. Similarly, the robo-drilling stage and the milling stage pull only one Kanban size at a time and hence the production lead times for replenishing the voids will be equivalent to the time it takes to mill and turn one Kanban size respectively. Thus there are two Kanban loops and the same is described in Fig. 11.

Since a pull process is being followed, equations are listed in the reverse order starting from the EDM-CC stage.

The production lead time for the stage that represents the batch process from Wire EDM to Critical Clean for a total quantity of 336 parts with a Kanban size of $K$ parts is given by the following equation.

\[
PLT_{EDM-CC} = \left[ t_{EDM, hv} \times K \times \frac{336}{K} + K(t_{de-burr, hv} + t_{lap, hv} + t_{pass, hv} + t_{VCN, hv} + t_{CC, hv}) + \frac{time_{clean, pull}}{60\text{valve}_{daily}} \right] \quad (5.7)
\]
where $PLT_{EDM-CG}$ is expressed in days, and $\frac{336}{K}$ is the total number of times that the Kanban size has to go through the EDM to critical clean process to stock 336 parts in the uncoated finished goods inventory.

Similarly, the production lead time for the robo-drilling stage for a Kanban size of $K$ parts is given by equation (5.8):

$$PLT_{Robodril} = \left[ \frac{K_{t_{robo,hv}}}{60valve_{daily}} \right]$$

where $PLT_{Robodril}$ is expressed in days.

The production lead time for the milling stage for a Kanban size of $K \geq 56$ parts is as follows:

$$PLT_{Milling} = \left[ \frac{K_{t_{milling,hv}}}{60milling_{daily}} \right]$$

where $PLT_{Milling}$ is expressed in days.

However, if $K = 28$ parts, for practical considerations and co-ordination purposes, the production lead time for the milling stage is given as:

$$PLT_{Milling} = \left[ \frac{56t_{milling,hv}}{60milling_{daily}} \right]$$
This is because utilizing the NC milling department for producing just one tray increases the valve cell’s utilization of the NC milling department that mills many other parts. Moreover, it is easier to have the robo-drill machines work on one tray each (therefore two trays in total) even though for robo-drill buffer replenishment purposes, the two robo-drill machine operators can co-ordinate and replenish the buffer when the two machines in total produce 28 parts. Thus, effectively the Kanban size remains 28, but for practical purposes and easy co-ordination, it is easy for the robo-drill workstation to withdraw two trays, i.e. two Kanban sizes (so that either machine can work on one tray each) thereby placing an order of two Kanban sizes on the milling machine. This special case is justified in Section 5.4 and discussed in detail in the next chapter.
The production lead time calculation for the turning stage is given by equation (5.11):

\[ PLT_{Turning} = \left[ \frac{Kt_{turn, hv}}{60\text{valve}_{daily}} \right] \]  (5.11)

where \( PLT_{Turning} \) is expressed in days.

The production lead times calculated thus can be used for calculation of base stock levels using Equations (5.3) and (5.4). The base stock level to be maintained at each stage is the maximum demand over the net replenishment time. The daily demand data for 212 stators based on annual demand is given by Table 14.

<table>
<thead>
<tr>
<th>Demand Data</th>
<th>Number of Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu )</td>
<td>64</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>58.6</td>
</tr>
</tbody>
</table>

Using the data from Table 15, the net replenishment time and the base stock levels for each in-process buffer can be calculated. Service times quoted by each stage to the next is zero.

For a Kanban Size of \( K \) parts Equations (5.1), (5.3) and (5.4) can be used to give the net replenishment time in days and the base stock level from for the EDM-CC stage summarized in Equations (5.12) and (5.13).

\[ \tau_{EDM-CC} = s_{Robodrill} + PLT_{EDM-CC} + r - s_{EDM-CC} \]  (5.12)

where \( \tau_{EDM-CC} \) is expressed in days.
Since the net replenishment time estimates how many days of stock should be held to be able to quote a service time of zero to the next stage, between any two instants of part withdrawal from the EDM-CC stage, the maximum demand will be equal to the EOQ of 330 parts. Referring to equation (5.4), the base stock level of the uncoated finished parts inventory is calculated as 330 plus the safety stock level as given in equation (5.5).

\[ \text{Base stock}_{EDM-CC} = 330 + z\sigma\sqrt{\tau_{EDM-CC}} \]  \hspace{1cm} (5.13)

where \( \text{Base stock}_{EDM-CC} \) is expressed in number of parts.

For the robo-drilling stage,

\[ \tau_{Robodrill} = S_{Milling} + PLT_{Robodrill} + r - s_{Robodrill} \]  \hspace{1cm} (5.14)

where \( \tau_{Robodrill} \) is expressed in days.

Referring to equation (5.4), the base stock level for the robo-drilling stage can be calculated as,

\[ \text{Base stock}_{Robodrill} = \mu \tau_{Robodrill} + z\sigma\sqrt{\tau_{Robodrill}} \]  \hspace{1cm} (5.15)

where \( \text{Base stock}_{Robodrill} \) is expressed in number of parts.
Similarly, the net replenishment time in days for the milling stage is given by equation (5.16):

\[ \tau_{\text{Milling}} = s_{\text{Turning}} + PLT_{\text{Milling}} + r - s_{\text{Milling}} \]  

(5.16)

The base stock level in number of parts for the milling buffer therefore is:

\[ Base \ stock _{\text{Milling}} = \mu \tau_{\text{Milling}} + z \sigma \sqrt{\tau_{\text{Milling}}} \]  

(5.17)

Finally, the net replenishment time for the turning stage is given by equation (5.21). Since turning indicates the start of the line and since raw material is assumed to be always available, the inbound service time is not shown in the equation for this stage.

\[ \tau_{\text{Turning}} = PLT_{\text{Milling}} + r - s_{\text{Turning}} \]  

(5.18)

where \( \tau_{\text{Turning}} \) is expressed in days.

Using equation (5.4), the base stock level for the turning buffer is given by equation (5.19),

\[ Base \ stock _{\text{Turning}} = \mu \tau_{\text{Turning}} + z \sigma \sqrt{\tau_{\text{Turning}}} \]  

(5.19)

where \( Base \ stock _{\text{Turning}} \) is in number of parts.
5.3.1.1 Lead time and Base Stock Levels for a Kanban size of 84
Substituting $K = 84$ in Equations (5.7) to (5.11), the production lead time or $PLT_i$ is calculated for each stage and added to the review period, $r = 0.5$ days, to obtain the overall lead time $L_i$. $\tau_i$ is calculated from $L_i$ using Equations (5.12), (5.14), (5.16), and (5.18). All service times between stages are set to zero. Demand data from Table 15 is used and the results are summarized in Table 16.

<table>
<thead>
<tr>
<th>Stage i</th>
<th>PLT$_i$ (Days)</th>
<th>$r$ (Days)</th>
<th>$L_i$ (Days)</th>
<th>$\tau_i$ (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM-Critical Clean</td>
<td>1.9</td>
<td>0.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Robo-drill</td>
<td>0.7</td>
<td>0.5</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Milling</td>
<td>0.5</td>
<td>0.5</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Turning</td>
<td>0.3</td>
<td>0.5</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Using $z = 2$ which corresponds to a service level of 98% and the $\tau_i$ values obtained for $K = 84$ as shown in Table 16, Equations (5.13), (5.15), (5.17) and (5.19) are used to calculate the base stock levels for each stage/in-process. The results of these calculation are summarized in Table 17. Equation (5.5) is used to calculate the Safety stock $SS_i$ levels by using the standard deviation in daily demand from Table 15 and the $\tau_i$ values as input.
Table 17 Safety Stock and Base Stock Levels for $K = 84$

<table>
<thead>
<tr>
<th>Stage i</th>
<th>Service level</th>
<th>$\tau_i$ (Days)</th>
<th>$SS_i$ (# Parts)</th>
<th>Base stock $i$ (# Parts)</th>
<th>Base Stock (# Trays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM-Critical</td>
<td>98%</td>
<td>2.5</td>
<td>185</td>
<td>515</td>
<td>18</td>
</tr>
<tr>
<td>Clean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robo-drill</td>
<td>98%</td>
<td>1.2</td>
<td>128</td>
<td>205</td>
<td>7</td>
</tr>
<tr>
<td>Milling</td>
<td>98%</td>
<td>0.9</td>
<td>114</td>
<td>175</td>
<td>6</td>
</tr>
<tr>
<td>Turning</td>
<td>98%</td>
<td>0.8</td>
<td>106</td>
<td>158</td>
<td>6</td>
</tr>
</tbody>
</table>

Note that the number of Base stock trays is obtained by dividing the number of base stock parts by 28 since one tray holds 28 parts.

5.3.1.2 Lead time and Base Stock Levels for a Kanban size of 56 parts

Substituting $K = 56$ in Equations (5.7) to (5.11), $PLT_i$ is calculated for each stage and added to the review period, $r = 0.5$ days, to obtain the overall lead time $L_i$. $\tau_i$ is calculated from $L_i$ using Equations (5.12), (5.14), (5.16), and (5.18). All service times between stages are set to zero. Demand data from Table 15 is used and the results are summarized in Table 18.

Table 18 Production lead time and net replenishment time for different stages for $K = 56$

<table>
<thead>
<tr>
<th>Stage i</th>
<th>$PLT_i$ (Days)</th>
<th>$r$ (Days)</th>
<th>$L_i$ (Days)</th>
<th>$\tau_i$ (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM-Critical Clean</td>
<td>1.8</td>
<td>0.5</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Robo-drill</td>
<td>0.5</td>
<td>0.5</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Milling</td>
<td>0.3</td>
<td>0.5</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Turning</td>
<td>0.2</td>
<td>0.5</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Using $z = 2$ which corresponds to a service level of 98% and the $\tau_i$ values obtained for $K = 56$ as shown in Table 18, Equations (5.13), (5.15), (5.17) and (5.19) are used to calculate the base stock levels for each stage/in-process. The results of these calculation are summarized in Table
19. Equation (5.5) is used to calculate the Safety stock $SS_i$ levels by using the standard deviation
in daily demand from Table 15 and the $\tau_i$ values as input.

<table>
<thead>
<tr>
<th>Stage $i$</th>
<th>Service level</th>
<th>$\tau_i$ (Days)</th>
<th>$SS_i$ (# Parts)</th>
<th>Base stock$_i$ (# Parts)</th>
<th>Base Stock (# Trays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM-Critical Clean</td>
<td>98%</td>
<td>2.3</td>
<td>178</td>
<td>508</td>
<td>18</td>
</tr>
<tr>
<td>Robo-drill</td>
<td>98%</td>
<td>0.9</td>
<td>115</td>
<td>177</td>
<td>6</td>
</tr>
<tr>
<td>Milling</td>
<td>98%</td>
<td>0.8</td>
<td>105</td>
<td>156</td>
<td>6</td>
</tr>
<tr>
<td>Turning</td>
<td>98%</td>
<td>0.7</td>
<td>99</td>
<td>144</td>
<td>5</td>
</tr>
</tbody>
</table>

5.3.1.3 Lead time and Base Stock Levels for a Kanban size of 56 parts (lot splitting)
If a Kanban size of 56 parts is used but lot splitting as a technique is employed in the processes
from de-burring to critical cleaning, i.e. the lots are not from de-burring to lapping for instance in
batches of 56 parts but are moved as a lot of 28 parts first (one tray size) and 28 parts later even
though the Kanban size is 56 parts, then the production lead time of the EDM-CC stages is given
as [1]:

$$PLT_{EDM-CC} = t_{EDM,hv} \times 56 \times 4 + t_{lap,hv} \times 28 \times 2 + (t_{de-burr,hv} + t_{pass,hv} + t_{VCN,hv} + t_{CC,hv} + ct_{part}) \times 28 \over 60 \text{valve daily}$$ (5.20)

where $PLT_{EDM-CC}$ is expressed in days and $ct_{part}$ is the cleaning time per part in minutes.
The above is modeling that EDM finishes 56 parts and sends the Kanban size for de-burring. However, in the processes from de-burring to critical clean the parts are pushed in lots of 28. Since in the processes from de-burring to critical clean, lapping is the slowest, lots of 28 parts will be coming out at the rate of lapping.

The lead time and base stock levels for all stages are calculated in a similar fashion as that for Kanban sizes of 84 and 56 shown in Sections 5.3.1.1 and 5.3.1.2. The results are summarized in Tables 20 and Table 21.

### Table 20 Production lead time and Net replenishment time for \( K = 56 \) with lot-splitting

<table>
<thead>
<tr>
<th>Stage i</th>
<th>( PLT_i ) (Days)</th>
<th>( r ) (Days)</th>
<th>( L_i ) (Days)</th>
<th>( \tau_i ) (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM-Critical Clean</td>
<td>1.8</td>
<td>0.5</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Robo-drill</td>
<td>0.5</td>
<td>0.5</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Milling</td>
<td>0.3</td>
<td>0.5</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Turning</td>
<td>0.2</td>
<td>0.5</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Comparing Table 18 and Table 20, we see that there is a reduction in lead time when lot splitting is employed albeit small. This calculation reveals that if a Kanban size of 56 parts or 84 parts is used, lot splitting helps move parts faster as it eliminates the wait to batch time. Table 21 summarizes the base stock levels for all stages for a Kanban size of 56 parts with lot splitting.

### Table 21 Safety Stock and Base stock levels for \( K = 56 \) with lot splitting

<table>
<thead>
<tr>
<th>Stage i</th>
<th>Service level</th>
<th>( \tau_i ) (Days)</th>
<th>( SS_i ) (# Parts)</th>
<th>Base stock ( i ) (# Parts)</th>
<th>Base Stock (# Trays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM-Critical Clean</td>
<td>98%</td>
<td>2.3</td>
<td>177</td>
<td>507</td>
<td>18</td>
</tr>
<tr>
<td>Robo-drill</td>
<td>98%</td>
<td>0.9</td>
<td>115</td>
<td>177</td>
<td>6</td>
</tr>
</tbody>
</table>

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5.3.1.4 Lead time and Base Stock Levels for a Kanban size of 28

Substituting $K = 28$ in Equations (5.7) to (5.11), $PLT_i$ is calculated for each stage and added to the review period, $r = 0.5$ days, to obtain the overall lead time $L_i$. $\tau_i$ is calculated from $L_i$ using Equations (5.12), (5.14), (5.16), and (5.18). All service times between stages are set to zero. Demand data from Table 15 is used and the results are summarized in Table 22.

Using, $z = 2$ and the $\tau_i$ values obtained for $K = 28$ parts, as shown in Table 22, Equations (5.14), (5.17), (5.20) and (5.23) are used to calculate the base stock levels for each stage/in-process. The results of these calculation are summarized in Table 23.

| Table 22 Production lead time and net replenishment lead time for $K = 28$ |
|-----------------|---|---|---|---|
| Stage i         | $PLT_i$ (Days) | $r$ (Days) | $L_i$ (Days) | $\tau_i$ (Days) |
| EDM-Critical Clean | 1.6 | 0.5 | 2.1 | 2.1 |
| Robo-drill      | 0.2 | 0.5 | 0.7 | 0.7 |
| Milling         | 0.3 | 0.5 | 0.8 | 0.8 |
| Turning         | 0.1 | 0.5 | 0.6 | 0.6 |

Table 23 Safety stock and base stock levels for $K = 28$ parts
<table>
<thead>
<tr>
<th>Stage i</th>
<th>Service level</th>
<th>$\tau_i$ (Days)</th>
<th>$SS_i$ (# Parts)</th>
<th>$Base stock_i$ (# Parts)</th>
<th>Base Stock (# Trays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM-Critical Clean</td>
<td>98%</td>
<td>2.1</td>
<td>171</td>
<td>501</td>
<td>18</td>
</tr>
<tr>
<td>Robo-drill</td>
<td>98%</td>
<td>0.7</td>
<td>100</td>
<td>147</td>
<td>5</td>
</tr>
<tr>
<td>Milling</td>
<td>98%</td>
<td>0.8</td>
<td>105</td>
<td>156</td>
<td>6</td>
</tr>
<tr>
<td>Turning</td>
<td>98%</td>
<td>0.6</td>
<td>91</td>
<td>130</td>
<td>5</td>
</tr>
</tbody>
</table>

From Table 16, Table 17, Table 18, Table 19, Table 20, Table 21, Table 22, and Table 23, it can be seen that a Kanban size of $K = 28$ parts results in shortest lead time and lesser base stock levels at each stage as compared to other Kanban sizes. This can be attributed to lesser wait to batch time for a 28 part lot size as compared to other lot sizes. Though a Kanban size of 28 provides maximum lead time reduction as compared to other batch sizes, it might lead to a considerable increase in the utilization of shared resources like milling and the processes from de-burring to critical clean. Batch sizes and their impact on current machine utilizations will be discussed later in the chapter.
5.3.2 Modeling & Calculating Average Inventory levels

The average inventory level calculations are done to analyze how much inventory on average will the system hold. Though not the primary objective of our project, it is important to ensure that the average WIP levels for the stages remains in total lesser than those currently observed on the shop floor.

The methodology for average inventory level calculations for all stages is the same except for the uncoated finished parts buffer. This is because the base stock held for this buffer is always 330 parts plus some safety stock, because as discussed earlier between any two instants of when the finished goods inventory places an order on the uncoated finished parts inventory, the maximum demand on this buffer will be 330 parts. By cutting the lead time till robo-drilling, the system has been designed to ensure that the net replenishment time for this buffer is lesser than the time between orders even for the highest monthly demand observed by the company.

The methodology for average inventory calculation is first discussed for the uncoated finished part inventory and then for all other stage buffers.

Therefore, for the uncoated finished part inventory, refer to Fig.12.

As can be seen from Fig. 12, when the uncoated stator inventory places an order for 336 parts at the start of the production lead time period, the inventory position indicated by the blue dashed line rises to the base stock level and remains at this position till a quantity of 336 parts is withdrawn triggering another order of 336 parts on the fabrication line and another production
lead time period. Note that the small difference between 336 parts and 330 parts has been neglected for simplicity. The actual inventory level is represented by

![Diagram of inventory level calculation](image)

Fig. 12: Average inventory level calculation for uncoated finished part inventory

the solid black line. It can be seen from Fig. 12, that from the start of production till the end of production of 336 parts, the actual inventory level rises till it becomes constant once 336 parts are produced and waiting to get pulled for coating when signaled by the finished goods inventory.

The demand rate influences the number of days it would take on average for a quantity of 336 parts to get consumed. The average inventory level can therefore be estimated by dividing the
area of the trapezium formed by the inventory level pattern by the base of the trapezium i.e. the number of days of demand covered and add the quantity obtained to the safety stock.

Moreover, for a Kanban size $K$, we know the $PLT_{EDM-CC}$ from equation(5.7). If demand rate is given as $\mu$ parts per day, then a quantity of 336 parts will be consumed in the following number of days:

$$Number \ of \ days \ of \ demand \ covered = \frac{336 \ parts}{\mu \ parts/day} = \frac{336}{\mu}$$ (5.21)

Area of the trapezium formed by the inventory level pattern is given as:

$$Area \ of \ trapezium = \frac{1}{2} \times (\text{Sum of parallel sides}) \times \text{height}$$

$$= \frac{1}{2} \times [Number \ of \ days \ of \ demand \ covered$$

$$+ (\text{Number \ of \ days \ of \ demand \ covered} - PLT_{EDM-CC})]$$

$$\times (\text{Base stock}_{EDM-CC} - SS_{EDM-CC})$$ (5.22)

where the quantity expressed in Equation 5.22 is in units of $[days \times parts]$. 94
Moreover, using equation (5.5) and tailoring it for the EDM-CC stage, safety stock for the EDM-CC uncoated finished part buffer is given in equation (5.23) as:

\[ \text{Safety stock}_{\text{EDM-CC}} = z\sigma\sqrt{\tau_{\text{EDM-CC}}} \]  

(5.23)

where \( \text{Safety stock}_{\text{EDM-CC}} \) is expressed in number of parts.

From Fig. 11 it can be seen that, the average inventory level can be estimated as shown in equation (5.24):

\[ \text{Average inventory volume}_{\text{EDM-CC}} = \frac{\text{Area of trapezium}}{\text{Number of days of demand covered}} + \text{Safety stock}_{\text{EDM-CC}} \]  

(5.24)

where \( \text{Average inventory volume}_{\text{EDM-CC}} \) is expressed in number of parts.

Equations (5.21) to (5.24) can be combined to give the average inventory volume in parts for the uncoated finished stator inventory as:

\[ \text{Average inventory volume}_{\text{EDM-CC}} = \frac{1}{2} \left[ \frac{336}{\mu} + \left( \frac{336}{\mu} - \text{PLT}_{\text{EDM-CC}} \right) \right] \times 336 + \left( z\sigma\sqrt{\tau_{\text{EDM-CC}}} \right) \]  

(5.25)
For all other in-process buffers, the average inventory level is obtained by subtracting the minimum inventory level obtained from the maximum inventory level,

Since the maximum inventory level possible is the base stock minus the demand over the lead time, i.e. the time when an order arrives; therefore the maximum inventory level expressed in number of parts for stage i is given as:

\[ Maximum \ inventory \ level_i = (Base \ stock_i - \mu \times PLT_i) \]  \hspace{1cm} (5.26)

Assuming a review period of every \( r \) units between when an operator checks for depletion after which he replenishes the void immediately, the minimum inventory level expressed in number of parts at a stage i observed therefore will be given by:

\[ Minimum \ inventory \ level_i = (Base \ stock_i - \mu \times (PLT_i + r)) \]  \hspace{1cm} (5.27)

Therefore, the average inventory level at stage i or \( Average \ inventory \ level_i \) expressed in number of parts observed, is given by equation (5.28) as:

\[
Average \ inventory \ level_i = \frac{Maximum \ inventory \ level_i - Minimum \ inventory \ level_i}{2}
\]  \hspace{1cm} (5.28)
Substituting Equations (5.4), (5.26), (5.27) in equation (5.28) and adding safety stock, we get:

$$Average\ inventory\ level_i = \frac{\mu r}{2} + z\sigma\sqrt{\tau_i}$$

(5.29)

5.3.2.1 Average Inventory level for $K = 84$ parts

Substituting $r = 0.5$ days, demand data from Table 15 and using $\tau_i$ for all stages from Table 16 into Equations (5.25) and (5.29), the expected inventory levels at all stages for a Kanban size of 84 parts is summarized in Table 24.

<table>
<thead>
<tr>
<th>Stage i</th>
<th>Average inventory leveli (# Parts)</th>
<th>Average inventory level (# Trays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM-Critical Clean</td>
<td>457</td>
<td>16</td>
</tr>
<tr>
<td>Robo-drill</td>
<td>144</td>
<td>5</td>
</tr>
<tr>
<td>Milling</td>
<td>130</td>
<td>5</td>
</tr>
<tr>
<td>Turning</td>
<td>122</td>
<td>4</td>
</tr>
</tbody>
</table>

The number of trays is obtained by dividing the average inventory level by 28 parts.

5.3.2.2 Average Inventory level for $K = 56$ parts

Substituting $r = 0.5$ days, demand data from Table 15 and using $\tau_i$ for all stages from Table 18 into Equations (5.25) and (5.29), the expected inventory levels at all stages for a Kanban size of 56 parts is summarized in Table 25.

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Table 25 Average Inventory levels at all stages for $K = 56$ parts

<table>
<thead>
<tr>
<th>Stage i</th>
<th>Average inventory level$_i$ (# Parts)</th>
<th>Average inventory level (# Trays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM-Critical Clean</td>
<td>456</td>
<td>16</td>
</tr>
<tr>
<td>Robo-drill</td>
<td>131</td>
<td>5</td>
</tr>
<tr>
<td>Milling</td>
<td>121</td>
<td>4</td>
</tr>
<tr>
<td>Turning</td>
<td>115</td>
<td>4</td>
</tr>
</tbody>
</table>

5.3.2.3 Average Inventory level for $K = 56$ parts with Lot Splitting

Substituting $r = 0.5$ days, demand data from Table 15 and using $\tau_i$ for all stages from Table 20 into Equations (5.25) and (5.29), the expected inventory levels at all stages for a Kanban size of 56 parts with lot splitting is summarized in Table 26.

Table 26 Average Inventory levels at all stages for $K = 56$ parts with lot splitting

<table>
<thead>
<tr>
<th>Stage i</th>
<th>Average inventory level$_i$ (# Parts)</th>
<th>Average inventory level (# Trays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM-Critical Clean</td>
<td>456</td>
<td>16</td>
</tr>
<tr>
<td>Robo-drill</td>
<td>131</td>
<td>5</td>
</tr>
<tr>
<td>Milling</td>
<td>121</td>
<td>4</td>
</tr>
<tr>
<td>Turning</td>
<td>115</td>
<td>4</td>
</tr>
</tbody>
</table>

5.3.2.4 Average Inventory level for $K = 28$ parts

Substituting $r = 0.5$ days, demand data from Table 15 and using $\tau_i$ for all stages from Table 22 into Equations (5.25) and (5.29), the expected inventory levels at all stages for a Kanban size of 28 parts is summarized in Table 27.
Table 27 Average Inventory levels at all stages for $K = 28$ parts

<table>
<thead>
<tr>
<th>Stage i</th>
<th>Average inventory (# Parts)</th>
<th>Average inventory (# Trays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM-Critical Clean</td>
<td>455</td>
<td>16</td>
</tr>
<tr>
<td>Robo-drill</td>
<td>116</td>
<td>4</td>
</tr>
<tr>
<td>Milling</td>
<td>121</td>
<td>4</td>
</tr>
<tr>
<td>Turning</td>
<td>107</td>
<td>4</td>
</tr>
</tbody>
</table>

From Table 27, it can be seen that for a batch size of 28 parts, the average inventory levels at stages go down due to the reduction in the production lead time in sourcing parts in lots of 28 parts.

5.3.3 Comparison of Expected Inventory levels with Current System Average WIP
As mentioned in Section 5.3.2, the average WIP levels in the proposed system should be lesser than those observed in the current system. This is a constraint on the system. Table 28 attempts to draw a comparison in average inventory levels obtained using different Kanban sizes in the proposed system and current inventory levels presented in Table 6 obtained on the shop floor.
Table 28 Comparison of expected WIP levels in the current system and proposed system

<table>
<thead>
<tr>
<th>Stage</th>
<th>Average number of trays in current system</th>
<th>Expected number of trays in proposed system, K=84</th>
<th>Expected number of trays in proposed system, K=56</th>
<th>Expected number of trays in proposed system, K=28 (lot splitting)</th>
<th>Expected number of trays in proposed system, K=28</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robo-drilling</td>
<td>0</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Milling</td>
<td>11</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Turning</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td><strong>Sum Total</strong></td>
<td><strong>15</strong></td>
<td><strong>14</strong></td>
<td><strong>13</strong></td>
<td><strong>13</strong></td>
<td><strong>12</strong></td>
</tr>
</tbody>
</table>

| Percentage Reduction in Inventory (%) | -  | 6.7 | 13.3 | 13.3 | 20 |

From Table 28, it can be seen that the expected WIP in the proposed system is lesser than the current WIP levels on the shop floor for all Kanban sizes. However, the greatest WIP reduction observed is for a Kanban size of 28 parts. This can be attributed to the reduction in production lead time in sourcing 28 parts from stage to stage. Lesser lead time results in lesser variability.

Also, it is important to mention here that, although the company maintains an uncoated finished stator inventory, the inventory levels observed are of a fluctuating nature, that is, there is either a very high level of inventory of approximately 60 trays observed or a very low inventory level of just 2 trays observed. It is therefore difficult to estimate the average uncoated finished part inventory levels in the current system. However, the goal of the project is to achieve standardization of inventory management for the uncoated finished part inventory and the finished goods inventory to achieve responsiveness while avoiding inventory explosion.
5.3.4 Summary of In-Process Buffer Modeling Analysis
From Sections 5.3.1, 5.3.2 and 5.3.3, it can be seen that a Kanban size of \( K = 28 \) parts results in maximum lead time and inventory level reduction. However, before selecting the same as the Kanban size for implementation, an analysis of utilization of shared resources is done to verify the selection of a Kanban size of \( K = 28 \) parts.

5.4 Kanban size and utilization
Let the arrival rate of parts be \( r_a \) parts per hour, the time to process a single part be \( t \) hours, the time to perform a set-up be given by \( s \) hours, then for a batch/Kanban size of \( K \), the arrival rate of batches per hour is given as:

\[
\text{arrival rate} = \frac{r_a}{K} \tag{5.30}
\]

The effective process time for a batch, \( t_e \) in hours is given by the time to process the \( K \) parts in the batch plus the set-up time as:

\[
t_e = Kt + s \tag{5.31}
\]

So machine utilization or \( u_{\text{workstation}} \) is given as:

\[
u_{\text{workstation}} = \frac{\text{Process time for a Batch}}{\text{Time available for one Batch}} \tag{5.32}
\]
Equation (5.32) can be re-arranged to give:

\[ u_{\text{workstation}} = \frac{r_a}{K} \times (Kt + s) = \frac{r_a \left( t + \frac{s}{K} \right)}{K} \]  

(5.33)

For stability, we must have \( u_{\text{workstation}} < 1 \), or from equation (5.33), we get:

\[ K > \frac{sr_a}{1 - tr_a} \]  

(5.34)

Since the daily demand of 212 stators is known from Table 15, and the number of working hours for the valve cell and milling department are summarized in Table 14, the rate of arrival of parts \( r_a \) can be calculated by dividing the daily demand by the number of working hours per day for the machine.

The rate of arrival of batches is obtained by dividing the value for rate of arrival of parts by the Kanban size in question.

A set-up time of zero hours is used for all machines in the valve cell since there will be no set-ups for these machines in the high volume line.

For the high volume line, the only workstations that are shared resources with other parts are the milling machine and the processes from de-burring to critical clean. The utilization analysis is summarized in Table 29. Though turning, milling and robo-drilling are exclusive to the high
volume lines, their utilizations, although same for every batch size since there are no set-ups, are also presented. The set-up time for milling is 0.5 hours and the set-up time for Lapping is 1.5 hours. Since all processes from de-burring to critical clean are grouped, the utilization calculation for this entire group of processes uses a set-up time of 1.5 hours since the only process in this group of processes that requires a set-up is Lapping.

Table 29 Utilization of Machines for different Kanban Sizes

<table>
<thead>
<tr>
<th>Work station</th>
<th>Minimum batch size for stability (# parts)</th>
<th>Utilization of Workstation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K = 28 parts</td>
<td>K = 56 parts</td>
</tr>
<tr>
<td>Turning</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>Milling</td>
<td>4</td>
<td>53.5</td>
</tr>
<tr>
<td>Robo-drilling</td>
<td>0</td>
<td>53.3</td>
</tr>
<tr>
<td>Wire-EDM</td>
<td>0</td>
<td>27.2</td>
</tr>
<tr>
<td>De-burring to Critical Clean</td>
<td>11</td>
<td>66.1</td>
</tr>
</tbody>
</table>

For milling, Table 29 shows a 53.5% utilization if a batch size of just 28 parts is used and a utilization of 50 % if a batch size of 56 parts is used. From SAP, it is known that milling reserves a capacity of 50.3% for 212 stators and hence using a batch size of 56 is permissible but using a batch size of 28 parts is not possible.

To solve this, as mentioned in Section 5.3.1, even if a Kanban size of 28 parts is used for the pull system, the robo-drill stage will always order 2 trays of 28 parts from milling at any instant. As discussed in the next chapter, when EDM places an order for replenishment of 28 parts on robo-drill, the robo-drill workstation will still pull out 2 trays from the milled inventory so that the two robo-drill machines of the robo-drill work-station can work on one tray each. Through this,
simplicity in operation is achieved by having each robo-drill operator work on his/her tray, besides ensuring that always an order quantity of 56 parts or 2 Kanban cards be placed on milling to be under the limits of permissible utilization of the machine. This will be discussed in detail in the next chapter.

Moreover, the processes from de-burring to critical clean are shared by all stator types thus allowing the 212 stators to utilize these processes for only a little over 50% of their available time. There are two lapping machines dedicated to stators and multiple—at least more than three de-burring operators—working on stators. Similarly, there is simultaneous processing capability at passivation and cleaning processes.

However, the above utilization calculation for the stages from de-burring to critical clean assumes no simultaneous processing capability. For instance, it assumes that there is only one lapping machine.

Therefore, even though a utilization of 66% is obtained for a Kanban size of 28 parts, the actual utilization of the grouped processes by 212 stators can be conservatively estimated to be half of 66% i.e. slightly over 33%.

5.5 Conclusion on selection of Kanban size
A Kanban size of 28 parts results in maximum lead time and WIP level reduction. A utilization analysis of all machines in the high volume line shows capacity for supporting a Kanban size of 28 parts. A Kanban size of 28 parts is therefore used for implementation.
5.6 Scenario-Robodrill Cycle Time Reduction

Assume \( t \) is a time count in minutes. Since the EDM process is faster than the Robodrill process, the robodrill in-process buffer will eventually run out. For a base stock level of 5 trays for the robodrill in-process buffer, if \( t \) denotes the time count in minutes from the start of when EDM pulls the first tray to process and Robodrill works towards replenishing it to the time that EDM has to stop because there are no more trays left in the robodrill in-process buffer, a simple equation can be set-up using Table 13 and Table 23, to calculate the time when the robodrill buffer will run out of trays and how many trays the EDM machine would have produced by then:

\[
\frac{t}{(t_{robo, hv} \times 28)} + 5 = \frac{t}{(t_{EDM, hv} \times 28)}
\]

(5.35)

That is, the number of trays produced by EDM is the same as the number produced by the robodrill machine in addition to the 5 trays of the robodrill in-process buffer base stock. This equation is solved to give a \( t \) value of approximately 1198 minutes which corresponds to the production of approximately 10 trays by the EDM process before the robodrill in-process buffer runs out of parts.
Refer to Yan Zhuang’s work [14] on the robodrill process improvement. Since the cycle time per part for the robodrill has been reduced to 7.1 minutes per part, equation (5.35) can be re-written as:

\[
\frac{t}{(7.1 \times 28)} + 5 = \frac{t}{(t_{EDM,hp} \times 28)}
\]  

(5.36)

Solving equation (5.36), the value of \( t \) obtained is 1422 minutes and this corresponds to a continuous EDM production of 12 trays.

Since 12 trays is the order quantity placed on EDM, and since in the current system EDM can produce 10 trays till a stock out of the robodrill buffer occurs, this implies that in the system without the process improvement or in the current system, EDM would have to wait for 2 more trays from Robodrill as opposed to the system with the new tool. This corresponds to a time savings in overall lead time as shown in equation (5.42).

\[
\frac{t_{robo,hp} \times 28 \times 2 - t_{EDM,hp} \times 28 \times 2}{60} = 3.78 \text{ hours}
\]  

(5.37)

Hence, further improvements in lead time can be achieved with the new tool. Refer to Yan Zhuang’s thesis for detailed calculations.
6. Implementation of a Kanban System

This chapter discusses the implementation of a pull process in the valve cell at Waters Corporation through the use of Kanban cards.

6.1 Kanban System for 212 stators

The decision to implement a Kanban system to achieve pull production of 212 stators from finished goods inventory to the start of stator fabrication is made because of two reasons. Firstly, since the proposed system has a dedicated line only for the manufacture of 212 stators, this line is representative of a highly repetitive manufacturing environment. From Section 2.4.1, we know that a Kanban system tends well to highly repetitive manufacturing environments, that is, systems where parts flow in a fixed sequence at steady rates. This implies that a Kanban System can be implemented for the 212 stator dedicated line.

Secondly, though both systems help establish a WIP cap, however, as understood from Section 2.4.1, a Kanban system helps achieve more responsiveness through in-process buffers than a pure CONWIP set-up but can be more complex than a pure CONWIP line. But as already mentioned, the Kanban system is suitable for the high volume line because of a fixed processing sequence. Therefore, to achieve more responsiveness a decision for implementing a Kanban system is made to achieve pull production.
Fig. 13: Two Loops for the Kanban system implementation
6.2 Kanban Loops in System Implementation
As shown in Fig. 13, the pull process is established through two Kanban loops. As determined from Chapter 5, the Kanban size that is used for implementation is 28 parts that corresponds to one tray.

As mentioned in Chapter 5, the EOQ for finished goods inventory is determined to be 330 parts. That is whenever an order of parts is placed by the finished goods inventory, 330 parts are withdrawn from the uncoated finished stator inventory and sent for coating. Therefore, there is a requirement for replenishment of 330 parts in the uncoated finished parts buffer.

However, since the Kanban size is 28 parts, this implies that one Kanban card indicates an order quantity of 28 parts. Since an order of 330 parts cannot be issued by uncoated finished stator inventory on the system using Kanban cards as 330 is not divisible by 28, the nearest multiple of 28, i.e. an order quantity of 336 parts is issued on the system by the uncoated stator inventory. 336 parts correspond to an equivalent order quantity of 12 cards.

Moreover, there are in process buffers in the line till after robo-drilling after which there is series of push processes from EDM to Critical Clean which for all analyses are batched together as a stage. Therefore, trays can be pulled from the robo-drill in-process buffer after which they are processed through the EDM-CC stage.

Therefore, the pull system has two Kanban loops. Since the uncoated finished stator inventory must trigger production of 336 parts, the uncoated finished stator inventory sends 12 Kanban
cards to the Wire- EDM machine. However, since there is a robo-drill in-process buffer, the wire-EDM machine pulls out one tray or one Kanban card from the buffer and starts work on the parts. Therefore, the wire-EDM machine pulls one tray and therefore gives one Kanban card to the robo-drill stage at a time. After a tray is processed at Wire-EDM, it is immediately sent for the remaining processes in the line. This is repeated 12 times till 12 trays or 336 parts are processed through the EDM and the subsequent cleaning and inspection processes to replenish the uncoated finished stator inventory.

Since the wire-EDM machine only pulls one tray from the robo-drill stage, the robodrill workstation works on replenishing one tray and does so by generating triggers upstream as the robodrill station also pulls a tray from the upstream in-process buffer to replenish the void in its buffer.

Thus the system is divided into two loops, one from the uncoated finished stator inventory to the EDM machine, and the other from the EDM machine to the turning machine. This split is illustrated in Fig. 13.

6.3 Details of System Implementation
It has been discussed that because the EOQ is 330 parts, for Loop 2, the wire-EDM stage will receive an order quantity of 336 parts corresponding to 12 Kanban cards that read Wire-EDM as the supplier and Critical Clean, since it is the last stage in the process, as the consumer. As soon as wire-EDM finishes one tray, one of these 12 Kanban cards is sent along with the tray for the subsequent processes till Critical cleaning. Once the void in the uncoated finished stator
inventory is replenished, these 12 Kanban cards are issued to the wire-EDM station again when the next order for 336 parts arrives.

Loop 1 implementation involves a few more details. For simplicity, all in-process buffers associated with a stage are called super-markets. Therefore, there is a turning super-market with turned blanks, a milling super-market with milled blanks and a robo-drill super-market with robo-drilled blanks.

The first step in implementation is the calculation of base stock levels for these super-markets. Based on current demand, as explained in Chapter 5, base stock levels and hence the corresponding number of trays can be calculated for all super-markets. Based on these calculations, let the number of trays to maintain the calculated base stock level for the robo-drilling super-market be \( x \) trays, for the milling super-market be \( y \) trays and the turning super-market be \( z \) trays. Therefore, to implement a Kanban system in this loop, the \( x \) trays at the robo-drill super-market will each have a Kanban card reading Robodrill as the supplier and EDM as the consumer. Similarly there will be \( y \) Kanban cards at the Milling super-market, one card associated with each tray reading Milling as the supplier and Robodrill as the consumer. Again, there will be \( x \) trays with \( x \) Kanban cards in total at the Turning super-market that read Turning as the supplier and Milling as the consumer.

Assuming that Wire-EDM has pulled one tray from the robo-drill super-market, the pull process in Loop 1 is established in the following manner. When wire-EDM pulls one tray from the robo-
drill super-market, it leaves the Kanban card associated with it at the super-market. A Kanban card without a tray is a visual signal for the robo-drill workstation to manufacture one tray.

Since the robodrill workstation has to manufacture one tray, it pulls from the Milling super-market. As explained earlier in Chapter 5, to keep the stator utilization of milling within the specified limit, a policy to always pull two trays from the milling super-market is established, even if the robo-drill station is working to replenish only one tray. This also helps in simplifying operations as the two robo-drill machines of the robo-drill workstation can work on individual trays, while keeping a check on when the two machines together finish fabricating 28 parts to replenish the robo-drill super-market.

Therefore, Milling has to work to replenish two trays. Since the turning cycle time per part is almost half that of Milling, the milling station will pull one tray at a time from the turning super-market. By the time Milling fabricates one tray, Turning has the ability to replenish the void of one tray in its stock. Once, Milling completes its first tray, it will again pull a tray from the turning super-market triggering the turning of one more tray. This ways Milling replenishes 56 parts at once while maintaining a ‘pull one tray at a time’ policy from Turning.

6.4 Order Quantity Modification on Part Accumulation in Uncoated Finished Part Inventory
Since the EOQ from the finished goods inventory is that of 330 parts but the order quantity from the uncoated finished stator inventory is 336 parts, there will be part accumulation in the uncoated stator inventory. This presents an opportunity to once in a while place an order quantity of one Kanban card less than the 12 Kanban cards usually sent to the EDM station. Since 11
Kanban cards is equivalent to 308 parts and since at any instant the number of parts withdrawn from the uncoated finished part buffer is 330 parts, there should be a part accumulation of at least 22 parts in the uncoated finished parts inventory, for it to place an order of 11 Kanban cards than the usual 12 Kanban cards on the Wire EDM station. Therefore if part accumulation exceeds 22 parts, it is a signal for the uncoated finished part inventory to place an order of one Kanban card less.

A simple simulation illustrates this,

<table>
<thead>
<tr>
<th>Order no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order quantity placed at EDM (parts)</td>
<td>336</td>
<td>336</td>
<td>336</td>
<td>336</td>
</tr>
<tr>
<td>Quantity sent for coating (parts)</td>
<td>330</td>
<td>330</td>
<td>330</td>
<td>330</td>
</tr>
<tr>
<td>Quantity left (parts)</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

At the end of four orders, therefore, 24 parts are accumulated. Since 308 parts + 24 parts = 332 parts > 330 parts, eleven Kanban cards (equivalent to 308 parts) can be sent to EDM. Therefore,

<table>
<thead>
<tr>
<th>Order no.</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order quantity placed at EDM (parts)</td>
<td>308 (+24)</td>
<td>336</td>
<td>336</td>
<td>336</td>
<td>336</td>
</tr>
<tr>
<td>Quantity sent for coating (parts)</td>
<td>330</td>
<td>330</td>
<td>330</td>
<td>330</td>
<td></td>
</tr>
<tr>
<td>Quantity left (parts)</td>
<td>2</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

The quantity accumulated from the first four orders is shown in bracket under order number 6.
Also, the total part accumulation after this set of orders is 26 parts. Since 308 parts + 26 parts = 334 parts > 330 parts, therefore,
Within four orders the total part accumulation is 22 parts. Again, since 308 parts + 22 parts = 330 parts, this implies there will be no left over if 11 Kanban cards are issued in the next order.

Therefore,

<table>
<thead>
<tr>
<th>Order no.</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order quantity placed at EDM (parts)</td>
<td>308 (+26)</td>
<td>336</td>
<td>336</td>
<td>336</td>
</tr>
<tr>
<td>Quantity sent for coating (parts)</td>
<td>330</td>
<td>330</td>
<td>330</td>
<td>330</td>
</tr>
<tr>
<td>Quantity left (parts)</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

The total part accumulation after the above set of order is 24 parts again. This takes us back to the same situation as that attained after the first four orders of 12 Kanban cards are placed on the EDM station. Thus, the sequence is repeated.

**Conclusion of Kanban System Implementation**

A Kanban System as that discussed in this chapter is successfully implemented. Results of the implementation are presented in Chapter 7.
7. Results of Proposed System Implementation
This chapter discusses the results of the Kanban system implementation.

7.1 Kanban System Set-up
As noted in Chapter 6, the current daily demand for the month is used to establish the base stock levels for the in-process buffers/super-markets. The daily demand data for the current month is summarized in Table 30. (Decimals are retained for accuracy of calculations using these data).

<table>
<thead>
<tr>
<th>Demand Data</th>
<th>Number of Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily demand based on annual data ($\mu$)</td>
<td>92</td>
</tr>
<tr>
<td>Standard deviation in daily demand ($\sigma$)</td>
<td>24.49</td>
</tr>
</tbody>
</table>

A service level of 98% (which corresponds to $z = 2$) for each super-market is used and the $\tau_i$ values in days for $K = 28$ parts are the same as those summarized in Table 22 with a review period of half a day.

As explained earlier using the demand data for the current month, summarized in Table 30, the net replenishment times, $\tau_i$ days, calculated for each stage in Table 22, and using Equations (5.13), (5.15), (5.17) and (5.19), the safety stock and base stock levels for each super-market and the uncoated finished part inventory are calculated and presented in Table 31.
Table 31 Base stock and safety stock calculation for daily demand in current month

<table>
<thead>
<tr>
<th>Stage i</th>
<th>Service level</th>
<th>$\tau_i$ (Days)</th>
<th>$SS_i$ (# Parts)</th>
<th>$Base stock_i$ (# Parts)</th>
<th>Base Stock (# Trays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM-Critical Clean</td>
<td>98%</td>
<td>2.1</td>
<td>71</td>
<td>401</td>
<td>14</td>
</tr>
<tr>
<td>Robo-drill</td>
<td>98%</td>
<td>0.7</td>
<td>42</td>
<td>109</td>
<td>4</td>
</tr>
<tr>
<td>Milling</td>
<td>98%</td>
<td>0.8</td>
<td>40</td>
<td>113</td>
<td>4</td>
</tr>
<tr>
<td>Turning</td>
<td>98%</td>
<td>0.6</td>
<td>38</td>
<td>94</td>
<td>3</td>
</tr>
</tbody>
</table>

The number of trays is rounded-off and presented in Table 31.

Therefore the uncoated finished part inventory should have a base stock of 14 trays to ensure high responsiveness. The Robodrill super-market should have a base stock of 4 trays. The Milling super-market should maintain 4 trays and the Turning super-market should maintain 3 trays. The use of above base stock levels is expected to give 98% service level.

The system was set-up accordingly. At the start of experimentation, the level at the finished goods inventory was 758 parts which is below the re-order level [13]. Therefore, an order quantity of 330 parts is placed on the uncoated finished part inventory for replenishment. An order of 12 Kanban cards (which is 336 parts) is sent to the EDM workstation that pulls trays from the Robodrill super-market as explained in Chapter 6 that in turn generates triggers for milling and turning trays as well.

A marked difference from the safety stock levels in Table 23 is observed in Table 31 despite the net replenishment time $\tau_i$ days for a Kanban size of 28 parts not changing. This is because a higher standard deviation in daily demand is observed when using annual demand data as...
compared to the daily demand standard deviation observed when using current demand data which is as expected due to the long time frame associated with annual data.

Moreover, though the actual WIP levels will be presented in Section 7.2, the expected WIP levels and average uncoated finished part inventory levels are calculated as shown in Chapter 5. The demand data used however is obtained from Table 30. The average inventory levels for all stages for a Kanban size of 28 parts is summarized in Table 32.

Table 32 Expected inventory levels for all super-markets and uncoated finished part inventory

<table>
<thead>
<tr>
<th>Stage</th>
<th>Average inventory (# Parts)</th>
<th>Average inventory (# Trays)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDM-Critical Clean</td>
<td>333</td>
<td>12</td>
</tr>
<tr>
<td>Robo-drill</td>
<td>65</td>
<td>2</td>
</tr>
<tr>
<td>Milling</td>
<td>63</td>
<td>2</td>
</tr>
<tr>
<td>Turning</td>
<td>61</td>
<td>2</td>
</tr>
</tbody>
</table>

A comparison of expected WIP levels and current WIP levels observed (summarized in Table 6) is made in Table 33. Since the number of trays in Table 32 is obtained by rounding off to the closest whole number, the number of trays obtained in Table 6 for each stage also has been rounded off for better comparison.
Implementation results are discussed in Section 7.2.

7.2 Implementation Results
The actual lead time observed for a 336 part order quantity and the WIP levels observed during the implementation of the proposed system are summarized in the following sections.

7.2.1 Time Tracking during Implementation
This section presents the lead time and cycle time observed during implementation.

7.2.1.1 Lead Time observed during Implementation
The lead time observed for the first 100 parts to finish was 2 days and the lead time for finishing 336 parts was 3 days.

Table 34 Actual Lead time observed for 100 parts and 336 parts

<table>
<thead>
<tr>
<th>Number of Parts Finished (# parts)</th>
<th>Lead time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>332 (+4 parts scrap)</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 33 Comparison of expected WIP levels and current WIP levels for current month’s demand

<table>
<thead>
<tr>
<th>Supermarket/Buffer</th>
<th>Average number of trays in current system</th>
<th>Expected number of trays in proposed system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robo-drilling</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Milling</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>Turning</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td><strong>Sum Total</strong></td>
<td><strong>15</strong></td>
<td><strong>6</strong></td>
</tr>
<tr>
<td><strong>Percentage Reduction in WIP (%)</strong></td>
<td><strong>-</strong></td>
<td><strong>60</strong></td>
</tr>
</tbody>
</table>
The lead time or the time from start of fabrication to critical clean for a 100 part order in the current system as mentioned earlier is approximately 21 days. However, the lead time observed for the same quantity by implementing a pull system is exactly 2 days. This is due to the elimination of other part types from the line, the establishment of in-process buffers that cut the lead time involved in turning, milling and robo-drilling batches and reduction of batch size to 28 parts. The lead time for an order quantity of 336 parts is exactly 3 days.

7.2.1.2 Cycle Time Observed during Implementation

Table 34 provides an average time between successive trays. As can be seen the cycle time for a tray of 28 parts is approximately 2 hours.

<table>
<thead>
<tr>
<th>Successive Trays</th>
<th>Time between arrivals of successive trays (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tray 1-Tray 2</td>
<td>0.5</td>
</tr>
<tr>
<td>Tray 2-Tray 3</td>
<td>4.0</td>
</tr>
<tr>
<td>Tray 3-Tray 4</td>
<td>0.0</td>
</tr>
<tr>
<td>Tray 4-Tray 5</td>
<td>0.5</td>
</tr>
<tr>
<td>Tray 5-Tray 6</td>
<td>4.4</td>
</tr>
<tr>
<td>Tray 6-Tray 7</td>
<td>4.2</td>
</tr>
<tr>
<td>Tray 7-Tray 8</td>
<td>0.1</td>
</tr>
<tr>
<td>Tray 8-Tray 9</td>
<td>0.0</td>
</tr>
<tr>
<td>Tray 9-Tray 10</td>
<td>0.1</td>
</tr>
<tr>
<td>Tray 10-Tray 11</td>
<td>6.7</td>
</tr>
<tr>
<td>Tray 11-Tray 12</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Average time between successive trays = 1.9 hours = 2 hours(approx.)
7.2.1.3 Analysis of Times

Although the calculated lead time for replenishing a 336 part order as can be seen from Table 31 is 2.1 days, a lead time of 3 days is observed in the system. However, since the daily demand for the current month is 92 parts per day and the time between successive orders will approximately be 3.65 days since 336 parts will most probably be consumed in 3.65 days at a demand rate of 92 parts per day, a lead time of 3 days for finishing 336 parts is within the limit of 3.65 days.

It is also to be noted that the current month demand is the highest observed making the daily demand of 92 parts per day far above the average daily demand of 64 parts per day. Moreover, the reason for the deviation could partially be due to the fact that the implementation of the system required pulling capacity for the pilot line so other work was also being performed and partially due to the introduction of an entirely new system on the shop floor that takes time to get used to as some confusion was observed during implementation particularly in the de-burring to critical cleaning processes that are situated away from the shop floor.

Table 35 tracks and records the clock times of when a respective process is completed for all 12 trays as each tray is processed through de-burring, lapping, passivation, VCN cleaning and finally critical cleaning processes.

The block lines divide the table into 5 days that are represented by the 5 blocks created by the solid lines with implementation starting on 26th July which is a half day (Friday), continued for some time on 27th July (Saturday) which is a half day as well. Operations were then resumed on 29th July (Monday) and continued till 31st July (Wednesday). The experimentation was stopped after 336 parts (12 trays) were finished and stored in finished goods inventory.
It can be seen from Table 35, during the implementation many more trays were processed on Tuesday than Friday, Saturday and Monday partly due to an initial inertia towards the new system.

Inertia towards the system can also be observed from the trend of the total processing time per tray, corresponding to one Kanban card, as shown in Fig. 14. The first tray takes around 30 hours to finish processing from de-burring to critical cleaning and the last tray takes around 20 hours to finish. The trend of the graph is that of decreasing processing times per tray albeit some variations induced by confusion regarding the new process, change of operators at the change of shift etc.
7.2.2 WIP Levels Observed during Implementation

The WIP levels observed during implementation are summarized in Table 36.

The total WIP observed in the implemented system in the turning super-market or parts waiting for milling, milling super-market or parts waiting for robo-drilling and the robodrill super-market or parts waiting for EDM is around 5 trays as can be seen from Table 36. This is approximately equivalent to the expected WIP level results shown in Table 33.

Moreover, the total WIP in the system, taking into account the WIP observed through the deburring to critical clean processes as well, is limited by the number of Kanban cards. Since the number of Kanban cards is 12, the total WIP in the implemented system is 12 trays.

However, from Table 6 it can be seen that the total WIP in the current system for 212 stators is observed to be approximately 20 trays. This indicates an inventory reduction of approximately 40% from the current system.
Table 36 Average WIP levels observed during system implementation

<table>
<thead>
<tr>
<th>Process</th>
<th>Mean</th>
<th>Std dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIP waiting for Milling</td>
<td>2</td>
<td>0.3</td>
</tr>
<tr>
<td>WIP waiting for Robo-drill</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>WIP waiting for EDM</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>WIP waiting for De-burring</td>
<td>1</td>
<td>1.3</td>
</tr>
<tr>
<td>WIP waiting for Lapping</td>
<td>2</td>
<td>1.7</td>
</tr>
<tr>
<td>WIP waiting for Passivation</td>
<td>2</td>
<td>1.7</td>
</tr>
<tr>
<td>WIP waiting for VCN clean</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>Critical clean</td>
<td>1</td>
<td>1.3</td>
</tr>
</tbody>
</table>
7.3 ARENA Simulation for Verification
It is seen from Section 7.2 that the implementation of the proposed systems results in shorter lead times and reduction of WIP on the shop floor. However, the proposed system was tested only for five days. Therefore, an ARENA simulation was run to verify that the system works in the long run.

A pull system was established on ARENA using the logic that an inventory will release parts only if the stock level of the buffer/inventory associated with the next stage will be lesser than the base stock and if the machine associated with the next stage is available.

The simulation was run for a period of 30 days where the system reaches steady state in the first 20 days and results recorded for the next 10 days.

Fig. 15: ARENA simulation results
Since the current demand for 212 stators is 92 parts per day which corresponds to approximately 3.3 trays per day, therefore, in a 10 day period, approximately 33 trays are required at the finished goods inventory.

The simulation result verifies that this target can be achieved and shows the arrival of 33 trays at the finished good inventory available for assembly in 10 days. The simulation however does not model demand variation.

7.4 Conclusion from Results Obtained
The system shows capacity to support a 100% service level for average and current demand rates in the long run without however taking into account demand variation.
8. Conclusion and Recommendations
In this chapter a summary of the system design and implementation is presented. In addition, recommendations for future operations are provided.

8.1 Conclusion
A pull-type production system for the high volume 212 stators is designed and implemented. The objective of the proposed system was to improve on-time delivery performance of stators to the assembly department. This is achieved through a responsive fabrication line with WIP control and a standardized finished goods inventory management. Responsiveness in the fabrication of stators was achieved through line dedication for high volume (212 stators) and high mix parts respectively and the placement of in-process buffers to implement a Kanban based pull-type production process that establishes a WIP cap as well.

Through this line implementation, the overall lead time for 212 stators was reduced from 21 days to 3 days and this was supported with a WIP reduction of 40%. The standardization of the finished goods inventory was realized through the establishment of a mixed inventory review policy, in other words, the (s,S) policy with a re-order point that triggers production at appropriate times and a base stock level that eliminates the possibility of inventory explosion. A service level of at least 96% is expected even for a high demand month like August 2013 besides a 50% reduction in average finished goods inventory levels through the set-up of an upper control inventory limit.
8.2 Future Work
The following are recommendations to support the proposed system design—

1. Following the successful implementation of the Kanban system for the high volume line, supporting documentation should be developed in compliance with ISO 9000.

2. A similar pull-type production process could be implemented for the 213 stators that are the second most frequently produced parts in the valve cell after the 212 stators.

3. Though the continuation of a push-type production process is recommended for all other stator types in the high mix line, a policy of releasing orders based on an optimized set-up sequence is recommended to minimize waiting times in the line. This could also improve the robustness of the line during unexpected high demand periods.

4. Merging the valve cell and assembly inventories is recommended to improve visibility facilitating the elimination of unnecessary inventory that does not contribute to maintaining a high service level. This recommendation is in keeping with the corporate emphasis on developing a lean culture in operations.

5. A recommendation for developing IT capability that can continuously monitor finished goods inventory levels and production line WIP levels is made so that real-time feedback of the system can be obtained.

6. Establishment of a visual aid like a screen that keeps the operators on the floor abreast with the daily demand data is highly recommended especially for a pull based system like ours because once daily demand is satisfied, operators can work on replenishing the super-markets up to the respective base stock levels.
Appendix

General Terminology

Bottleneck – the production resource which limits the overall capacity. It is usually the production resource with the longest cycle time.

Capacity – maximum output rate of a process measured over a period of time

Cycle Time – average length of time between completion of two successive units on the assembly line.

Manufacturing Lead Time – time spent by each unit in the complete manufacturing or assembly process.

Operation Time – expected time required to complete a particular operation.

![Graph showing average time interval between 2 trays]

*Fig. 16: Average time interval between 2 trays*
Table 36: Symbols & Descriptions

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>Utilization of a workstation</td>
</tr>
<tr>
<td>$r_{arrival}$</td>
<td>Rate of arrival of parts at workstation</td>
</tr>
<tr>
<td>$P_{\text{effective}}$</td>
<td>Effective production rate for workstation</td>
</tr>
<tr>
<td>$rate_{\text{bottleneck}}$</td>
<td>Bottleneck throughput rate</td>
</tr>
<tr>
<td>$T_O$</td>
<td>Raw production process time</td>
</tr>
<tr>
<td>$WIP_{\text{critical}}$</td>
<td>Critical WIP level to ensure throughput rate</td>
</tr>
<tr>
<td>$WIP$</td>
<td>WIP level</td>
</tr>
<tr>
<td>$TH$</td>
<td>Throughput of process</td>
</tr>
<tr>
<td>$t_o$</td>
<td>Mean process time for a part</td>
</tr>
<tr>
<td>$\sigma_o$</td>
<td>Standard deviation of process time for a part</td>
</tr>
<tr>
<td>$c_o$</td>
<td>Coefficient of variation of process time for a part</td>
</tr>
<tr>
<td>$t_o(\text{batch})$</td>
<td>Mean process time for a batch</td>
</tr>
<tr>
<td>$\sigma_o(\text{batch})$</td>
<td>Standard deviation of process time for a batch</td>
</tr>
<tr>
<td>$c_o(\text{batch})$</td>
<td>Coefficient of variation of process time for a batch</td>
</tr>
<tr>
<td>n</td>
<td>Number of parts in a batch</td>
</tr>
<tr>
<td>$EOQ, Q^*$</td>
<td>Economic order quantity</td>
</tr>
<tr>
<td>R</td>
<td>Re-order level for continuous review policy</td>
</tr>
<tr>
<td>k</td>
<td>Ordering cost</td>
</tr>
<tr>
<td>h</td>
<td>Holding cost</td>
</tr>
<tr>
<td>D</td>
<td>Demand rate</td>
</tr>
<tr>
<td>$C_{\text{UI}}$</td>
<td>Underage cost per unit</td>
</tr>
<tr>
<td>$C_0$</td>
<td>Overage cost per unit</td>
</tr>
<tr>
<td>B</td>
<td>Base stock level in periodic review policy</td>
</tr>
<tr>
<td>$\text{VMI}$</td>
<td>Vendor managed inventory</td>
</tr>
<tr>
<td>$\text{MTTF}$</td>
<td>Mean time to fail for a machine</td>
</tr>
<tr>
<td>$\text{MTTR}$</td>
<td>Mean time to repair for a machine</td>
</tr>
<tr>
<td>$\text{time}_{\text{clean}}$</td>
<td>Cleaning time for 212 factory order</td>
</tr>
<tr>
<td>$\text{valve}_{\text{daily}}$</td>
<td>Hours of operation for valve cell per day</td>
</tr>
<tr>
<td>LT</td>
<td>Lead time for 212 factory order</td>
</tr>
<tr>
<td>$t_{\text{turn}}, t_{\text{mill}}, t_{\text{robo}}, t_{\text{EDM}}, t_{\text{de-burr}}, t_{\text{lapp}}, t_{\text{pass}}, t_{\text{VCN}}$ and $t_{\text{CC}}$</td>
<td>Cycle time per part in minutes for turning, milling, robo-drilling, EDM, de-burring, lapping, passivation, VCN and critical cleaning respectively.</td>
</tr>
<tr>
<td>$S_{212}, S_{213}, S_{215}, S_{230}, S_{236}, S_{237}, S_{250}, S_{251}$</td>
<td>Factory order sizes for 212 stators, 213 stators, 215 stators, 230 stators, 236 stators, 237 stators, 250 stators and 251 stators respectively in number of parts</td>
</tr>
<tr>
<td>$\text{hours}_{\text{req.workstation}}$</td>
<td>Hours required by the respective workstation per day to satisfy daily demand</td>
</tr>
<tr>
<td>$t_{\text{workstation}}$</td>
<td>Cycle time per part at the respective workstation</td>
</tr>
<tr>
<td>$u_{\text{workstation}}$</td>
<td>Utilization of the respective workstation</td>
</tr>
<tr>
<td>$\text{hours}_{\text{av.workstation}}$</td>
<td>Hours available to the respective workstation per day</td>
</tr>
<tr>
<td>$\text{downtime}_{\text{workstation}}$</td>
<td>Number of hours of workstation downtime per day</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>------</td>
<td>------------</td>
</tr>
<tr>
<td>$t_{\text{set-up, workstation}}$</td>
<td>Time for setup at the respective workstation in hours</td>
</tr>
<tr>
<td>PLT&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Production lead time for stage $i$</td>
</tr>
<tr>
<td>$r$</td>
<td>Inventory review period</td>
</tr>
<tr>
<td>$L_i$</td>
<td>Total lead time for stage $i$</td>
</tr>
<tr>
<td>$s_i$</td>
<td>Outbound service time quoted by stage $i$</td>
</tr>
<tr>
<td>$s_{i-1}$</td>
<td>Inbound service time from stage $i-1$</td>
</tr>
<tr>
<td>$\tau_i$</td>
<td>Net replenishment time for stage $i$</td>
</tr>
<tr>
<td>$z$</td>
<td>Service factor</td>
</tr>
<tr>
<td>RT&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Replenishment time of a stage $i$</td>
</tr>
<tr>
<td>Base stock&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Base stock level for stage $i$</td>
</tr>
<tr>
<td>SS&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Safety stock level for stage $i$</td>
</tr>
<tr>
<td>$t_{\text{turn, hv}}$, $t_{\text{mill, hv}}$, $t_{\text{robo, hv}}$, $t_{\text{EDM, hv}}$, $t_{\text{de-burr, hv}}$, $t_{\text{lap, hv}}$, $t_{\text{pass, hv}}$, $t_{\text{VCN, hv}}$, $t_{\text{CC, hv}}$</td>
<td>Cycle time per part in minutes for turning, milling, robo-drilling, EDM, de-burring, lapping, passivation, VCN and critical cleaning respectively for the high volume line</td>
</tr>
<tr>
<td>$K$</td>
<td>Kanban size</td>
</tr>
<tr>
<td>time&lt;sub&gt;clean, pull&lt;/sub&gt;</td>
<td>Additional cleaning time for the proposed system in minutes</td>
</tr>
<tr>
<td>PLT&lt;sub&gt;EDM-CC&lt;/sub&gt;</td>
<td>Production lead time for stage EDM to CC</td>
</tr>
<tr>
<td>PLT&lt;sub&gt;Robodrill&lt;/sub&gt;</td>
<td>Production lead time for stage robo-drill</td>
</tr>
<tr>
<td>PLT&lt;sub&gt;Milling&lt;/sub&gt;</td>
<td>Production lead time for stage milling</td>
</tr>
<tr>
<td>PLT&lt;sub&gt;Turning&lt;/sub&gt;</td>
<td>Production lead time for stage turning</td>
</tr>
<tr>
<td>milling&lt;sub&gt;daily&lt;/sub&gt;</td>
<td>Hours of operation per day for milling work station</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Demand rate in parts per day</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation of demand in parts per day</td>
</tr>
<tr>
<td>$t_{\text{EDM-CC}}$, $t_{\text{Robodrill}}$, $t_{\text{Milling}}$, $t_{\text{Turning}}$</td>
<td>Net replenishment time for stage EDM-CC, robo-drill, milling, turning, respectively in days</td>
</tr>
<tr>
<td>$S_{\text{EDM-CC}}$, $S_{\text{Robodrill}}$, $S_{\text{Milling}}$, $S_{\text{Turning}}$</td>
<td>Outbound service times from stages EDM-CC, robo-drill, milling, turning, respectively in days</td>
</tr>
<tr>
<td>Base stock&lt;sub&gt;EDM-CC&lt;/sub&gt;, Base stock&lt;sub&gt;Robodrill&lt;/sub&gt;, Base stock&lt;sub&gt;Milling&lt;/sub&gt;, Base stock&lt;sub&gt;Turning&lt;/sub&gt;</td>
<td>Base stock levels for stage EDM-CC, robo-drill, milling, turning, respectively in number of parts</td>
</tr>
<tr>
<td>$r_a$</td>
<td>Arrival rate of parts per hour</td>
</tr>
<tr>
<td>$s$</td>
<td>Setup time in hours</td>
</tr>
<tr>
<td>$t$</td>
<td>Process time for a single part</td>
</tr>
<tr>
<td>$t_e$</td>
<td>Effective process time for a batch in hours</td>
</tr>
</tbody>
</table>
Fig. 17: Kanba card used for implementation
References


13. Yao, B., On-Time Delivery Performance Improvement in a Valve Manufacturing Cell: Design of Pull-Type Production System with Standardized Inventory Management, in Department of Mechanical Engineering. 2013, Massachusetts Institute of Technology.