Priority Queuing for Raw Material Receiving
by
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B.S. Mechanical Engineering, Lehigh University, 2008

Submitted to the Mechanical Engineering Department and the MIT Sloan School of Management in Partial Fulfillment of the Requirements for the Degrees of

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and
Master of Business Administration

In conjunction with the Leaders for Global Operations Program at the Massachusetts Institute of Technology

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Abstract

The Amgen Manufacturing Ltd. facility in Juncos, Puerto Rico faces a challenge encountered by manufacturers across industries: How can they make the best use of their existing resources? As production volume and product mix increase, how are costs kept from increasing as well? This LGO internship looked to answer those questions in the context of raw material receiving for biopharmaceutical manufacturing.

Over the course of the seven month project, an analytical planning tool centered on scheduling optimization and priority queuing was developed, highlighting areas for improvement. Based on insight gained from the tool, a plan was established which can reduce turnaround time (TAT) by 50% and work in process (WIP) by 45% in the raw material sampling area. The improvements will not only provide financial and operational benefits to the organization, but serve as a foundation for continuous improvement as the findings from this project are applied elsewhere.

This project highlights the importance of understanding how process inputs affect process output. In the case of raw material sampling, the variable mix of incoming materials exceeded the capacity for processing, particularly for solid materials, elevating the average TAT and WIP. Aligning sampling’s capabilities to the input work makes it more flexible and better able to handle future demand. However, the ideal state for the area involves working with the upstream group, supply chain, to level-load arrivals. In this case, WIP can be reduced over 60% from its current level while maintaining TAT adherence at the 50% improved rate. Further utilization gains are possible, but only through value stream analysis and enhanced collaboration between functional groups.

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### Glossary of Selected Terms

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<thead>
<tr>
<th>Term</th>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amgen Manufacturing Limited</td>
<td>AML</td>
<td>Amgen Inc.'s main manufacturing facility located in Juncos, Puerto Rico, where this project was based.</td>
</tr>
<tr>
<td>First In First Out</td>
<td>FIFO</td>
<td>Also known as first-come first-served (FCFS), FIFO is the most basic service discipline since arrivals are processed exactly in the order they arrive.</td>
</tr>
<tr>
<td>Food and Drug Administration</td>
<td>FDA</td>
<td>Food and Drug Administration is charged with the responsibility to oversee the biopharmaceutical industry.</td>
</tr>
<tr>
<td>Good Manufacturing Processes</td>
<td>GMP</td>
<td>FDA guidelines to specify the design, operation, and monitoring of biopharmaceutical manufacturing.</td>
</tr>
<tr>
<td>Incoming Quality Assurance</td>
<td>IQA</td>
<td>The functional group responsible for sampling raw materials which arrive to the facility.</td>
</tr>
<tr>
<td>Last In First Out</td>
<td>LIFO</td>
<td>Also known as last-come first-served (LCFS), LIFO is a queuing discipline where the items arriving most recently are served first.</td>
</tr>
<tr>
<td>Quality Control</td>
<td>QC</td>
<td>The functional group in charge of testing raw materials which have been sampled by IQA.</td>
</tr>
<tr>
<td>Service In Random Order</td>
<td>SIRO</td>
<td>Random order of service schemes, sometimes called service in random order (SIRO), is based on randomly choosing customers from the queue for service.</td>
</tr>
<tr>
<td>Turnaround Time</td>
<td>TAT</td>
<td>The length of time from when a raw material is received at the facility to when sampling begins, one of the primary measures of performance in the sampling area.</td>
</tr>
</tbody>
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1 Introduction

This chapter provides an introduction to the thesis project, relevant background information, and a summary of the thesis contribution.

1.1 Project Motivation

The Amgen Manufacturing Ltd. facility in Juncos, Puerto Rico faces a challenge encountered by manufacturers across industries: How can they make the best use of their existing resources? What can be done to reduce variation and stabilize processes? As production volume and product mix increase, how are costs kept from increasing as well? This thesis answers these questions in the specific context of raw material receiving for biopharmaceutical manufacturing.

1.2 Context

1.2.1 Biopharmaceutical Manufacturing

Biotechnology as we know it today came out of some major scientific discoveries in the last 60 years. The biggest breakthroughs came in understanding the role of DNA. Scientists discovered that DNA provides the instructions for construction and operation of a living organism and that segments of the DNA, called genes, contain the information required for a cell to produce specific proteins. These proteins play vital roles in the health of an organism; however, some diseases affect the body's ability to properly produce certain proteins leading to health issues. Diseases like anemia, arthritis, and some types of cancer can be linked to problems with specific proteins in the body.

Fortunately, some diseases can be treated using therapeutic proteins. Through genetic engineering, the foundation of biopharmaceutical drugs, scientists can cut and paste together segments of DNA. These modified sequences, called recombinant DNA, produce proteins outside the body in genetically modified host cells. The proteins can be extracted from the cells, purified, and made ready for therapeutic use [1].

The process to create therapeutic proteins is challenging even under the most controlled of laboratory conditions. Exacting care must be taken to prevent contamination,
maintain strict environmental conditions to promote cell growth, and efficiently separate proteins from their host cells. Scaling up from the development level to a volume viable for commercial production is the purpose of biopharmaceutical manufacturing. Across the industry, companies have set up highly specialized facilities for manufacturing biologic products.

Manufacturing facilities are regulated by government health agencies. In the United States, the Food and Drug Administration (FDA) is charged with the responsibility to oversee the biopharmaceutical industry. Every step along the production process from raw materials to shipping of the final product requires the use of tight process controls and testing to ensure the highest quality product. Known within the industry as Good Manufacturing Practices (GMP), these guidelines specify the design, operation, and monitoring of biopharmaceutical manufacturing. Parameters like cleanliness, personnel training, batch sizes, equipment controls, environmental monitoring, and documentation practices are all regulated [2]. Strict industry oversight by regulatory bodies adds additional complications to an already complex process.

1.2.2 Amgen Inc.

Amgen Inc. is the world's largest independent biotechnology company and one of the leaders in biopharmaceutical research and manufacturing. Since 1980, the company has been delivering innovative therapeutics for a range of illnesses in the areas of nephrology, oncology, osteoporosis, and inflammation. Amgen's products have helped millions of patients live healthier, more fulfilling lives and the company strives to deliver every dose to every patient every time. Amgen's success is fueled by their unwavering commitment to serve patients with quality and reliability [3].

Headquartered in Thousand Oaks, California, Amgen grew from a small startup in 1980 to the 20,000-employee company it is today. Amgen's first major commercial product was Epogen, introduced in 1989 to treat patients suffering from anemia. This success allowed Amgen to follow up with additional investments in research and development and the company now spends over $3 billion annually on new products. Amgen's continued success is supported by internal development of pipeline drugs, acquisitions to develop its
portfolio, and international expansion; Amgen has a presence in more than 75 countries around the globe and recently acquired Onyx Pharmaceuticals [4].

In order to support its new product development and manufacturing of approved drugs, Amgen relies on a global network of manufacturing and research sites positioned to take advantage of strategic resources. Major research and development centers are located in biotech hubs like Thousand Oaks, California and Cambridge, Massachusetts; distribution centers centrally located in Louisville, Kentucky and Breda, Netherlands; and manufacturing sites distributed across Rhode Island, Puerto Rico, Ireland, and Singapore [5].

Amgen's current operational and strategic positions allow for it to be highly successful, but continued success is not guaranteed. Changes to reimbursement plans, tighter regulations in manufacturing, higher standards of efficacy for new drugs, biosimilar and generic competition, and expiring patents are just some of the challenges facing Amgen in the near future. In order to retain its status as one of the world's premier biotechnology companies, Amgen is looking to unlock the full potential of its existing resources and drive gains in efficiency to become more competitive. This means advocating for improvements across the organization, particularly in manufacturing.

1.2.3 Amgen Manufacturing Ltd.

Amgen Inc.'s largest manufacturing site is located in Juncos, Puerto Rico. This site covers 1.7 million square feet and supports bulk manufacture of commercial products through mammalian cell culture, purification, and small-molecule solid dosage plants. The site includes interplant services like fill/finish, Quality Control (QC), Incoming Quality Assurance (IQA), and Process Development (PD). Ancillary operating services like engineering, supply chain management, human resources, Information Services (IS), and finance are all co-located on site. The Environmental, Health, and Safety (EH&S) group even operates a wastewater treatment plant.

The manufacturing facility in Juncos, Puerto Rico operates as Amgen Manufacturing Ltd. (AML), a wholly-owned subsidiary of Amgen Inc. [6] Incorporated in Bermuda, AML takes advantage of the highly-skilled workforce, relatively low labor cost, and tax advantages afforded to the island territory of Puerto Rico. Manufacturing companies
operating in Puerto Rico are allowed to bypass standard value-added import duties and repatriate earnings to the United States with little taxes [7]. These financial and operating incentives have stimulated growth in the medical device and pharmaceutical industries in Puerto Rico. Manufacturing accounts for 46% of Puerto Rico’s gross domestic product [8], more than the island’s tourist and service industries, half of which is attributed to biotech manufacturing [9].

Operating on a small island in the Caribbean is not without risk. Puerto Rico is prone to hurricanes, earthquakes, and other natural disasters which can disrupt manufacturing operations and the supply chain. Since most of the raw materials required for manufacturing are produced off the island, virtually every chemical, compound, and component must be imported. Since many materials are considered hazardous to transport by air, shipping is the primary method of import to the island. AML holds operating inventory and safety stock at virtually every step along the manufacturing process to ensure business continuity and prevent stock outs to patients. Another challenge is Puerto Rico’s degrading economic situation [10]. As the government struggles to raise funds, infrastructure to support a robust supply chain comes into question, qualified workers begin to look for work off the island, and increased tax pressure is applied to the biotech industry. Despite these challenges, AML remains a critical piece of Amgen’s manufacturing capability.

1.2.4 Raw Material Receiving at Amgen

In order to support AML’s manufacturing, testing, and development needs, the facility receives thousands of necessary chemicals, compounds, and components. Manufacturing alone requires salts, acids, sugars, resins, excipients, cleaning agents, tubing, bags, and vials among other materials. Each lot to arrive at the facility must have its contents inspected or sampled and tested to confirm identity, ensure quality, and verify purity. The tests and assays involved include numerous reagents and solutions which must also go through the receiving process. The diagram depicted in Figure 1 shows the reagents and solutions required for acceptance testing of one material, Ferric Ammonium Citrate, used in manufacturing [11]. It highlights the wide range and variable nature of materials received at the facility.
Figure 1 - Reagents and Solutions for Ferric Ammonium Citrate Acceptance
The value stream for raw material receiving includes multiple functional groups and handoffs. The overall system works in mostly a push configuration. Material moves from one group to the next as work is completed rather than as needed like in a pull scenario. Generally, the manufacturing group establishes their production schedule with a one to two year planning horizon based on demand forecasts. The supply chain group orders materials months in advance using enterprise resource planning (ERP) software. When raw materials arrive at the plant the Incoming Quality Assurance (IQA) group receives them and either samples or inspects the material. Samples are passed along to the Quality Control (QC) group for testing. Accepted materials then return to the responsibility of IQA who releases materials for disposition as needed by manufacturing.

![Figure 2 - Raw Material Value Stream with Functional Groups](image)

In addition to challenges presented by the varying array of materials required, various material types require strict environmental controls for sampling. For example, solids must be sampled in an enclosed area with a particulate capture system while liquids must be sampled in an area with a vapor capture system. Aseptic drug substance, the protein which is later combined with an excipient to formulate drug product, transferred from other manufacturing sites also requires strict environmental controls and must be sampled on the same day it arrives.
Tested and inspected materials have different target turnaround times (TAT) defined as the number of days from when the material is received until either sampling or inspection is performed. Prior to the start of the LGO internship, the target TAT for tested materials was set at 10 days. This was the level at which the sampling group could reliably sample with 95% adherence to the target TAT. Through applying lean initiatives, after a few months the sampling group was able to decrease their TAT by 40% while maintaining the same adherence level. However, to reach their ultimate goal the group needs to achieve an additional 50% improvement from current levels to drive TAT down to three days. This target was established as the ideal for the system prior to the internship and not established based on a particular business or process need.

Figure 3 - Categorization of Incoming Raw Material
Many of the improvements enacted reduced the time required to sample the incoming material. For sampled material, processing time is generally understood as a function of the material type and the quantity of containers. Inspected materials typically require one hour of processing independent of factors like material type or volume. The mean processing time for all materials is approximately four hours, but yet the turnaround time is a number of days. This is because of the complex queue of raw materials waiting to be tested. Additional complications arise from the fact that the sampling group extends its planning horizon for duration less than the average TAT of received materials. For example, at the start of the internship the IQA sampling group would schedule tasks two to three days in advance of when sampling would occur, but the target TAT at that point was nearly ten days. As a result of such a short planning horizon, materials which had already spent some time in the queue proved nearly impossible to keep under the target TAT if a processing delay arose.

The raw material receiving process at AML is complex and highly variable. While applying lean tools and implementing productivity improvements have achieved gains in reducing target turnaround time, there is still room for additional advancements. This thesis focuses on research and actions taken with the purpose of further reducing TAT in the sampling group.

Progress was achieved by extending the planning horizon of the sampling group through introduction of a linear programming-based scheduling tool. As noted in later chapters, this tool considered a multitude of factors, the most important being the process by which the tool considered the queue of material arrivals.
1.3 Hypothesis

A dynamic priority queue is the most appropriate system for achieving desired adherence to target turnaround time for complex raw material receiving operations like those found in biopharmaceutical manufacturing. Additionally, advanced planning and scheduling techniques applied to a variable turnaround time process will improve stability and cut average cycle time.

1.4 Thesis Summary

AML has already applied many of the standard operational improvement protocols like lean tools to eliminate waste in the process, but still seeks to drive further improvement. However, biopharmaceutical manufacturing consists of complex industry, regulatory, and logistical constraints which require an innovative approach. Owing to these factors, this thesis explores advanced planning and scheduling techniques like non-preemptive priority queuing in the context of raw material receiving. While research and application focused on biopharmaceutical manufacturing, the results and conclusions can be applied to other industries where intricate constraints dictates operations of the system.

This thesis is organized as follows: after an introduction to the problem, the review of applicable reference material is presented in Chapter 2 - Discussion of Selected Queuing. This section is followed by an overview of the scheduling tool development in Chapter 3 - Scheduling Tool Development. Practical analytical knowledge gained through the scheduling tool is discussed in Chapter 4 - Predictive Queue Modeling which ties in closely with Chapter 5 - Pilot Application & Outcomes. Finally, the tool's application and conclusions gained through onsite work are presented in Chapter 6 - Conclusions & Recommendations.

2 Discussion of Selected Queuing Approaches

This chapter focuses on reviewing relevant literature in the field of queuing theory and queue management. The insight gained from these references forms the basis for analysis going forward. While queuing and scheduling are separate fields, it is important to understand the connection between the two. The following subsections explore the
potential queuing disciplines which were considered as the basis for the scheduling tool and discuss the benefits and drawbacks of each as they relate to raw material receiving. Material arrivals are the input to the sampling system and relate directly to the order in which materials are processed according to the schedule. An additional benefit to reviewing selected queuing approaches is their involvement in further improvements to the scheduling tool. Ideally, the output of the scheduling tool can be used to adjust the arrival times of incoming raw materials to reduce TAT and better align material arrivals with the resources available for their processing. This is discussed in greater detail in Section 6.4 - Project Continuation

For the purpose of this review, when considering various queuing models, the material arrival into the system will be modeled as a discrete independent and identically distributed (iid) process with work volume expressed in the number of hours required for processing. Material arrivals cannot be considered as a true Markov chain process since in the majority of cases knowing the volume of queued work at time \( t \) implies no information about the volume of work at \( t+1 \). Queues for sampling should also be considered non-preemptive since once a task is begun it cannot be interrupted. A task lasting longer than one shift rolls over to the subsequent shift until processing is complete and while the task is interrupted by shift changeovers it retains its position in the queue and is not preempted by another task. Also, there is no abandonment of tasks in the system. While outsourcing sampling to a third party would be equivalent to abandonment, for the purpose of this study abandonment of tasks in process or in queue will be ignored. A more substantive discussion of this topic is provided in Section 3.2 - Inputs.

2.1 Laws of General Queuing Systems

When looking at queuing systems like that present in the raw material sampling area, it is important to first consider the relevant performance measures. The sampling area metrics track turnaround time in days for each task performed by the sampling group. TAT is commonly referred to as sojourn time or response time in academic literature and defined as the sum of the wait time and service time [12]. The focus is on wait time and efforts are concentrated in making gains in that area. A graphical representation comparing
selected queuing disciplines is provided in Figure 8 - Comparison of Variance in Different Service Disciplines.

For a steady-state system it helps to recall the Little’s Law stating:

\[ L = \lambda W \]

*Equation 1 - Little’s Law*

where \( L \) is the expected number of units in the system, \( W \) is the expected time spent by a unit, and \( \lambda \) is the rate at which units arrive to the system [13]. This formula holds true for the queue as well:

\[ Q = \lambda W_q \]

*Equation 2 - Little’s Law for Queues*

where \( Q \) is the expected length of the queue and \( W_q \) is the expected wait time spent by a unit in the queue. As the number of items in the queue increases, the average waiting time increases as well. Therefore, it is important to keep the queue length short when TAT is a critical measure.

Another relevant metric is utilization: the fraction of the time a server is non-idle. The sampling area in reality consists of multiple servers since there are various workers spread across shifts and dedicated spaces for solid and liquid sampling. However, in a general sense utilization can be expressed as:

\[ \rho = \frac{\lambda}{\mu} \]

*Equation 3 - Utilization Expression*

where \( \lambda \) is the rate of arrivals to the system, like in the equations above, and \( \mu \) is the service rate of the system. For the system to be stable, the utilization must be less than one [12], but due to the variable nature of arriving work volume the sampling area often experiences work arriving at a rate greater than it can process resulting in growing queues. In scenarios
where the arrival rate $\lambda$ exceeds the service rate $\mu$ the waiting time can be expected to grow over time. The graph below in Figure 5 - Utilization versus Wait Time illustrates the relationship between utilization and relative expected wait time.

![Figure 5 - Utilization versus Wait Time](image)

Clearly, wait time increases in a non-linear fashion with utilization. The figure below, Figure 6 - Service Time Histogram, illustrates the variable nature of service time required for arriving tasks to the sampling group over a one month period of time using real material receipts. Most tasks require one worker a full shift to complete, but there are a number of shorter-duration tasks. Under most circumstances, a shift lasts 8 hours, but actual working time can vary. At the same time, a number of tasks require longer times resulting in heavier tails. The mean value is approximately five hours to complete a task. There is a large cluster around the 8 hour mark, but even removing these data points does not allow a continuous fit distribution to fit the remaining points with an acceptable degree of uncertainty.
Coupled with the service times shown in Figure 6 - Service Time Histogram, it is important to note the arrival numbers each day over the same period of time. On average, 2.9 different materials arrived to the facility each day. The number of materials arriving each day over the sample period is illustrated below in Figure 7 - Daily Material Arrivals Histogram.
2.2 Stacked Queues

Two of the simplest service disciplines are first-in first-out (FIFO) and last-in first-out (LIFO) queuing schemes. As their names imply, these two methods determine the order of material processing based on the order in which they arrived.

2.2.1 First In First Out

Also known as first-come first-served (FCFS), FIFO is the most basic service discipline since arrivals are processed exactly in the order they arrive. It is considered the fairest system to all customers in the queue. Through applying probability and queuing theory to a system with interarrival and service times exponentially distributed, it can be shown that the mean sojourn (response) time for a FIFO system may be expressed as:

\[
\bar{T} = \frac{1}{\mu} \cdot \frac{1}{1 - \rho}
\]

Equation 4 - FIFO Mean Response Time

where \( \bar{T} \) is the mean response time comprising wait time and service time, \( \mu \) is the service rate, and \( \rho \) is the utilization. Additionally, it can be shown that the variance in response time under a FIFO system is:

\[
\sigma_{\text{FIFO response}}^2 = \frac{1}{\mu^2} \cdot \frac{1}{(1 - \rho)^2}
\]

Equation 5 - FIFO Response Time Variance

where the variance is a function of service rate \( \mu \) and utilization \( \rho \). These expressions assume Poisson arrival and exponential service processes with a single server and form the basis of a relative comparison between service disciplines [14].

2.2.2 Last In First Out

Also known as last-come first-served (LCFS), LIFO has many practical considerations, like in a warehouse where items are stacked one on top of another. It is far easier to add and remove items from the top of the stack than the bottom. This leads to issues with impatience and abandonment when the system is operating near capacity and it may take a
very long time for the item at the bottom of the stack to be processed. In some scenarios, like biopharmaceutical manufacturing where raw materials have expiration dates, this service type is less than ideal. However, on the basis of comparison, it can be shown that LIFO systems have the same mean response times as FIFO systems [15]:

\[
\bar{T} = \frac{1}{\mu} \cdot \frac{1}{1 - \rho}
\]

*Equation 6 - LIFO Mean Response Time*

where \( \bar{T} \) is the mean response time comprising wait time and service time, \( \mu \) is the service rate, and \( \rho \) is the utilization.

### 2.3 Random Order of Service

Random order of service schemes, sometimes called service in random order (SIRO), is based on randomly choosing customers for service. It has the benefit of being extremely flexible operationally. It can be shown that the mean sojourn time for a SIRO system, like the other disciplines, is also:

\[
\bar{T} = \frac{1}{\mu} \cdot \frac{1}{1 - \rho}
\]

*Equation 7 - SIRO Mean Response Time*

where \( \bar{T} \) is the mean response time comprising wait time and service time, \( \mu \) is the service rate, and \( \rho \) is the utilization. This happens to be the same mean response time as using a FIFO or LIFO system. Additional calculations show that the variance for a SIRO system can be expressed as:

\[
\sigma_{\text{SIRO}}^2 = \frac{1}{\mu^2} \cdot \frac{1}{(1 - \rho)^2} \left( 1 + \frac{2\rho^2}{2 - \rho} \right)
\]

*Equation 8 - SIRO Response Time Variance*

where the variance is a function of service rate \( \mu \) and utilization \( \rho \). Note the similarities to the FIFO variance since SIRO variance is greater than FIFO variance by only a factor that is a function of utilization. For example, in a system which is 40% utilized a SIRO strategy
would experience 20\% additional variance compared to a FIFO strategy while a 80\% utilized system would experience more than double the variance compared to a FIFO strategy [16].

For application in biopharmaceutical raw material receiving where the objective is to stabilize the process and reduce TAT a SIRO system would be less than ideal, especially considering the variable priority nature of material arrivals.

2.4 Priority

The final service discipline for review is priority queuing where customers of various priorities arrive to the system and are queued not according to their arrival order or service time, but by order of priority. Arriving customers are assigned a priority class and within this priority class customers are served in a FIFO fashion. This is most applicable to biopharmaceutical manufacturing since different raw material types have different requirements in terms of inspection and sampling. The wait time for each priority class is a function of the arrival and service rates for that priority class. As the name implies, it is generally understood that when keeping all other components equal, higher priority classes experience a shorter mean wait time as compared to lower priority classes. Comparing to other disciplines, high priority classes exhibit shorter mean wait times and variance than a FIFO system while lower classes take longer [12].

2.5 Summary of Queuing Strategies

After reviewing various service disciplines, it becomes apparent that the mean waiting time is not dependent on the queuing method, but the variance is dependent on method. Additionally, variance is minimized when items are processed in the order which they arrive as shown in the FIFO strategy and variance is maximized when items are processed in the LIFO strategy [17]. A comparison of wait time variance for LIFO, FIFO, and SIRO strategies is shown below in Figure 8 - Comparison of Variance in Different Service Disciplines.
The chart shows the relative variance of different service disciplines at the same arrival and service rates, illustrating how the variance for queue strategies is bounded by FIFO and LIFO. Clearly the choice for minimizing variance in waiting time is using a FIFO queue strategy. However, taking into account the complex nature of biopharmaceutical raw material receiving, a priority system is a more attractive choice. Different material types have various sampling and shelf life requirements.

3 Scheduling Tool Development

In order to stabilize and reduce TAT in the AML raw material sampling area, a dynamic scheduling tool was developed to extend the planning horizon. As mentioned previously, the sampling group operated with a planning horizon shorter than the area's cycle time, but can now use the scheduling tool to extend their planning horizon. The scheduling tool was developed as a custom application using Visual Basic, Microsoft Excel, and the OpenSolver add-in for Excel. Commercial software was explored, but for ease of operation, the tool was custom-written for the IQA sampling group. The scheduling tool is designed to be run periodically by the sampling area manager. Any time a constraint or input changes, the manager can simply rerun the schedule to determine the new optimal and correct the working plan if the change affected the objective function to the point it altered the output.
Since even complex scenarios can be solved in a matter of minutes, the tool serves as a dynamic aid in the scheduling process, but from a practical view does not need to be run more often than daily.

### 3.1 Assumptions

Before diving into the details of the scheduling tool, a number of practical, operational, and technical assumptions should be stated:

- All input tasks include estimated completion time. A degree of variation should be assumed.
- Only tasks estimated to take longer than one shift are allowed to be completed over multiple days. For example if the shift time is eight hours, a nine hour task would be split into eight hours and one hour, with the one hour segment performed on the day following the scheduled date for the eight hour segment, while a seven hour task would never be split.
- A full shift of work is assigned the specified number of hours. This time includes breaks and other non-task activities associated with the normal course of work.
- Due to the fact that delivery can occur any time during the day, for non-Drug Substance tasks the material is considered available for processing the day following the day it is scheduled to be delivered. Drug Substance tasks are sampled immediately.
- Due dates falling on Saturday or Sunday are automatically rolled back to Friday. Inspected materials arriving on Friday are always due on Sunday, causing them to be scheduled for Friday, the same day they are due. This is not a fault in the tool, but a shortcoming in the method for assigning due dates.
- By default, the timeframe for the schedule begins with the arrival date of the earliest material and finishes with the latest due date. However, the option exists to use the current date as the start day allowing for past-due and backlog tasks. Past due tasks are automatically reassigned a new due date in well into the future so that they may be scheduled as resources are available. The tool places emphasis on materials which can still achieve their target due dates over past due materials.
• When assigning shifts, the tool considers shifts to be consecutive and not overlapping. Any number of shifts of any length can be assigned, even if the resulting sum totals more than a day.

• The tool considers a date range for scheduling based on the arrival date and due dates of all the input tasks. When setting up the tool, only these date ranges are available for selection. However, if no solution is found, the tool will attempt to relax the constraints and prompt the user to push back due dates in an attempt to find a feasible solution.

• The ability to add quick tasks, which is discussed in more detail in Section 3.4.4 - Distinct Subjective Constraints, through the interface window is only provided to create tasks less than one shift in duration and not for adding substantial work. Extra tasks are not saved and the constraints applied to them will not be considered properly after the data is saved or loaded.

3.2 Inputs

The goal of the scheduling tool is to generate a work plan which allows area management to make better use of their resources. This means considering all the system inputs and how they relate to the desired output. Inputs as in terms of work volume are not entirely stochastic, but can be assumed to be non-deterministic. The diagram shown in Figure 9 - Scheduling Tool Inputs maps out how the different input types lead to the generation of a sampling schedule.
Most of the input data comes from tasks. A task at its most basic is any material which must be sampled or inspected by the IQA group. Most of the data for tasks comes from three sources: the inbound material list generated by the ERP system, the transferred material schedule, or the production agenda. While these resources generate data in Excel file format, Microsoft Access is used to aggregate the three to a common format which can then be queried over a range of dates to produce data which can be fed into the scheduling tool. The information presented in Table 1 - Sample Input Data is an example of what the queried data ready for the scheduling tool looks like. The input data forms the basis for decision variables and constraints.
<table>
<thead>
<tr>
<th>PO Number</th>
<th>Spec Number</th>
<th>Material</th>
<th>Inspected / Tested</th>
<th>Received Date</th>
<th>Due Date</th>
<th>Type</th>
<th>Hours Required</th>
<th>Worker A</th>
<th>Worker B</th>
<th>Worker C</th>
<th>Worker D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000001</td>
<td>RMS-001</td>
<td>Material A</td>
<td>Tested</td>
<td>10/15/2013</td>
<td>10/21/2013</td>
<td>Solid</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1000002</td>
<td>RMS-002</td>
<td>Material B</td>
<td>Tested</td>
<td>10/15/2013</td>
<td>10/21/2013</td>
<td>Solid</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1000003</td>
<td>RMS-003</td>
<td>Material C</td>
<td>Inspected</td>
<td>10/15/2013</td>
<td>10/16/2013</td>
<td>IQA Staging Area</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1000004</td>
<td>RMS-004</td>
<td>Material D</td>
<td>Inspected</td>
<td>10/15/2013</td>
<td>10/16/2013</td>
<td>IQA Staging Area</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1000005</td>
<td>RMS-005</td>
<td>Material E</td>
<td>Inspected</td>
<td>10/15/2013</td>
<td>10/16/2013</td>
<td>IQA Staging Area</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1000006</td>
<td>RMS-006</td>
<td>Material F</td>
<td>Aseptic</td>
<td>10/15/2013</td>
<td>10/15/2013</td>
<td>Drug Substance</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1000007</td>
<td>TBD</td>
<td>Material G</td>
<td>Thawing</td>
<td>10/15/2013</td>
<td>10/15/2013</td>
<td>Drug Substance</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1000008</td>
<td>RMS-008</td>
<td>Material H</td>
<td>Tested</td>
<td>10/16/2013</td>
<td>10/22/2013</td>
<td>Liquid</td>
<td>6.25</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1000009</td>
<td>RMS-009</td>
<td>Material I</td>
<td>Aseptic</td>
<td>10/16/2013</td>
<td>10/16/2013</td>
<td>Drug Substance</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1000010</td>
<td>TBD</td>
<td>Material J</td>
<td>Thawing</td>
<td>10/16/2013</td>
<td>10/16/2013</td>
<td>Drug Substance</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1000011</td>
<td>RMS-011</td>
<td>Material K</td>
<td>Tested</td>
<td>10/17/2013</td>
<td>10/23/2013</td>
<td>Liquid</td>
<td>5.375</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1000012</td>
<td>RMS-012</td>
<td>Material L</td>
<td>Inspected</td>
<td>10/17/2013</td>
<td>10/18/2013</td>
<td>IQA Staging Area</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1000013</td>
<td>RMS-013</td>
<td>Material M</td>
<td>Tested</td>
<td>10/17/2013</td>
<td>10/23/2013</td>
<td>Liquid</td>
<td>3.625</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1000014</td>
<td>RMS-014</td>
<td>Material N</td>
<td>Tested</td>
<td>10/17/2013</td>
<td>10/23/2013</td>
<td>Solid</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1000015</td>
<td>RMS-015</td>
<td>Material O</td>
<td>Inspected</td>
<td>10/17/2013</td>
<td>10/18/2013</td>
<td>IQA Staging Area</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1000016</td>
<td>TBD</td>
<td>Material P</td>
<td>Aseptic</td>
<td>10/17/2013</td>
<td>10/17/2013</td>
<td>Drug Substance</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 - Sample Input Data

Each row in the table represents a single task. It is identified by the material name, its acceptance specification, and the Purchase Order (PO) number. The aggregation process automatically categorizes the material type, calculates the due date based on material priority, estimates the number of hours required for processing based on the material type and number of containers, and tabulates a capability matrix for the four workers. In this example, each of the four workers A through D has been properly trained to sample or inspect the materials listed as shown by the binary indicator 1. If the worker did not have the necessary capability to sample the material a 0 would appear in the corresponding cell. Worker capability is just one of the constraints considered by the scheduling tool.

3.3 Decision Variables

The integer linear program uses binary decision variables to decide whether or not a task is processed on a given day by a given worker. The scheduling tool automatically sets the time horizon starting with the date of the earliest delivery and ending with the latest due date. Therefore, the number of decision variables is the product of the number of shifts in the planning horizon, the number of workers, and the number of tasks. These binary decision variables are denoted by the variable $C_{ijk}$ where each task $i$ is completed on day $j$ by worker $k$. The tool allows for multiple shifts, but since each worker can only work one shift per day the subscript refers to a specific day and not a shift for the worker. Also, in this
example there is only one shift per day so the two terms are used interchangeably. In the example shown in Table 1 - Sample Input Data there are nineteen tasks \( i \), nine days \( j \) with one shift per day over the planning horizon, and four workers \( k \). While there are only sixteen rows of tasks shown in the example, one specific condition of the area operations dictates that all aseptic sampling requires two workers on the same shift to perform the task. For this reason a duplicate task is created and constrained to be completed at the same time as the main task. The example given would result in 684 binary decision variables which are more than the default capability of Microsoft Excel’s Solver. OpenSolver was used to overcome this issue.

### 3.4 Constraints

The scheduling tool is based on a linear program and operates off decision variables, an objective function, and constraint. This section presents some of the applicable constraints considered by the tool when solving. Additional constraints explicit to the application structure of the tool, like how to deal with weekends and logical conditions not pertinent to the study of priority queuing or scheduling, are omitted.

A feasible solution was subject to meeting all the constraints imposed on the mixed integer linear program. Under certain situations a feasible solution is not possible, like when the volume of work exceeds capacity over a given period of time.

The most basic constraint mandates that all tasks must be completed once.

\[
\sum_{j=1}^{9} \sum_{k=1}^{4} c_{ijk} = 1 \quad \text{for } i = 1 \text{ to } 19
\]

*Equation 9 - Task Completion Constraint*

#### 3.4.1 Resources

Since working time is the basic unit considered in the scheduling tool, workers cannot be assigned more work in a shift than they have hours available to work. By default, each worker has eight hours available per shift. Each task, \( T_i \), has a processing duration associated with it. For example, \( T_1 \) from Table 1 - Sample Input Data requires 8 hours to process. A worker could complete this one task and no others in a single shift
\[ \sum_{i=1}^{19} T_{i} C_{ijk} \leq 8 \quad \text{for } j = 1 \text{ to } 9, k = 1 \text{ to } 4 \]

Equation 10 - Working Hours Constraint

### 3.4.2 Due Date

Tasks have the constraint that processing cannot begin before they arrive and must be completed before they are due. The quantities \( A_i \) and \( D_i \) denote the arrival day of task \( i \) and the due date of task \( i \), respectively.

\[ A_i < \sum_{j=1}^{9} jC_{ijk} \leq D_i \quad \text{for } i = 1 \text{ to } 19 \]

Equation 11 - Due Date Constraint

### 3.4.3 Capabilities

Tasks may only be assigned to workers who have been properly trained to sample that specific material. Capability is a binary input; a value of 1 denotes the ability to sample the material and 0 means that worker cannot sample the material. This value is represented by the binary quantity \( B_{ik} \) where each worker \( k \) may or may not have the capability to perform each task \( i \).

\[ C_{ijk} \leq B_{ik} \quad \text{for } i = 1 \text{ to } 19, k = 1 \text{ to } 4 \]

Equation 12 - Capability Constraint

### 3.4.4 Distinct Subjective Constraints

One of the challenges of scheduling in a real environment is that the global optimal solution may not be operationally feasible. Often, distinct, subjective constraints must be applied to the system to meet the practical realities of running the area. For example, workers may be required to attend training sessions or request vacation time which would limit the range of possible solutions. While less than ideal, these subjective constraints must be considered when creating a schedule to direct operation of the area. The example below in Equation 13 - Subjective Constraint shows how worker three must attend a half-day training on day five and consequently only has four hours available to perform tasks.
\[ \sum_{i=1}^{19} T_i C_{i,5,3} \leq 4 \quad \text{for } i = 1 \text{ to } 19 \]

Equation 13 - Subjective Constraint

3.5 Objective Function

The goal of the project is to reduce TAT in the IQA sampling area. Therefore, the objective function of the linear program is to minimize total turnaround time for all tasks in the planning horizon. This method, while by no means the only useful objective function as discussed in Section - 3.6 Alternate Objective Functions, proves to be very practical and effective in generating a realistic schedule.

\[
\min \left[ \sum_{i=1}^{i} \left( \sum_{j=1}^{j} \sum_{k=1}^{k} j C_{ijk} - A_i \right) \right]
\]

Equation 14 - Objective Function

3.6 Alternate Objective Functions

Optimizing the linear program with the objective of minimizing total turnaround time for the system proved to be practical and produced realistic results. However, alternate objective functions were explored to see how the system would react when solving based on other objective function. For example, a quadratic cumulative loss function applying a higher cost to tasks performed later in the planning horizon was explored in an attempt to force tasks to be completed as early as possible. This produced similar results to the turnaround time function, but at a slightly lower adherence rate.

3.7 User Interface

The scheduling tool developed for the AML sampling group features a user-friendly interface to facilitate the insertion of subjective constraints on the system. Using VBA form tools, the interface consists of a number of drop-down lists which allows a manager to assign tasks to specific workers, assign tasks to specific dates, set vacation and working time, and insert additional non-working tasks, like training. The interface, which is depicted below in Figure 10- Scheduling Tool Interface, also allows for additional control of
the solver output, like checking a box to generate graphs to visually represent the rate at which work is done in the area.

![Sampling Schedule Tool](image)

**Figure 10- Scheduling Tool Interface**

4 **Predictive Queue Modeling**

One important benefit of the scheduling tool besides creating a working schedule for the sampling area is that it works as a model to evaluate potential future scenarios. This chapter discusses the scheduling tool's application in predictive modeling to compare various "what if" situations.

4.1 **Comparison of Queuing Strategies**

As noted in Chapter 2 - Discussion of Selected Queuing Approaches, the queue type selected impacts the variance of time needed to process items in the queue. For a time-critical operation like incoming raw material sampling for biopharmaceutical manufacturing, it is important to keep variance to a minimum. Intuitively, a FIFO system would make sense due to the fact that it has the lowest variance in wait time. Considering how different material types have different requirements, a priority queuing system is
worth investigating as well. The scheduling tool allows both scenarios to be modeled and compared on the basis of adherence to target turnaround time. By removing the priority classes assigned to arriving materials and adding a constraint that a task may only be undertaken if the task which arrived immediately before that task has been completed, the scheduling tool can operate under the discipline of FIFO queuing and analyze TAT adherence.

Using the same exact set of input data and resources, the scheduling tool can consider both FIFO queues and priority queues. Maintaining the same objective function for both scenarios and applying the tool allows for comparison between the two strategies. The table below compares target turnaround time adherence and average TAT in days for both strategies at different target levels. The data presented is based on simulated results and verified against actual results.

<table>
<thead>
<tr>
<th></th>
<th>FIFO Queue</th>
<th>Priority Queue</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Day TAT Adherence</td>
<td>48%</td>
<td>77%</td>
</tr>
<tr>
<td>5 Day TAT Adherence</td>
<td>67%</td>
<td>92%</td>
</tr>
<tr>
<td>Average TAT - Solid</td>
<td>4.2</td>
<td>3.1</td>
</tr>
<tr>
<td>Average TAT - Liquid</td>
<td>3.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Average TAT - Inspected</td>
<td>2.8</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 2 - Comparison of Modeled Queues

Table 2 - Comparison of Modeled Queues shows how the priority queue does a better job of meeting target turnaround times than does the FIFO queue when holding other factors constant. As would be expected, the average TAT for the FIFO shows a tighter range than the priority queue. While not a universal statement about the performance of the different queue types, as the target adherence is dependent on input tasks and resources, this example shows there is a clear distinction between the two strategies.

The graph below in Figure 11 - Comparison of Modeled Queues Graph shows work available and completed on a cumulative basis. Available work is quantified by the sampling group as the number of hours of processing required to complete all the tasks in the system, both materials in progress but not yet completed and queued materials waiting for processing. The graph illustrates how a similar volume of work is completed each day
using the different queuing strategies. Due to the order in which tasks are assigned, it shows that the priority strategy does a better job of adhering to target TAT than the FIFO system. The scheduling tool assigns due dates based on a material's priority class. The highest priority materials must be sampled on the day they arrive while lower priority materials are allowed more time before they are due. The scheduling tool then determines queue order such that materials are processed before their due date if feasible.

![Graph showing comparison of modeled queues](image)

**Figure 11 - Comparison of Modeled Queues Graph**

### 4.2 Consideration of Subjective Limitations

Oftentimes, the area manager needs to consider what effect subjective limitations will have on the sampling area's output. For example, holidays, sick days, vacation time, training, special projects, and company-wide events can all impact the regular working schedule. The manager does not always have visibility into when these events will occur, but can model their effect. Another benefit of the scheduling tool is near real time corrections to the working schedule based on available resources. If one morning a worker calls in sick, then the manager can quickly re-run the day's schedule to determine the new
optimal solution and alert downstream processes to any potential impacts. Including this functionality allows the tool to simulate the response to unexpected constraints.

Using the same data set from the above section on Comparison of Queuing Strategies it is possible to construct a schedule to model potential disruptions. Adding constraints to simulate six vacation or sick days and one half-day training for the four workers involved shows what impact these common events can have on the sampling schedule. In a system with high utilization like the IQA sampling area, even small changes in the available resources can significantly impact overall performance. The information presented in Table 3 - Comparison of Constrained Schedule compares the performance of the constrained and unconstrained schedules in this hypothetical example using the priority discipline.

<table>
<thead>
<tr>
<th></th>
<th>Constrained Schedule</th>
<th>Unconstrained Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Day TAT Adherence</td>
<td>72%</td>
<td>77%</td>
</tr>
<tr>
<td>5 Day TAT Adherence</td>
<td>85%</td>
<td>92%</td>
</tr>
<tr>
<td>Average TAT - Solid</td>
<td>3.3</td>
<td>3.1</td>
</tr>
<tr>
<td>Average TAT - Liquid</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Average TAT - Inspected</td>
<td>1.2</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 3 - Comparison of Constrained Schedule

5 Pilot Application & Outcomes

Once thoroughly validated, the tool serves to assist analytical measures to improve operations in the sampling area. By allowing the simulation of various scenarios, the scheduling tool can be used to assess the effectiveness of alternate operational strategies in the IQA sampling area.

5.1 Sensitivity Analysis

As was noted in Section 4.2 - Consideration of Subjective Limitations, since the sampling area is very highly utilized, small changes in available resources can have a substantial impact on the TAT performance. Recall from Figure 9 - Scheduling Tool Inputs the numerous factors which make up the system inputs. The scheduling tool allows for
sensitivity analysis to be performed on these inputs. The sensitivity analysis shows where small changes in resources can have a disproportionally large impact on performance.

Using one month of material receipts as a representative baseline, each of the applicable inputs was analyzed for its sensitivity. By varying the system inputs and checking the overall performance in an iterative manner, it became apparent that the solid raw material testing area was critically utilized. This model-based observation was reinforced by qualitative assessments from the sampling area management.

5.2 Proposed Improvement

Using the knowledge that the solid sampling area is limiting the sampling throughput, options to expand capacity can now be considered. In the case of the project at AML, it was discovered through discussions with the front line workers that solid capacity could be expanded by converting the liquid sampling area into a dual purpose sampling area with minimal capital expenditure.

In the graph depicted below as Figure 12 - Queue Length Comparison shows how queue length fluctuates over time in response to arrivals under a priority policy. Throughout the project, work was considered in hours rather than quantity or volume. Since a single material could require an hour or a shift for sampling depending on the material type and number of containers, keeping track of the hours of work in the queue or in process proved much more valuable than simply considering the number of items. The blue lines represent the total volume of work in the queue and the red lines represent solely solid materials. Clearly the queue is comprised almost entirely of solid materials. Increasing capacity for solid sampling also reduced the size of the queue. The queue lengths which could be expected in a scenario where the solid testing capacity has been expanded is shown by the dashed lines. It demonstrates how a relatively small change in capacity composition can have a major impact on queue length and by extension the performance of the system.
5.3 Driving Continuous Improvement

While increasing the capacity in the solid material sampling area would cut the queue length and improve target turnaround time adherence by allowing materials to be processed in a more timely manner in accordance with their due date, there is still additional opportunity for improvement. Simply adding capacity reacts to the issue without correcting the cause; the arrival rate and mix of received materials is highly variable. However, if the arrivals were to be level-loaded, even better performance could be achieved without adding resources. Table 4 - Comparison of Improved States outlines the degree of improvement which could be expected as compared to the current state and increased capacity proposed state.

<table>
<thead>
<tr>
<th>Current State</th>
<th>Proposed State</th>
<th>Level-Load State</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Day TAT Adherence</td>
<td>78%</td>
<td>88%</td>
</tr>
<tr>
<td>5 Day TAT Adherence</td>
<td>85%</td>
<td>97%</td>
</tr>
<tr>
<td>Average Queue Length (hrs. of work)</td>
<td>47.6</td>
<td>25.8</td>
</tr>
</tbody>
</table>

Table 4 - Comparison of Improved States
The level-loaded state is straightforward in concept, but actually achieving this sort of system would be challenging in practice. The sampling group would have to work with the upstream operation, supply chain ordering, in order to smooth the rate of arrivals. The two groups would need to increase communication and share visibility into how one operation affects the other. The scheduling tool helps highlight a number of the connections, but ultimately organizational improvements will need to be established to make the level-loaded state a reality.

6 Conclusions & Recommendations

This chapter reviews the information presented in this thesis, drawing conclusions and suggesting improvements over the current standard.

6.1 Key Findings

The project at AML was an excellent opportunity to apply academic principles and industry strategies to a real environment. Ultimately the lessons learned can be summarized as:

- It is critical to understand the relationship between inputs and outputs in a system.
- Advanced planning and scheduling techniques can be used to promote process awareness and make the best use of existing resources.
- The ideal process state cannot be reached unless there is substantial communication and coordination between groups up and down the value stream.

6.2 Suggested Actions

Developing the scheduling tool for the IQA sampling area at AML proved to be a tremendous success. This effort and the learnings associated with it can be of value to other groups within the organization, particularly the downstream groups in the raw material receiving value chain like the QC raw material test lab. The scheduling tool can be easily reconfigured for a different set of inputs and criteria. However, it is impractical to create a custom tool for every lab and functional area that requests one. Amgen should evaluate
enterprise-level scheduling tools for roll-out to a broader range of applications based on the requirements outlined by the IQA sampling group. While an over-arching application coordinating activities across the value stream is not necessary, a common software package which could be used by multiple functional areas to assist in scheduling would be more conducive to technical support than a number of custom tools.

6.3 Scheduling Tool Improvements

The table below outlines a number of technical and operational improvements which could be made to the scheduling tool in the future to improve its performance and functionality.

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic comparison to FIFO</td>
<td>The scheduling tool can be easily adapted to a FIFO policy as opposed to the priority system. Including an automatic comparison between the two would be useful to quantify the level of improvement provided by the priority system.</td>
</tr>
<tr>
<td>Smart relaxation of due dates</td>
<td>When no solution is found, relaxing the constraints by adjusting the due dates one day and trying again is most desirable. The tool should automatically add delays one day at a time until a solution is found.</td>
</tr>
<tr>
<td>Incremental scheduling</td>
<td>When no schedule is feasible, all that is known is that the entire schedule failed, not at what point the schedule failed. A good way to highlight when issues arise would be to use incremental scheduling after the solver fails for the whole schedule. It would need to start with a short time period of arrivals and then add additional arrivals one day at a time until the schedule fails. That way additional resources could be added at the appropriate time period or a particular constraint identified that was causing the schedule to fail. This method was used early on in the development process to learn which constraints were causing problems.</td>
</tr>
</tbody>
</table>
Feasibility

If the tool encounters the situation where it cannot find a solution on the first try, it should remove the due dates from non-critical tasks to check if a solution is even possible before asking to push back due dates. It may be the case that due to conflicting constraints or erroneous inputs that no amount of delays will ever allow for a solution. The tool would pick this up before asking to push back due dates.

Aseptic

All DS tasks are supposed to be performed on the day they arrive so queue length graphs would not provide any information, but aseptic arrival charts might be useful.

Additional

Currently, the solver uses an objective function based on reducing cumulative TAT. However, using quality loss functions based on assigning penalties to missing a target date could provide better results and increased adherence.

Table 5 - Scheduling Tool Improvements

6.4 Project Continuation

In an effort to preserve the learning gained from this project, a continuation plan was put in place before the project’s conclusion. The plan consisted of recording and transferring ownership of the scheduling tool. A representative from the information services group was given the scheduling tool files and trained in their use so that technical support could be provided in the future. A document recording the tool’s design including commented code was created and distributed within the Operations Improvement group for future reference and application in other functional areas of the organization.

Another point for further investigation arising as a result of this project is the notion of using the scheduling tool output to determine the queue input. By creating a feedback look where the optimized sampling schedule can be directed upstream to the supply chain group, supply chain can then order materials such that they are delivered at a time when resources are immediately available to sample the material. This process change would allow even further reductions in TAT and significantly cut the volume of queued materials beyond the level-loaded state proposed in Section 5.3 - Driving Continuous Improvement.
References


