Reagent Usage Optimization In 
High Volume Diagnostics Testing

By

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Reagent Usage Optimization In
High-Volume Diagnostics Testing

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and Master of Science in Civil and Environmental Engineering

ABSTRACT

Company X provides healthcare diagnostics testing services. The company competes in the market by providing cost effective, short turn-around-time (TAT) solutions and a large variety of test selections. Reducing operating costs is a major area of ongoing improvement for Company X, and this effort includes reducing reagent costs in high volume diagnostics platforms across the nation. The objective of this thesis is to identify the major causes of reagent waste, and reduce unnecessary reagent consumption on a specific high volume testing platform which can test multiple different assays. The project targeted finding measures to mitigate reagent waste which can be employed in all sites.

The current state analysis identified quality control testing that exceeded regulatory requirements and minimum standards defined in the SOPs and unoptimized distribution of assays to instruments as causes of unnecessary reagent consumption. The analysis also identified patient tests repeated due to mechanical errors in the instruments as another cause of reagent waste. Countermeasures are developed to mitigate these issues.

In order to reduce reagent consumption due to superfluous quality control testing, a workflow study is conducted. The workflow study targets the minimization of quality control testing and instrument calibrations by optimizing the load distribution over similar instruments within a laboratory site. The optimal distribution of patient test volumes to instruments is modeled and solved as a linear programming problem. In addition to workflow optimization, process standardization and preventive maintenance strategies are explored.

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Chapter 1

Introduction

This chapter provides an introduction to the thesis; and discusses the problem statement, the project scope, the project goals, and the relevant company context to ground subsequent chapters in the thesis.

Company X is a leading enterprise in providing diagnostics testing services. The company competes in the market by providing cost effective, short turn-around-time (TAT) solutions and a large variety of test selections. Reducing operating costs is a major area of ongoing improvement for Company X, and this effort includes reducing reagent costs in high volume diagnostics platforms across the nation. Reagents are chemical substances used in chemical reactions to identify the target compound and determine patient test results. The objective of this project is to identify the major causes of reagent waste and reduce unnecessary reagent consumption on a specific high volume testing platform which can test multiple different assays. This platform is deployed across more than twenty Company X sites. The project targets finding methods to mitigate reagent waste which can be employed in all sites.

1.1 Problem Statement

Company X handles massive amounts of clinical testing each day which contributes to achieving economies of scale. The competitive landscape includes in-hospital laboratories, physician practices, other large commercial laboratories, and smaller local laboratories spread across the nation. One of the key competitive advantages of Company X is the fact that it can offer cost-effective solutions with the highest quality due to the economies of scale in its operations.
At this large scale, any small operational improvement achieved on one specific platform or one specific process can add up to significant annual savings accumulated across the sites nationwide. Therefore operational excellence and continuous improvements are key principles in Company X business model. One important component of overall operational excellence strategy is laboratory excellence which targets optimizing capacity and facility footprint, automating processes and applying lean manufacturing principles. Expenditures in diagnostic testing reagents and laboratory supplies are significant factors in Company X cost structure.

Our project attempts to reduce reagent waste on a specific high volume diagnostics platform which is capable of testing multiple different assays. Any use of reagent that does not lead to patient test results is considered as reagent waste in the context of this study which is further discussed in Section 1.2. The platform is capable of processing more than thousand patient tests per day. The ongoing migration of new tests to the platform provides an ample opportunity to maximize the impact of waste reduction efforts. The specifics of platform and assay information are not disclosed in this thesis due to the confidentiality requirements.

Even though the project targets a specific proprietary high volume diagnostics platform; the findings, methods, and conclusions offered in this thesis can be applicable to other diagnostics testing platforms, and even to other industries with similar operational characteristics.

1.2 Reagent Waste Definition

Reagents are chemical agents used in chemical reactions to identify the target compound and determine patient test results. In the context of this thesis, any use of reagent that does not lead to patient test results is considered as waste. According to this definition, the following items are all examples of reagent waste:
• Repeated patient tests due to instrument errors
• Reagent usage in Quality Control (QC) testing
• Reagent usage in instrument calibration
• Expired reagents

Quality control (QC) testing and instrument calibrations are required processes in diagnostics testing, however they do not directly lead to patient test results. Thus any usage of reagent in these procedures is considered waste in the context of this thesis and one of the goals of the project is to reduce reagent usage while fulfilling the regulatory requirements and standard operating procedure (SOP) documents. However, we are not suggesting that QC testing is actually wasteful; the issue is whether the percentage of reagent use devoted to patient tests can be increased without any reduction in accuracy.

1.3 Project Scope

The thesis focuses on reagent savings in the analytical processes of laboratory testing.

The pre-analytical and post-analytical processes are out of the scope of this thesis. The analytical phase of the laboratory testing includes the following processes:

• Loading samples on analyzer
• Adding samples and reagent
• Mixing
• Incubating
• Detecting
• Producing results
• Reviewing results
• Repeating tests (if necessary)
• Releasing results
Any potential reagent waste occurring in the processes listed above are within the scope of this project. The pre-analytical testing phase includes the following processes which are out of the scope of this project:

- Ordering
- Collecting
- Transporting
- Receiving
- Sorting

The post-analytical testing phase includes the following processes which are out of the scope of this project:

- Postprocessing storage
- Reporting results
- Accessing results
- Interpreting results
- Clinical actions

Due to the confidentiality requirements and protection of intellectual property, the thesis does not disclose instrument identification, instrument vendor information and the name of the assays that are examined in the project. The assays names are disguised with generic names such as “assay #1”, “assay #2”, etc. The instances of high volume diagnostics testing platform are referred to as instruments and analyzers.

1.4 Project Goals

This section aims to summarize the main project goals with more details and intermediate steps as listed below.

- Determine and quantitate key drivers of reagent waste on the specific high volume testing platform
• Compare and contrast processes at four sites including New England site
• Stratify the collected data by assay, site, and instrument
• Develop appropriate mitigation strategies
• Determine key factors for optimal load balancing between instruments, and develop a model for national use
• Create and leverage communication opportunities for the learnings above

Developing mitigation strategies to reduce reagent waste and developing a load balancing model for national use are the higher priority targets among the goals stated above. Additionally, software tools such, as python scripts and excel macros, are developed to automate intermediate tasks and achieve the main goals during the project. The development and use of these software tools are explained in more detail in the relevant chapters of this thesis. However the software codes of these tools are not included on the thesis in order to comply with the intellectual property restrictions.

1.5 Relevant Organizational Structure

Company X tests are performed in accordance with Standard Operating Procedure (SOP) documents. The SOP documents define various testing procedures for assays, including requirements for quality control, reagent, calibration, expected values, specimen, equipment and supplies. The procedures defined within the SOPs uniformly meet or exceed regulatory requirements. The SOPs are authored and maintained by Best Practices Teams which consist of medical, regulatory and laboratory experts across the organization. The SOP documents can be updated only by authorized Best Practices Teams within the organization. Each individual laboratory within the organization is responsible for following SOPs in their diagnostics testing. There are cases where local laboratory teams exceed the standard requirements defined in SOPs
which lead to superfluous reagent consumption. The thesis addresses standardization efforts and workflow improvements to address these superfluous reagent usage cases in subsequent chapters.

The high volume diagnostics testing instruments, which are examined as a part of the research project, are operated by trained medical technologists (med techs) in each individual laboratory. Medical technologists report to shift supervisors who are responsible for the related area of the lab, and shift supervisors report to laboratory managers within the site. The medical technologists are frontline employees who operate the diagnostics instruments daily and their day to day activities were closely monitored during the project that has led to this thesis. Their tasks include, but are not limited to, loading patient samples, reagents, quality control materials onto the instruments; preparing reagents for use; removing tested patient sample vials and used reagent cartridges from the instruments; running quality control tests and instrument calibration procedures; reviewing test outputs and releasing test results to ordering physicians if standards in the related SOPs are met; and reporting any potential instrument failures and test abnormalities to shift supervisors. It is critically important for medical technologists to interpret and implement the SOPs correctly. Each medical technologist is trained before they are assigned to operate a specific instrument and their competence is assessed periodically. Company X values cross-training of its medical technologists as an operational effectiveness principle. Medical technologists within the same clinically related area of the lab can rotate across different diagnostic testing platforms within the lab on a weekly basis, based on shift supervisor’s discretion.

Company X emphasizes process improvements and provides channels for collecting innovative ideas from local teams. In many cases local laboratory teams in individual sites come up with operational best practices that are beyond the specifications defined in SOP documents.
However these locally developed best practices are not always shared across different sites effectively. The thesis also addresses effective transfer of these locally developed best practices in the subsequent chapters.

1.6 Thesis Overview

The thesis is structured as follows. **Chapter 2** discusses the current state of the target high volume diagnostic testing platform and its performance metrics in terms of load volumes, test failures and reagent waste. This analysis involves quantitative metrics and qualitative observations from four visited laboratory sites, in addition to quantitative metrics collected remotely from other unvisited national sites. **Chapter 3** discusses preventive maintenance analysis and countermeasures to reduce reagent waste. It also discusses statistical methods to identify most common mechanical errors and instrument failures. **Chapter 4** discusses the workflow optimization study to reduce reagent waste. The chapter examines the modelling of optimized load balancing problem as a linear programming (LP) problem. It also includes application of the optimized model on certain cases to illustrate potential reagent savings. Finally, **Chapter 5** consolidates the findings of the previous chapters and provides final conclusions and recommendations. It also suggests areas for further investigation.
Chapter 2

Current State Analysis

This chapter discusses the current state analysis performed on the target platform, the data collection methods used, and the major issues identified that cause reagent waste. The chapter also introduces the process flow of the testing procedure on the target analyzer, and the basic terminology that is used in the rest of the thesis. As a part of the current state analysis, the operations at four different regional laboratory sites are observed. The medical technologists who operate the diagnostics instruments are surveyed and the instrument logs are analyzed. The current state analysis identified superfluous quality control testing that exceeded regulatory requirements and minimum standards defined in the SOPs, and unoptimized distribution of assays to instruments as major causes of unnecessary reagent consumption. The analysis also identified patient tests repeated due to mechanical errors in the instruments as a cause of reagent waste. These findings will be discussed in further detail in the rest of this chapter.

2.1 Process Description and Terminology

As described in Chapter 1, medical technologists operate the analyzers. Medical technologists’ responsibilities include loading reagent kits, quality control samples, and patient samples (usually in batches) to the instrument before the start of each run. Figure 2-1 illustrates an example of a batch of patient samples before they are loaded to the analyzer. The laboratory information system (LIS) identifies the tests ordered for each patient sample through the automated barcode reading system integrated in the analyzer. Once a batch of patient samples is started, the medical technologists do not intervene until the run ends, unless there is a technical
problem that disrupts the run and requires operator intervention. The length of one run is dependent on the number of patient samples loaded to the instrument and number of tests ordered. The duration of the run where operator intervention is not needed is called “walk away” time. During this period, operators work on activities such as loading other analyzers, preparing reagents, preparing patient samples, and releasing results.

Figure 2-1: An example batch of patient samples

The patient test results are determined by the analyzer based on the analytical principle for that assay. The test-specific reagent material and patient sample are combined in the incubator subsystem of the analyzer, which enables the reagent to react with the target compound present in the sample. This reaction generates luminescence which is measured by the analyzer. If the measured luminescence is above an assay-specific threshold, the sample is considered to be reactive, i.e. the target compound is detected in the patient sample. If the measured luminescence is below an assay-specific threshold, the sample is considered to be non-reactive, i.e. the target compound is not detected in the patient sample. If the test fails to generate a
luminescence reading due to a mechanical error, then no result is generated and the test is considered incomplete, which is an example of reagent waste. Further explanation of the chemical process to generate test results is beyond the scope of this thesis.

Certain laboratory terms are used repeatedly in this thesis, and they are explained below in the context of this study.

- **Billable Tests**: These are the tests “ordered” by Company X clients and they exclude the quality control (QC) tests and repeat tests. In other words, billable tests are defined as those that generate revenue for Company X organization. Repeat tests performed to achieve a billable test must not be counted in billable test count provided that the original test was counted.

- **Failed Tests**: In this thesis, failed tests refer to tests that are not completed, i.e. “Incomplete Tests”, and thus do not produce patient test results due to mechanical errors such as instrument errors, insufficient sample errors or reagent integrity errors. Additionally, failed tests may be caused by interfering substances or unique characteristics of a patient’s sample that prevent completion of the specific chemical reaction. To clarify, failed tests do not refer to tests that may generate false negative or false positive results in the context of this thesis; rather, they failed because they did not yield reliable information.

- **Repeat Tests**: This refers to tests that are repeated due to failures that prevent producing patient test results. In other words, failed tests result in repeat tests and they cause reagent waste. Whenever a test fails to produce a result due to a mechanical error, the analyzer automatically reschedules to rerun the test on the sample. If the instrument cannot reschedule a repeat test for the sample due to a technical issue, the medical
technologist can take corrective action and manually reload the patient sample at a later batch.

- Quality Control (QC) Tests: These tests are performed using Quality Control samples at specific intervals to examine a measurement procedure and verify that it is performing according to pre-established specifications. In the event of an unacceptable quality control result, corrective action is taken to fix the method problem, and all patient test results from the time of the previous acceptable quality control result are repeated.

- Quality Control Samples: These samples are intended to simulate patient samples in QC testing. The quality control samples are treated in the same manner as the patient test samples and their results are examined to determine that the measurement procedure meets performance requirements. Quality control sample kits are provided by external vendors. For qualitative assays, they include negative and positive controls.

  Each assay has its own specific type of reagent kit. Reagent kits are provided by vendors and they typically contain vials of liquid reagents specific to assay type. The analyzer has slots for a certain number of reagent kits to be loaded on it. In order to run a specific test on the analyzer, the test-specific reagent kit must be loaded in the instrument. For example, if the operator plans to test three different types of assays on the instrument in a run, there should be at least three different reagent kits loaded in the instrument, one for each type of assay.

  Each reagent pack includes vials of liquid reagents sufficient to run a certain number of tests. When a reagent pack in the analyzer depletes, the medical technologist replaces it with a new reagent regent pack to be able to continue testing. As discussed
earlier, the main goal of this thesis to reduce reagent consumption. Therefore getting the
most number of billable test results from a reagent pack is a target condition.

2.2 Data Collection Methods

The data collection methods used in this research can be classified under two categories,
(1) quantitative data collection methods and (2) qualitative data collection methods. The
quantitative methods include monthly test statistics, instrument error logs and maintenance
services reports collected from multiple sites. The qualitative data collection methods include
observing the operations during day and night shifts, speaking with shift supervisors, lab
managers and the instrument vendor representatives, and surveying medical technologists at
multiple sites.

2.2.1 Reagent Waste Survey

The survey included the following combination of open and closed ended questions:

1. Your site location?

2. How long have you been working on the target platform?

3. Which shift do you most often work at?

4. Which shift is generally used for maintenance of the target platform on your site?

5. How do you decide which instruments to load patient samples? Do you try to load each
   instrument equally? (Please explain briefly.)

7. Do you have the perception that some of the target instruments in your lab are more
   reliable (less prone to failures) than others?

8. What factors do you think contribute most to the reagent waste on the target platform?
   (NOTE: In the context of this survey, any usage of reagent that does not lead to patient
test results is regarded as "waste".)
9. What factors or events other than listed above do you think may be contributing to unnecessary reagent consumption? Please explain.

10. What recommendations would you have to minimize the reagent consumption on target instruments?

The results of this survey are used to determine the areas of focus on reagent waste mitigation. Many of the recommendations and process improvement ideas from the survey results are integrated in the One-point Lesson (OPL) documents discussed in Chapter 4.

2.2.2 Test Performance Statistics

As a part of the quantitative analysis, the monthly test performance results from seven different sites are collected and studied. The monthly test performance reports include the total number of tests successfully completed and failed for each type of assays on each instrument in a site. An example of monthly test performance statistics for an observed site is illustrated in Table 2-1.
### Table 2-1: Monthly aggregate test performance statistics from a site

In the context of this thesis, we define “assay” as a quantitative or qualitative test of a substance to determine its components. In other words, assays are tests to detect the presence or the concentration of infectious agents or antibodies in a patient sample. For example, Hepatitis A Antibody (IgM) and Hepatitis B Antibody (IgM) are two different assays to detect Hepatitis A and Hepatitis B infections respectively. However, Hepatitis assays are not among the assays studied in this thesis; they are just given as examples to readers in order to clarify what we refer to as assays.

In Table 2-1 above, failed tests refer to the tests that did not generate results due to mechanical or instrument errors, causing reagent waste. In addition to the aggregate statistics from a site, the instrument level monthly statistics are also collected and analyzed for each

<table>
<thead>
<tr>
<th>Assay Type #</th>
<th>Samples Tested</th>
<th>Failed Tests</th>
<th>Sample Failure Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assay Type #1</td>
<td>7,578</td>
<td>140</td>
<td>1.85%</td>
</tr>
<tr>
<td>Assay Type #2</td>
<td>19,061</td>
<td>316</td>
<td>1.66%</td>
</tr>
<tr>
<td>Assay Type #3</td>
<td>1,545</td>
<td>24</td>
<td>1.55%</td>
</tr>
<tr>
<td>Assay Type #4</td>
<td>1,347</td>
<td>16</td>
<td>1.19%</td>
</tr>
<tr>
<td>Assay Type #5</td>
<td>636</td>
<td>12</td>
<td>1.89%</td>
</tr>
<tr>
<td>Assay Type #6</td>
<td>2,438</td>
<td>30</td>
<td>1.23%</td>
</tr>
<tr>
<td>Assay Type #7</td>
<td>2,566</td>
<td>26</td>
<td>1.01%</td>
</tr>
<tr>
<td>Assay Type #8</td>
<td>4,209</td>
<td>103</td>
<td>2.45%</td>
</tr>
<tr>
<td>Assay Type #9</td>
<td>4,186</td>
<td>58</td>
<td>1.39%</td>
</tr>
<tr>
<td>Assay Type #10</td>
<td>6,868</td>
<td>107</td>
<td>1.56%</td>
</tr>
<tr>
<td>Assay Type #11</td>
<td>4,902</td>
<td>68</td>
<td>1.39%</td>
</tr>
<tr>
<td>Assay Type #12</td>
<td>4,799</td>
<td>70</td>
<td>1.46%</td>
</tr>
<tr>
<td>Assay Type #13</td>
<td>7,926</td>
<td>75</td>
<td>0.95%</td>
</tr>
<tr>
<td>Assay Type #14</td>
<td>420</td>
<td>8</td>
<td>1.90%</td>
</tr>
<tr>
<td>Assay Type #15</td>
<td>868</td>
<td>13</td>
<td>1.50%</td>
</tr>
<tr>
<td>Assay Type #16</td>
<td>770</td>
<td>17</td>
<td>2.21%</td>
</tr>
<tr>
<td>Assay Type #17</td>
<td>2,558</td>
<td>30</td>
<td>1.17%</td>
</tr>
<tr>
<td>Site Aggregate</td>
<td>72,677</td>
<td>1,113</td>
<td>1.53%</td>
</tr>
</tbody>
</table>
An instrument on the observed site. An example of monthly test performance statistics for an observed analyzer (instrument) is illustrated in Table 2-2

<table>
<thead>
<tr>
<th>Assay Type</th>
<th>Samples Tested</th>
<th>Failed Samples</th>
<th>Sample Failure Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assay Type #1</td>
<td>0</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Assay Type #2</td>
<td>495</td>
<td>19</td>
<td>3.84%</td>
</tr>
<tr>
<td>Assay Type #3</td>
<td>0</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Assay Type #4</td>
<td>0</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Assay Type #5</td>
<td>634</td>
<td>12</td>
<td>1.89%</td>
</tr>
<tr>
<td>Assay Type #6</td>
<td>2,436</td>
<td>30</td>
<td>1.23%</td>
</tr>
<tr>
<td>Assay Type #7</td>
<td>2,564</td>
<td>26</td>
<td>1.01%</td>
</tr>
<tr>
<td>Assay Type #8</td>
<td>4,203</td>
<td>103</td>
<td>2.45%</td>
</tr>
<tr>
<td>Assay Type #9</td>
<td>4,179</td>
<td>57</td>
<td>1.36%</td>
</tr>
<tr>
<td>Assay Type #10</td>
<td>0</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Assay Type #11</td>
<td>0</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Assay Type #12</td>
<td>0</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Assay Type #13</td>
<td>0</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Assay Type #14</td>
<td>0</td>
<td>0</td>
<td>NA</td>
</tr>
<tr>
<td>Assay Type #15</td>
<td>864</td>
<td>13</td>
<td>1.50%</td>
</tr>
<tr>
<td>Assay Type #16</td>
<td>768</td>
<td>17</td>
<td>2.21%</td>
</tr>
<tr>
<td>Assay Type #17</td>
<td>2,556</td>
<td>30</td>
<td>1.17%</td>
</tr>
<tr>
<td>Monthly Totals</td>
<td>18,699</td>
<td>307</td>
<td>1.642%</td>
</tr>
</tbody>
</table>

Table 2-2: Monthly test performance of an observed analyzer

As illustrated in Table 2-2 above, the “samples tested” column has value of zero for some types of assays. This simply means that the observed analyzer is not used for testing that type of assay during that observed month. In other words, other analyzers on site are used for the tests that are not performed by the observed analyzer. As discussed in further detail in Chapter 4, it is not efficient to have all analyzers on a site to test each type of assay. Such a scenario goes against the consolidation principle, and it causes more reagent waste due to increased number of quality control tests and calibrations required. It should be noted that some sites have more
analyzers than other sites due to the differences in the billable test volumes of each site. During
the data collection process, initially the monthly statistics for each analyzer on an observed site
are obtained and processed. Then the individual analyzer monthly statistics are aggregated to
obtain monthly aggregate site statistics.

In addition to the monthly test performance statistics, the instrument error logs and
maintenance services reports are analyzed as further discussed in Chapter 3. The outcomes of
the quantitative data analysis and the survey are discussed and summarized in the following.

2.3 Analysis Results and Identification of Key Drivers of Reagent Waste

The monthly test performance statistical analysis illustrated in Section 2.2.2 are
performed for 57 individual analyzers distributed over seven different sites. The monthly
aggregate site statistics are generated for each of the seven sites. The reagent waste survey is
performed in person with medical technologists on four visited sites. Furthermore, day and night
shift operations on these sites four sites are observed in person. The instrument error logs and
service maintenance reports from one site are analyzed. As a result of these analyses, the
following conclusions are reached.

1. The most significant source of reagent waste is the unoptimized distribution of assays
over instruments which results in larger number of quality control tests and calibrations on each
site. The mitigation of this issue is one of the main topics of this thesis, and it is explained in
further detail and addressed in Chapter 4 through workflow optimization.

2. There are discrepancies observed in the workload volume among analyzers on the
same site. This causes an unbalanced workload distribution with overloaded and underutilized
instruments. An example of an unbalanced monthly workload distribution across analyzers on an
observed site is illustrated in Figure 2-3. Even though this situation may not necessarily cause reagent waste in the short term, it is not a desired situation due to extended wear and tear on overloaded instruments. This elevated degradation can cause instruments errors and failures in the long term. Mitigating this issue is also addressed in Chapter 3 through preventive maintenance and in Chapter 4 through workload balancing.

![Total Tests per Instrument](image)

**Figure 2-3:** Monthly workload distribution over analyzers on an observed site

3. There are discrepancies observed in test performance rates among different sites. The average monthly test failure rate aggregated over seven sites is 1.58%. Certain sites have better test performance, i.e. lower sample failure rates, than other sites. When site operations are closely observed, we realize that the better performing sites have developed some better operational practices, particularly in reagent preparation and handling. These best practices are addressed in Chapter 4 through the generation of One-point Lesson (OPL) training documents and workflow standardization.

4. There are cases of excessive quality control testing by laboratory staff on certain sites which cause unnecessary reagent consumption. This issue occurs due to the different interpretations of the SOP documents by the local laboratory staff. The medical technologists are
exceeding the standard requirements, and performing quality control testing more frequently than the specified frequency. This can be regarded as a conservative approach in quality control by the operators, but is causing financial loss due to superfluous reagent use without meaningful gain in quality control. In other words, the excessive amount of quality control testing exceeding the standard requirements is not operationally justifiable which is discussed in further detail in Section 4.1.2. This issue is addressed in Chapter 4 through workflow optimization.

5. There is also reagent waste caused by excessive instrument calibrations in some sites. The consolidation through optimized workload distribution discussed in Chapter 4 addresses this issue partially. However the reagent consumption through instrument calibrations is significantly less than the reagent consumption through quality control testing. Instrument calibration tests for a specific assay are performed usually in every two to four week periods, whereas quality control testing for each assay is performed multiple times during a day. Therefore, more focus is given on reducing quality control testing rather than reducing calibrations in this study.

6. Instrument and component failures, that require vendor field engineer intervention, are observed between periodic maintenance windows, causing failed test batches and instrument downtimes. This issue is studied through analyzing maintenance service reports, and preventive maintenance recommendations are presented in Chapter 3.

7. Based on error logs analysis, reagent integrity issues are identified to be the most common errors that cause mechanical failures and failed tests. Reagent integrity issues are followed by patient sample integrity issues in terms of significance in instrument errors. The former are caused by improper preparation and handling of reagent kits. Debris accumulated on reagent septum and air bubbles in reagent tubes are typical examples of improper reagent
handling, and they cause pipetting operations fail. The best practices to tackle reagent integrity issues and other mechanical errors are address in One-point Lesson (OPL) documents described in Chapter 4.
Chapter 3

Preventive Maintenance Countermeasures

The purpose of this chapter is to present the analysis done on maintenance activities on the target analyzer platform, provide insights about the maintenance procedures and propose preventive maintenance recommendations to reduce instrument failures and downtime.

The findings in this chapter are mainly based on analysis of all maintenance activities performed by the Field Service Engineering (FSE) team on five analyzers located in the New England site for the time-period of 10 months from the beginning of January, 2017 to the beginning of November, 2017. In other words, all service records generated by field services engineers are analyzed and then classified by the type of maintenance service. The most frequently occurring fault descriptions and replaced parts are recorded and analyzed.

The information and insights presented in this chapter come from the following information sources:

1. Service report files stored in the laboratory
2. Conversations and observations with medical technologists and shift supervisors
3. Conversations and observations with field service engineers
4. Best practices documents for target assays

The next section summarizes the types of maintenance activities performed on the target platform and the schedule for each type of periodic maintenance services.

3.1 Types of Maintenance Services

This section summarizes the types of maintenance services performed by the vendor’s field service engineers (FSE) on the target instrument. The maintenance activities can be classified as (1) scheduled maintenance services (visits), (2) non-scheduled maintenance services
which usually require repairs and parts replacement); and (3) instrument installation, validation, and upgrade related services. The name for each service type is identified from the “Service Type” field on the service reports (worksheets) generated by the field service engineers.

3.1.1 Scheduled (Periodical) Maintenance Services

i. Monthly Preventive Maintenance (PM) Service (High Volume Inspection Visit)

These are monthly preventive maintenance procedures which are provided to high throughput (>500 results/day/analyzer) sites. The main purpose of this procedure is to perform cleaning procedures and inspect analyzer parts for potential hardware defects. The procedures in the monthly PM visit include lubrication, mechanical calibrations, checking washer components, checking tubings, replacing syringes (for analyzers with >1000 results/day throughput), going through instrument error logs and requalification testing.

The only mechanical part that is replaced regardless of its observed condition in monthly PM visits is the syringe component on analyzers that are classified in High Throughput Level-2 (>1000 results/day) category.

The monthly high-volume maintenance usually takes up to four hours if no unexpected issues are observed. When monthly inspection visit coincides with a 6-months or a 12-months preventive maintenance visit, it is performed as a part of the 6/12 months visit.

ii. 6-Months Preventive Maintenance (PM) Service

The 6-months preventive service is much more comprehensive than the monthly service and it can take eight hours or more to complete. The procedures in the 6-months PM service include system cleaning, lubrication, recalibrations, requalification tests, backup of system logs, maintenance of all main mechanical systems such as inner parts, washer modules, pumps, tubes, cabinet, reagent module, pipettors.
At each 6-months visit, the components included in the 6/12 Month PM Kit are replaced in the analyzer. These replaced parts include syringe, washer tubings, washer and reader needles.

iii. 12-Months Preventive Maintenance Service

The 12-months maintenance service includes all 6-months maintenance procedures and it additionally includes the maintenance of the incubator belt system. The exact list of replaced parts is not shared with the client. The replaced parts in the 6-months and 12-months maintenance services are indicated on service reports as 6/12 Month PM Kit.

Additionally the 3-way valve component is replaced at every 12-months on analyzers which are classified as High-Throughput Level-1 (>500 results/day) or above.

3.1.2 Non-scheduled Maintenance Services

Non-scheduled services are particularly important for the purpose of this study since they are performed due to unexpected issues which usually require repairs and part replacements. They may also cause reagent waste and unexpected downtimes.

i. Repair Service

Repair services are performed due to incidents reported by the medical technologists operating the analyzer. These incidents may include repeated Reagent Integrity Errors (RIE), Target Not Reached (TNR) Errors or any type of incident that disrupts analyzer operations or compromises test results. Repair services sometime include only maintenance of the failing parts but they may also require replacement of parts to return the analyzer back to its proper functioning state.

ii. Proactive Call Service

Proactive call services include unplanned maintenance services and repairs due to the incidents, which are not reported by the operators, but observed by the field service engineers.
during scheduled visits. The incidents that trigger proactive calls may include scenarios such as
the field engineer observing errors in the instrument logs, observing cracks on incubator belts, or
observing worn out washer pump shoes, etc.

iii. Repeated Intervention Service

The repeated intervention service includes maintenance services to fix issues that were
not fixed by previous repairs. The field service engineer comes back to fix an issue that was not
resolved by earlier attempts.

3.1.3 Instrument Installation and Upgrade Services

These are planned service visits that are usually part of the initial installation of analyzers
in the lab, and the validation of assays on analyzers, and the various hardware and software
upgrades on the analyzers. Since they are planned activities, they do not cause unplanned
downtime on the instruments. They are not part of preventive maintenance efforts and they are
not the focus of this report. The list of all service types is included in Table 3-1.

<table>
<thead>
<tr>
<th>No</th>
<th>Service Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Apps Assay Programming/Validation</td>
</tr>
<tr>
<td>2</td>
<td>Apps Customer Training - Initial</td>
</tr>
<tr>
<td>3</td>
<td>Apps Customer Support Follow Up</td>
</tr>
<tr>
<td>4</td>
<td>Apps Troubleshooting Reagent</td>
</tr>
<tr>
<td>5</td>
<td>Host Linking</td>
</tr>
<tr>
<td>6</td>
<td>HW Upgrade</td>
</tr>
<tr>
<td>7</td>
<td>Installation</td>
</tr>
<tr>
<td>8</td>
<td>LAS Pipettor Upgrade</td>
</tr>
<tr>
<td>9</td>
<td>Preventive Maintenance (6-Months)</td>
</tr>
<tr>
<td>10</td>
<td>Preventive Maintenance (12-Months)</td>
</tr>
<tr>
<td>11</td>
<td>Proactive Call</td>
</tr>
<tr>
<td>12</td>
<td>Repair</td>
</tr>
<tr>
<td>13</td>
<td>Repeated Intervention</td>
</tr>
<tr>
<td>14</td>
<td>Scheduled Visit (Monthly High Volume Inspection)</td>
</tr>
<tr>
<td>15</td>
<td>SW Upgrade</td>
</tr>
</tbody>
</table>

Table 3-1: List of all service types observed in the study
3.2 Current Preventive Maintenance Schedule

This section summarizes the preventive maintenance schedule in place. Two High Throughput Levels are defined based on the number of tests performed per day per analyzer. The preventive maintenance schedule for each level is described below.

3.2.1 Maintenance Schedule for High Throughput Level-1

High Throughput Level-1 maintenance schedule applies to instruments which generate between 500 and 1000 tests results per day. The schedule proposes an accelerated cycle of three preventive maintenance service visits per year performed by the field service engineer (FSE) with alternating 6-Months PM and 12-Months PM procedures every 4 months. In other words, this is an accelerated preventive maintenance schedule, where the 6-Months PM procedure is performed by the end of the 4th month of the one year cycle, the 12-Months PM procedure is performed by the end of the 8th month of the one year cycle, and another 6-Months PM procedure is performed by the end of the 12th month of the one year cycle as displayed in Table 3-2. Additionally the field service engineer performs monthly (high-volume) inspection visits. The Company X medical technologists perform “User Weekly Maintenance” each week and “User Monthly Maintenance” each month as usual.
Table 3-2: High Throughput Level-1 Maintenance Schedule

Basically the High-Throughput Level-1 imposes an accelerated maintenance schedule with three visits during a year with each visit 4 months apart. On a regular, non-accelerated schedule for instruments generating less than 500 test results per day, there are only two preventive maintenance visits per one year cycle, with a 6-Months PM procedure performed by the end of the 6th month of the one year cycle, and a 12-Months PM procedure performed by the end of the 12th month of the one year cycle.

### 3.2.2 Maintenance Schedule for High Throughput Level-2

High Throughput Level-2 maintenance schedule applies to instruments which generate more than 1000 test results per day. This schedule proposes a further accelerated timeline of four preventive maintenance service visits per year performed by field service engineer (FSE) with alternating 6-Months PM and 12-Months PM procedures every 3 months. Additionally the field service engineer performs monthly (high-volume) inspection visits. At High-Throughput Level-2, the operator maintenance schedule is also accelerated. The Company X medical technologists
perform the “User Weekly Maintenance” each day and the “User Monthly Maintenance” each week at this accelerated schedule.

As displayed in Table 3-3, the High Throughput Level-2 schedule proposes an accelerated cycle where the 6-Months PM procedure is performed by the end of the 3th month of the one year cycle, the 12-Months PM procedure is performed by the end of the 6th month of the one year cycle, and another 6-Months PM procedure is performed by the end of the 9th month of the one year cycle, and another 12-Months PM procedure is performed by the end of the 12th month of the one year cycle.

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Frequency</th>
<th>Daily</th>
<th>Weekly</th>
<th>Monthly</th>
<th>Every 3 months</th>
<th>Every 6 months</th>
<th>Every 9 months</th>
<th>Every 12 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator Weekly Maintenance</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operator Monthly Maintenance</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FSE Monthly Inspection Visit</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FSE 6-Months PM Procedure</td>
<td></td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FSE 12-Months PM Procedure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FSE 3-Way Valve Replacement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-3: High Throughput Level-2 Maintenance Schedule

3.3 Analysis of Service Reports

This section presents the analysis done on maintenance activities performed by vendor Field Service Engineering (FSE) team on five analyzers instruments located in New England site for the time-period of 10 months from the beginning of January, 2017 to the beginning of November, 2017.
3.3.1 The List of Replaced Parts

After each maintenance visit that includes instrument part replacement, the field engineer records the replaced part name and the part number under the “Used Material” section on the service report (worksheet). The list of all replaced parts observed in this study with their part numbers is included in Appendix A.

3.3.2 The Frequency of Different Maintenance Services

The occurrence of each type of maintenance service on each instrument is summarized in Table 3-4 below. Note that, in New England site, Analyzer #4 and Analyzer #5 were installed in January, 2017. The instruments Analyzer #1, Analyzer #2 and Analyzer #3 were installed prior to 2017. In this study, our focus is more on the “Repair” and “Proactive Call” types of maintenance services since they cause non-scheduled repairs and part replacements, and they may also cause reagent waste and unscheduled downtimes.

<table>
<thead>
<tr>
<th>Service Type</th>
<th>Instrument</th>
<th>Analyzer #1</th>
<th>Analyzer #2</th>
<th>Analyzer #3</th>
<th>Analyzer #4</th>
<th>Analyzer #5</th>
<th>Total</th>
<th>Service per Analyzer (Average for 10 months period)</th>
<th>Service per Analyzer (Average per Month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assay Programming/Validation</td>
<td>Analyzer #1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>11</td>
<td>2.2</td>
<td>0.22</td>
</tr>
<tr>
<td>Customer Training - Initial</td>
<td>Analyzer #2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>0.4</td>
<td>0.04</td>
</tr>
<tr>
<td>Customer Support Follow-Up</td>
<td>Analyzer #3</td>
<td>3</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>13</td>
<td>2.6</td>
<td>0.26</td>
</tr>
<tr>
<td>Apps Troubleshooting Reagent</td>
<td>Analyzer #4</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>0.4</td>
<td>0.04</td>
</tr>
<tr>
<td>Host Linking</td>
<td>Analyzer #5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0.6</td>
<td>0.06</td>
</tr>
<tr>
<td>HW Upgrade</td>
<td>Analyzer #1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Installation</td>
<td>Analyzer #2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>0.6</td>
<td>0.06</td>
</tr>
<tr>
<td>LAS Pipettor Upgrade</td>
<td>Analyzer #3</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>0.4</td>
<td>0.04</td>
</tr>
<tr>
<td>Preventive Maintenance</td>
<td>Analyzer #4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>11</td>
<td>2.2</td>
<td>0.22</td>
</tr>
<tr>
<td>Proactive Call Service</td>
<td>Analyzer #5</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>4</td>
<td>19</td>
<td>3.8</td>
<td>0.38</td>
</tr>
<tr>
<td>Repair Service</td>
<td>Analyzer #1</td>
<td>9</td>
<td>6</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>19</td>
<td>6.6</td>
<td>0.66</td>
</tr>
<tr>
<td>Repeated Intervention</td>
<td>Analyzer #2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>0.6</td>
<td>0.06</td>
</tr>
<tr>
<td>SW Upgrade</td>
<td>Analyzer #3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 3-4: Summary of service types performed per instrument

Repair Service and Proactive Call Service are unscheduled services that we target to minimize. Our study shows that a total of 33 Repair visits and 19 Proactive Call services are performed in New England site for the first 10 months of 2017. This translates into each
instrument having 0.66 Repairs services and 0.38 Proactive Call services on average per month performed on it. That means an average a total of 1.04 (=0.66+0.38) repairs per instrument per month. These services are in addition to the monthly scheduled visits on each instrument.

Our target is to particularly reduce the number incidents that trigger repair services, which cause instrument downtimes and reagent usage, through preventive maintenance measures.

### 3.3.3 Analysis of Most Frequently Replaced Parts

Table 3-5 below summarizes the most frequently replaced parts and their replacement frequencies. Note that there are two entries for the syringe component. The syringe component is replaced in scheduled monthly inspection visits and also in scheduled 6/12-Months PM visits regardless of its observed condition. These replacements are represented on the first row of the table. However, the syringe component also fails, and thus is replaced between scheduled PM activities. The failure of syringe component causes pipetting errors.

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Analyzer #1</th>
<th>Analyzer #2</th>
<th>Analyzer #3</th>
<th>Analyzer #4</th>
<th>Analyzer #5</th>
<th>Total</th>
<th>Replacements per Instrument (10 months period)</th>
<th>Replacements per Instrument (Average per Month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Syringe (Scheduled Replacements)</td>
<td>6</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>24</td>
<td>4.8</td>
<td>0.48</td>
</tr>
<tr>
<td>3-Way Valve</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>15</td>
<td>3</td>
<td>0.3</td>
</tr>
<tr>
<td>Washer Aspiration Pressure Shoe</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>12</td>
<td>2.4</td>
<td>0.24</td>
</tr>
<tr>
<td>Washer Aspiration Tube Type-1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>12</td>
<td>2.4</td>
<td>0.24</td>
</tr>
<tr>
<td>Syringe (Non-Scheduled Replacements)</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>10</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>Washer Probe Rinsing Pressure Shoe</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>10</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>Sample Pipettor</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>8</td>
<td>1.6</td>
<td>0.16</td>
</tr>
<tr>
<td>Left Pipettor Sliding Plate</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>1.2</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>Incubator Belt &amp; Pulleys Repair Set</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>1.2</td>
<td>0.12</td>
</tr>
<tr>
<td>Tubbing Debubbler and Filter</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Pusher Door Set Washer-Incubator</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Left Pipettor Bearing</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Reagent Probe</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>0.8</td>
<td>0.08</td>
</tr>
<tr>
<td>New Filter System Liquid</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>0.8</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Probe Rinsing Pump</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>0.8</td>
<td>0.08</td>
</tr>
<tr>
<td>Photomultiplier Distance Ring</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>0.8</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Washer Aspiration Pump</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>0.4</td>
<td>0.04</td>
</tr>
<tr>
<td>Pusher Door Set Incubator-Washer</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>0.4</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table 3-5: Statistical summary of part replacements
As illustrated in the Table 3-6, the most frequently replaced parts (following the scheduled syringe replacements) are the 3-way valve, the pressure shoes of washer aspiration pump (WAP), the Alitea tube of washer aspiration pump (WAP), and the pressure shoes of wash probe rinsing pump (WPRP). The five most frequently replaced parts are denoted by red bars in Figure 3-1 below.

![Frequency Chart of Part Replacements](image)

**Figure 3-1:** Frequency Chart of Part Replacements
3.4 Conclusions and Recommendations

3.4.1 Recommendations for Preventive Maintenance Schedule

The reagent syringe is one of the most failure-prone components, and therefore it is replaced at every monthly (high-volume) inspection visit regardless of its observed condition. This is a helpful practice to prevent unexpected failures and unscheduled downtimes. It is observed that the syringe component still frequently fails between scheduled visits, which further justify its periodic replacement.

Based on the analysis of other most frequently failing parts, it may be useful to consider the periodic replacements for the following parts besides the syringe.

- **3-Way Valve**
  This component is replaced once a year on high throughput level analyzers regardless of its condition at the scheduled maintenance visit. However our analysis shows that the average monthly replacement frequency of this component is about 0.3 replacements per instrument per month. Therefore almost every 3.3 months, the component is replaced due to a Repair or Proactive Call type service.

- **Washer Aspiration Tube**
  Our analysis shows that the average monthly replacement frequency of this component is 0.24 replacements per instrument per month. Therefore almost every 4 months, the component is replaced due to a Repair or Proactive Call type of service.

- **Washer Aspiration Pump and Washer Probe Rinsing Pump Pressure Shoes**
  Worn pressure shoes cause leakages in pump modules. Our analysis shows that the average monthly replacement frequency of washer aspiration pump (WAP) pressure shoes is 0.24 replacements per instrument per month and washer probe rinsing pump (WPRP) pressure
The combined replacement frequency for pressure shoes (WAP and WPRP) are about 0.44 replacements per instrument per month.

It is recommended to consider replacing these parts at every two months or at every three months intervals during high volume inspection visits regardless of their observed conditions to prevent failures between scheduled PM visits. This proposed proactive replacement cycle will match the unscheduled repair and replacement cycle of these frequently failing parts, and mitigate the risk of the disruptions in operations due to part failures. Besides these parts, it is observed that “Sample Pipettor“ was replaced due to a repair or a proactive call at least once in each instrument during the study period. Therefore that part can also be included in a periodic replacement schedule regardless of its observed conditions.

3.4.2 Recommendations for Operators and Lab Managers

The following enhancements can be considered for improved operational efficiency.

- **Electronic Record Keeping of Service Reports**

  Currently the service reports generated by vendor field engineers are stored in physical folders in each lab. In addition to physical records, these reports can be stored in an electronic database for a more efficient tracking and identification functionality. The Company X organization is currently transitioning to an electronic Asset Management system that will track the replacements of failing components, instrument downtimes and the most frequently occurring fault descriptions more efficiently through the current physical records.

- **Visual Inspection and Replacement of Basic Parts by Medical Technologists**

  The medical technologists who receive advanced training on the target analyzer platform are enabled and authorized to do simple hardware fixes such as removing cuvette jams (which may fix TNR errors) and manually checking and tightening the syringe component (which may
Having more medical technologists receive the advanced training will improve turn-around times for fixing minor physical issues.

The 6-months and 12-months preventive maintenance visits are complex procedures that require the services of dedicated field engineers. The medical technologists can be trained on visual inspection checks that are parts of monthly (high-volume) inspection visits. This can enable the detection of potential issues between monthly inspection visits and also enable the triggering of proactive calls, not only by field engineers, but also by the medical technologists.

- **Capability of Instrument Logs Analysis**

  The Company X organization has access to instrument logs of all analyzers in its labs, however it does not currently possess the tools to effectively analyze these log files and identify the exact distribution of errors occurring. Having access to such tools through the Asset Management software and collaboration with vendor on this topic will provide the Company X organization better visibility into its operations.
Chapter 4

Workflow Optimization

This chapter discusses methods to achieve an optimized workflow that meets financial goals of the Company X organization and the clinical needs at the same time. In other words, the goal of workflow optimization is to achieve the highest quality at low costs. As discussed in Chapter 1, the clinical quality standards are defined in Standard Operating Procedure (SOP) documents authored by Company X Best Practice Team (BPT) and adhere to all relevant regulatory requirements.

The workflow optimization model and tools developed in this research employ two interrelated key strategies:

1. Standardization
2. Consolidation

The subsections of this chapter explain each strategy and how they can be implemented. We use the terminology of “Billable Tests”, “Failed Tests”, “Quality Control Tests”, “Quality Control Samples” and “Repeat Tests” defined in Chapter 2 throughout this chapter.

4.1 Standardization of Processes

The standardization strategy targets employing standardized methods and equipment as described in the following documents:

- Company X Standard Operating Procedure (SOP) documents
- Vendor approved Analyzer User Guides, and Instructions for Use (IFU) documents
- Vendor approved Best Practices documents

Exceeding the performance requirements defined in these documents often lead to superfluous reagent and lab material usage which will be further discussed in Section 4.1.2. In
addition to the procedures defined in these documents, local laboratory teams often create best
practices that optimize the workflow and improve efficiency. However these locally developed
best practices are not always shared across all sites effectively. This section also addresses
effective transfer of these locally developed best practices through trainings and documentation.

The main areas where standardization strategy can be applied to improve consumption
reduction included in this thesis are:

- Standardization of instrument maintenance
- Standardization of reagent preparation and specimen preparation
- Standardization of Quality Control testing

4.1.1 Reducing Mechanical Errors through Standardization

As discussed in Chapter 2, tests repeated due to mechanical errors constitute a
significant source of reagent waste. As discussed in Chapter 3, employing preventive
maintenance measures help reduce mechanical errors and minimize instrument downtimes. In
addition to preventive maintenance measures, a series of training documents called One-Point
Lessons (OPLs) are developed to capture and distribute best practices related to instrument
operations, troubleshooting, and maintenance.

One-Point Lessons are concise training documents that share basic knowledge,
improvement ideas and troubleshooting tips. The lessons are further classified in terms of
enhancing (1) safety, (2) quality, (3) productivity, (4) cost, and (5) delivery. An example of an
OPL is shown in Figure 4-1.
Figure 4-1: Example One-Point Lesson

This OPL document demonstrates proper methods to clean the debris inside reagent septum in order to avoid leaving fiber particles behind which can cause pipetting errors.

One-Point Lessons are created based on laboratory staff's input and instrument vendor documentation. Creation of One-Point Lessons should be viewed as a continuous improvement process conducted by laboratory operations personnel. The Best Practices Teams should encourage medical technologists who operate the target platform, and the shift managers to create new OPLs, and also update the existing OPLs if need be.

In order to fully realize potential benefits from this knowledge creation process, OPLs should be integrated in the online learning platform of the organization. The medical technologists operating the target platform should be required to review the material as a part of their training. In an ideal situation, operators should also take an online multiple-choice test to verify that they grasped the information captured in the OPLs. This program will enable the nationwide circulation of the best practices developed by local teams. The key to the success of
this program is standardization of knowledge creation in the OPL format and the empowerment of frontline employees in the process.

4.1.2 Reducing Superfluous Quality Control Testing

As discussed earlier in this chapter, another source of reagent waste is the superfluous amount of quality control testing that exceeds quality control frequency requirements defined in SOPs and regulatory requirements. This non-standardized superfluous quality control testing causes financial burden, loss of productivity; and it does not bring meaning improvement in quality assurance which will be further discussed in this section.

In qualitative laboratory testing, quality control material includes two levels: the negative and positive controls, which are provided within the manufacturer’s kit [1]. For some assays, an additional low positive control sample is used.

The general quality control testing flow is as follows. (The numbers used in the described flow are hypothetical due to confidentiality requirements, and they are simplified for illustrative purposes.)

1. The positive and negative control samples are run at the beginning of each shift to ensure the instrument produces the expected results.

2. The patient samples ("billable tests") are run after the initial quality control testing.

3. At intervals of every 100 patient tests, the positive and negative control samples are run alternatively to verify that the test process is being performed correctly. At this point, if any of the quality control tests produces an unacceptable quality control result, corrective action is taken to fix the problem. All patient tests from the time of the previous acceptable quality control results are repeated. This alternation scheme between the positive and the negative control
samples may not be applicable to all assays in diagnostics testing, but it is applicable to the assays in the scope of this study.

4. Each shift is closed with running the positive and negative control samples.

The flow of statistical quality control is illustrated in Figure 4-2.

![Figure 4-2: Quality Control Testing Process Flow](image)

The general acceptance criteria for Quality Control testing are that the produced QC results are within ±2 Standard Deviation (SD) of the accepted mean value established by historical results. Standard industry practice sets the ±2 SD tolerance window according to the Westgard rules [2]. If these conditions are satisfied, the run is considered to be ‘in control’, and the medical technologists may report patient results. Each time the control test results fall out of the acceptance criteria specified, the run is considered to be ‘out of control’ (failed) and patient results must not be reported.
The selection of QC testing frequency for each assay is determined by Best Practices Teams in SOPs, and it is a function of several factors, including analytical stability of measurement procedure, and the risk of harm to a patient from clinical action being taken before a significant error is detected [3]. The determination of the optimum QC frequency is beyond of the scope of this study.

During the research project that led to this thesis, it is observed that medical technologists in different national laboratories are performing quality control testing more frequently than the specified frequency.

One particular case observed is the operator performing QC test at the end of a batch of 100 patient tests, and then repeating the QC at the beginning of the next batch of 100 patient tests within the same shift. This practice causes QC testing to be performed at a frequency that is doubled value of the required frequency.

Another case observed is that medical technologists running both negative control and positive control samples after every 100 patient tests, whereas the SOP recommends running negative controls and positive controls alternately after every 100 patient tests.

These practices, that exceed the SOP requirements, are often times employed due to their convenience and practicality. For instance, testing both negative control and positive controls at every 100 patient tests interval relieves the operator from tracking whether the negative or positive control test is run at the previous QC test. Similarly, testing QC both at the beginning and at the end of consecutive batches makes it easier for the operator to ensure that QC control test is not missed.

These practices certainly do not degrade the quality assurance; however they cause unnecessary usage of reagents, quality control material waste, and laboratory materials waste due
to superfluous quality control testing. It is critically important for the medical technologists to follow the requirements in the latest version of SOP documents. It is also recommended that shift supervisors track the QC testing statistics from the Laboratory Information System (LIS) and detect potential cases where superfluous amount of Quality Control testing is performed for an assay.

In addition to superfluous quality control testing, there is reagent waste due to unoptimized distribution of assays to the instruments in a lab, which is discussed in Section 4.2.

### 4.2 Consolidation Strategy

Consolidation is a strategy that targets reducing operating costs per billable test. Testing can be consolidated from multiple sites to a single site; or from multiple analyzers in a single facility to a single analyzer within the same facility. This thesis focuses on consolidating tests on analyzers within a single laboratory. Company X business model heavily utilizes consolidation strategy by collecting patient samples and processing them in a centralized regional laboratory instead of branch offices. Our research does not address consolidating tests across multiple sites using a transportation network.

Consolidation creates larger test batches and larger runs which improves testing efficiency by distributing quality control and calibration costs over more patient tests. Consequently, the cost per billable patient test is reduced.

However there are many parameters that need to be factored in to create an optimum consolidation strategy. The target analyzer platform is used to test seventeen different assays when this research is conducted. However our model is flexible to accommodate different number of assays. The daily billable test volumes vary among assays. There are multiple units of
the target analyzer platform in each facility. Each instance of target analyzer platform has a
certain daily capacity, and it is not possible to consolidate all tests in one single analyzer.

Furthermore, laboratory management targets to sustain load balancing across analyzers to
prevent overloaded and under loaded analyzers. All these factors create constraints that make the
consolidation strategy not a trivial task. The following sections in this chapter define how all
these parameters can be used to build a mathematical model to achieve an optimal workload
distribution of different assays over multiple analyzers in a single site.

4.2.1 Optimal Load Distribution as an Analytical Model

This section describes the construction of an analytical model that targets to minimize
quality control testing and instrument calibrations by optimizing the load distribution over
instruments in laboratory sites. This optimal distribution of assays and billable test volumes to
instruments on sites is modeled as a linear programming (LP) problem with instrument capacity,
merge rules and load balancing as linear constraints.

Linear Programming (LP) is a special case of mathematical programming (mathematical
optimization). It is a technique for the optimization of a linear objective function (such as lowest
cost or maximum profit), subject to linear equality and linear inequality constraints.

Linear programming is a widely used field of optimization for several reasons. Many
practical problems in operations research can be expressed as linear programming problems. A
linear program can be formulated in the standard form as below [4].

\[
\begin{align*}
\text{minimize} & \quad cx \\
\text{subject to} & \quad Ax = b \\
& \quad x \geq 0 \\
\end{align*}
\]

where
x: the vector of variables to be solved for (also called decision variables)

A: a matrix of known coefficients
c and b: vectors of known coefficients

The expression "cx" is called the objective function, and the equations "Ax=b" are called the constraints [4].

The model presented in this thesis is developed using an objective function and linear constraints derived from a specific high volume diagnostics platform. However, this model can be applied to load distribution problems of other high volume diagnostics platforms used in healthcare testing by modifying the constraints and objective function using platform specific parameters. Furthermore, this model can be generalized to apply to other industries with similar characteristics. Thus it is useful to a broad academic and industrial community.

4.2.1.1 Verbal Problem Statement

This section provides a verbal statement of the optimization problem before the mathematical formulation of the problem in the next section. The process is described in bullet points.

- The target platform is capable of testing certain number of different types of assays. A certain amount of reagent material is used for every test executed. Reagent material usage is a significant cost item which we try to minimize in this study.

- After testing every 100 patient samples, a Quality Control (QC) test are performed. The positive and negative control samples are run alternatively after every 100 patient tests. QC testing is similar to patient testing except the fact that the QC test is performed on a QC sample (with a known positive or negative) value, instead of on a real patient sample.
• If QC test result is correct (consistent with the expected result), then another 100 patient samples are tested until the next QC test. If the QC test result is wrong, corrective action is taken and the last 100 patient tests are repeated.

• QC testing is a required procedure for the validity of real patient test results. However excessive QC testing (i.e. QC done more frequently than every 100 patient tests) results in unnecessary use of reagents.

• Each site has a certain number of instruments (e.g. 3, 5, 8, etc.) and different weekly volumes of incoming “billable” patient tests.

Objective:

Distribute the total number of billable tests to multiple instruments on the site in a way that minimizes the total number of QC tests that needs to be done daily. This optimal solution is bound by some constraints.

Constraint-1: Instrument Daily Capacity Constraint

The number of tests run on one instrument per days should not exceed a certain threshold, such as 1000 tests per instrument per day.

Constraint-2: Total Daily Volume Constraint

The sum of all billable tests performed over all instruments on the site should equal to sum of all billable tests ordered for the site.

Constraint-3: Load Balancing Constraint

The test volumes on each instrument should be balanced. In other words, there should not be significant differences in daily test volumes between instruments. Acceptable volume difference among instruments should be set by the lab manager.
For instance, it may not be acceptable to have one instrument performing 900 tests daily whereas another instrument in the same lab is doing only 600 tests daily. However, it may be acceptable to have one instrument performing 780 tests and other instrument 720 tests daily. Both scenarios result in the same total number of tests (1500 tests) daily with different load balancing configuration. A 780/720 allocation is preferable to a 900/600 allocation because it is a more evenly balanced load distribution. A balanced workload reduces the risks of having wear and tear, and deterioration on overloaded instruments over time.

**Constraint-4: Merge Rules**

It is recommended that certain assays are combined into a single aliquot and hence tested on the same instrument to reduce labor, lab material, QC testing and disposal costs. For instance, certain assays that are often ordered together are good candidates to be addressed by merge rules.

### 4.2.1.2 Mathematical Problem Statement

In this section, we implement the problem in a mathematical form and apply the linear programming.

**OBJECTIVE FUNCTION:**

\[
\text{Minimize } \sum_{j=1}^{n} \sum_{i=1}^{17} Q_{ij}
\]

where

i: Assay type
j: Instrument number
n: Total number of instruments on the site
Qij: Number of QC tests done daily for assay i on instrument j

\[Q_{ij} = 2 \text{ tests ("shift start QC") + 2 tests ("shift end QC") + [Vij*QC_Frequency]} -1 \text{ for } V_{ij} \neq 0\]
Vij: Number of tests performed daily for assay i on instrument j

[ ]: Denotes ceiling function

We use the ceiling function and the “-1” term in the Qij equation to obtain the accurate QC test count required as illustrated in the numeric example below.

**DECISION VARIABLES:**

**Vij:** Number of tests performed daily for assay i on instrument j

where \( i = 1 \) to 17 and \( j = 1 \) to \( n \)

**Illustrative Example:**

Given QC_Frequency = 0.01 (i.e. executing a QC test after every 100 patient tests)

- **For \( Vij = 185 \)**
  \[
  Qij = 2 + 2 + \left\lceil 185 \times 0.01 \right\rceil - 1 = 4 + \left\lceil 1.85 \right\rceil - 1 = 4 + 2 - 1 = 5
  \]
  That is to start the shift with 2 QC tests, then perform 100 patient tests, then perform 1 QC test, and then perform the remaining 85 patient tests, and then end the shift with 2 QC tests. This flow sums up to a total of 5 QC tests executed to perform 185 patient tests during a daily shift.

- **For \( Vij = 200 \)**
  \[
  Qij = 2 + 2 + \left\lceil 200 \times 0.01 \right\rceil - 1 = 4 + \left\lceil 2 \right\rceil - 1 = 4 + 2 - 1 = 5
  \]
  That is to start the shift with 2 QC tests, then perform 100 patient tests, then perform 1 QC test, and then perform the remaining 100 patient tests, and then end the shift with 2 QC tests. This flow sums up to a total of 5 QC tests executed to perform 200 patient tests during a daily shift.

- **For \( Vij = 215 \)**
  \[
  Qij = 2 + 2 + \left\lceil 215 \times 0.01 \right\rceil - 1 = 4 + \left\lceil 2.15 \right\rceil - 1 = 4 + 3 - 1 = 6
  \]
  That is to start the shift with 2 QC tests, then perform 100 patient tests, then perform 1 QC test, and then perform another 100 patient tests, and then perform 1 QC test, and then perform the remaining 15 patient tests, and end the shift with 2 QC tests. This flow sums up to a total of 6 QC tests executed to perform 215 patient tests during a daily shift.
CONSTRAINTS:

Constraint-1: Instrument Daily Capacity

For j = 1 to n

\[ \sum_{i=1}^{17} Vij < \text{Daily Instrument Capacity (e.g. 1000 tests/day)} \]

j: Instrument number

i: Assay type

Constraint-2: Total Daily Volume Constraint

For i = 1 to 17:

\[ \sum_{j=1}^{n} Vij = Vi \]

j : Instrument number

i: Assay type

Vi: Total billable daily test volume for assay type i

In other words, the sum of tests of assay i over all instruments should equal to total daily volume of tests for assay i.

Constraint-3: Load Balancing Constraint

For j = 1 to n:

| Xj − Xk | ≤ B  for k ≠ j

B: Load balancing upper limit set by the user

Xj = Total number of daily tests done on instrument j

\[ Xj = \sum_{i=1}^{17} Vij \]

Alternative notation:

| Xj − Xk | ≤ B  ↔  -B ≤ Xj − Xk ≤ B
**Example:** For B = 150 tests and for j = 3 (i.e. 3 instruments on site)

\[
\begin{align*}
|X_1 - X_2| & \leq 150 \iff -150 \leq X_1 - X_2 \leq 150 \\
|X_2 - X_3| & \leq 150 \iff -150 \leq X_2 - X_3 \leq 150 \\
|X_1 - X_3| & \leq 150 \iff -150 \leq X_3 - X_1 \leq 150
\end{align*}
\]

**Constraint-4: Merge Rules**

Certain assays are grouped to be tested on the same instruments to reduce lab material waste.

**Example:** Assay-1 and Assay-2 assays grouped together.

Call Assay-1 Type: \( g \) and Assay-2 Type: \( h \)

Then for \( j = 1 \) to \( n \):

\[ X_{gj} \neq 0 \text{ for } X_{hj} \neq 0 \]

Note that this model assumes instruments are identical in terms of performance for each assay. In other words, this model does not consider the possibility that some instruments perform better than others for certain assays in test error performance. A model that assumes some instruments perform better than other others for certain assays may be a part of future work.

**4.2.1.3 The Software Tool Development**

The linear optimization model described in this thesis is implemented in a software program using Python programming language. The developed Python program “Load Distributer Tool” solves the modeled LP problem using site specific inputs from the users; and proposes a feasible optimal solution.

The software program uses the following publicly available Python libraries: NumPy (a scientific computing package for Python) and PuLP (a linear programming modeler package for Python). Documentation to apply these tools are created and shared with process owners at Company X.
The purpose of the Load Distributor Tool is to propose an optimal distribution of assays and tests to analyzers on a site to meet the following goals:

- Achieve balanced load distribution among instruments on a site
- Reduce the number of quality control tests
- Not to exceed maximum capacity constraints on instruments
- Satisfy the assay merge rules

Merge rules target to reduce labor, supply, QC and disposal costs by grouping assays that require similar procedures, such as specific cleaning procedures after the tests are performed.

The user inputs of the program are:

- The number of analyzers on the site
- The maximum daily test capacity on instruments
- The load balancing upper bound
- The daily volume of billable tests for each assay type

The source code of the software tool is not included in this thesis due to intellectual property requirements.
4.2.2 Case Studies

This section aims to illustrate how the mathematical model described in this chapter can be used, by presenting a case where the optimal load distribution is applied to a laboratory site that has a certain number of instruments, and a certain incoming billable test volume profile. The savings in quality control testing to achieve the same outcomes are calculated and presented.

As discussed in Chapter 1, the assays names are disguised with generic names such as “assay #1”, “assay #2”, etc. The numbers presented are simplified hypothetical values due to the confidentiality requirements.

4.2.2.1 Illustrative Case

In this section, we apply the model to a certain site and compare the numbers for the current state scenario under the unoptimized configuration and the proposed state under the optimized configuration. We quantify the potential reduction in QC count.

In this case, the observed site has five analyzers and these analyzers are capable of testing seventeen different assays. The numbers used in the case are simplified for illustrative purposes.

The current state under unoptimized configuration:

The Table 4-1 illustrates the distribution of the billable tests over the instruments under unoptimized configuration, where the total number of billable tests is 3986 for one day time period.
Table 4-1: Distribution of billable tests on instruments for one day period under unoptimized configuration

These tests are distributed across five instruments in a configuration where instrument #1 is performing 712 tests whereas instrument #4 is performing 926 tests. Therefore there is a significant unbalance of workload between two instruments. The instrument #4 is performing 30.06% more test load than instrument #1.

The following Table 4-2 displays how many QC tests should be done on each instrument to accommodate the distribution of tests given in Table 4-1.

<table>
<thead>
<tr>
<th>Assay # / Instrument #</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>Assay Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assay #1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Assay #2</td>
<td>0</td>
<td>175</td>
<td>140</td>
<td>118</td>
<td>39</td>
<td>472</td>
</tr>
<tr>
<td>Assay #3</td>
<td>0</td>
<td>159</td>
<td>131</td>
<td>113</td>
<td>36</td>
<td>439</td>
</tr>
<tr>
<td>Assay #4</td>
<td>367</td>
<td>163</td>
<td>10</td>
<td>0</td>
<td></td>
<td>842</td>
</tr>
<tr>
<td>Assay #5</td>
<td>0</td>
<td>0</td>
<td>116</td>
<td>77</td>
<td>345</td>
<td>538</td>
</tr>
<tr>
<td>Assay #6</td>
<td>0</td>
<td>116</td>
<td>167</td>
<td>195</td>
<td>49</td>
<td>527</td>
</tr>
<tr>
<td>Assay #7</td>
<td>0</td>
<td>131</td>
<td>188</td>
<td>217</td>
<td>55</td>
<td>591</td>
</tr>
<tr>
<td>Assay #8</td>
<td>112</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>112</td>
</tr>
<tr>
<td>Assay #9</td>
<td>113</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>113</td>
</tr>
<tr>
<td>Assay #10</td>
<td>96</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>96</td>
</tr>
<tr>
<td>Assay #11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>41</td>
<td>0</td>
<td>41</td>
</tr>
<tr>
<td>Assay #12</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>25</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>Assay #13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Assay #14</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>77</td>
<td>0</td>
<td>77</td>
</tr>
<tr>
<td>Assay #15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>63</td>
<td>0</td>
<td>63</td>
</tr>
<tr>
<td>Assay #16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Assay #17</td>
<td>24</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>Analyzer Total</td>
<td>712</td>
<td>744</td>
<td>752</td>
<td>926</td>
<td>852</td>
<td>3986</td>
</tr>
</tbody>
</table>
Table 4-2: The resulting QC tests performed under unoptimized configuration

In addition to the unbalanced workload distribution, the total number of QC tests that need to be done under this configuration is relatively high at 154 as illustrated in Figure 4-4 due to the lack of consolidation.

**The proposed state under optimized configuration:**

As a next step, we enter the number of total billable tests for each assay in our mathematical optimization model with number of instruments, \( n = 5 \). We use instrument daily capacity value of 800, which means no instrument will be performing more than 800 tests per day. Under these conditions, the achieved optimized workload distribution is illustrated in Table 4-3 which displays the total number of billable test equal to 3986. Therefore the optimized model achieves the same number of billable tests as in the unoptimized configuration illustrated in Table 4-1 with a balanced workload distribution.
As illustrated in Table 4-3 above, maximum number of tests performed per instrument is 798 and the minimum number of tests performed per instrument is 797, achieving almost even load balancing among five instruments. This optimized allocation is desirable over the unoptimized allocation since no instrument is overloaded in the optimized configuration. Also, due to the consolidation tending nature of the optimization algorithm, we observe Instrument 1 performing many of the assays with the small billable test volumes.

The resulting QC tests numbers per instrument under the optimized configuration is illustrated in Table 4-4 below.
<table>
<thead>
<tr>
<th>Assay # / Instrument #</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>Assay QC Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assay #1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>Assay #2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>6</td>
<td>11</td>
</tr>
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<td>Assay #3</td>
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<td>6</td>
<td>11</td>
</tr>
<tr>
<td>Assay #4</td>
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<td>6</td>
<td>19</td>
</tr>
<tr>
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<td>0</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>Assay #6</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>5</td>
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<td>12</td>
</tr>
<tr>
<td>Assay #7</td>
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<td>8</td>
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<td>5</td>
<td>0</td>
<td>13</td>
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<td>5</td>
<td>0</td>
<td>5</td>
</tr>
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<td>5</td>
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<td>4</td>
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<tr>
<td>Assay #11</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Assay #12</td>
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<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>Assay #13</td>
<td>4</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Assay #14</td>
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</tr>
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<td>Assay #15</td>
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<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Assay #16</td>
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<td>0</td>
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<td>4</td>
</tr>
<tr>
<td>Analyzer QC Total</td>
<td>40</td>
<td>15</td>
<td>15</td>
<td>25</td>
<td>18</td>
<td>113</td>
</tr>
</tbody>
</table>

Table 4-4: The resulting QC tests performed under optimized configuration

As illustrated in Figure 4-4 above, the total number of QC tests performed under the optimized configuration is equal to 113. In other words, the optimized configuration reduces the QC test count from 154 to 113 achieving the same amount of billable tests. This translates into a reduction of QC testing by 26.6% compared to the unoptimized configuration. This reduction is achieved through consolidation.

As illustrated in this case, our workload optimization model achieves two desirable outcomes (1) savings in reagent consumption by reducing the Quality Control testing and (2) load balancing among instruments preventing overloaded and under-loaded instruments.
Chapter 5

Conclusions and Recommendations

This concluding chapter reviews the main findings of the research, the recommendations and suggested areas of future investigation.

5.1 Summary of Findings

The project that led to this thesis aims to reduce reagent usage on a specific high volume diagnostics platform deployed at Company X laboratories nationwide. In order to identify the sources of reagent waste, both quantitative and qualitative data collection methods are employed. The daily operations in four different regional laboratories are observed. Medical technologists, shift supervisors and laboratory managers are surveyed and interviewed. Monthly test statistics are collected from seven different sites. Instrument error logs and service reports from the New England site are collected and analyzed to identify most frequent errors and part replacements.

The analysis leads to the following main areas for improvement:

- Discrepancies in test success and failure performance among instruments, and among sites.
- Uneven workload distribution among instruments resulting over-loaded and under-loaded instruments
- Reagent waste due to frequent quality control (QC) testing and calibrations which can be eliminated through optimized distribution of assays to instruments
- Instrument and component failures between periodic maintenance windows
5.2 Recommendations

In order to mitigate the issues in the section above, the following strategies are developed:

- Optimized load distribution model in accordance with instrument capacity, load balancing constraints and merge rules
- Effective transfer of learnings and best practices developed across the sites nationwide
- Enhanced preventive maintenance recommendations in order to reduce instrument failures and downtimes

5.2.1 Operational Recommendations

1. One-Point Lessons (OPLs) described in Chapter 4 should be shared across all sites. They should ideally be incorporated into Company X’s internal online learning platform, and operators who are assigned to operate the platform should take online tests to validate their knowledge on these best practices. The generation of more OPLs by operators should be encouraged and overseen by the Best Practices Team (BPT).

2. The preventive maintenance recommendations described in Chapter 3 should be reviewed with the instrument vendor. The feasibility and costs of the proposed changes should be discussed, and the necessary changes should be selected and implemented in preventive maintenance schedule based on these discussions.

3. The optimized workload distribution model presented in Chapter 4 should be applied to all sites through the software tool developed in order to minimize QC testing and instrument calibrations on each site. The merge rules should be integrated into the operations of specimen management teams on different sites.
5.2.2 Technological Integration Recommendations

During the data collection phase of this study, several technical difficulties faced by laboratory staff are observed, and recorded. Resolving these technical difficulties through technology integration would provide Company X organization better and faster visibility into its operations. These technical integration improvement areas are described below.

**Integration between LIS and Analyzer Software**

The Laboratory Information System (LIS) used by Company X organization perfectly keeps track of each billable patient test, QC tests and repeat tests using the barcodes on vials. However, the analyzer software is not capable of differentiating between patient tests and QC tests using these Company X barcodes. Therefore, the analyzer software identifies QC tests as patient tests and the electronic counters on the analyzer displays QC test counts as zero. This does not create a problem in reporting the test results to the ordering customers; however it makes it difficult for operators and shift supervisors to track how many QC tests are performed on a daily or weekly basis on each instrument.

**Instrument Logs Analysis Tools**

The medical technologists excel at operating the instruments, however they and shift supervisors have very limited tools to diagnose issues and detect most frequent errors occurring within instruments. There is a strong dependency on the instrument vendor in evaluating instrument performance. It is a very lengthy and manual process for operators to collect logs and search through them for errors through text editor software. Providing easy to use log analysis tools to operators and shift supervisors, and performing log analysis on a weekly or a monthly basis using these tools can help to identify instruments that underperform and the root causes for underperformance.
5.3 Areas of Future Investigation

Company X is a leading clinical services provider which employs a large variety of different diagnostics platforms from different vendors in its facilities. The best practices, analytical models and methods presented in this thesis are derived from analyzing a specific high volume diagnostics platform that is capable of testing certain assays. However, as described in Chapter 5, these methods and the mathematical optimization model can be applied to other diagnostics testing platforms that have similar operating principles, using reagents in performing tests and performing quality control tests at predefined frequencies. In order to apply the model to different diagnostic platforms, the model constraints and coefficients need to be modified accordingly.

The mathematical model described in this thesis is based on batch processing mode and performing QC tests at intervals of patient test counts, such as performing QC test after every 100 patient tests. With other continuous flow instruments, Company X uses a time based interval for QC testing frequency, such as performing QC test every 2 hours. Both approaches have advantages and disadvantages. A time based QC control frequency approach reduces the complexity of tracking the count of patient tests for the medical operators, on the other hand it can increase the number of QC tests performed.
5.4 Closing Remarks

Company X is a distinguished enterprise that makes highest quality healthcare diagnostics more affordable and accessible for millions of patients every year. It is also an astonishing research ground for any investigator who wants to observe, study, and contribute to the discipline of operations management in healthcare. Company X possesses operational know-how and expertise in healthcare that can be used a model for healthcare diagnostics all over the world, especially in developing countries. I am grateful for the hospitality and support I received during the six months I worked at the New England facility and during my visits to other regional facilities. I would like to thank the entire Company X team who supported my research, provided their time, and allowed me to gain a remarkable learning experience.
References

http://www.who.int/diagnostics_laboratory/quality/control/en/


Appendix A

List of Replaced Parts and Their Part Numbers

<table>
<thead>
<tr>
<th>Part Name</th>
<th>Part Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-Way Valve (Ceramic)</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>3-Way Valve (Plastic)</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>6/12 Month PM Kit</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Washer Aspiration Tube Type-1</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Washer Aspiration Tube Type-2</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Back Panel</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Cooling Module</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Cuvette Loading Flap</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Distance Ring</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Guiding Sealing</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Guiding Sheets (Repair Set)</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Incubator Belt &amp; Pulleys Repair Set</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Probe Rinsing Pump Type-1</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Left Pipettor Bearing</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Left Pipettor Sliding Plate</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Level Sensor Intermediate Tank</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Analyzer Dilutor</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>New Filter System Liquid</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Washer Aspirator Pressure Shoe</td>
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</tr>
<tr>
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</tr>
<tr>
<td>Pusher Door Set Incubator - Washer</td>
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</tr>
<tr>
<td>Pusher Door Set Washer- Incubator</td>
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</tr>
<tr>
<td>Reader Barcode</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>Reagent Probe</td>
<td>xxxxxxxxxx</td>
</tr>
<tr>
<td>RFID Antenna Printed Circuit Board</td>
<td>xxxxxxxxxx</td>
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<td>Sample Pipettor</td>
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<td>Washer Aspiration Pump</td>
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<tr>
<td>Washer Dispense Pump</td>
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