Analysis of a Diagnostics Firm's Pre-Analytical Processes

By

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B.S. Mechanical Engineering, United States Coast Guard Academy, 2009

Submitted to the MIT Sloan School of Management and the Department of Mechanical Engineering in partial fulfillment of the requirements for the degrees of

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ABSTRACT

Quest Diagnostics provides diagnostic information to clinicians, allowing them to make informed decisions on the appropriate course of treatment for their patients. Quest advertises an 8am next-day turnaround time for a subset of clinical tests, a service that provides competitive advantage for Quest. When this 8am turnaround time goal is missed, it causes ripple effects throughout the customer support organization resulting from increased client complaints. This research approaches Quest's late-release challenges through an analysis of phlebotomy services, courier route planning, and specimen accessioning to find precisely the source and cause of challenges preventing Quest from achieving their turnaround time goals.

Prior to this research, Quest hypothesized that their logistics network could provide a consistent in-flow of patient specimens into their Marlborough, MA facility, improving the lab's likelihood of reaching their turnaround time goals. A simulation of a new demand-focused vehicle routing solution suggested that creating routes to provide a steady inflow of specimens would increase operating costs by 72%; what appeared to be an attainable, low-cost solution was found to be quite the opposite. We then provide an analysis of pre-analytical processes outside of logistics. Patient service centers (PSC) will soon provide 47% of the total specimen-volume to the Marlborough laboratory compared to 36% currently, thus evaluation of PSC processes and methodologies were conducted to identify ways to release a larger percentage of specimen volumes during midday courier pickups. Recommendations for process improvements to provide couriers with more patient samples during midday pickups are provided. Specimen accessioning processes and staffing were also analyzed, revealing that between 17%-24% of the subject tests results were unable to be resulted prior to 8am due to insufficient staffing for a second-stage accessioning task.

Alterations to Quest's logistics network proved to be costly and low-impact, whereas slight alterations to phlebotomy-service processes and in-lab staffing could provide far higher value to Quest's customers with less impact to operations. By redirecting their focus to these other pre-analytical processes, Quest could focus their efforts on higher impact, lower cost options to improve operations and meet their turnaround time goals.

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To my wife and sons, thank you for making my life whole. Without you, I would be a much different man.

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Chapter 1

Introduction

In an ideal world, doctors would receive the diagnostic results they need right away[1], allowing them to change the course of treatment as necessary to treat their patients as soon as possible. Because instant turnaround of lab tests at the point-of-care is extremely difficult to manage [1], clinicians often turn to companies like Quest Diagnostics to offset costs and provide diagnostic insights. Patients provide samples to clinicians or at off-site outpatient phlebotomy locations at the doctor's request. Those specimens are then retrieved by a courier and brought to a laboratory. Upon entering the laboratory, each sample is individually checked for accuracy of demographic information, centrifuged if necessary, aliquoted (i.e. divided) into a sufficient number of test tubes, and released to the technical laboratory. The technical laboratory will then analyze the sample and generate diagnostic information for release to the doctor.

The research described in this thesis describes how the processes separating the doctor from their patients' results can be improved so that doctors receive clinical test results before they come into work the following day. Quest Diagnostics, a corporation that provides phlebotomy, courier, diagnostic testing, and diagnostic information delivery services, proved to be an ideal match for this research.

1.1 Thesis Objectives

Quest Diagnostics operates a fast-paced, low error-tolerance business that affects millions of patients each year. In order to continue to provide the highest service levels to their clients, Quest requires in-depth analysis of pre-analytical phlebotomy processes, logistics route planning, and specimen accessioning practices. Quest's Marlborough laboratory advertises an 8am release-time for a subset of their clinical tests, but sometimes falls short of this objective. The business theorized that small, low cost alterations to their logistics network would improve their performance in this regard. This research tests this hypothesis

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[1] Ideally, test results would be available while the patient is still at the initial appointment. Any delay is an inconvenience and anxiety for the patient as well as an interruption in problem solving continuity for clinicians.

and suggests that, perhaps, other pre-analytical processes should receive more attention to enable the business to meet this goal.

1.2 Thesis Overview

Chapter 2 will provide background on Quest Diagnostics and their departments relative to this research. Chapter 3 will describe the diagnostic delivery process currently used by Quest Diagnostics and similar businesses in this market. Chapter 4 provides a demand-focused vehicle route planning formulation that provides a means of deploying a network-wide, demand-focused, routing strategy. Chapter 5 provides non-logistics related opportunities relating to the objective. Chapter 6 provides a summary of findings and recommendations.

Further supporting documentation is provided in the appendices. Appendix A provides a conventional vehicle routing problem, with time windows, for comparison. Appendix B provides sample code written in IBM ILOG CPLEX optimization programming language (OPL) for the demand-focused vehicle routing problem with time windows (DVRPTW). Appendix C provides variable notations used in Chapter 4.

1.3 Literature Review

This section will draw on examples of research from similar industries and provide context as to how they relate to business operations at Quest Diagnostics. Literature from operations research, process excellence and pathology all pertain to this research.

1.3.1 Vehicle Route Planning

Many academics within the operations research community have studied the applications of vehicle route planning algorithms for industries such as mail delivery, maintenance services, and school bus routing [2]. Similar to these industries, medical diagnostic firms like Quest Diagnostics also operate extensive logistics networks with thousands of vehicles and tens of thousands of customers that need to be served daily [3]. With such a complicated network of vehicles, costs are certainly of concern. Many researchers have evaluated exact and heuristic solutions to the vehicle routing problem similar to Quest's with cost as the focal point. Ellabib et al. describe the mathematical approach to commonly accepted formulations of the vehicle routing problem, with time windows (VRPTW) [4]; Appendix A provides this conventional VRPTW formulation. Baker reviews the traveling salesman problem (TSP) in terms of time window constraints, solving relaxed variations of linear optimization problems to generate solutions to the TSP [5]. This provided insight into time-window mathematical formulation later formed in Chapter 4. Simchi-Levi explains analytical approaches to the VRPTW and applies the VRPTW to a manufacturing environment [6]. Previous research has been done on Quest's logistics networks, focusing on turnaround time and service levels. Price analyzed the vehicle network at Quest, approaching Quest's turnaround time in a new "service based logistics optimization" model for a small segment of Quest's clients in Brighton, MA [7].

Quest uses a cost-focused vehicle routing program to design their courier routes. Logistics operating costs are the primary focus for businesses that specialize in logistics only, and where transportation services provide a majority of their revenue stream, like FedEx's FedEx Ground segment. For scale comparison, FedEx Ground operates over 80,000 vehicles across its 538 facilities in the US and Canada, whereas Quest operates roughly 3,000 vehicles [8]. Scale aside, similarities in motivation between the two organizations are certain: lower costs. Quest, however, generates the majority of its revenues through testing rather than logistics. The first objective of this research is to test the hypothesis that Quest can use their logistics network to provide level in-flow of specimens into their lab. We will find that Quest's objectives are not aligned with those of businesses such as FedEx, which leads us to further exploration of alternate methodologies.

Other differences exist between Quest's logistics operations and large commercial transportation companies. UPS, for example, publishes firm "latest drop off times," which clients accept without much question. If a commercial transportation company dictates a no-later-than time for drop offs, their clients are likely to adhere to these. For Quest, clients typically dictate pickup time-windows. This difference is largely due to the nature of Quest's business, the criticality of their product, and competition within the market. This complicates the logistics network, driving costs upwards as customer demands increase. The e-grocery home delivery business also serves a market-type with consumer-defined time-windows, which studies show has made the home-delivery market for groceries extremely difficult to operate [9]. Large commercial transportation companies also publish clear delivery commitments across their service levels, often with money-back guarantees [10]. Quest's service levels are highly variable depending on location, client, and test type.

The vehicle routing problem solution we form in Chapter 4 combines many elements of these works. While traditional VRP solutions focus on reducing costs, the formulation in Chapter 4 attempts to quantify a solution to the VRPTW that allows for more efficient operations at the hub/depot laboratory. This is a unique concept: using a courier/logistics network in a reverse supply chain to balance the flow of materials through a production environment. This provides us with a more tailored routing solution for Quest's needs in order to compare intended outcomes to those they currently experience.

1.3.2 Medical Laboratories

Quest operates modern medical laboratories, many of which operate similarly to manufacturing facilities given technological progression in the industry. For traditional manufacturing processes, a product flows through a production line as value is added to it. The product is then delivered to consumers. In the medical laboratory industry, consumers provide a product that flows through a process as value is extracted *from* it. Comparisons between manufacturing and large-scale laboratory operations are widely documented [11] [12] [13]. Balanced flow in medical laboratory pre-analytical processes has been proven important [12], yet cost and quality must still be considered.

Clinicians order tests through varying mediums. Some clients order tests electronically where others request them on paper or through non-electronic medium. Chapter 5 describes how this inconsistency in requisition medium complicates laboratory operations. These complications suggest a need for reverse supply chain integration could be applicable for Quest's client network [14]. Operational efficiencies aside, we can assume the likelihood of errors associated with electronic orders are less than those ordered otherwise. Davis et al. show the effectiveness of electronic ordering of prescriptions for patients, showing that order errors were approximately eight times more likely when not using computerized order entry systems. Additionally, turnaround times for prescriptions decreased dramatically as well [15].

1.3.3 Patient Service Centers

Patient Service Centers (PSC) are outpatient clinics where patient samples are taken. PSC operations are explained in more depth in Chapter 3, but can simply be described as a clinic with (typically) a waiting room, draw room, and a staff of one or more phlebotomists serving the patients. Outpatient clinics are notoriously individual patient-centered, often at the expense of the greater patient population's service quality as a whole. Incentives driving this behavior are described in Chapter 2, but relative literature discussing patient satisfaction and service importance are provided for context. We investigate means of returning greater value to the patient by improving test release time and quality at the expense of initial service quality. This section will frame our hypothesis that patients will be willing to wait longer if (1) they have guided expectations of wait time duration for the clinic and (2) the quality of their diagnosis improves as a result. Improving test release time for patients drawn in PSCs is a byproduct of a multi-function effort to reduce late-night in-flow of specimens into their Marlborough lab.

One-to-one comparisons can be made between Quest's phlebotomy services and competitor phlebotomy services. Mijailovic, et al., for instance, provide a means of optimizing outpatient phlebotomy staffing across 14 sites to decrease patient wait times [16]. Minimizing patient wait-times appears to be the focus for other healthcare outpatient operations as well, such as outpatient oncology infusion centers where phlebotomy and lab services account for the majority of patient wait-times prior to beginning infusion [17]. We will discuss how patient waiting times are indeed important for Quest's phlebotomists to consider, but may have downstream impacts on test release timeliness. In fact, Matthews et al. suggest that patients knowledgeable about the healthcare system as a whole, as well as their treatment specifically, will have more realistic expectations than those without such knowledge [18]. This suggests that proper patient-education on the part of the provider may improve patient experience, regardless of small increases in wait time.

Outside of healthcare, further correlations can be made. Automotive repairs, for instance, show strong correlation to phlebotomy services. In phlebotomy, a patient wishes to be served quickly and receive quality results quickly. From a systems perspective, these two objectives (initial care and diagnosis) often oppose each other. Similarly, customers of an automotive repair business wish to have their vehicles serviced quickly and have the service completed properly. Hsai and Pu propose an important distinction between importance of service and satisfaction with service [19]: performing well in an area the customer cares less about has less impact than performing well in an area the customer cares more about. In the case of auto repairs, customers will typically prefer product quality over service quality, meaning that having their vehicle fixed properly is more important than other aspects relating to customer service.

We propose tools and methodologies common to other businesses, including small batch and one-piece flow for post-draw process steps. For some blood samples, the blood must clot for 30 minutes prior to centrifuging. A centrifuge must spin for 15 minutes for serum and plasma samples [20], which is a lengthy time considering that the time it takes to draw these samples is often under a minute. The bottleneck in a Patient Service Center is certainly these post-draw processes, and phlebotomists prefer to wait for multiple samples before centrifuging because of this. Similarly, in gear manufacturing plants, along with other low-carbon steel product manufacturing plans, heat treatment furnaces are often the bottleneck steps in the process with cycle times in excess of 15 hours. Workers often wait until the furnace is full to run a batch, increasing the machines' efficiencies while delaying the manufacturing process as a whole. In similar studies, batch size reductions and single-piece flow for heat treatment processes have shown to reduce wait times by up to 20 days [21]. Persoon et al. discuss the benefits of one-piece flow of specimens through a diagnostic process consistent with the Toyota Production System (TPS) [11], a practice later discussed in Chapter 5 regarding phlebotomy practices relating to manifesting. A single-piece flow process within the phlebotomy clinic shows system-wide impacts that return greater value to patients than simply improving patient wait times.

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Chapter 2

Company Background

Quest Diagnostics is the world's leading provider of medical diagnostic testing information services, having delivered an estimated 20 billion test results over the past decade [3]. Each year, they serve approximately one third of the U.S. population, half of all U.S. physicians, and half of the hospitals in the United States.

Quest operates over 2,200 patient service centers and has 4,000 organic phlebotomy technicians in physician offices (IOP), providing unmatched scale for reaching clients across their operating territories. Quest also provides services to clients who employ their own phlebotomists, and such accounts provide a large percentage of their sample volume. Servicing this network of tens-of-thousands of client locations are 3,000 courier vehicles and 25 aircraft, as well as a fleet of logisticians who ensure specimens are brought from the field to the performing laboratories in a timely and efficient manner [3].

Quest Diagnostics reported full-year revenues of $7.435BB, $7.146BB, and $7.383BB in 2014, 2013, and 2012 respectively. Quest generates roughly 55% of its revenues from routine clinical testing services, which physicians use in the detection, diagnosis, evaluation, monitoring, and treatment of diseases and various medical conditions. These tests consist of analyzing an array of specimens including whole blood, serum, plasma, urine, and other patient specimens. Roughly 34% of the company's revenue comes from gene-based, esoteric, and anatomic pathology testing services [3].

2.1 Healthcare and the Diagnostics Industry

The importance of the diagnostic information services industry is not easily ignored. While the industry (as a whole) accounts for only 1.6% of Medicare costs and 5% of hospital costs, their products influence 60-70% of healthcare decisions [22]. The diagnostic information services industry is also highly competitive. Quest Diagnostics recognizes three general types of clinical competitors: commercial clinical, hospital-affiliated, and in-physician-office laboratories. The largest commercial clinical competitor is Laboratory Corporation of America Holdings, Inc. There are many hospital-affiliated competitor laboratories across Quest's various areas of operations, as well [3].

Companies in this industry compete on a number of factors including test-menu completeness, quality, pricing, and reputation. Quest Diagnostics has the most comprehensive test menu in the market. This research focuses on how a business within this industry can maintain competitive advantage through timeliness of result reporting, which is of paramount importance to clinicians and patients alike. We define turnaround time as the time between Quest receiving a requisition and when a clinician receives the result. Turnaround time is of paramount importance to any clinical laboratory as a distinguishing performance characteristic [23]. As such, earlier release times improve a firm's standing relative to their competitors. Market analysis concludes that 88% of clinicians need lab results within 24 hours, and 43% need results before 8am the next day [24]. To bring value to its clients and to improve its position in the market, Quest Diagnostics strives for an 8am release time for a large subset of routine clinical pathology testing. This enables clinicians to review test results before they begin seeing patients each day.

2.2 Quest's Organizational Specifics

This section provides an overview of both the national and local organizations within Quest Diagnostics. It includes company reporting-structure, information regarding technical departments, as well as performance expectations and incentive structures for each of the relevant organizations. Of great relevance are the functional silos within the organization, across both the national and local businesses.

2.2.1 General Organization

Quest has eight business units located throughout the United States. Each of these business units has an operations executive with functional directors supporting patient services, logistics, and lab operations. There is a national organization that supports and provides direction to the functional groups within Operations. This group assists regional business units with staffing, doctrine, process, and enterprise-wide initiatives.

This organization is functionally segmented locally and nationally. This functional segmentation leads to functional optimization, such as cost minimization for logistics functions and staffing minimization for lab operations. Sales is also functionally segmented from operations, leading to competing objectives that are discussed in the following section.

2.2.2 Functional Area Objectives

Functional staffing arrangements motivate incentives and business objectives within each functional area's operation. Each functional area will be described in detail in Chapter 3.

The logistics organization within each business unit has a clear objective: pickup and deliver specimens at the lowest cost while meeting the constraints of their client base. They are viewed as a cost center. The logistics organization reduces costs by decreasing the amount of vendor-supported routes they run and by working with the national organization to re-route their couriers to minimize operating costs.

Patient Services, which operates Quest's patient sample collection centers, is a true patient-facing functional group and is evaluated on patient satisfaction and average patient wait times, amongst other criteria. At times, these competing objectives adversely affect their ability to release specimens to couriers in a timely manner, causing a higher volume of tests to enter the lab in the evenings.

The sales organization is incentivized to increase revenues and bring new business into the organization [25]. The sales organization may, at times, offer enhanced service levels to larger clients, which increase revenues but also increase operational complexity. As an example, a large client of the Northern Business unit requires all same-day test requisitions to be delivered to a Quest Rapid Response Laboratory (RRL) rather than their core lab in Marlborough. This strains the logistics network immensely, forcing 22 different courier routes to transit through RRLs before returning to Marlborough with the rest of their client volumes.

Specimen management, a group that provides front end services in the lab, is evaluated on adherence to processor efficiencies, thus they staff their stations to ensure each employee is nearly 100% utilized for the entirety of their shift. This is later discussed in 5.3.2 as a contributing factor to the late-release of tests. They are also evaluated on data-entry quality, which necessitates quality control steps in their processes.

Collectively, these functional objectives do not always align to allow the business to achieve its operational goals. Late release of specimens from PSC's affects specimen arrivals into the lab. Cost cutting in logistics amplifies late arrivals of specimens into the lab as well. Varying service levels across clients also has direct downstream impact on the lab's ability to function smoothly. Chapter 6 provides general commentary from a systems perspective relating to these objectives.

2.2.3 Recent Developments

In 2012, Quest launched a new vision: Empowering Better Health with Diagnostics Insights. This vision was accompanied by three aspirational goals: a healthier world; build a valuable company; and create an inspiring workplace. Later that year, Quest Diagnostics introduced a five-point business strategy intended to support their vision and goals, which consisted of restoring growth, driving operational excellence, simplifying the organization, refocusing on diagnostics information services, and delivering disciplined capital deployment.

2.3 The Northern Business Unit

Quest's Northern Business unit, which serves patients from every state in New England, up-state New York, western Pennsylvania, northern West Virginia and Northeast Ohio, is headquartered in Marlborough, MA. The Marlborough location services clients from New England while others serve the more western territories. Prior to 2014, the New England client volumes were analyzed at two laboratories in Cambridge, MA and Wallingford, CT. The Cambridge lab has since closed (at least for the non-stat menu type testing) and a portion of the Wallingford, CT volumes will be absorbed into the Marlborough location in late 2015. This research focuses primarily on operations run out of the Marlborough location.

2.3.1 Consolidation of the New England Business

Pursuant to driving operational excellence, Quest's Northern Business unit is currently undergoing significant transformation both in terms of physical layout and scale of service area. The New England business will soon be analyzing specimens from tens of thousands of patients per day in a single laboratory. Consequentially, relocation of Quest's Cambridge personnel to Marlborough produced a large turnover in its Cambridge-based operations workforce. Future consolidation of the Wallingford laboratory into Marlborough is expected to produce similar effects. Evaluation of pre-analytical processes for this business unit is crucial to their success during the transition.

A primary driver for the level loading initiative is the expected increase in requisition volume expected for the Marlborough Lab in the second half of 2015. Quest hopes to offset their early-day inflow deficiencies with specimens previously delivered to their Wallingford site. The Marlborough laboratory features a new automated specimen delivery system, expected to increase capacity and decrease operating expenses for this increased volume.

2.3.2 Automation and the Lab of the Future

In 2014, Quest Diagnostics opened a new and state-of-the art laboratory in Marlborough, MA. This laboratory houses some of the most advanced automated clinical laboratory testing equipment in the industry. It features a fully customized, automated delivery system capable of performing many tasks previously performed by technicians. This system is capable of aliquoting, centrifuging, de-capping, and receiving thousands specimens per hour [26]. For their patients and customers, this laboratory is expected to bring faster and more consistent results.

This laboratory will provide significant economies of scale for Quest, allowing them to properly distribute specimens within the laboratory. The automated laboratory will serve as a flagship laboratory for Quest, hoping to continue improving on its functionality while building best practices for future installations across the enterprise. Providing this automated laboratory with sufficient volume through its operating hours is essential. The following chapters describe how pre-analytical processes may be improved to achieve this goal and maximize the utility of the lab.

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Chapter 3

Diagnostic Delivery Process

A patient will see a doctor for a number of reasons, often with symptoms pointing towards various diagnoses. In order determine which diagnoses best explain the symptoms, doctors will often call on Quest to provide further insights. The patient will provide the required specimen, after which the specimen is prepared for transport and sent to a laboratory for testing. Roughly 50% of all physicians rely on the information Quest provides [3], thus the geographies Quest services are spread out to remote and urban areas alike. Both geography types play a role in complicating this process, prolonging the time between the patient's appointment and when the doctor can provide them with an accurate diagnosis. Many of the obstacles and complications throughout the diagnostic delivery process have improvement potential, but this research will focus primarily on phlebotomy, logistics, and accessioning operations. Additional industry-specific terms, along with an explanation of the diagnostics delivery process, are given below to provide the necessary context and background.

3.1 Service Levels and Specimen Types

Differentiating service levels allows us to focus on the requisition types discussed in this thesis.

3.1.1 Service levels and Client Expectations

As explained in Chapter 2, customer service and adherence to client expectations are extremely important in this industry as the market is full of competition. There are three generally accepted service levels that clinicians may request, though the specific turnaround times for each service level may vary depending on client agreements.

STAT – These tests are generally resulted within 4 hours of patient draw. This type of test must be (1) ordered as a STAT by the client and (2) offered as a STAT test by the receiving laboratory [27]. STAT tests involve a separate, reactive logistics network outside of the focus of this research. Quest employs full-time drivers and uses contract courier services to satisfy STAT testing demand due to their time-sensitive nature. Additionally, within the laboratory, STAT tests have priority for check-in and testing.

Same-Day – Results will typically be released prior to 5pm on the same day the test was received. These tests necessitate midday pickups at nearly every client in Quest's territory. To ensure same day result, couriers must collect these samples prior to 11am.

Routine – These tests represent the largest portion of Quest's volume and are the primary focus of this research. These tests can be picked up at any time and are resulted the following day prior to 8am.

3.1.2 Specimen Types

General classifications for specimens are based upon sample type and sample temperature. Biopsies, urine, blood, semen, stool, and bodily fluids (such as spinal fluid) are examples of specimen types. We use the term specimen to broadly describe all of the aforementioned. Different specimens require different levels of care within Quest's operations. Biopsies, for example, require a chain-of-custody and signature from every person receiving the specimen throughout the process. Standard blood samples, on the other hand, require no chain-of-custody.

For blood samples, specialized specimen containers are used to provide coagulation or anti-coagulation depending on the test required. The most common anti-coagulant used is K_2EDTA, while sodium citrate is often used for coagulation. Serum separation tubes (SST) contain a lithium heparin gel additive (in addition to clot activation additives) for serum-only testing. Blood collection is typically accomplished easily and safely with vacutainer technology, which combines strong polyethylene terephthalate plastic containers, an internal vacuum in the tube for more efficient draws, and a closure that protects phlebotomists from coming in contact with patient blood [28]. Additionally, specimens are segregated by temperature required for delivery. Frozen specimens are transported with dry ice, refrigerated specimens are transported with insulated bags, and room temperature or ambient specimens are transported in courier bags.

3.2 Patient Service Centers and In Office Phlebotomists

Patient service centers and in-office phlebotomists are staffed with Quest employees who perform phlebotomy services. There are over 300 of these locations in the New England area, though the exact number is in constant flux. Patient service centers are isolated outpatient locations, while in-office phlebotomists are located within partner practices. Quest uses expected patient volumes to determine PSC and IOP staffing. Their hours vary by location, though 8am – 5pm with midday lunch hour is common. The employees at these locations serve two primary functions: collect patient samples and prepare samples for transport to the performing laboratory. They serve many other miscellaneous functions including billing and some consultation, but this research will focus primarily on the collection and preparation of samples.

3.3 Logistics Operations at Quest Diagnostics

The logistics operation in Marlborough is highly complex with over 100 routes, based off of 2014 data [7]. Each day, a courier will visit multiple client locations, patient service centers, and various laboratories in the Quest network. It is an unconventional reverse supply chain where materials are retrieved from clients and brought to a depot location where value is extracted and delivered back to clients in the form of information. Also, whereas most reverse supply chains focus on remanufacturing or recycling [29], Quest's primary clinical product is derived through this network. Below is a table comparing forward supply chains, reverse supply chains, and Quest's reverse supply chain, in general terms.

Forward Supply Chain	Reverse Supply Chain	Quest's Reverse Supply Chain
Based on profit and cost optimization	Based on environmental principals as well as profit/cost optimization	Based on profit and cost optimization
Relatively easier and straightforward forecasting for product demand	More difficult forecast for product returns	Relatively easier and straightforward forecasting for demand
Less variation in product quality	Stochastic product quality	Stochastic specimen quality[1]
Processing times and steps are well defined	Processing times and steps depend on condition of returned product	Processing times and steps depend on condition of specimen provided.
Goods are transported from one location to many other locations	Returned products collected from many locations arrive in one facility	Specimens are gathered from many locations and brought to several performing lab sites[2].
Consistent inventory management	Inconsistent inventory management	Complex inventory management due to IT systems[3]

1. Specimens of varying quality are received by the lab, to include: spilled, not centrifuged, thawed, and insufficient quantity.
2. Quest operates many labs other than their hub locations that perform tests within their STAT and Same-day test menus.
3. Lab tests are ordered through a variety of systems, and Quest operates logistics software separate from their laboratory information systems (LIS).

Table 3-1: Comparison of supply chains **[30]**.

The remainder of this section will provide further information as to how routes are generated and how couriers, whom are interchangeably referred to as Route Service Representatives (RSRs), perform logistics operations at Quest. The following sections are intended to provide information on routine routes carried out by RSRs and do not represent the full scale of Quest's logistics operations.

3.3.1 Route Maintenance

A basic route infrastructure has been built over many years and through multiple acquisitions and agreements. These routes are altered for three primary purposes:

1 – An RSR is unable to carry out their route.

2 – A client requirement is added or removed from the logistics network. This may be for a new client taken on from sales, from a PSC or IOP opening or closing, or from new business requirements for current clients.

3 – An effort is made to reduce costs by cutting routes or reorganizing stops.

When an RSR calls out of work, supervisors and team leads within the logistics department must quickly reassign clients on those routes to neighboring routes or call upon the services of partner courier companies. This work is done primarily through Program A (discussed in 3.3.2) and manual entry. Breaking up routes adds variability to the demand arrival forecasts, as specimens will tend to come in later and further complicate the 8am test release objective of the business.

When a client is brought on, there is a joint meeting including operations to discuss customer requirements. Requirements that complicate the addition of a client to a route include:

- Pickup location: the client may leave specimens in a Quest drop box outside of their facility or require a face-to-face pickup. Clients may lock their doors without granting the RSR access, making their no-later-than pickup time uncompromising.
- Pickup Time: Some clients require late pickups, as they want to be sure they have sufficient time to prepare specimens for pickup.
- Pickup Windows: Narrow time windows further complicate the addition of a client to a route and, additionally, introduce precedence relationships between client arrival times [31].

3.3.2 Logistics Software Systems

Logistics uses four primary IT systems and software tools to carry out their operations. Table 3-2 and Figure 3-1 describe the software's role in the operation, which function uses it, what data can be derived from it, the reliability of the data, and the communication relationship between them.

Software	Function
QRoute	Software loaded into RSR scanners that provide route information to the RSR as well as a means for the RSR to transcribe notes and client volumes. Contains minimal patient information.
Program A	Master repository for Quest's logistics operations that maintains client demographics and route information. Contains minimal patient information.
RPSA	Route Planning Software A, which utilizes a conventional vehicle route planning algorithm to provide low cost routes with minimal client time-window violations.
QLS	Quest Diagnostics' Laboratory Information System. This system contains all client information, patient information, test result information, as well as other lab specific information. This is an IT product used across the enterprise by multiple functional groups.

Table 3-2: Overview of Quest's logistics-related software.

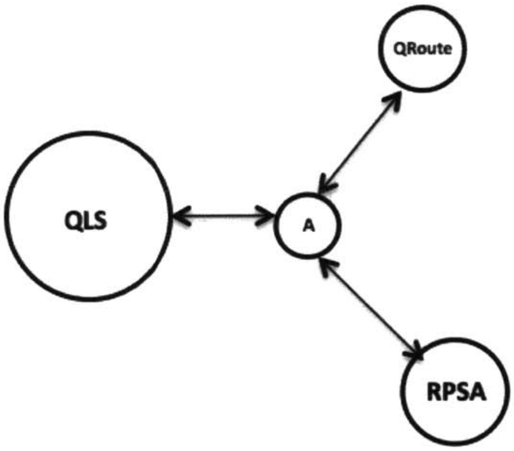

Figure 3-1: Relationship between the various software tools within Quest Logistics. Size denotes relative reliability with regards to its primary function based off the author's observation.

3.4 Specimen Management

Processors within specimen management ensure data integrity and specimen quality from the time a specimen enters the laboratory until the specimen is discarded. This is one of the largest single departments within the lab with significant staffing across three shifts, allowing the department to operate 24/7. Personnel in this department accession, transport, centrifuge, aliquot, store, and dispose of all patient samples within the laboratory.

3.4.1 Accessioning, Overview

We define accessioning as ordering an assay in the laboratory information system [12]. The accessioning process is highly variable depending on the client being accessioned. Some accounts require special processes, while others request test codes from their own test menu that the processors must de-code before the test can be completed.

3.4.2 Requisition Types

Clients order tests through two basic mediums: electronic or manual requisitions. An electronic requisition may be ordered through a Care360 account or through their electronic medical record (EMR) via a bi-directional interface. Manual requisition mediums vary, ranging from hand-written paper requests to Care360 "result-only" orders. Additionally, any order placed under an electronic requisition that faults during transmission must be handled as a manual requisition.

3.4.3 Accessioning Stations

The below table provides details for the basic function of each of the accessioning stations.

Station	Requisition	Explanation
A	Manual	Station where the minimum information necessary to release a test to the technical laboratory is entered into IDAA.
B	Manual	Stations where the remaining fields not filled by A-station are entered. All patient information is checked for accuracy.
C	Manual and Electronic	Single-accession Care360 station used by PSC's and IOP's. Specimens accessioned in C-station are able to immediately enter the technical laboratory upon arrival.
D	Electronic	Location where electronic orders are processed and information is verified for Care360 and bidirectional interface orders.
E	Electronic	Station for processing specimens in an older version of IDAA.
J	Manual	Station that combines A and B station, rarely used.

Table 3-3: Overview of accessioning stations within specimen management's clinical operations.

3.5 Specimen Testing within Clinical Pathology

Clinical pathology involves many subdivisions of pathology, but this thesis is focused primarily on those subdivisions that are affected by the automated specimen delivery system described in Chapter 2. This section primarily serves to provide the reader with context on analyzer throughput for analysis in later chapters. Specific analyzer types and quantities are not provided.

3.5.1 Hematology

Hematology is the study of blood. Testing within the department is done with various machines, but the machines that interface with automation are listed below with the total number of machines, throughput of each individual machine, and daily volumes provided.

Analyzer C – Manufactured by Supplier A, provides urine cell and urine chemistry analysis capabilities and an array of test methods. Quest uses these analyzers for urinalysis and other high-volume tests.

Analyzer B – This machine is a whole blood analyzer. This analyzer is mostly used for complete blood count (CBC) testing.

Analyzer D – Manufactured by Supplier C, the Analyzer D is used to perform erythrocyte sedimentation rate (ESR) testing.

3.5.2 General Chemistry

General Chemistry is the other primary department of clinical pathology. There are a variety of analyzers that support operations within this department, but the highest volume machines in this department are listed below with basic, relevant information.

Analyzer A – Quest uses the Analyzer A for a huge volume of tests daily, with thousands coming from cholesterol testing alone. The Analyzer A performs over ¾ of the total 8am TAT test menu.

Analyzer E – They use these platforms to perform human chorionic gonadotropin (hCG) and thyroid (TSH and TS4) testing within their 8am TAT test menu.

Analyzer F – The Marlborough lab uses these analyzers for A1C testing on their 8am TAT test menu. These tests are used to diagnose diabetes and other serious conditions.

3.6 Test Release

Depending on the client, the requisition type, and machine performing the test, Quest offers various test release options. For electronic orders, results are normally distributed directly to the EMR through a bi-directional interface or released through Care360. Manual accounts are primarily released through Care360, but may also be released by fax, automatic dial service, or by paper transported via the courier network.

Clinicians monitor test release times closely. Without timely reporting, clinicians are unable to serve their patients efficiently. Based on call-center data gathered over an eighteen month period for inbound calls to the Marlborough lab, clinicians made over twenty thousand individual calls to Quest regarding pending test results. These calls required approximately 2,000 hours of avoidable support staff resources. In subsequent chapters, various methods of reducing this impact on support staff are evaluated.

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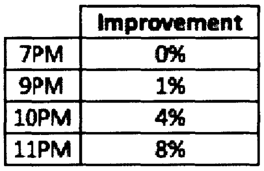
Chapter 4

Formulation of New Demand-Focused VRPTW

Balancing output from suppliers and leveling the manufacturing system are both fundamental process improvement methodologies [14]. We've discussed Quest's inherent need to alter traditional vehicle routing solutions to fit their unique need to level inbound specimen flow. In this chapter, we first discuss the limited success from attempts to manually alter route solutions from a traditional cost-minimizing route solver. We then suggest a new route solution model and reflect on its strengths and weaknesses relative to Quest's courier network.

Quest's Marlborough Logistics team has attempted to manually level the inflow of specimens into Marlborough through courier relays and vendor routes. Additionally, members from the national logistics organization teamed up with local supervisors to further level specimen arrivals, committing significant resource hours to achieve the balanced flow objective. An overview of progress over a seven-month period is shown below in Table 4-1, showing increases in cumulative arrivals by specific times throughout the day.



	Improvement
7PM	0%
9PM	1%
10PM	4%
11PM	8%

Table 4-1: Relative improvement gains observed over a seven-month period between November 2014 and June 2015.

This relatively small improvement suggests that manual alteration of routes is minimally effective relative to the goals the business has set. This required transitioning from a classical VRPTW solution objective to one that truly drives operational capacity for the business. For Quest, this requires understanding specimen availability across their clientele and observing the relationship between cost and hour-to-hour volume inflow variability.

This new model uses quadratic constraints and objectives as well as geographic and demand data for clients. The following sections provide an algebraic framework, while Appendix B provides the formulation in optimization programming language, written in IBM ILOG CPLEX. The model involves a group of drivers *K*, a set of stop locations *C*, and a set of stop numbers *L*.

4.1 Objective Function

Many formulations were considered, however the functions expressed in (4.1) and (4.2) proved computationally efficient. The model seeks to minimize the maximum single-hour demand delivered to the hub laboratory. This is a single-criterion optimization that does not consider simultaneously reducing the total number of drivers and reducing cost commonly found in the bi-criterion VRPTW [2]. Such alterations can be implemented by adding cost to (4.2) with an appropriate scalar multiple relative to the demand volume.

We first define a variable D_l^k as the amount of demand a driver *k* has stop *l*. We also define the variable $x_{l,i}^k$, which is one if and only if driver *k* visits location *i* on stop *l*. This variable is defined as binary in (4.8).

Variable *D* will be equal to the volume the driver received from previous stops as well as demand received at the current stop, short any demand previously released at the depot. This is shown algebraically in (4.1). The $D_{l-1}^k * x_{l,0}^k$ term is zero unless the driver arrives at the depot node, in which case the accruing demand will be reset for the next leg of the trip. The stop number (*l*) element for *x* and *D* serves as a timestamp used for each driver.

$$D_l^k = D_{l-1}^k + d_{i*}x_{l,i}^k - D_{l-1}^k * x_{l,0}^k, \forall k \in K, \forall l \in L, l \neq 0 \tag{4.1}$$

Equation (4.1) is a quadratic equality that provides additional computational complexity. This equation was replaced with three quadratic inequalities [32], shown below as (4.1.1 – 4.1.3), where A is some integer larger than the total demand across the client network.

$$D_l^k - d_{i*}x_{l,i}^k \leq \mathrm{A} * \left(1 - x_{l,0}^k\right), \forall k \in K, \forall l \in L, l \neq 0 \tag{4.1.1}$$

$$D_l^k - d_{i*}x_{l,i}^k \geq D_{l-1}^k - \mathrm{A} * \left[1 - \left(1 - x_{l,0}^k\right)\right] \tag{4.1.2}$$

$$D_l^k - d_{i*}x_{l,i}^k \leq D_{l-1}^k, \forall k \in K, \forall l \in L, l \neq 0 \tag{4.1.3}$$

$$D_l^k \geq 0, \forall k \in K, \forall l \in L \tag{4.1.4}$$

These three inequalities perform the same function as the single equality in (4.1). For example, if the driver arrives at the depot on stop *l*, (4.1.1) becomes $D_l^k \leq 0$, forcing the demand to reset to 0 given nonnegativity constraint. If the driver is at any stop other than the depot, then equations (4.1.2 and 4.1.3) force the following inequality:

$$D_{l-1}^{k} + d_{i*}x_{l,i}^{k} \leq \; D_{l}^{k} \; \leq D_{l-1}^{k} + d_{i*}x_{l,i}^{k}.$$

Now, we minimize the maximum single-hour volume returning to the depot with objective function (4.2). This objective will target the single highest-volume hour and redistribute driver stops to minimize inbound volume.

$$\min\{max \textstyle\sum_{k\in K}(D_{l-1}^{k} * x_{l,0}^{k})\} \forall l \in L \qquad (4.2)$$

4.2 Model Constraints

The first constraint, listed as (4.3), restricts all drivers (*k*) to begin at the depot node. This variable takes the form $x_{0,0}^{k}$ for a single depot case but is specific to each driver and, thus, can be used for a larger scale vehicle routing network such as Quest's New England logistics network, which has many remote hub locations.

$$x_{0,0}^{k} = 1, \forall k \in K \qquad (4.3)$$

Much like (4.3), (4.4) requires all drivers (*k*) must return to the depot node (0) for their last stop. The size of L must be large enough as to not constrain the model from exercising all route options. Thus, L should be equal to or greater than twice the total number of clients to allow the model to consider visiting each client as an independent, single stop trip. This is an instance of the most expensive case but would be within the feasible solution region if not for a cost constraint.

$$x_{L,0}^{k} = 1, \forall k \in K, L = 2 * C + 1 \qquad (4.4)$$

Constraint (4.5) is a conservation of flow constraint that only allows driver (*k*) to go to destination (*i*) on stop (*l*) if they were at some other node before (*i*). This constraint proved unnecessary in application given the requirements of (4.3), (4.4), and (4.11) but is listed as flow constraints are common for most network flow models.

$$x_{l,i}^{k} \leq \textstyle\sum_{j\in C} x_{l+1,j}^{k}, \forall k \in K, i \neq j \qquad (4.5)$$

The time window constraint adds significant computational complexity to the VRP formulation. Given the syntax used in DVRPTW, (4.6) is used to constrain any driver (*k*) to arrive at client location (*i*) only between that clients specified early (e_i) and late (l_i) times. The arrival variable takes the form a_l^k and is independent of the client. The arrival variable is explained further by (4.7).

$$x_{l,i}^k * e_i \leq a_l^k \leq x_{l,i}^k * l_i, \forall i \in C, \forall k \in K \tag{4.6}$$

Time accrues in this model based on travel ($t_{i,j}$) and service (s_i) times. A driver (*k*) will arrive at client (*j*) on stop (*l+1*) after arriving at client (*i*) on stop (*l*), servicing client (*i*), and travelling from client (*i*) to client (*j*). The $x_{l,i}^k * x_{i+1,j}^k$ term creates a quadratic constraint.

$$a_{l+1}^k \geq a_l^k + \left[t_{i,j} * x_{l,i}^k * x_{i+1,j}^k\right] + x_{l,i}^k * s_i \tag{4.7}$$

A large number of clients in Quest's network have multiple daily stops. To avoid confusion, every client stop is treated as a separate instance of the client class. For example: Client *Y* requires five stops throughout the day. Each of Client *Y*'s five stops will be treated as independent clients (i_1-i_5).

Variable $x^k_{l,i}$ is binary, (4.8) provides this constraint.

$$x_{l,i}^k \in 0{,}1, \forall k \in K \tag{4.8}$$

We then formulate a universal cost constraint in (4.10). From this constraint, shadow pricing can be used to evaluate business decisions regarding flow volumes. This is a quadratic constraint.

$$\$(\text{Some dollar amount}) \geq \textstyle\sum_{k \in K} c_{i,j}^k * x_{l,i}^k * x_{l+1,j}^k \,;\ \forall\, i,j \in C, i \neq j \tag{4.10}$$

As mentioned previously, equation (4.11) combined with (4.3) and (4.4) satisfies flow conservation constraint. This constraint requires that all clients (*i*) be visited exactly once.

$$\textstyle\sum_{k \in K} x_i^k = 1, \forall i \in C, i \neq 0 \tag{4.11}$$

Constraint (4.12) constrains all drivers to a standard workday with some latitude. An organization may want to constrain part-time and full-time employees' work durations separately, and in such a case (*K*) can be broken up into part-time and full-time groups. (4.12) restricts the difference between a driver's start and end time to be within a specific hour range.

$$7 \leq a_L^k - a_0^k \leq 9;\ \forall k \in K \tag{4.12}$$

Collectively, these constraints and objective function form the DVRPTW. Section 4.3 will provide explanation of the model as it was applied to a fictional scenario involving six clients and a single driver.

4.3 Application of the DVRPTW

A model was built to evaluate how the DVRPTW produced routes versus a conventional VRPTW. The program software, IBM ILOG CPLEX Optimization Studio made available through IBM's Academic Initiative, limited the size of the simulation significantly. As such, six stops of equal distance from the depot node where created with common demands to assess the relationship between cost and arrival volume variability. While this simulation illustrates only how a single driver travelling across six client locations can provide a more steady flow, the simulation provides intuitions for how cost drives volume inflow into a depot node within a network flow model.

Figure 4-1 shows the resulting arrival inflow relationships, correlating a worst-case (red) arrival scenario to an optimal (dark blue) arrival pattern and associated costs. Costs are benchmarked off of the minimum hourly arrival scenario. This benchmark is appropriate given the current cost-minimizing software solution that Quest uses to generate route options. The minimum cost arrival scenario proves to be 58% of the cost of the model's optimal solution.

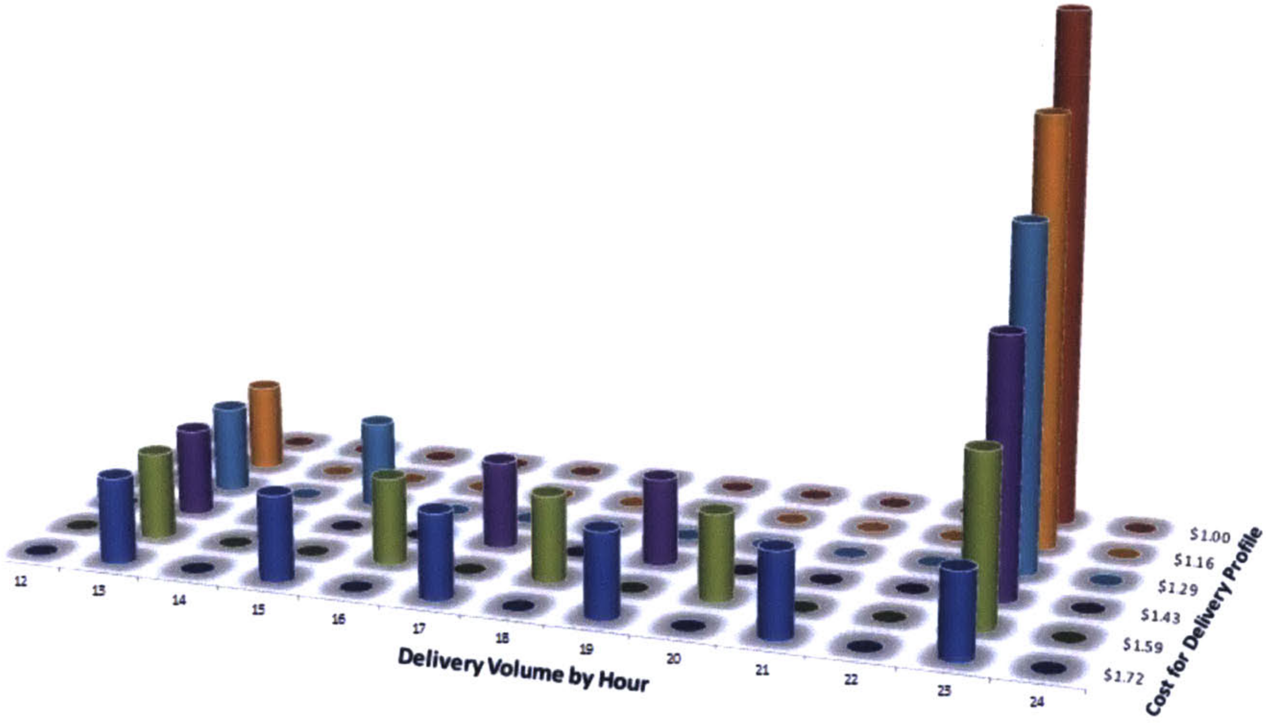


Figure 4-1: Six arrival patterns with associated cost. The Total Cost constraint in equiation (4-10) was manipulated to form the different arrival scenarios.

The $1.00 solution shows the arrival profile for a cost minimization VRPTW. The $1.72 solution shows the arrival profile for the DVRPTW without cost constraints. Cost values reflect normalized operating costs for each delivery profile. Figure 4-1 shows a clear difference between the extreme cases in terms of cost: a 72% increase for a perfectly level flow. However, many arrival scenarios exist between the most and least expensive options. Solving this model with more clients, drivers, and vendors would provide additional options for Quest to bring a percentage of their volumes in earlier. Any shift in requisition volumes to earlier times creates an opportunity for improved analyzer efficiency, decreased turnaround times, and higher likelihood of achieving their 8am clinical test reporting goals.

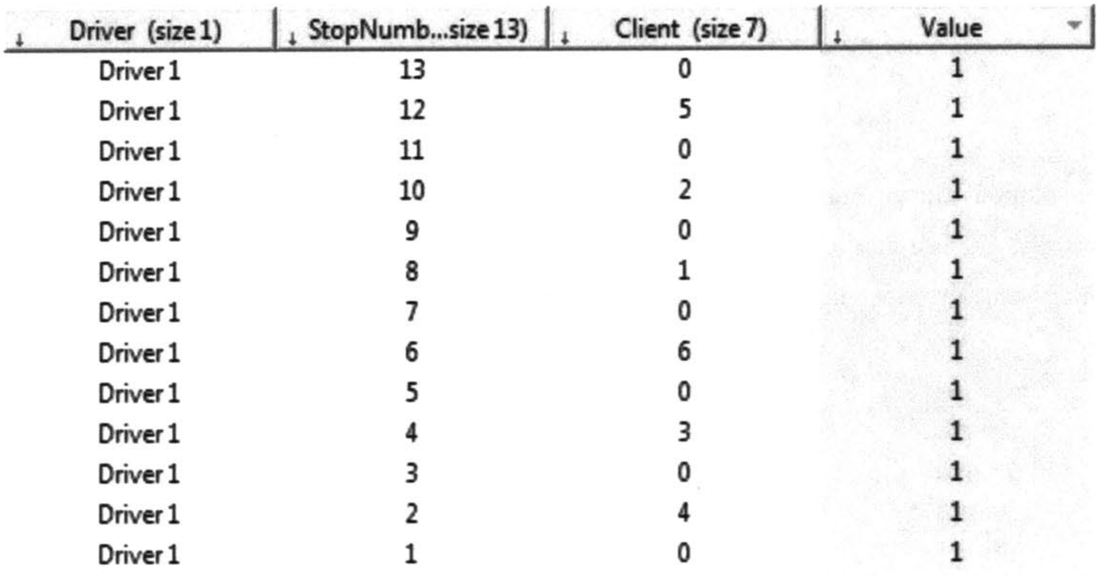
Determining how much more Quest is willing to spend in order to achieve the desired flow would require monetization of the benefits. This would require analysis of in-lab staffing, analyzer utilization, potential footprint reduction, and many other factors as they relate to the various arrival inflow profile possibilities. Understanding the financial benefit of creating a steady flow is truly valuable. Quest should analyze the benefit and appropriately investment in their logistics network.

4.4 Comparing Cost and Arrival Profile

In the course of running multiple simulations with varied objective functions, general relationships between cost and demand inflow variability were observed. Relating cost to benefit is the most valuable analysis for a business. By applying a cost-benefit comparison model to Quest's arrival profile initiative, Quest would be able to build a business case for purchasing increased functionality for their routing software. Through a small simulation, we are able to draw on general relationships between cost-based network solutions and demand-focused solutions.

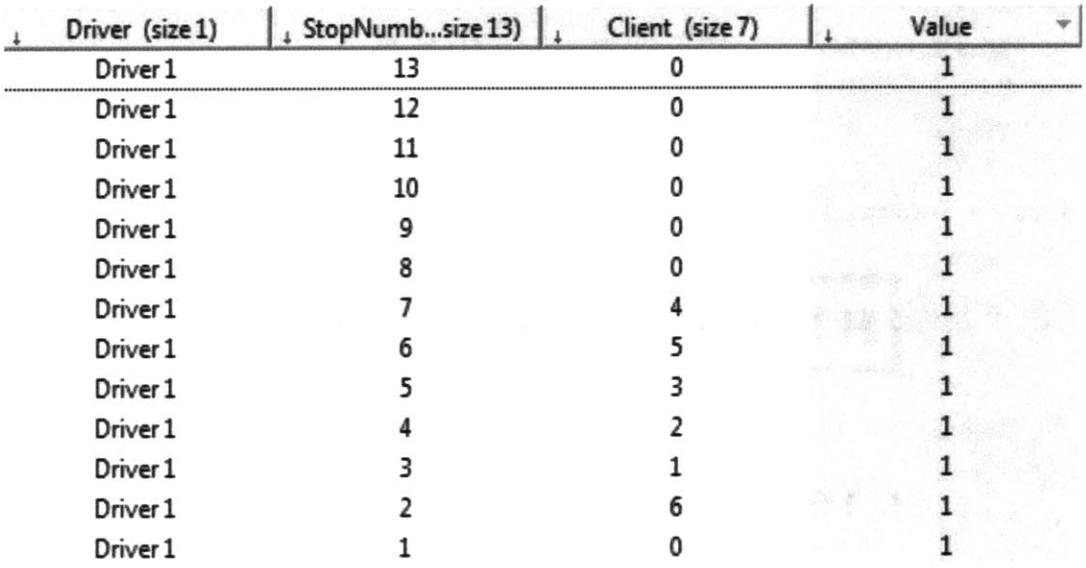
The CPLEX model output in Table 4-2 shows the result of the model running to minimize the maximum single-hour arrival volume developed under the DVRPTW. This shows consistent return to a depot location, providing as steady a flow as possible given the simulation's constraints. While realistic driver routes would not consist of route behavior shown in Table 4-2, the solution shows the manner in which a route would be generated without cost constraints.

When changing the model to, instead, maximize the maximum single-hour arrival pattern, the route solution shown in Table 4-3 is produced. This route solution shows all client demands being collected one-after-another and finally returning to the depot with a singular truckload full of all six client's requisition volumes. This solution, without a cost constraint, would provide a solution without regard for distances between clients. Thus, *n!* different solutions would provide the same, cost-focused route solution. For a model with six clients, 720 solutions exist.



Driver (size 1)	StopNumb...size 13)	Client (size 7)	Value
Driver 1	13	0	1
Driver 1	12	5	1
Driver 1	11	0	1
Driver 1	10	2	1
Driver 1	9	0	1
Driver 1	8	1	1
Driver 1	7	0	1
Driver 1	6	6	1
Driver 1	5	0	1
Driver 1	4	3	1
Driver 1	3	0	1
Driver 1	2	4	1
Driver 1	1	0	1

Table 4-2: Program Output for stop sequence for minimizing the maximum hourly volume coming into the depot node.



Driver (size 1)	StopNumb...size 13)	Client (size 7)	Value
Driver 1	13	0	1
Driver 1	12	0	1
Driver 1	11	0	1
Driver 1	10	0	1
Driver 1	9	0	1
Driver 1	8	0	1
Driver 1	7	4	1
Driver 1	6	5	1
Driver 1	5	3	1
Driver 1	4	2	1
Driver 1	3	1	1
Driver 1	2	6	1
Driver 1	1	0	1

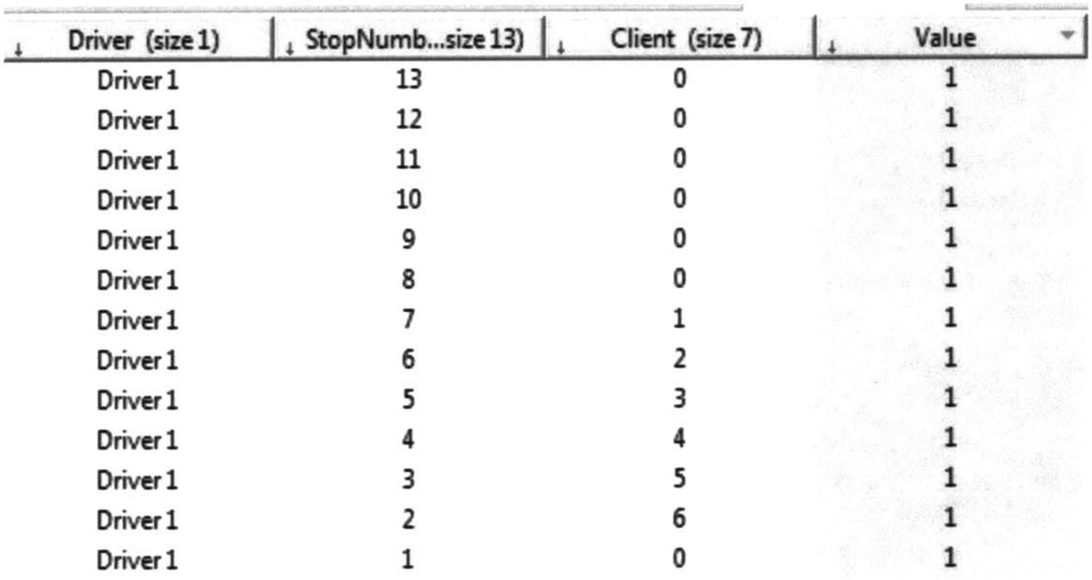
Table 4-3: Program Output for stop sequence for maximizing the maximum hourly volume coming into the depot node.

As demands vary across the field of nodes and clients, and as cost vectors begin to vary, the optimal solution pool will become smaller. Further analysis was done with the DVRPTW model in order to simulate cost minimization and cost maximization for comparison. Equations (4.13) and (4.14) provide the objective functions for these models and are used to compare cost-related route solutions to demand-focused solutions.

$$minimize \sum_{k\in K}(c^k_{i,j} * x^k_{l,i} * x^k_{l+1,j}) \tag{4.13}$$

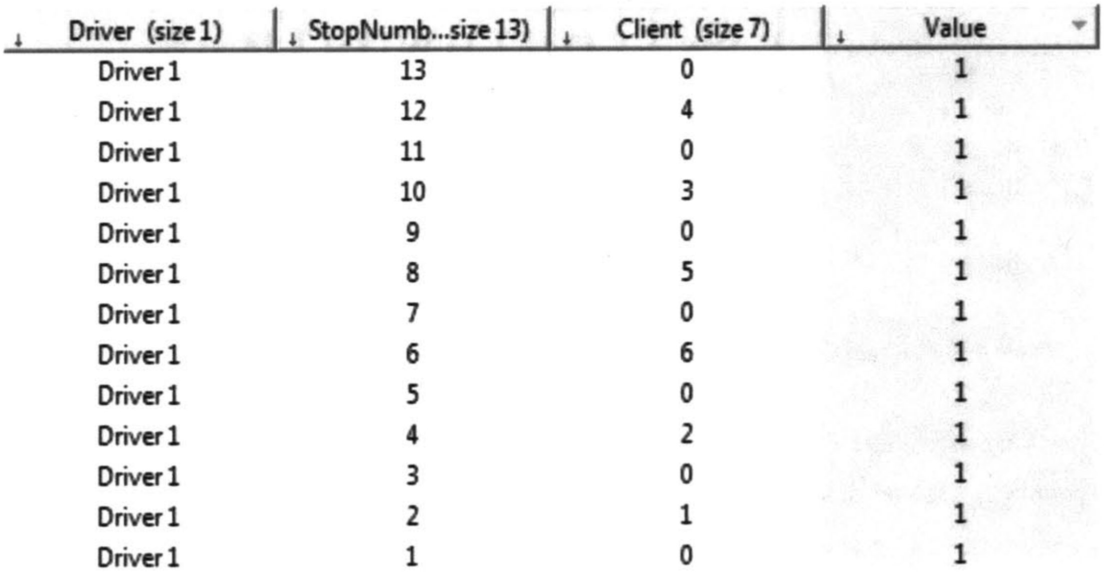
$$maximize \sum_{k\in K}(c^k_{i,j} * x^k_{l,i} * x^k_{l+1,j}) \tag{4.14}$$

The route solutions correlating to objective functions (4.13) and (4.14) are provided in Tables 4-4 and 4-5, respectively. We see that a model solving the minimum cost route option solves very similarly to a model maximizing the maximum hourly demand inflow.



Driver (size 1)	StopNumb...size 13)	Client (size 7)	Value
Driver 1	13	0	1
Driver 1	12	0	1
Driver 1	11	0	1
Driver 1	10	0	1
Driver 1	9	0	1
Driver 1	8	0	1
Driver 1	7	1	1
Driver 1	6	2	1
Driver 1	5	3	1
Driver 1	4	4	1
Driver 1	3	5	1
Driver 1	2	6	1
Driver 1	1	0	1

Table 4-4: Program solution scenario to minimize cost. This solution scenario is identical to the solution shown in Table 4-3.



Driver (size 1)	StopNumb...size 13)	Client (size 7)	Value
Driver 1	13	0	1
Driver 1	12	4	1
Driver 1	11	0	1
Driver 1	10	3	1
Driver 1	9	0	1
Driver 1	8	5	1
Driver 1	7	0	1
Driver 1	6	6	1
Driver 1	5	0	1
Driver 1	4	2	1
Driver 1	3	0	1
Driver 1	2	1	1
Driver 1	1	0	1

Table 4-5: Program solution scenario to maximize total cost. Compare this solution to Table 4-2.

This observation shows the adverse cost-related effects of optimizing to a steady flow at the depot. Were a business able to quantify the potential savings and monetize the efficiencies gained by creating steady flow, this model would provide a baseline for analyzing shadow pricing for those gained efficiencies. This also shows that optimization models can be altered to solve for different objectives fairly simply. With this information in hand, Quest may be able to provide recommendations to their route optimization vendor to repurpose their current product to suit new business needs. Optimization software, such as their RPSA product described in Chapter 3, could be modified to solve for routes that provide a more steady flow of specimens into Quest's Marlborough laboratory.

4.5 Results and Findings

The demand-focused vehicle routing solutions suggest that creating a route network that provides a steady flow of specimens into Quest's Marlborough facility would be cost prohibitive. Fuel, maintenance and repair costs alone would likely increase by as much as 70%. Attempts to manually alter routes have proven, over time, to consume significant resource-hours. Further, such attempts are often undone during routine route maintenance as described in Chapter 3. The optimization software used to provide Quest with the lowest-cost courier networks will generate route solutions counter to the demand-focused objective.

While providing a "level" inflow of specimens may be cost prohibitive, several route solutions exist that balance between a cost minimization solution and a solution provided by DVRPTW. The business should quantify and monetize the benefit of leveling inflow on their in-lab operations to provide this constraint and frame the business-case for route adjustments. Savings could come from labor reduction in off-peak hours, analyzer consumables, physical lab footprint reduction, and reduction in expected call volume relating to late reporting of test results to clients. This model provides a powerful tool that would allow Quest to make informed decisions regarding their courier network.

These findings suggest that focusing on processes outside of logistics may yield significant gains. For Quest's reverse supply chain, the courier network is constrained by client and PSC/IOP-provided volumes. By increasing the number of specimens available during midday courier pickups, specimens will arrive more steadily into the lab. Further, in-lab processes may be altered such that the ultimate goal, releasing clinical test results prior to 8am, may be realized with minimal effort and little cost impact. These opportunities are explored in Chapter 5.

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Chapter 5

Assessing Opportunities in Specimen Management and Patient Service Centers

In testing Quest's hypothesis that their logistics network could provide a consistent in-flow of patient specimens into their Marlborough facility, we've came to two basic conclusions. First, manually altering routes to achieve consistent and level in-flow of samples strains resources and produces minimal results. Secondly, by using a model that optimizes to a desired in-flow profile rather than cost, we conclude that approaching Quest's specimen-flow problems with a logistics-only functional focus is cost prohibitive. In this chapter, we look at the delivery of specimens from the patient to the lab analyzers as a system to determine if there are other areas that may produce greater value with less operational impact.

5.1 Data Collection for Patient Services and Specimen Management

Phlebotomists use Care360 to accession patient samples. This software interfaces with both IDAA and QLS, providing highly accurate and readily available data for accessioning times and volumes. Specimen Management uses IDAA for accessioning all clinical specimens. Cognos, an IBM business analytics product, was used to pull information from IDAA regarding accessioning times and volumes across both the patient service centers and specimen management. Additional information regarding process specifics was gathered by PSC visits and discussions with PSC personnel.

5.2 Patient Service Center Opportunities

Quest phlebotomists perform many tasks outside of their core function, such as payment collection and patient counseling. Additionally, they accession all requisitions prior to courier pickup. A simplified patient cycle is shown in Table 5-1.

Step	Explanation
1	Check in patient: gather basic information, determine tests required, and verify insurance or payment information. Generate Accession Labels
2	Collect sample: PSCs perform a wide variety of draws and collections. The phlebotomist will label all of the patient samples and require patients to verify the information on the samples is correct
3	Perform centrifugation, mixing, and other tasks as required by test type
4	Manifest patient sample for delivery

Table 5-1: Simplified single-patient process for phlebotomist at a Quest PSC.

5.2.1 Daily Arrival Patterns and Requisition Volumes

Patient arrivals are stochastic but a general pattern is shown below in Figure 5-1, normalized to a PSC that would serve 32 patients per day. Phlebotomists are likely to experience their heaviest volumes in the morning. This trend is fairly consistent across the phlebotomy sites, largely due to fasting requirements for many blood and urine tests.

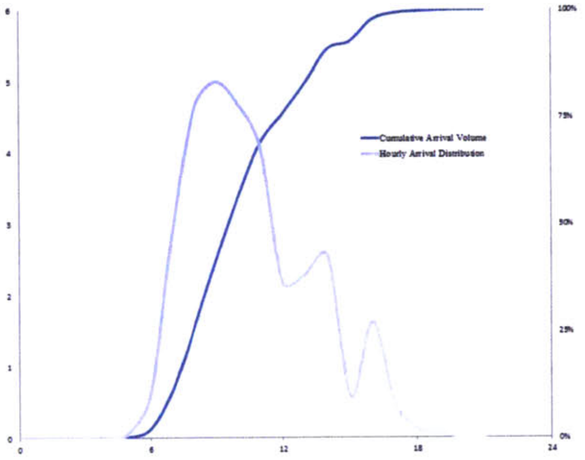


Figure 5-1: Average patient arrival profile (hourly on left axis and cumulative on right) to a New England PSC.

PSC-based requisitions account for a large percentage of Marlborough's overall requisition volume. With transition from Wallingford to Marlborough, on average, nearly half of Marlborough's volume will be from Patient Service Centers and in-office phlebotomists. Further, nearly one-third of the total, full day requisition volume will be drawn prior to noon each day throughout the region at PSCs. Ensuring phlebotomists manifest all available specimens is critical to achieving improved turnaround times.

5.2.2 Manifesting Process

Manifesting is a process through which PSC and IOP personnel release specimens from their clinics, providing traceability in the event of specimen loss. Before releasing specimens to couriers, the phlebotomists create manifests for every accessioned specimen. They often manifest only a portion of the specimens they have accessioned for the midday pickup. The process in Table 5-1 described a single patient cycle. Functional objectives described in Chapter 2, as well as generally high patient visitation volumes immediately prior to driver pickups as shown in Figure 5-2 below, attribute to partial manifesting by phlebotomists. We observed midday manifest-to-accession (MTA) ratios as low as 3%. In May 2015, we monitored MTA across thirteen randomly selected PSC's. We found that 29% of their daily specimen volumes were released for the midday pick up, suggesting that phlebotomists at these sites released only 55% of available specimens.

Low manifest-to-accession ratios can be attributed to process and timing. Figure 5-2, below, shows the relationship between patient arrival times and driver arrival times, showing driver arrivals aligning with higher-volume patient arrival times. This midday pickup is driven by the need to collect same-day requisitions and ensure they are resulted back to clinicians by 5pm each day. If they were able to shift midday pickups to a later time, allowing for more time for phlebotomists to finish their post-draw processes, Quest would likely see an increase in midday pickup volumes.

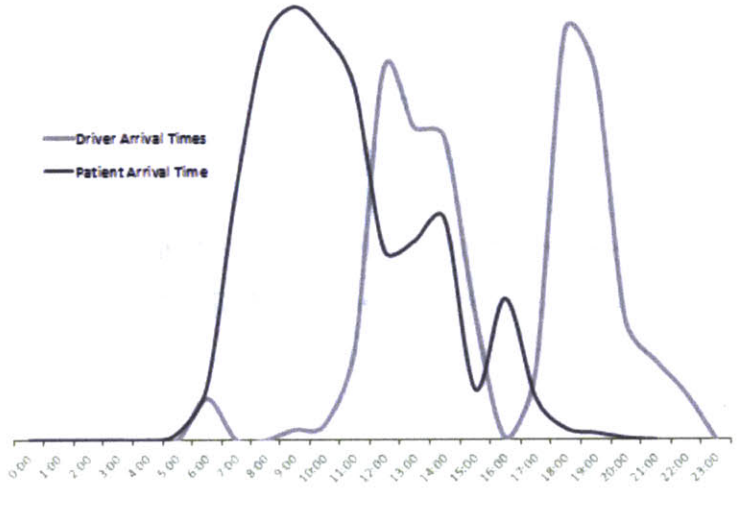


Figure 5-2: Comparison between patient arrival times and courier arrival times.

Currently, Quest does not monitor average cycle times for specimens (accession to manifest) or MTA ratios for its PSCs. Given the remote nature of these clinics and the difficulty of providing direct oversight, the opportunity for phlebotomists to stray from standard practices is ever-present. Treating patient samples within the PSC similar to a one-piece flow approach may improve MTA ratios [11]. Our review of organizations successfully adopting single-piece, or small batch, flow supports this argument.

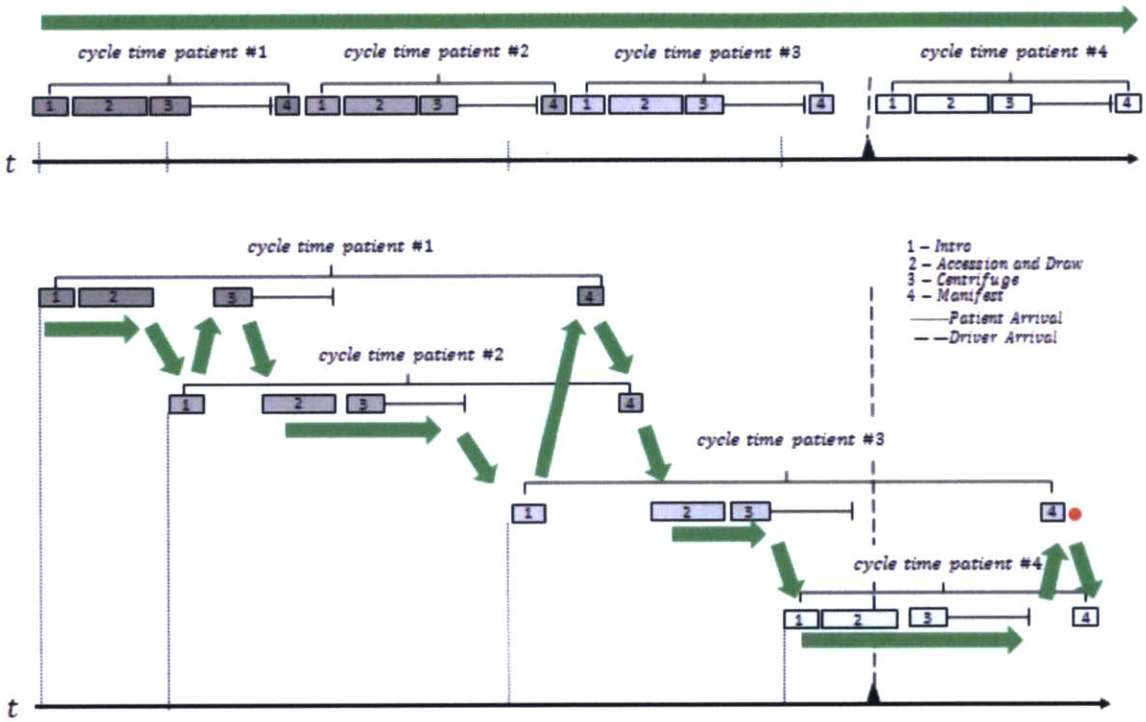


Figure 5-3: One-piece flow (upper) versus current process (lower).

The one piece flow process shown in Figure 5-3 shows less cycle-time per patient and, additionally, shows how single piece flow enables the higher probability of 100% MTA during the first driver pickup. The current process enables process reentry, often causing confusion and delay. The advantage to the current process is a decrease in patient wait-times, but this at the expense of later test-release times. Research suggests that lowering patient wait times at the expense of later-release times does not result in a more satisfactory performance in the eyes of the patient [17] [18]. Patient #3's manifest process step is shown to have occurred after the driver pickup, thus delaying the delivery of the patient's sample and further perpetuating operational problems.

5.2.3 Results and Findings

A huge opportunity exists to control the flow of single-accession specimens into Marlborough to increase efficiencies and reach the business's 8am test release goals. Methodologies in Chapter 4 describe how this could be achieved through alterations to the courier network, but similar system impact could be made at little-to-no cost by simply increasing the average MTA across the enterprise. This is achievable through closer adherence to single-piece flow. This effort would require significant training across the patient service centers and in-office-phlebotomist clinics, fundamentally changing the focus from individual patients to the patient-population as a whole. This initiative may also require some client and patient education, acknowledging that patient wait times may increase with the eventual goal of providing results more quickly.

Monitoring cycle times, here defined as the time between accessioning and manifesting, may prove to be the best indicator of adherence to single-piece flow. Longer cycle-times suggest that single-piece flow is being ignored, while shorter cycle-times suggest a steady flow of patient samples through the PSC and IOP processes. Direct relationships between manifest counts and accession quantities each morning will be difficult to monitor in the near term given the limitations in manifesting software. Currently, the manifesting module used by phlebotomists to accession patient requisitions lacks export functionality. Scan data from QRoute and Program A, which are described in Table 3-2, may be used to compare collective PSC and IOP morning and full-day volumes. Tables 5-2 and 5-3 show expected relative volumes to compare against daily scan data.

5.3 Specimen Management

A representative graph of total specimen volumes coming into Quest's Marlborough facility is shown below in Figure 5-4. This graph shows a day's volume from 6/17/15 and is populated using figures from Program A as well as RSR route sheet totals and is generally accepted as a fair representation of actual volumes entering the lab. The exact quantity arriving per hour is largely unknown as there is no single IT solution that allows Quest to match a patient order that is accessioned through IDAA back to Program A to develop an accurate arrival pattern. Further complicating the data integrity, clients often report differing units of volume to drivers (number of tubes versus number of requisitions or patients being served). The only true assessment of actual production volumes comes from IDAA volume counts, but a lag exists between when the courier provides the lab with specimens and when those specimens are accessioned. The variation in lag between specimen arrival and accessioning and the inaccuracy of specimen arrival volumes are common to similar businesses in this industry [12].

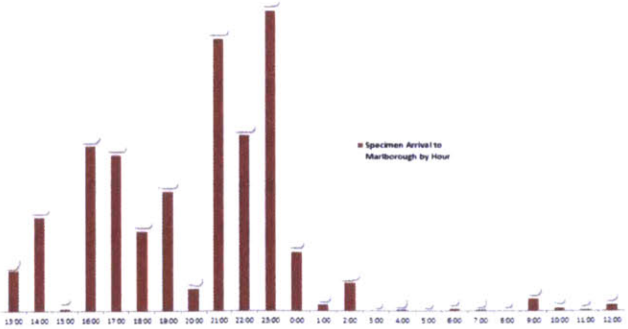


Figure 5-4: Specimen Arrival profile on 6/17/15 for Marlborough lab.

5.3.1 Manual Requisitions and their Impact on Specimen Management

The following figures reflect average arrival volumes of specimens into the Marlborough lab and associated current-state throughput for accessioning stations. Figure 5-5 shows the output of an analysis that identified average manual requisition arrival to the lab in Marlborough (red), the average A-station productivity (blue), and the average B-station productivity (green) per hour over the course of a weekday. Data used for this was pulled from IDAA and represents average throughput across three weeks in May and June 2015. This pattern was derived through matching clients to respective routes, identifying accounts with manual requisition volumes, determining average manual requisition quantity, and identifying any mid-route transfers. Arrival volumes were scaled proportionally to reflect clinical pathology tests only as the data did not classify specimen type.

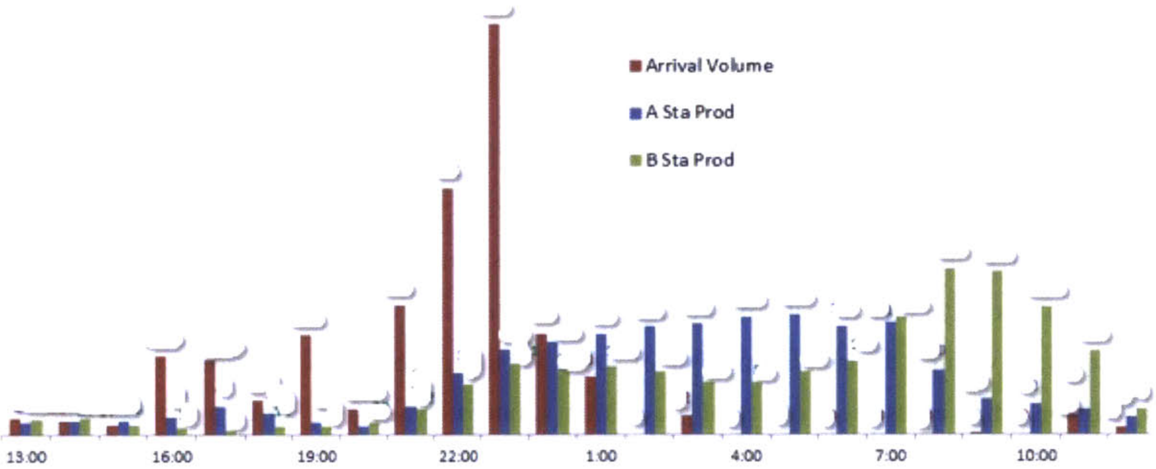


Figure 5-5: Graph of manual requisition average arrival profile, A-Station hourly throughput, and B station hourly throughput as of 6/11/15.

The early-morning focus, as shown in Figure 5-5, is clearly to process specimens through A-station to ensure they are analyzed in the technical departments before 8am. This focus on providing specimens to the technical lab, however, affects completion of B-station process steps. A significant manual requisition backlog at A-station is built during the second shift and is shown in Figures 5-6 and 5-7. Quest currently designs their specimen management processor-staffing model to ensure all employees are productive throughout their entire shift, and building a backlog for third shift ensures higher processor utilization.

Figures 5-6 and 5-7 show the resultant queues for A and B-station, derived from comparing hourly requisition arrival expectations to historic productivity and throughput values. These figures are important in showing where the largest queue times are and identifying the scale of these queues. The aforementioned staffing model, aimed to maintain near-100% processor utilization, can surely be satisfied by staggering processor start-times through the second and third shifts, as they do now, only with increased staffing beginning shortly before or after midnight.

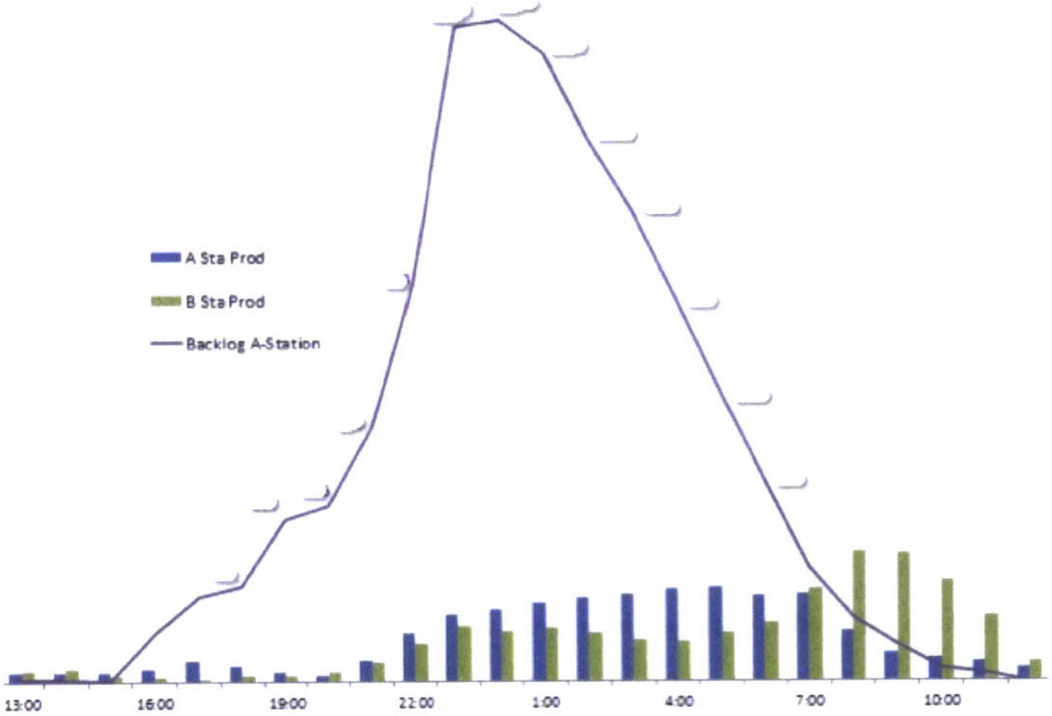


Figure 5-6: Graph showing average daily A-station backlog based on hourly differences between expected specimen volumes arriving and average productivity.

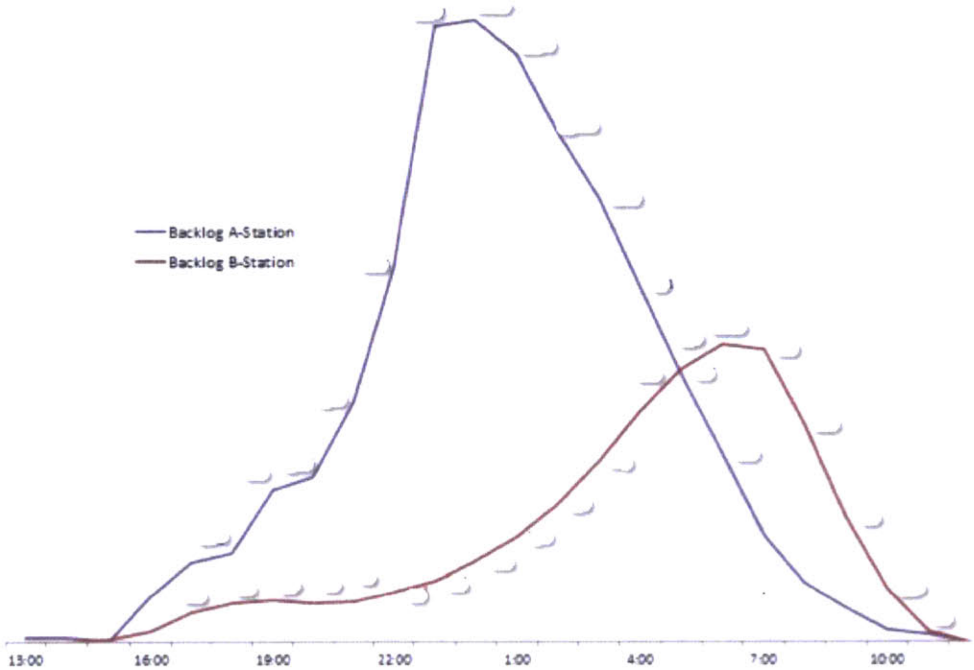


Figure 5-7: Graph comparing A-station backlog to B-station backlog. B-station backlog was calculated by comparing A-station throughput to B-station throughput by hour.

During the midnight to 6am hours, staffing within Specimen Management is clearly weighted towards A-station. This is evidenced by the peak time differences in Figure 5-7. This figure also shows, clearly, that B-station processing is occurring well past 8am, on average, for the previous day's requisitions. The information provided in the following section will compare the volume of tests processed through B-station after 8am to those tests analyzed after 8am.

5.3.2 Throughput and Staffing

Manual requisitions account for nearly one-fifth of all requisitions accessioned within specimen management. These requisitions, as previously discussed, must pass through both A and B process stations before clinicians can receive test results. Figure 5-8 shows a pictorial relationship between processing stations, lab testing, and resulting. Expected throughput for an experienced processor is λ_A and λ_B requisitions-per-hour for A and B stations, respectively. Throughput for technical department processes varies by platform. Table 5-3 provides general overview of the average queue times for each analyzer, though most fall between one and three hours.

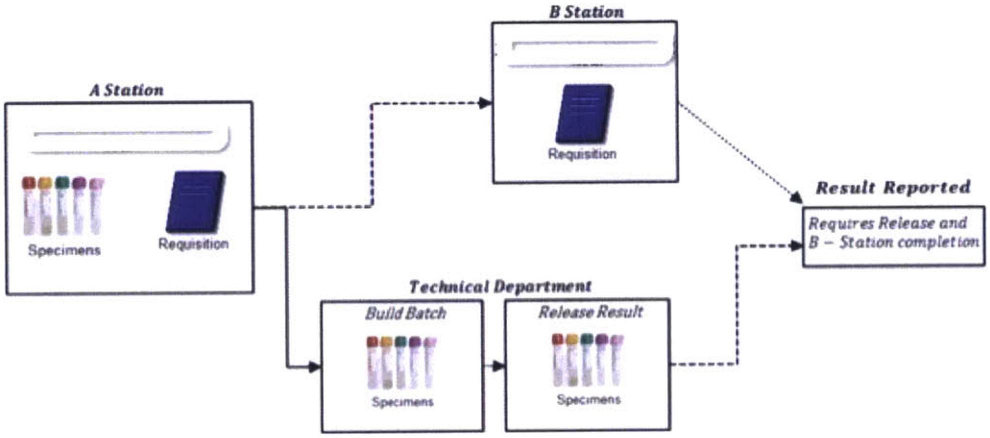
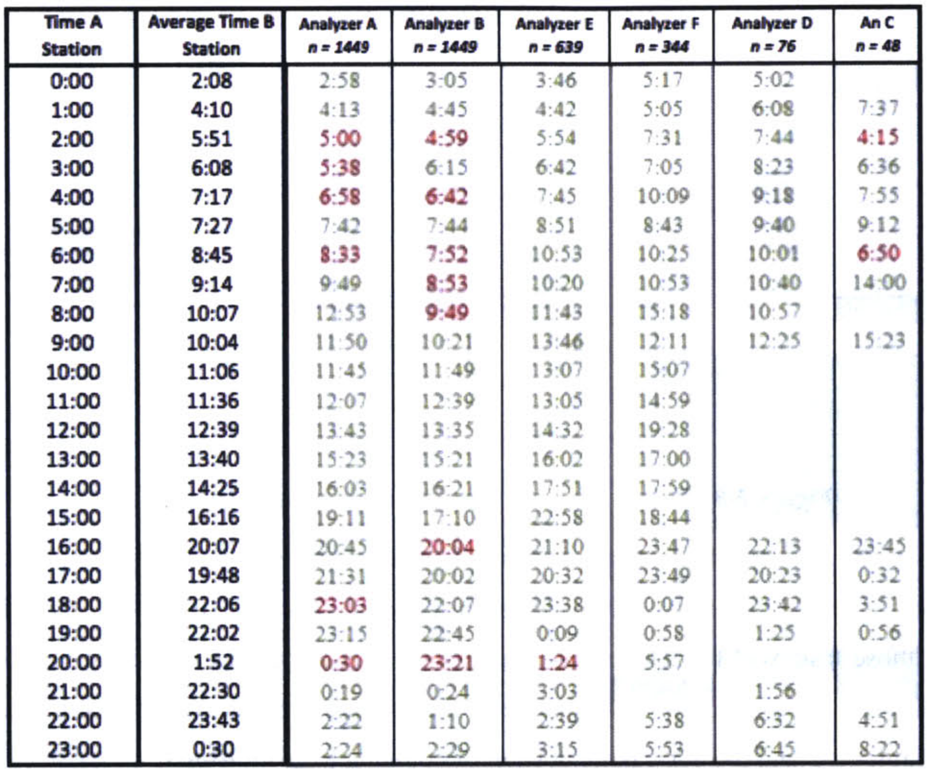


Figure 5-8: Basic in-lab manual requisition processing pathway.

This figure shows the general flow of requisitions documentation and test specimens. Tests are sent through B-station and the technical laboratories in parallel. Thus, if B-station lags the technical laboratory, then those tests will be delayed. To identify the likelihood and frequency of this happening, Quest's turnaround time (TAT) report was analyzed for average process and connection timing and is summarized in Tables 5-2 and 5-3 for a large portion of common 8am TAT tests.

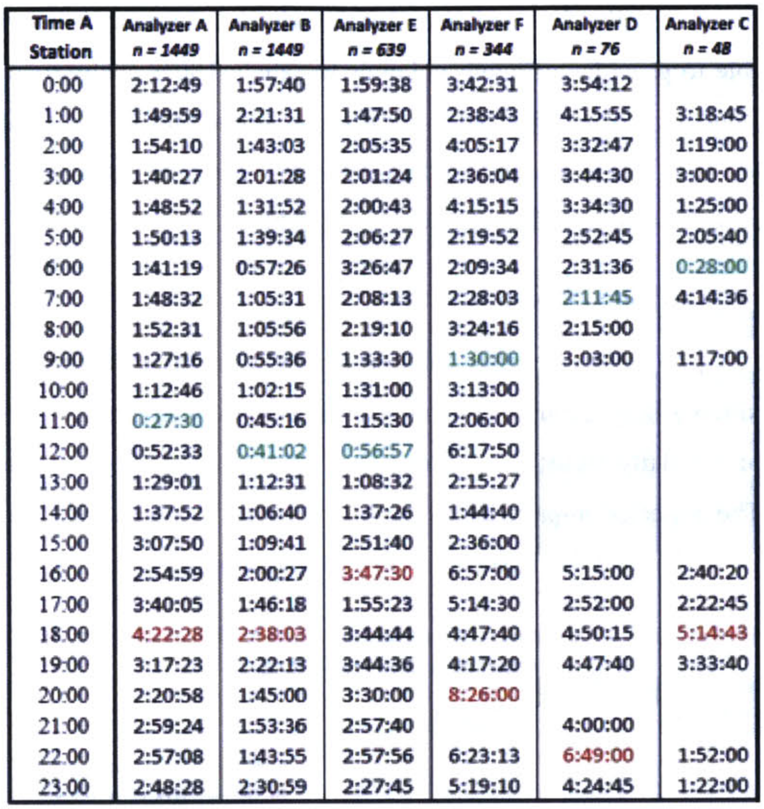
Table 5-2 shows the relative balance between B-station completion time and test-release time from the test's respective analyzers. Of those requisitions accessioned between midnight and 7am, one quarter are processed through B-station after 8am while only one twentieth are analyzed after 8am. Of those requisitions accessioned through A-station between midnight and 6am, one fifth are processed through B-station after 8am. Less than one fiftieth of requisitions processed through A-station between midnight and 6am have analyzer release times after 8am. This difference, again, strengthens the argument for increased and dedicated processors to remain at B-station. The bottleneck within this process remains within Specimen Management during the busiest and highest-volume hours in Marlborough.



Time A Station	Average Time B Station	Analyzer A *n = 1449*	Analyzer B *n = 1449*	Analyzer E *n = 639*	Analyzer F *n = 344*	Analyzer D *n = 76*	An C *n = 48*
0:00	2:08	2:58	3:05	3:46	5:17	5:02	
1:00	4:10	4:13	4:45	4:42	5:05	6:08	7:37
2:00	5:51	5:00	4:59	5:54	7:31	7:44	4:15
3:00	6:08	5:38	6:15	6:42	7:05	8:23	6:36
4:00	7:17	6:58	6:42	7:45	10:09	9:18	7:55
5:00	7:27	7:42	7:44	8:51	8:43	9:40	9:12
6:00	8:45	8:33	7:52	10:53	10:25	10:01	6:50
7:00	9:14	9:49	8:53	10:20	10:53	10:40	14:00
8:00	10:07	12:53	9:49	11:43	15:18	10:57	
9:00	10:04	11:50	10:21	13:46	12:11	12:25	15:23
10:00	11:06	11:45	11:49	13:07	15:07		
11:00	11:36	12:07	12:39	13:05	14:59		
12:00	12:39	13:43	13:35	14:32	19:28		
13:00	13:40	15:23	15:21	16:02	17:00		
14:00	14:25	16:03	16:21	17:51	17:59		
15:00	16:16	19:11	17:10	22:58	18:44		
16:00	20:07	20:45	20:04	21:10	23:47	22:13	23:45
17:00	19:48	21:31	20:02	20:32	23:49	20:23	0:32
18:00	22:06	23:03	22:07	23:38	0:07	23:42	3:51
19:00	22:02	23:15	22:45	0:09	0:58	1:25	0:56
20:00	1:52	0:30	23:21	1:24	5:57		
21:00	22:30	0:19	0:24	3:03		1:56	
22:00	23:43	2:22	1:10	2:39	5:38	6:32	4:51
23:00	0:30	2:24	2:29	3:15	5:53	6:45	8:22

Table 5-2: Comparison between A-station completion time, B-station completion time, and analyzer completion time for a sample of 8AM TAT tests. Red font indicates those times where the analyzers result tests before B-station completion time.

Other intuitions that Table 5-2 provides us are: with the Analyzer B, on average, all tests processed through A-station prior to 6am are resulted prior to 7:52am whereas B-station delays test reporting until 8:45am. For all other machines, the analyzer queues and processing times appear to delay reporting rather than B-station queues and completion timing. Table 5-3 and Figure 5-9 below provide average queue times for each of the machines on the 8am test-release menu. Interestingly, the longest queue times for most of the machines hover around 6pm.



Time A Station	Analyzer A n = 1449	Analyzer B n = 1449	Analyzer E n = 639	Analyzer F n = 344	Analyzer D n = 76	Analyzer C n = 48
0:00	2:12:49	1:57:40	1:59:38	3:42:31	3:54:12	
1:00	1:49:59	2:21:31	1:47:50	2:38:43	4:15:55	3:18:45
2:00	1:54:10	1:43:03	2:05:35	4:05:17	3:32:47	1:19:00
3:00	1:40:27	2:01:28	2:01:24	2:36:04	3:44:30	3:00:00
4:00	1:48:52	1:31:52	2:00:43	4:15:15	3:34:30	1:25:00
5:00	1:50:13	1:39:34	2:06:27	2:19:52	2:52:45	2:05:40
6:00	1:41:19	0:57:26	3:26:47	2:09:34	2:31:36	0:28:00
7:00	1:48:32	1:05:31	2:08:13	2:28:03	2:11:45	4:14:36
8:00	1:52:31	1:05:56	2:19:10	3:24:16	2:15:00	
9:00	1:27:16	0:55:36	1:33:30	1:30:00	3:03:00	1:17:00
10:00	1:12:46	1:02:15	1:31:00	3:13:00		
11:00	0:27:30	0:45:16	1:15:30	2:06:00		
12:00	0:52:33	0:41:02	0:56:57	6:17:50		
13:00	1:29:01	1:12:31	1:08:32	2:15:27		
14:00	1:37:52	1:06:40	1:37:26	1:44:40		
15:00	3:07:50	1:09:41	2:51:40	2:36:00		
16:00	2:54:59	2:00:27	3:47:30	6:57:00	5:15:00	2:40:20
17:00	3:40:05	1:46:18	1:55:23	5:14:30	2:52:00	2:22:45
18:00	4:22:28	2:38:03	3:44:44	4:47:40	4:50:15	5:14:43
19:00	3:17:23	2:22:13	3:44:36	4:17:20	4:47:40	3:33:40
20:00	2:20:58	1:45:00	3:30:00	8:26:00		
21:00	2:59:24	1:53:36	2:57:40		4:00:00	
22:00	2:57:08	1:43:55	2:57:56	6:23:13	6:49:00	1:52:00
23:00	2:48:28	2:30:59	2:27:45	5:19:10	4:24:45	1:22:00

Table 5-3: Average queue time for 8am TAT platforms relative to A-station accessioning time for a sample of 8AM TAT tests. Red font identifies maximum queue times, green identifies minimum queue times.

For the machines that see the highest daily volumes, Analyzers A and B, average queue times from specimens fall steadily throughout the night as the highest volume hours pass. Figure 5-9 shows this trend. This is counterintuitive, as the majority of the day's tests enter Quest's Marlborough laboratory at 11pm. We would expect the average queue times to somewhat mirror the A-station backlog profiles shown in Figures 5-6 and 5-7.

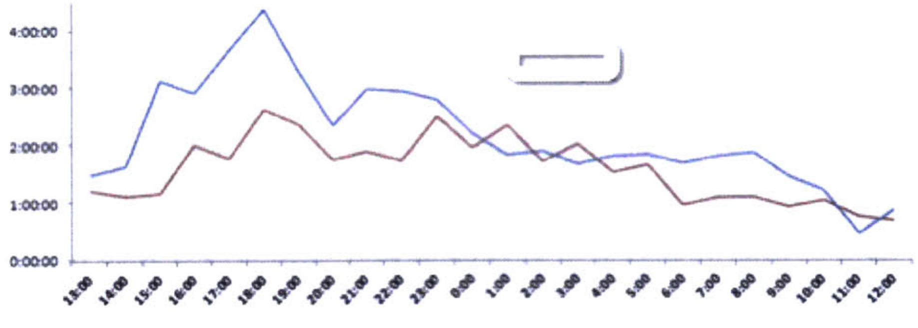


Figure 5-9: Average queue time for Analyzer A (Blue) and Analyzer B (Red) for 8am TAT testing.

This declining queue time profile for analyzers in the clinical laboratory suggests that A-station processors may be unable to provide sufficient volumes to satisfy 100% analyzer utilization. This is an important observation, but manual requisitions only account for a fifth of the total day's volume, all others being electronic and single accessioned specimens. Still, this suggests that the technical departments can keep up with the demand throughout each night.

5.3.3 Transitioning Manual accounts to Electronic

Staffing alterations are not, however, the only solution available to attain similar results. In June 2015, Quest was able to transition a large group of clients from manual requisitions to electronic. Specifically, 30 clients with a total of 215 daily requisitions transitioned from "results only" manual requisitions to bi-directional interfaces. The expected impact, based off of the author's calculations, on manual requisition arrival and subsequent A-station backlog is shown below in Figure 5-10.

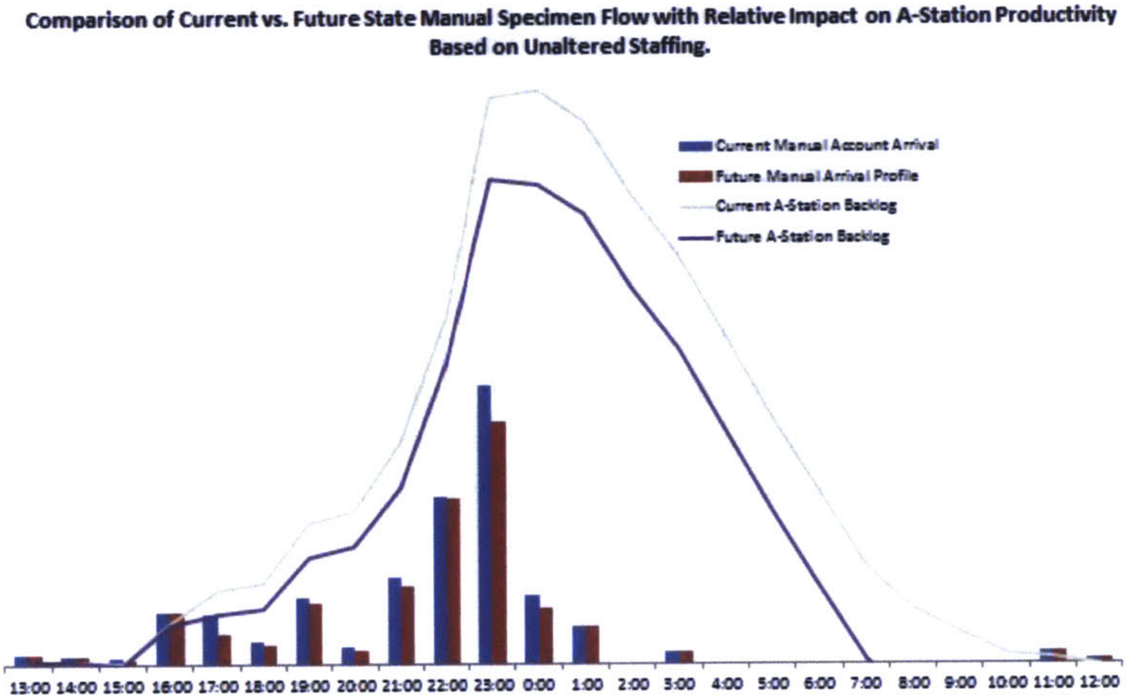


Figure 5-10: Comparison of current versus future stat manual specimen flow with relative impact on A-station backlog based on an un-changed staffing model after a set of clients transitioned from manual to electronic requisitions.

The impact is significant, pulling expected queue-end time for A-station to 7am from 10am. A joint effort to push A-station completion to some time prior to 5:00am, B-station completion prior to 8:00am, and continuing to push clients to transition to electronic requisition systems is necessary to fully integrate the supply chain.

5.3.4 Results and Findings

Staffing is a contributing factor for Quest's timely-release problems for 8am TAT tests. Since the majority of manual requisitions enter the Marlborough facility prior to midnight, providing additional staffing to allow for A-station completion prior to 5am would increase the likelihood of releasing results prior to 8:00am. As mentioned in 2.2.3, specimen management bases their staffing model on getting maximum output out of their processors. Thus, queues often build until a time that processor efficiencies will be highest. Succinctly, "...we must *not* seek to optimize every resource in the system. A system of local optimums is not an optimum system at all; it is a very inefficient system" [33]. Quest's diagnostic delivery process, as a whole, does not benefit from this staffing approach, which currently optimizes non-bottleneck efficiencies.

Additionally, transitioning clients and electronic medical record vendors from manual to electronic requisitions would significantly impact operations within Specimen Management. As mentioned in Chapter 1, submitting tests electronically reduces ordering errors, which also reduces the time a requisition spends in Specimen Management. The benefits of transitioning clients and vendors to electronic ordering are widespread. Elimination of manual requisitions should be the goal, and growing electronic medical record technology will be of assistance in the future.

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Chapter 6

Conclusion and Recommendations

6.1 Summary of Findings and Recommendations

This research originally focused on developing a demand-focused vehicle routing problem solution in order to address the incredibly high volume of patient specimens arriving in Quest's Marlborough lab between 9pm and 1am each night. Specifically, the task was to provide an affordable routing scenario solution to bring the lab roughly 2,500 specimens per hour between the hours of 11am and 11pm. This led to the development of a small scale DVRPTW model that provided intuitions regarding the relationship between cost and specimen inflow volume variability, assuming all other processes remained unchanged. Further discussion with senior leadership revealed a different focus, which led to an analysis of how Quest Diagnostics could meet an 8am release-time for a subset of clinical tests. This analysis required analyzing opportunities at pre-analytical process steps within the Diagnostic Delivery System.

A summary of findings from each pre-analytical focus-area is provided below, followed by a set of recommendations pertaining to the 8am test-release goal and general operational improvements.

6.1.1 Logistics Network

The demand focused vehicle routing problem could be deployed, at a large scale, on Quest's courier network to provide a route schematic for a steady flow of specimens into their Marlborough facility. Creating a perfectly balanced flow of specimens would prove to be an extremely expensive endeavor, given that a small-scale comparison between a minimum cost objective and level flow objective yielded a 72% increase in operating costs. A demand-focused vehicle routing problem, solved solely to provide steady demand in a reverse supply chain, solves similarly to cost *maximization* vehicle routing solutions. Additionally, there is no indication that providing a more steady flow of specimens into Marlborough would improve Quest's current 8am test-release goal without substantial staffing alteration.

Adding demand-related functionality to their current route planning software would bring little improvement without fully understanding the financial benefits to operations of being able to level inbound flow across the enterprise. Thus, Quest should monetize the benefit of having balanced and level flow and determine their willingness to pay for increased logistics services. Many iterations of the

DVRPTW would have to be run, with varying costs for each iteration, in order to truly compare costs and benefits of level flow. Cost benefits would likely come from reagent utilization, staffing, analyzer footprint, and a decrease in customer call volumes relating to late test release.

6.1.2 Patient Service Centers

From a process perspective, significant improvement possibilities exist within the PSC's. Across the clinics, varying configurations for physical set up, equipment locations, and essential consumables were found. Single-piece flow is rarely observed and batch creation for centrifuging and manifesting can be improved to allow for increased service levels for patients. Specific to manifesting, all PSC's should be manifesting throughout the day to ensure the largest volume of specimens are taken with the morning pickup. A metric should be developed and monitored to assess PSC performance to this standard.

As Quest's client-base continues to increase, single-accession requisition volume from the PSC's could likely be used to offset capacity issues as the lab approaches capacity. Given the PSC's ability to single-accession requisitions through Care360 for any externally developed requisition, another large opportunity, specific to the 8am release-time goal, is to accession more manual requisitions at the PSC's. This cuts down on both A and B-station queues for specimen management and allows for immediate input to the automated system upon entry for pre-accessioned specimens.

Patient Service Centers will provide a growing percentage of Marlborough's specimen volumes. These locations provide Quest with the greatest latitude to make changes to both pickup times and relay location transfers. With this latitude comes an opportunity for Quest to push their average pickup times later in the day for all PSC and IOP locations, providing phlebotomists with more time to manifest those morning-drawn specimens that should go out with the midday pickup. This would require careful analysis of current same-day test release times to ensure the labs performing same-day testing would be able to release same-day labs prior to 5pm.

6.1.3 Specimen Management

By increasing specimen management's capacity during peak hours, the 8am test-release time goal is more easily achievable. As evidenced by findings in section 5.3, when the supply of processors matches the demand of the specimen in-flow, the bottleneck of the system resides within the technical departments. When staffing is constructed to improve processor efficiencies, the bottleneck becomes the B-station data entry process.

Additionally, analysis suggests that significant improvements are gained through transitioning clients from manual to electronic interfaces. Quest should continue to pursue transitioning larger volume manual clients to, at a minimum, submitting requisitions electronically through Care360. Long-term strategy across the enterprise should be to transition all accounts to bi-directional interfaces and push configuration management throughout their reverse-supply chain. This will increase operational efficiency and decrease errant orders from clinicians.

Quest should also challenge the segregation of A and B-station processes. The expected processing time at B-station is 48 seconds per requisition and the expected processing time for A-station is 80 seconds. Thus, J-station expectation (prior to automation) is roughly 128 seconds. Expected processing time for A-station with automation (due to decreased requirements for pour-offs and aliquoting) will decrease to 67 seconds per requisition, driving J-station expectations down to less than 115 seconds. After automation is fully operational, will it be advantageous to merge A and B-station in Marlborough?

Quest should also consider evaluating which process steps truly add value and remove those that do not as they overly complicate and prolong the courier and accessioning processes. Examples of this include chain-of-custody requirements, signatures required for frozen specimens, and segregation of large client specimens with independent and special processes.

6.2 Turnaround Time in a Competitive Healthcare Marketplace

The health care market, and more specifically the Diagnostic Information Services market, is unique given the relationship between health plans, patients, and clinicians. Quest's largest payers, those who actually pay the bill, are health plans and patients. For Quest, clinicians and large independent physician associations are "clients", in essence, as these practices are ordering tests and often giving direction to their patients regarding testing location. While they have no stake in test pricing, they are most likely to hold Quest accountable for service quality disruption.

Quest partners with clients including major health plans to define test release times acceptable to both parties. Although test release times may vary, a significant number of Quest payers do not place a limitation on turnaround time. In view of this observation, Quest could better leverage its partnerships on constraints which are more important and beneficial to both parties, such as driving down operating costs and increasing operational efficiency.

This maze of payers, patients, and clients creates a dynamic between revenue and operating costs. Price appears to be the true driver for market position amongst health plans, and if the price-point they offer could drop by virtue of the efficiencies gained by later release, perhaps this is the direction Quest should pursue. The opportunity for creating service tiers, offering faster clinical results for higher paying health plans, would likely overly complicate the accessioning practices as well. Assuming that Quest's market share would drop as a result of increased TAT, determining the break-even point between decreased revenue and decreased operating costs would be a first step. Assuming third-shift employees demand roughly 15% higher salaries, establishing large savings early is achievable.

Quest should certainly reconsider their position on TAT as a differentiator. This push to release tests later would create a fast-paced, high volume operation during first shift. During first shift, all functional managers are present and the problem-solving capabilities of the lab are presumably at their highest.

6.3 Closing Remarks

Continued research efforts between Quest Diagnostics and the MIT Leaders for Global Operations program will continue to present opportunities for both parties. I suggest that further research effort be placed in PSC operations to develop standard work and refine their processes. This, coupled with further research into front-end operations, would provide a high return for Quest and a quality research topic for future students. Additional opportunity exists for research into methodologies for decreasing analyzer-consumable waste for machines enterprise wide. This is a national objective that requires thorough analysis of manufacturing-like concepts including machine batch sizing, inventory controls, and process improvement.

Quest Diagnostics is a remarkable company that provides first-rate service to clinicians and patients. I am grateful for the hospitality and support they provided during the six months I was on site at their Marlborough location. Thank you to those who supported my research, lent me your time, and provided me with a fantastic experience.

Appendix A

Formulation of a Conventional Vehicle Routing Problem with Time Windows

This appendix is a complete description of the model formulation of a classical VRPTW as described in [4], modified to omit capacity concerns given the nature of the cargo in Quest's operations.

Given graph G, where $\mathrm{G} = (\mathrm{V}, \mathrm{A})$, V to denote all client locations within the subset *C* as well as the depot location *0*, A to denote a set of arcs x_{ij}^k between points *i* and *j* within V for driver k belonging to K.

Each customer $i \in C$ has an average demand d_i, an expected service duration s_i, and a time-window tuple for pickup or delivery $\{e_i, l_i\}$. The depot location has a time window of $\{e_0, l_0\}$. b_i^k denotes the time that driver k arrived at client *i*.

Data regarding time (t_{ij}), cost (c_{ij}), and distance (d_{ij}) between points in V are known. Conventional formulation of VRPTW shown below:

$$minimize \sum_{k \in K} \sum_{i \in C} \sum_{j \in C} c_{ij} x_{ij}^k$$

$$subject\ to:$$

$$\sum_{k \in K} \sum_{j \in C} x_{ij}^k = 1, \forall i \in C: every\ customer\ visted\ once.$$

$$\sum_{j \in C} x_{0j}^k = 1, \forall k \in K: every\ driver\ leaves\ the\ depot.$$

$$\sum_{j \in C} x_{i,0}^k = 1, \forall k \in K: every\ driver\ returns\ to\ the\ depot.$$

$$\sum_{i \in C} x_{i,h}^k - \sum_{j \in C} x_{h,j}^k = 0, \forall h \in C, \forall k \in K: \text{ ensures conservation of flow.}$$

$$b_i^k + s_i + t_{ij} + M\left(1 - x_{ij}^k\right) \leq b_j^k, \forall i, j \in V, k \in K: ensures\ time\ acrues\ properly.$$

$$e_i \leq b_i^k \leq l_i, \forall i, j \in V, k \in K: ensures\ drivers\ comply\ with\ timewindow\ constraints.$$

$$x_{ij}^k \in \{0,1\}, \forall i, j \in V, k \in K: binary\ constraint\ for\ x.$$

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Appendix B

DVRPTW Code

The below code is written in OPL (Optimization Programming Language) developed for ILOG CPLEX. This formulates the demand-focused vehicle routing problem discussed in this thesis.

The following shows data required for the model.

```
{string} Driver = ...;
{string} StopNumber = ...;
{string} Client = ...;
{string} driver_origin = ...;
float driver_begin[Driver] = ...;
float driver_finish[Driver] = ...;
float demand[Client] = ...;
float early_time[Client] = ...;
float late_time[Client] = ...;
float service_time[Client] = ...;
float Time_ij[Client,Client] = ...;
float dist_ij[Client,Client] = ...;
float Cost_ij[Client,Client] = ...;
```

The following shows the model's decision variables.

```
dvar boolean X[Driver,StopNumber,Client];
dvar float+ a[Driver,StopNumber];
dvar int+ d[Driver,StopNumber];
```

The following shows select decision expressions from the model to represent the larger scale model. The below will show inputs required for a single-driver case.

These below expressions provide easily callable instances for limiting cost, time, or distance as shown in the constraints section below.

```
dexpr float StartTime1 = sum( s in StopNumber: s=="1", k in Driver: k=="Driver 1")a[k,s];
dexpr float EndTime1 =  sum( s in StopNumber: s=="25", k in Driver: k=="Driver 1" )a[k, s];
dexpr float TotalTime1 = EndTime1-StartTime1;
dexpr float TotalCost = sum ( i in Client, j in Client, ns in StopNumber: ns!="1", s in
StopNumber: intValue(s) == intValue(ns)-1, k in Driver ) Cost_ij[i,j] * X[k,s,i]*X[k,ns,j];
dexpr float TotalDistance = sum(i in Client, j in Client, s in StopNumber:s!="1", ps in
StopNumber: intValue(ps)==intValue(s)-1, k in Driver)X[k,ps,i]*X[k,s,j]*dist_ij[i,j];
```

The following represent travel times from stop *i* to *j*. These are shown as decision expressions as OPL more easily processes quadratic constraints within decision expressions. These lines would be repeated for desired instances of drivers and number of stops the drivers would be limited to...

```
dexpr float Timeij_X11i_X12j = sum ( i in Client: i =="0", j in Client, ps in StopNumber:
ps=="1", s in StopNumber: s=="2", k in Driver: k=="Driver 1" )
Time_ij[i,j]*X[k,ps,i]*X[k,s,j];
dexpr float Timeij_X12i_X13j = sum ( i in Client, j in Client, ps in StopNumber: ps=="2", s in
StopNumber: s=="3", k in Driver: k=="Driver 1" ) Time_ij[i,j]*X[k,ps,i]*X[k,s,j];
...
```

The following expressions represent service durations at different customer locations associated to stop numbers.

```
dexpr float service_X11j = sum ( i in Client, s in StopNumber: s=="1", k in Driver: k=="Driver
1" ) service_time[i]*X[k,s,i];
dexpr float service_X12j = sum ( i in Client, s in StopNumber: s=="2", k in Driver: k=="Driver
1" ) service_time[i]*X[k,s,i];
...
```

The following expressions represent early and late pickup times for stops as they associate to chosen clients.

```
dexpr float early_X12j = sum ( i in Client, s in StopNumber: s=="2", k in Driver: k=="Driver
1" ) early_time[i]*X[k,s,i];
dexpr float early_X13j = sum ( i in Client, s in StopNumber: s=="3", k in Driver: k=="Driver
1" ) early_time[i]*X[k,s,i];
...

dexpr float late_X12j = sum ( i in Client, s in StopNumber: s=="2", k in Driver: k=="Driver 1"
) late_time[i]*X[k,s,i];
dexpr float late_X13j = sum ( i in Client, s in StopNumber: s=="3", k in Driver: k=="Driver 1"
) late_time[i]*X[k,s,i];
...
```

The following expressions represent demand received at stops as they associate to chosen clients.

```
dexpr float demand_X12j = sum ( i in Client, s in StopNumber: s=="2", k in Driver: k=="Driver
1" ) demand[i]*X[k,s,i];
dexpr float demand_X13j = sum ( i in Client, s in StopNumber: s=="3", k in Driver: k=="Driver
1" ) demand[i]*X[k,s,i];
...
```

The following expression is the objective function of the model.

```
minimize max(s in StopNumber, k in Driver)d[k,s];
```

The following expressions provide the model constraints.

```
subject to {

/*The below constraints can be used to constrain Cost, Distance and Time for routes as
desired*/
forall (k in Driver)
        Total_Cost:
        TotalCost <=2000;
Total_Time1:
        TotalTime1<=8;
Total_Time2:
```

```
       TotalTime2<=9;
forall (k in Driver)
  Total_Distance:
       TotalDistance <=400;


/*ClientsMustBeServiced is a constraint that places a must-serve constraint on all of the
clients that are not the depot node. This says that, for all clients, sum of X across all
drivers and all stops equals exactly one. This does not have any constraint on sequence or on
the stop numbers per driver. This ran alone will cause all clients to be services on the same
driver stop number and the depots not to be served.*/

forall ( i in Client: i!="0" )
  ClientsMustBeServiced:
       sum ( k in Driver, s in StopNumber )
               X[k,s,i] == 1;

/*DriversOnlyUseStopNumOnce is a constraint that limits the number of times a single driver
can use a single stop to be one (exactly). this creates multiple instances of depot arrivals,
which for scale is fine as tij, Cij, distij "0"-->"0" = 0. This, combined with
ClientsMustBeServiced, ensures every client is served and that drivers are only using stop
numbers once.*/

forall ( k in Driver, s in StopNumber )
  DriversOnlyUseStopNumOnce:
       sum ( i in Client )
               X[k,s,i] == 1;

/* DriversStartAtDepot requires that X_k,0,0 =1. DriversEndAtDepot requires that X_k,8,0 =
1.*/

forall (k in Driver, s in StopNumber: s== "13", i in Client: i=="0")
  DriversEndAtDepot:
       X[k,s,i]==1;

forall (k in Driver, s in StopNumber: s=="1", i in Client: i=="0")
  DriversStartAtDepot:
       X[k,s,i] ==1;

/*The below constraints frame the "a" decision variable*/

//// T1 (Always simply equal to the driver's start time)

forall(k in Driver, s in StopNumber: s=="1")
  T1:
       a[k,s]>=driver_begin[k];
forall(k in Driver, s in StopNumber: s=="1")
  T_1:
       a[k,s]<=driver_begin[k];

/*Please note, for stops 2-25, the driver will begin seeing customers and must follow time
windows required by the clients.
Arrival at any stop must be no less than the (travel time from previous stop to current stop)
+ (arrival time at previous stop) + (servicetime at previous stop)*/

//// T1_2

forall(k in Driver: k=="Driver 1", s in StopNumber:s=="2",ps in StopNumber: ps=="1")
  T1_2:
       a[k,s]>=a[k,ps]+Timeij_X11i_X12j+service_X11j;
forall(k in Driver: k=="Driver 1", s in StopNumber:s=="2")
```

```
  T1_2_Early:
        a[k,s]>=early_X12j;
forall(k in Driver: k=="Driver 1", s in StopNumber:s=="2")
  T1_2_Late:
        a[k,s]<=late_X12j;

//// T1_3
forall(k in Driver: k=="Driver 1", s in StopNumber:s=="3",ps in StopNumber: ps=="2")
  T1_3:
        a[k,s]>=a[k,ps]+Timeij_X12i_X13j+service_X12j;
forall(k in Driver: k=="Driver 1", s in StopNumber:s=="3")
  T1_3_Early:
        a[k,s]>=early_X13j;
forall(k in Driver: k=="Driver 1", s in StopNumber:s=="3")
  T1_3_Late:
        a[k,s]<=late_X13j;


...

///////////DEMAND////////////

/*This section will discuss accruing demand as the driver advances throughout their day*/
/* Please note, for stop numbers 3-25, three inequalities are used to replace the single
quadratic equality constraint:
d[k,current_stop] = (1-X[k,curret_stop,depot])*d[k,previous_stop] + demand_Xkstopj
*/

//// D1 (Both Drivers) (ALWAYS 0)
forall(k in Driver, l in StopNumber:l=="1")
  D1:
        d[k,l]== 0;

//// D1_2
forall(k in Driver: k=="Driver 1", s in StopNumber:s=="2", i in Client: i=="0")
  D1_2:
        d[k,s]==demand_X12j;

/* Please note, for stop numbers 3-25, three inequalities are used to replace the single
quadratic equality constraint:
d[k,current_stop] = (1-X[k,current_stop,depot])*d[k,previous_stop] + demand_Xkstopj
*/

////  D1_3
forall(k in Driver: k=="Driver 1", s in StopNumber:s=="3", i in Client: i=="0")
  D1_3_1:
        (d[k,s] - demand_X13j)<=30000*(1-X[k,s,i]);
forall(k in Driver: k=="Driver 1", s in StopNumber:s=="3", ps in StopNumber: ps=="2", i in
Client: i=="0")
  D1_3_2:
        (d[k,s] - demand_X13j)<=d[k,ps];
forall(k in Driver: k=="Driver 1", s in StopNumber:s=="3", ps in StopNumber: ps=="2", i in
Client: i=="0")
  D1_3_3:
        (d[k,s] - demand_X13j)>=d[k,ps]-30000*(1-(1-X[k,s,i]));

//// D1_4
forall(k in Driver: k=="Driver 1", s in StopNumber:s=="4", i in Client: i=="0")
  D1_4_1:
        (d[k,s] - demand_X14j)<=30000*(1-X[k,s,i]);
forall(k in Driver: k=="Driver 1", s in StopNumber:s=="4", ps in StopNumber: ps=="3", i in
Client: i=="0")
```

```
  D1_4_2:
        (d[k,s] - demand_X14j)<=d[k,ps];
forall(k in Driver: k=="Driver 1", s in StopNumber:s=="4", ps in StopNumber: ps=="3", i in
Client: i=="0")
  D1_4_3:
        (d[k,s] - demand_X14j)>=d[k,ps]-30000*(1-(1-X[k,s,i]));

...
}
```

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Appendix C

DVRPTW Variable Notation

Variable	*Description*
$G(V,A)$	Graph of verticies and arcs representing client locations and connections between them
C	Subset of client locations
K	Subset of all drivers
L	Subset of stop numbers $\{1, 2, \ldots L\}$ equal to twice the client volume
$x_{l,i}^{k}$	Boolean variable denoting whether or not driver k visits client i on their l^{th} stop.
a_{l}^{k}	Arrival time of driver k at their l^{th} stop.
D_{l}^{k}	Demand accumulated by driver k through stop l

Data	*Description*
d_i	(data) Demand available at client i.
A	(scalar) Some integer larger than the demand of the entire client network
e^i	(data) Early arrival constraint for client i.
l^i	(data) Late arrival constraint for client i.
s^i	(data) Service duration for client i.
t_{ij}	(data) Travel time between client i and j.
c_{ij}	(data) Cost for travel between client i and j.
d_{ij}	(data) Distance between client i and j.

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