Developing Domain-specific Simulation Objects for Modeling Clinical Laboratory Operations

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Abstract

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Clinical laboratories play a critical role in patient diagnosis, treatment planning and prevention of disease. The inherent complexity of clinical laboratories lies both in the volume and variety of specimen types, which varies by time of day/week and hospital census; different handling and processing requirements based on patient characteristics; the diversity of lab equipment and specialized instruments to perform the tests; and the requirements for appropriately credentialed staff on a 24/7 schedule. Although clinical laboratories reflect many aspects of traditional production systems, the medical profession is, as are most specialized areas of practice, much more willing to entertain modeling approaches that describe their systems with domain-appropriate terminology and semantics. This thesis discusses the development of a framework for creating domain-specific simulation objects for modeling clinical laboratories. These objects are developed based on the chemistry laboratory at Seattle Children's Hospital. In addition, three case studies are conducted to demonstrate the applicability of the objects.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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how I was doing.

At last, I want to thank myself for pulling this through. I had a hard time during the thesis process. But I learned a lot.

DEDICATION

To my dear mother.

To my childhood dream, which is to be a scientist.

Chapter 1

INTRODUCTION

The clinical laboratory plays an important role in hospitals, clinics, and healthcare system as a whole. It processes different specimens, such as fluids (e.g., blood, urine), gases (e.g., breath), or tissue (e.g., biopsy) obtained from patients by healthcare workers in order to provide physicians and other healthcare professionals with information to "detect and predict disease, confirm or reject a diagnosis, establish prognosis, guide patient management, and monitor efficacy of therapy" (Kurec, 2000). Every day, large numbers of specimens arrive at laboratories to undergo a wide variety of tests. These specimens need to be handled differently based on their types and associated tests which require different lab equipment and specialized instruments. The lab instruments are operated by laboratory technologists (LTs) who have necessary skills. Facing the increasing workload and the requirement of reporting the results more quickly, laboratories are interested in understanding how their performance is affected by potential changes in their configuration and operating policies.

1.1 Research Motivation

Due to its ability to handle variation, simulation modeling is a useful method for evaluating the performance of clinical laboratories. However, the development of simulation models is time consuming and requires domain knowledge in addition to knowing how to use simulation software (Sadowski and Grant, 1999). Hiring a model builder to perform a simulation study may not be efficient. Since a model builder is typically not familiar with important aspects of the domain, there may be a disconnect in what the domain expert expects and what the model builder builds.

There are many advantages to be gained from developing a simulation tool specialized for clinical laboratory domains. With pre-defined functions and encapsulated domain knowledge, the simulation tool can be easily understood and used by both engineers and domain experts. Such a simulation tool can facilitate better communication between engineers and domain experts, leading to greater confidence in model results. It can also help domain experts gain insights about their problems when building a model (Heim, 2001). Using the proposed tool, lab experts and engineers could more efficiently examine a variety of lab configurations, gain insights, identify their problems, propose solutions, and test different strategies to improve the performance of their laboratory operations.

1.2 Research Objective

The primary objective of this research is to develop a collection of simulation objects that will provide laboratory professionals and engineers the means to quickly assemble models of their environment with the required level of fidelity. The simulation objects provide sufficient flexibility to analyze a variety of complex clinical laboratory configurations and evaluate alternative operation strategies and policies. A secondary objective is to show the applicability of the simulation objects by constructing models using the objects in case studies.

Chapter 2
LITERATURE REVIEW

Background material related to this thesis contains diverse topics which include domain-specific modeling, the ontology used for computer programming, and previous work done to analyze clinical laboratory operations. The concept of domain-specific modeling is applied to this research to develop simulation objects that are focused on clinical laboratory domains. Moreover, a computer science ontology is used to structure the knowledge and assist in defining objects that need to be modeled. Although different techniques have been applied to support decision making on operations in clinical laboratories, few have used a simulation approach.

2.1 Domain-specific Modeling

A domain-specific language (DSL) may be defined as, "a programming language or executable specification language that offers, through appropriate notations and abstractions, expressive power focused on, and usually restricted to, a particular problem domain" (van Deursen et al., 2000). Domain-specific modeling (DSM) is a methodology which involves systematic use of a DSL to represent the various facets of a system (Rivera et al., 2009). Many papers have examined the use of DSLs and how they can be used in model building. Mernik et al. (2005) discussed the decision making and methodologies for developing a DSL by distinguishing different phases and identifying patterns in each phase. Wegeler et al. (2013) introduced an evaluation strategy for validating the DSM applications. Miller et al. (2010) compared general purpose language (GPL) and simulation programming language (SPL) with an embedded DSL. Miller et al. (2010) concluded that using a DSL could narrow the gap in the model

and program by making a map between the model and the code more obvious. DSL can also reduce the development time, since less code is required, and the code is written in a form that can be easily understood by the people who work in the domain. Moreover, compared to GPLs and SPLs, DSLs can be updated and extended more readily. Many GPLs have changed little in the past few years (e.g., C), which makes them hard to keep up with the advancing modeling methodologies. SPLs have some limitations including language constructs and the requirement of learning a new language. Embedded DSLs can reduce these problems.

According to Setavoraphan and Grant (2008), conceptual modeling (CM) and domain specific simulation environments (DSSE) are recognized as critical steps to improve the quality and efficiency of discrete event simulation. DSSEs leverage the power of DSM languages to provide the model engineers with the building blocks necessary to develop systems rapidly and correctly (Gray et al., 2007). The advantages of using a DSSE, which is summarized by Valentin and Verbraeck (2005), includes better understanding of the simulation model by problem owner, because the concepts of the domain can be recognized in the simulation model (Pater and Teunisse, 1997; Kasputis and Ng, 2000); easier generation of new simulation experiments (Pater and Teunisse, 1997; Altiok et al., 2001); easier validation of the model, because a lot of functions have been pre-defined and validated; less instances of model constructs, because common concepts of the domain have been represented, and these concepts do not need to be coded again (Kasputis and Ng, 2000; Altiok et al., 2001).

2.2 Ontology for Computer Programming

Gruber (2009) defined ontology as an "explicit specification of a conceptualization," which implies that, "the objects, concepts, and other entities that are presumed to exist in some area of interest and the relationships that hold among them." In the context of computer and information science, an ontology defines "a set of representational primitives with which to model a domain of knowledge or discourse" (Gruber,

2009). The purposes of developing an ontology are summarized by Noy and McGuinness (2001):

- **Sharing common understanding of the structure of information among people or software agents.** If different knowledge sources use the same underlying ontology of the terms in a domain, it is easy for people to combine the knowledge and distill the crucial points.

- **Enabling the reuse of domain knowledge.** A large ontology can be built on several existing ontologies with each describing a portion of the large domain. A unique method for developing ontologies can also be shared among different domains.

- **Making explicit domain assumptions.** An ontology can help identify assumptions explicitly. This makes it easier to understand the implications of the assumptions and to revise the assumptions when the knowledge of the domain changes.

- **Separating the domain knowledge from the operational knowledge.** The configuration of a product can be described by its components. These components can be implemented independently. An ontology can be used to configure a made-to-order product.

- **Analyzing domain knowledge.** It is possible to analyze domain knowledge once a declarative specification of the terms is available.

Ontologies have proven to be a useful way to structure knowledge and model a specific domain by providing a formal conceptualization (O'Leary, 1998).

In this thesis, an ontology for a clinical laboratory is created to capture the structure and knowledge of the laboratory domain. The focus of this ontology is to share

a common understanding of the laboratory domain with the domain experts and to identify different objects that need to be modeled.

2.3 Analyzing Clinical Laboratory Operations

Different techniques can be used to improve many aspects of laboratory performance. Techniques used for strategy planning include Graphs, Brainstorming, Fishbone Diagrams, Storyboarding, Pareto Analysis, and Delphi Analysis. Total Quality Management (TQM), Continuous Quality Improvement (CQI), and Six Sigma approaches are useful for quality management (Kurec, 2004).

There are several papers on applying different techniques to laboratories to improve their performance and reduce costs. Sunyog (2003) introduced the improvement in DSI Laboratories by applying Lean and Six Sigma methodologies. Rutledge et al. (2010) at Seattle Children's Hospital (SCH) applied Lean strategy, from the Toyota production system, to their laboratory operations to improve the test turnaround time (TAT) and reduce errors. Marinagia et al. (2000) used a patient-wise planning and scheduling approach for managing patient tests in a hospital environment using a multi-agent blackboard-based architecture. However, very few studies have applied a simulation approach for analyzing clinical laboratory operations.

Chapter 3

METHODOLOGY TO DEVELOP SIMULATION OBJECTS

Object-oriented (O-O) modeling is typically used to break down complex problems into smaller problems that can be individually addressed (Wu, 1990; Garrido, 2009). The O-O paradigm is a methodology used for producing reusable software components. It requires developers to identify a set of objects from the problem domain, and the operations of the domain can then be expressed by the interaction between the objects (Anglani et al., 2002). The approach to O-O modeling in this research is introduced in Section 3.1. To develop objects for a specific domain, detailed observation was performed to better understand the problem area, followed by an initial domain analysis in which the objects were defined. Important aspects related to the objects were then documented and the information was used as a basis for modeling the objects with simulation software. The performance of the objects were verified and validated to ensure they correctly reflected the important aspects of the corresponding real world objects before putting them to use. The details of the domain analysis are presented in Section 3.2.

3.1 Approach to Object-Oriented Modeling

O-O principles are used to identify critical components of the clinical laboratory environment and to develop the allied simulation objects. The implementation of a domain-specific O-O framework has several advantages (van Deursen, 1997):

- **To guide the design of the framework.** If a method or a class cannot be expressed by a language construct, then it is likely that this is not representing

a natural concept of a domain.

- **To encourage the usage of black-box construction.** With black-box construction (Goyal et al., 2012), the code can be protected, therefore reducing the chances of misusing the models.

3.1.1 Observation and Domain Analysis

Lubart (1994) believes that, "A problem well put is half solved". It is therefore important to have a good understanding of the clinical laboratories before designing the objects. All the activities in the laboratory were observed in order to determine the objects in the collection. There are patient-related activities and non-patient-related activities. Patient-related activities are the activities associated with performing tests on specimens, while non-patient-related activities are the activities that have no impact on the test performance. This research focuses on patient-related activities, since the TAT is the main metric that is used to measure the performance of a lab. The tests performed in the lab were categorized based on the analytical instrument needed to perform them. Each test was observed separately to capture the characteristics of it.

In many instances, model builders may know little about a new domain and the experts in those areas may have limited understanding of simulation concepts, therefore it may require a period of time for model builders and domain experts to reach a common understanding. During the process of simulation modeling for a specific domain, an initial analysis should be conducted to evaluate the critical areas of expertise. Many of these elements will be candidates for various modeling components and parameters. The resulting collection of objects created for a specific domain, which represents how the real systems operate, would be understood by both model builders and domain experts (Glassey and Adiga, 1990).

In O-O modeling, objects represent abstractions in order to reduce the complexity

of the real world. However, they still need to have a sufficient level of validity in order to make the model convincing and appropriate for decision making. Therefore, modelers and their partner experts have to decide which aspects of the domain are most important and how to implement them as simulation models (Wang et al., 2013). Here, domain analysis was conducted to structure the domain knowledge and share common understandings with the experts in clinical laboratories, as well as define the collection of objects that need to be modeled and the important aspects of them.

3.1.2 Conceptual Modeling

As the domain analysis was undertaken, information about each of the critical elements was developed in a standard format that was eventually used to guide the design and construction of the simulation objects for this particular domain. In this case, each laboratory test and the necessary instruments, resources, and credentialed staff requirements were recorded. One important part of the documentation is a set of annotated flow charts that identify the major sequence of activities. The complete set of annotated flow charts for the conceptual model is included in Appendix A. The flowcharts were verified with laboratory experts to assure that they were good reflections of the processes as performed in the laboratory. Then high-level flowcharts were created to streamline the annotated flowcharts, and to assist in organizing the activities for each instrument into objects. High-level flowcharts are included in Appendix B. An example high-level flowchart for specimens to be analyzed on an LC/MS instrument is shown in Figure 3.1. This led to an object being created for the LC/MS instrument.

The flowcharts and additional function explications are, in effect, the conceptual models of the primary activities that occur in clinical labs. They are the specifications for the simulation objects that were created and help define the details and characteristics of those objects and accompanying processes.

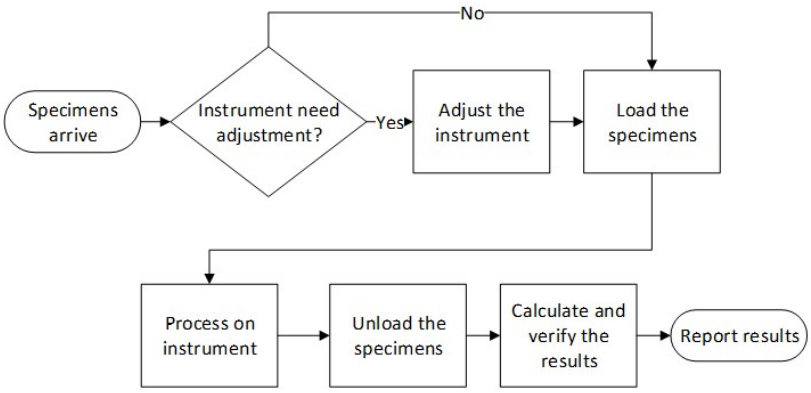

Figure 3.1: Flowchart of analytical processes on an LC/MS instrument.

3.1.3 Object Construction

The conceptual models were then translated into discrete-event simulation (DES) language constructs, which are the objects. The simulation language used to implement the objects in this research is Simio. Simio is an O-O simulation modeling framework that also supports a seamless use of multiple modeling paradigms including event, process, object, and agent-based modeling (Pegden and Sturrock, 2010). Simio is used as the development framework because of its flexibility and its facilities for building families of domain-specific objects. Further details of object construction are described in Chapter 4.

Before the simulation objects are used, all object models were individually verified for correct results and validated for their ability to adequately reflect the important aspects of the problem domain. The objects were presented to laboratory experts to assure that they correctly represent the reality. Example applications were developed to create an appropriate context in which to demonstrate, to laboratory experts, the performance of particular clinical lab simulation objects. Based upon their observations and feedback, programming revisions and corrections were implemented. Sometimes the changes were a result of improper translations from the conceptual

model documentation, and in several cases, errors and omissions were identified in the clinical laboratory object specifications that had to be corrected before any changes could be made to the programming code (i.e., simulation objects). Continuous revisions were made to the model objects as the laboratory experts gained a better appreciation for what could be accurately represented.

Additionally, historical data will be used as input to validate the objects. By comparing the output of each object with the historical output, the objects can be tested to determine whether they reflect the real system. Continued revision should be made to the objects until an acceptable validity is reached.

3.2 Domain Description

The clinical laboratory is at the core of a complex three-phase system that must smoothly and reliably integrate pre-analysis, analysis, and post-analysis processes. The pre-analysis phase refers to the activities from the time the laboratory tests are ordered by care providers, when samples are collected from the patient and transported to the labs under proper environmental conditions (e.g., room temperature, frozen). The analysis phase refers to the laboratory activities to prepare the specimens, perform the tests and produce the results, such as chemical assays on one or more instruments. The post-analysis phrase refers to patient reporting and result interpretation by health care professionals (McPherson and Pincus, 2007).

Although the ultimate objective is to develop a set of simulation objects for modeling clinical laboratories, the initial project focused on the chemistry laboratory at Seattle Children's Hospital (SCH), which is one of their more complex laboratory operations in terms of equipment, analytical processes, and reference client services. Furthermore, this research is mainly concerned with the analysis phase of the testing process.

3.2.1 Chemistry Laboratory at Seattle Children's Hospital

The chemistry laboratory at SCH provides a broad range of testing and analysis services for both SCH patients and a large number of external reference clients (i.e., other hospitals and clinics). Due to the number of testing services offered, limited equipment capacity, and availability of properly credentialed staff, a complex schedule determines when each analysis or suite of tests will be available. The challenge is to provide the tests with sufficient frequency that the resulting TAT meets the needs of patients and their care teams. Because of increasing demand for services, the laboratory has experienced some difficulties in maintaining target TATs during the past year. The chemistry laboratory was interested in understanding how changes to configurations of space, resources, and test schedules could improve their efficiency, meet TAT performance goals and support continued expansion of services and reference laboratory clients.

3.2.2 Domain Analysis for Modeling

There were two objectives for the clinical laboratory domain analysis: 1) to create a shared language, or ontology, for modelers and lab professionals to communicate unambiguously about clinical labs and associated operations, and 2) map the important elements and features of the domain into an organizing structure that would guide modelers developing the clinical lab simulation objects. To accomplish that, a clinical laboratory ontology was developed to identify the objects in the laboratory, as shown in Figure 3.2. This figure was used to understand how laboratory professionals perceive the clinical laboratory domain. The framework is an object hierarchy, or tree, and the process for constructing the ontology follows the work that was done by Wang et al. (2013).

At its most abstract level, the ontology of the laboratory represents instances of lab staff, specimens that arrive for analysis, a knowledge base used to store information of

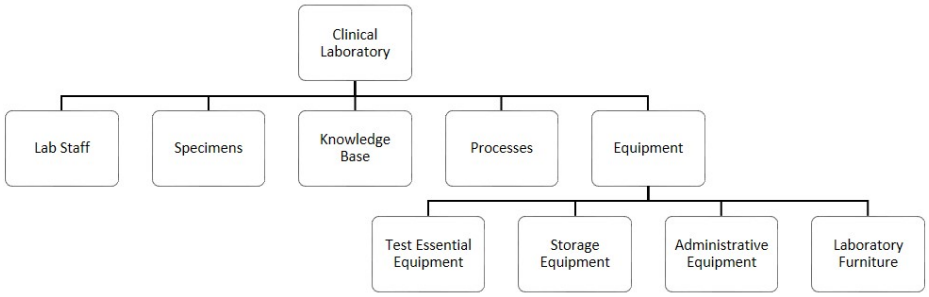

Figure 3.2: Ontology of the clinical laboratory.

documented test procedures, processes to perform patient-related activities and non-patient-related activities, and the variety of equipment necessary to store, prepare, and analyze the specimens. The equipment can be further divided into four categories. The most complex is test-essential equipment, which are generally complex instruments used to perform chemical tests. Storage equipment, where specimens are staged until analysis is initiated, can be temperature-controlled or uncontrolled. Other categories of equipment include: administrative equipment, such as printers, scanners, and computers; and laboratory furniture, such as benches, chairs and shelves.

The simulation object tree, consistent with the ontology, is shown in Figure 3.3. The simulation object tree illustrates all the objects that were developed in this thesis: LTs, specimens, the clinical lab process database, manual tasks, test-essential equipment, and storage.

The first object in the object tree is *lab technologist*, which is an instance of the lab staff. The second object is *specimen*. The third object in the object tree is *clinical lab database*, which corresponds to knowledge base in the ontology.

The *manual tasks* objects are instances of processes. There are two kinds of *manual tasks*, *specimen preparation* and *manual tests*. Each of them can be processed in batch or individually. The details of *manual tasks* objects are discussed in Chapter 4.

This study focused primarily on test-essential equipment because of the complex-

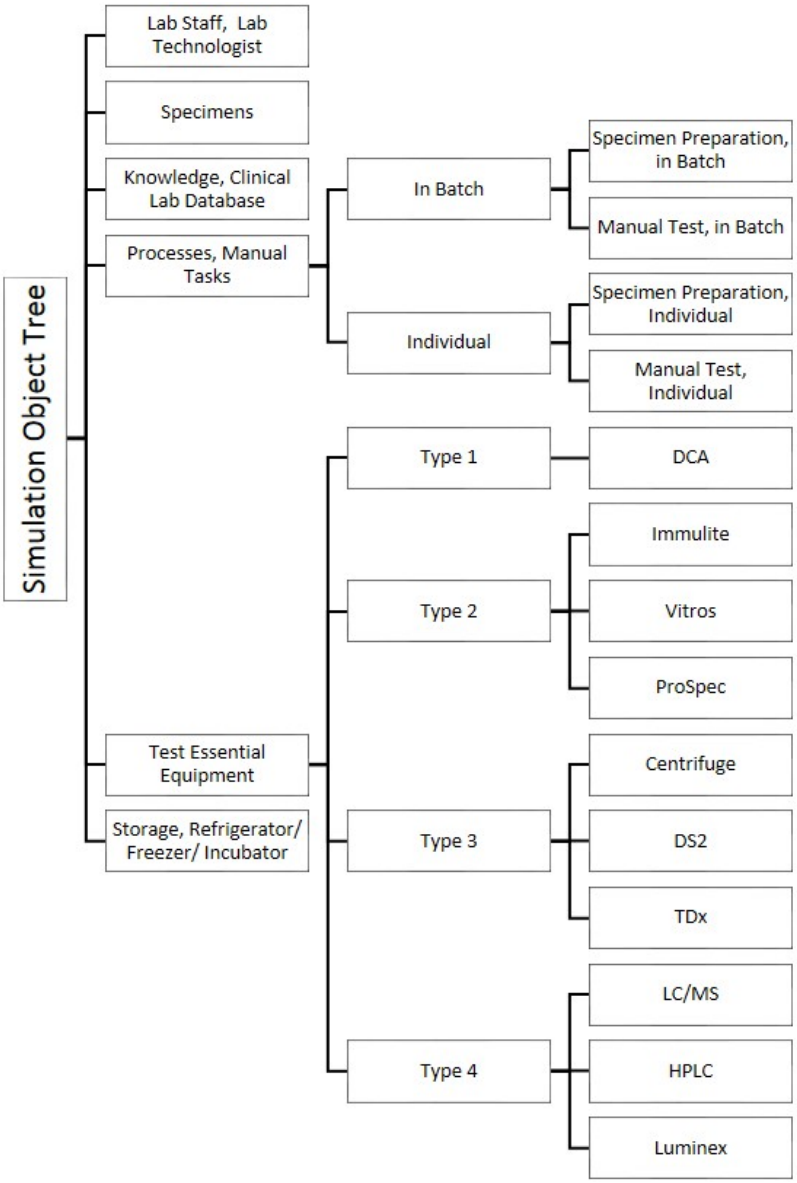

Figure 3.3: Simulation object tree.

Table 3.1: Test-essential equipment type based on processing logic.

	Input		Processing		
	Single	Batch	Single	Batch	Hybrid
Type 1	✓		✓		
Type 2		✓			✓
Type 3		✓		✓	
Type 4		✓	✓		

ity, uniqueness, and modeling challenges it presented, as well as the opportunities it provided to improve laboratory performance. Test-essential equipment has two specimen handling activities: place specimens into the equipment; process the specimens after they have been placed on the equipment. Based on these two activities, test-essential equipment is categorized into four types. The characteristics for each category are specified in Table 3.1. There are two types of logic to place specimens into the equipment: single and batch. When processing the specimens there are three types of logic: single, batch, and hybrid. If input is single, then the process is always single. The DCA instrument is the only object of this type. It is possible for instruments to have batch input, and have different processing logic from there. Each type of test-essential equipment is described in Table 3.2. Further details concerning each piece of test-essential equipment are provided in Table 3.3.

Since the function of storage equipment is not affected by temperature, there is only one type of object representing storage equipment.

Table 3.2: Four types of test-essential equipment

	Logic	Description
Type 1	Specimens are processed individually (single piece flow).	After a specimen arrives it is put into the equipment, processed, removed, and the result verified. The DCA instrument is modeled with Type 1 logic.
Type 2	Specimens are loaded as a batch. Each specimen may require a different number of assays. The processing time may be different for each specimen.	Each specimen may have multiple assays associated with it. The specimens are sampled one by one; the number of times each is sampled depends on how many assays are required for each specimen. Assays are processed concurrently. The number of specimens that can be processed together is based on the capacity of the instrument and the total number of assays on them. The results for a specimen will be reported when the last assay for that specimen is completed. Lab technologists verify instrument results. Immulite, Vitros, and ProSpec instruments are modeled with Type 2 logic.

Continued on next page

Table 3.2 – *Continued from previous page*

	Logic	Description
Type 3	Specimens are loaded as a batch. All the specimens in the batch are processed identically. The processing time for the batch is generally independent of the batch size.	The equipment will process the specimens, and the majority of the process time is fixed and does not depend on the batch size. After the specimens are removed, the results are verified. DS2, TDx instruments, and centrifuges are modeled with Type 3 logic (centrifuge does not verify results).

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Table 3.2 – *Continued from previous page*

	Logic	Description
Type 4	Specimens are loaded as a batch. Specimens are processed individually (single piece flow).	In most cases, specimens analyzed on Type 4 test-essential equipment are first prepared at other benches in the lab, collected into batches and then transported to the equipment. All specimens in the same batch will require the same kind of test. A set of test specimen references, controls and standards may be included in the batch if the test type of the current batch is different from the previous one. The specimens are processed one by one. After the specimens are removed the results are verified. LC/MS and HPLC instruments are modeled with Type 4 logic.

Table 3.3: Test essential equipment objects

Name	Description
DCA	The DCA Vantage Analyzer is the diabetes system that helps monitor glycemic control and detect early kidney disease. (Type 1)
Immulite	The Immulite instrument is a bench top immunoassay analyzer. The assays that can be performed on it include allergy, anemia, bone metabolism, diabetes. (Type 2)

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Table 3.3 – *Continued from previous page*

Name	Description
Vitros	There are two kinds of Vitros instruments. Vitros3600 is an immunoassay system using enhanced chemiluminescence technology as its measurement principle. Vitros5,1 is a chemistry system using potentiometric (direct ISE), colorimetric/rate, immuno-rate, and turbidimetric as its measurement principle. (Type 2)
ProSpec	ProSpec is an instrument that offers plasma protein testing including cardiac risk assessment, kidney disease, nutritional assessment and iron and anemia assessment. (Type 2)
Centrifuge	Centrifuge is a piece of lab equipment that puts specimens in rotation around a fixed axis to separate their components. (Type 3)
DS2	The DS2 instrument is an automated ELISA (enzyme-linked immunosorbent assay) system. (Type 3)
TDx	The TDx instrument is an automated system which performs assays for therapeutic drugs, hormones, clinical chemistries, specific proteins and toxic/abused drugs. (Type 3)
LC/MS	The LC/MS instrument is a system that uses liquid chromatography-mass spectrometry (LC-MS) techniques to separate, generally detect and potentially identify chemicals of particular masses in the presence of other chemicals. (Type 4)
HPLC	The HPLC instrument is a system that uses high-performance liquid chromatography (HPLC) to separate, quantify and identify the components in a mixture. (Type 4)

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Table 3.3 – *Continued from previous page*

Name	Description
Luminex	The Luminex instrument is a system that performs a variety of bioassays. (Type 4)

Chapter 4

OBJECT CONSTRUCTION

After domain analysis, which is used to identify the necessary collection of simulation objects with their relationships and common functionalities, the objects defined were implemented using the target simulation language. In this chapter the structure of different objects is introduced: lab technologists, specimens, clinical lab database, manual tasks, test essential equipment, and storage equipment.

Most objects include a unique icon for display in the model workspace and appropriately named input and output interfaces of the object (parameter names that correspond to the terminology used by lab professionals not modelers). Objects are configured by changing the parameters. An example of an object and its parameter fields is presented in Figure 4.1. Some parameters have numerical values (e.g., minimum batch size), and some parameters have probability distributions (e.g., maximum specimen wait time). Appendix C has parameter fields for all the objects.

4.1 Lab Technologists and Specimens

The lab technologist (LT) object is based on the worker object from the standard Simio library. This object can transport specimens from point to point in the labs and is used as necessary resources for specimen preparation and operating test-essential equipment.

Specimen is an entity object specified with attributes that carry information specific to a specimen, such as the list of tests to be completed and demographic data from patient records.

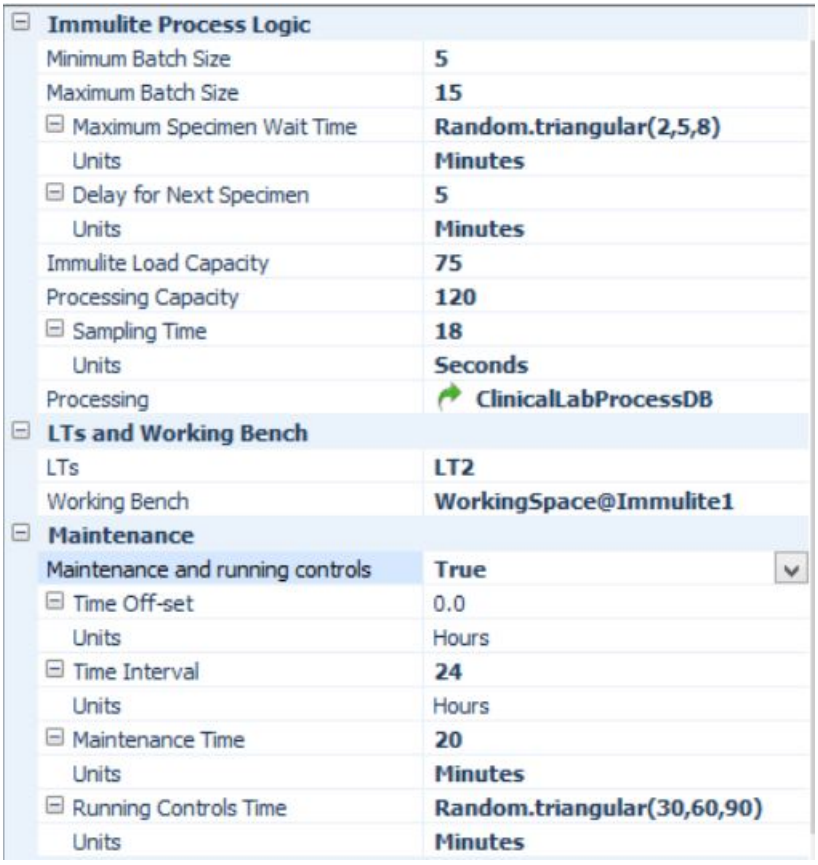

Figure 4.1: Processing parameters and process database references for an Immulite instrument simulation object.

4.2 Clinical Lab Database

The information associated with different kinds of tests and analyses is stored in a clinical lab database object. Specimen objects are assigned information concerning the list of tests that will be performed on them as they arrive to a lab model. The specimens carry the information through the system, and analytical instrument objects extract the necessary information from the database to process the particular TestIDs carried by the specimen objects (modeled as entities). Some information in the database is shown in Table 4.1. Also, additional information can be added into

Table 4.1: Clinical lab database

TestID	Each test is given a unique ID. A specimen has a test required for it.
Number of Units per Specimen	This indicates the number of units of resource required by one specimen to perform this kind of test. Sometimes a specimen needs to be divided into two aliquots, and sometimes one specimen contains three tubes.
Number of Controls and Standards	There are several controls and standards associated with each batch of specimens. They require resources. Also, to process controls and standards requires time as well. This parameter is for counting the resources used and calculating processing time.
Preparation Hands-On/ Hands-Off Time	Specimens may need some preparation before they can be put on analytical instruments. The specimen preparation step is separated into two parts: the hands-on process, which requires LTs; the hands-off process which does not require LTs. These two parameters represent the time to process one specimen. Specimens with no preparation requirements will have those two parameters set to zero.
Load Time	Time to place one specimen on the instrument.
Process Time	The time it takes for the analytical instrument to automatically process one specimen.
Unload Time	Time to remove one specimen from the analytical instrument.
Verify Time	Time for LTs to interpret and report the result for a specimen.
Sequence	The testing route a specimen follows through the lab operations.

the database table based on modeling needs.

The clinical process database is presented on a series of spreadsheets where each row represents one particular test and each column a piece of relevant information associated with the test. If the specimens are processed in a batch, and the time required for a step is not based on the batch size, the time doing this step for one specimen will be equal to the time for a batch of specimens. The advantages of using a data table is to reduce the work when new tests are added in the lab. All the domain experts need to do is to add another row which contains the information of the new test. Also, new columns can be added very easily based on the modelers' need. This gives modelers extra flexibility in using the objects created.

4.3 Manual Tasks

There is a wide variation in time needed to complete different manual tasks; some may require as short as five minutes while others can take several hours. An accurate model for a manual task will have to account for different tasks which can have a different number of steps. In order to model that complexity and make the objects more flexible in reflecting different kinds of processes, a manual task is divided into a series of hands-on and hands-off processes. Hands-on processes require LTs to complete while hands-off processes do not. Manual task objects provide one unit of manual task activity, which includes one hands-on process and one hands-off process. The process flow for a basic unit of a manual task object is as shown in Figure 4.2.

There are two kinds of manual tasks: specimen preparation and manual test/analysis.

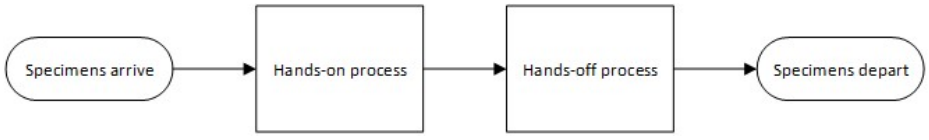

Figure 4.2: Process flow for manual tests and specimen preparation

Specimen preparation objects can be used to model processes on physical benches that perform the activities needed to get specimens ready to be examined by the analytical instruments. Specimens are processed based on the information of the tests required on them inside specimen preparation objects. Manual test objects can be used to model logical test processes which are done by LTs without the use of highly-automated analytical instruments. All the specimens entering a manual test object require the same test, therefore the process time for all specimens follows the same distribution.

Each of the two manual tasks, specimen preparation tasks and manual tests, has two types of process logic: one is batch and the other is single piece flow.

- **Processing In Batch**: Specimens arrive individually and are then batched based on batching logic. There are two processing steps in the manual processes: the hands-on and the hands-off processes. The time required for each step is calculated by adding the fixed process time for a batch and the individual process time multiplied by the batch size, which is as shown below:

$$ProcessTime = IndividualProcessTime \times BatchSize + FixedProcessTime$$

  For example, a batch of ten (batch size) specimens need to be prepared before going into an analytical instrument. The preparation of the specimens is a hands-on process which requires LTs to pipette a reagent, which is a "substance or compound that is added to a system in order to bring about a chemical reaction, or added to see if a reaction occurs" (McNaught and Wilkinson, 1997), into the specimens. Taking the reagent from the refrigerator and mixing it takes three minutes (fixed process time). This activity is not affected by the batch size. Next, pipetting the reagent into one specimen takes two minutes (individual process time). The resulting process time for the whole hands-on

process is calculated as, 2 x 10 + 3 = 23 minutes.

The output of this type of object is a batch of specimens. If it is necessary to output individual specimens for upstream processing, then the specimens would be subsequently unbatched.

- **Single piece flow**: Specimens arrive and are processed one by one based on the capacity of the hands-on and hands-off processes.

The modeler can choose to combine multiple instances of the manual task objects to model a complex manual task. An example is shown in Figure 4.3. This manual task is modeled as single piece flow containing four units of manual test objects. Each of the objects contain one hands-on and one hands-off process. If extra steps are required for this task, then additional manual test objects may be added to the model. This example shows that the manual task objects can be used to construct manual task models at different levels of complexity.

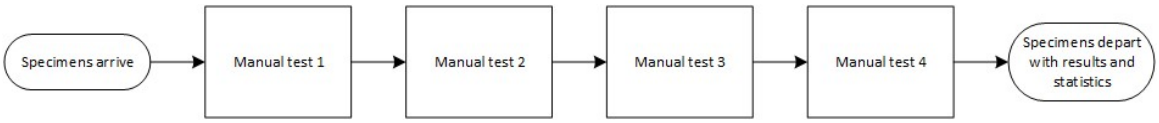

Figure 4.3: Model of a manual task containing four manual test objects.

4.4 Test-Essential Equipment

Test-essential equipment is used to either prepare specimens, or analyze specimens during testing. The processes on test-essential equipment follow a similar flow, as shown in Figure 4.4. After the specimens arrive, they are put into the equipment, processed (tests and analyses performed), and then removed from the equipment. For analytical instruments the results are verified and reported. The centrifuge is not an

analytical instrument, so for the centrifuge there are no verify and report results steps.

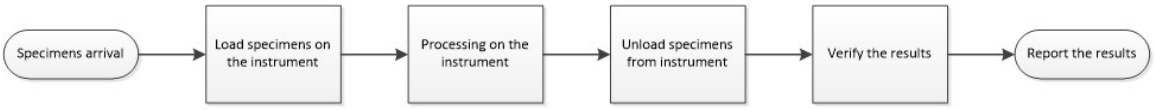

Figure 4.4: Process flow on test-essential equipment

When specimens arrive, they are placed into a queue to wait to be batched. A very important part of modeling the test-essential equipment is to reflect the alternative methods of batching, which is the gathering and grouping of specimens to balance throughput, TAT, and laboratory resource utilization. Most of the clinical lab simulation objects (e.g., test-essential equipment) use batching logic to organize specimens for subsequent process/analysis. The objective of the lab object batching logic is to represent specific policies the LTs are supposed to follow while processing specimens on the lab facilities. The batching logic uses four parameters to support exploration of a wide range of complex production control/dispatch strategies. The four parameters are:

1. **Maximum Batch Size**: this parameter determines the maximum number of specimens that may be in the same batch. This parameter may be a constraint of the instrument (its capacity), or the ability of LTs who are processing the batch. When the number of specimens reaches the maximum batch size, the specimens in the batch are processed.

2. **Minimum Batch Size**: this may be a function of the costs associated with initiating a series of assays, such as reagents or other supplies. The LTs are encouraged to wait until that minimum number of specimens is available. Unless there is sufficient demand, LTs do not usually process a specimen when it first arrives to the lab. They wait for more specimens to process together.

3. **Maximum Specimen Wait Time**: there may be situations when the number of specimens have not reached the minimum batch size and the specimens have been waiting for some period of time. Test procedures dictate how long specimens can wait. When the waiting time for any of the specimens exceeds the maximum specimen wait time, all specimens that are waiting are processed regardless of the number of specimens in the waiting queue.

4. **Delay for Next Specimen**: specimens are not always batched right after the number of specimens available reaches the minimum batch size. If there is another specimen coming soon, then it is reasonable to assume that LTs will wait for that specimen. So, when the number of specimens reach the minimum batch size the last specimen will be given a time window. If this time window elapses and no specimen arrives then all the specimens waiting are processed.

The specimens are batched whenever one of four situations occurs. The four situations for batching are illustrated in Figure 4.5. The horizontal axis (x-axis) represents time, and the vertical axis (y-axis) represents the number of specimens in the queue waiting to be batched.

- Situation 1: The number of specimens waiting does not reach the minimum batch size, but the time the first specimen has been waiting in the queue exceeds the maximum specimen wait time.

- Situation 2: The number of specimens in the queue reaches the minimum batch size, and the time between two arrivals does not exceed the delay for the next specimen. Specimens keep coming until the number of specimens waiting in the queue reaches the maximum batch size.

- Situation 3: The number of specimens in the queue reaches the minimum batch size, and there is no arrival of a specimen in the time window given by the delay

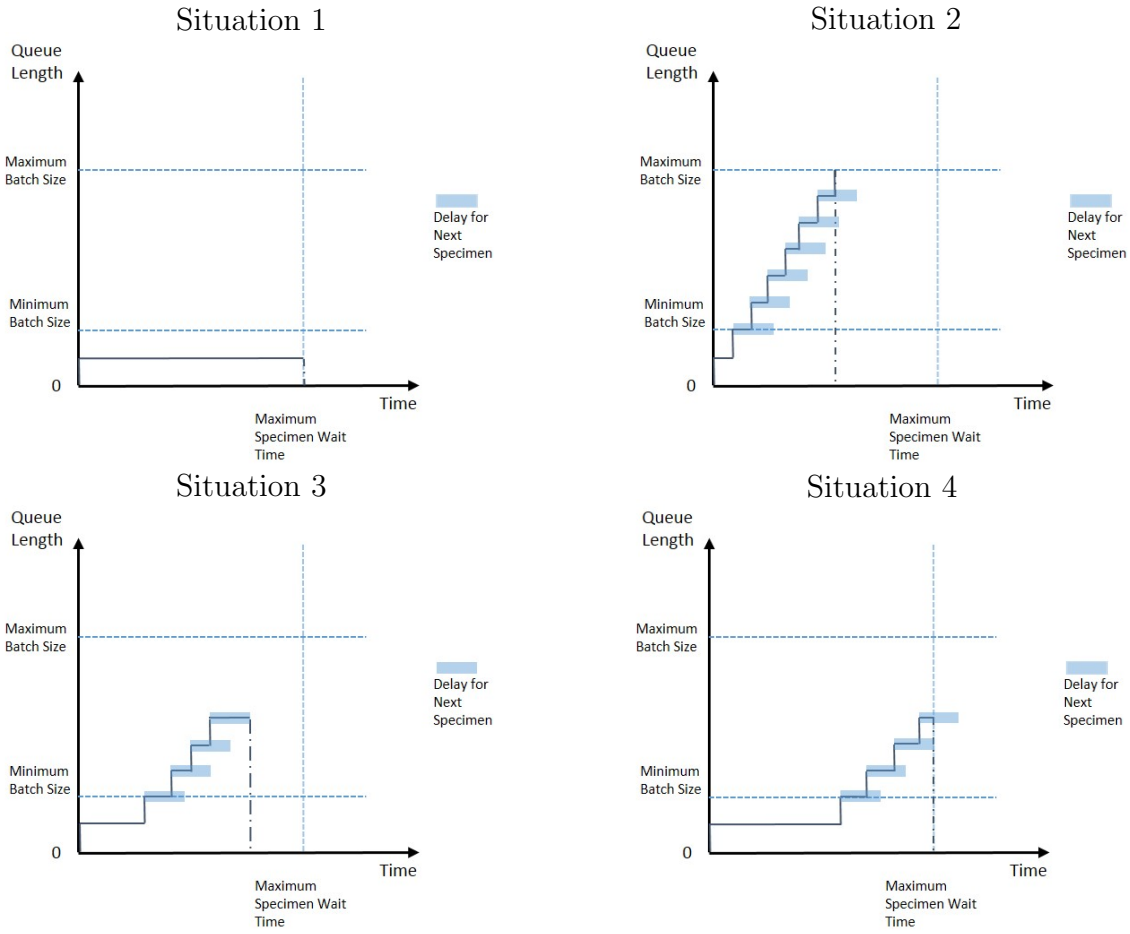

Figure 4.5: Batching logic controlled by four parameters.

for the next specimen.

- Situation 4: The number of specimens in the queue reaches the minimum batch size, and the time between two arrivals does not exceed the delay for the next specimen. Specimens keep coming until the time the first specimen has been waiting in the queue exceeds the maximum specimen wait time, even though the number of specimens in the queue has not reached the maximum batch size.

When test-essential equipment requires batch input (see Tables 3.1 and 3.2), specimens must be batched before they can be placed on the equipment. For Type 4

equipment, the specimens are batched ahead before getting prepared and brought to the equipment in a batch. While for Type 2 and Type 3 equipment, the specimens are batched when they arrive at the equipment and about to be placed on the equipment.

4.5 Storage

Refrigerators, freezers, and incubators are instances of the same storage simulation object, since temperature is a parameter of the object and does not affect its function. The conceptual model for a storage object is shown in Figure 4.6.

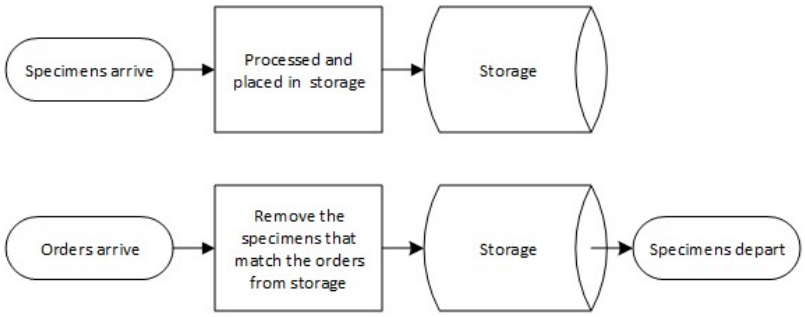

Figure 4.6: Conceptual model for storage object

When specimens arrive they are placed in a storage unit. The storage object is modeled as a detached queue. An order (i.e., entity), which carries the information about what kind of specimens are to be analyzed, will remove the specimens which match the information. In some instances, LTs are required for storing and removing specimens. This object can be used to model arrivals in the chemistry laboratory at SCH. The tests are scheduled on specific days of the week. The orders can be controlled to model different working schedules.

Chapter 5

CASE STUDIES

To demonstrate the applicability of the simulation objects created, three case studies are used to investigate lab performance. Case 1 is a bench level model which contains a small number of test instruments and associated preparation equipment representing a few benches in the lab. Case 2 is a complex model of the SCH chemistry laboratory which includes more instruments and preparation equipment representing the whole lab. After Case 1 was verified and validated, then Case 2 was built using Case 1 as a submodel. Case 3 demonstrates the ability to quickly construct models to investigate the impact on a chemistry lab during a radical increase in activity for another functional unit of the hospital. After Case 2 was verified and validated, then Case 3 was built around Case 2. So, Case 1 is inside Case 2 which is inside Case 3, giving tiered leveled, O-O models.

5.1 Case 1: Bench Level Models

A laboratory is made up of several logical or physical benches. Each bench may include analytical instruments and specimen preparation equipment. The use of the term "bench level" means that the model consists of a limited number of benches and instruments. This case demonstrates a bench level simulation model with three LC/MS instruments. Each instrument has a different capacity. There are multiple types of tests that are analyzed using LC/MS instruments. These tests are scheduled on different days of the week. Lab managers wanted to study how to schedule these tests to make better use of the three instruments and to investigate how many LTs would be needed to operate them.

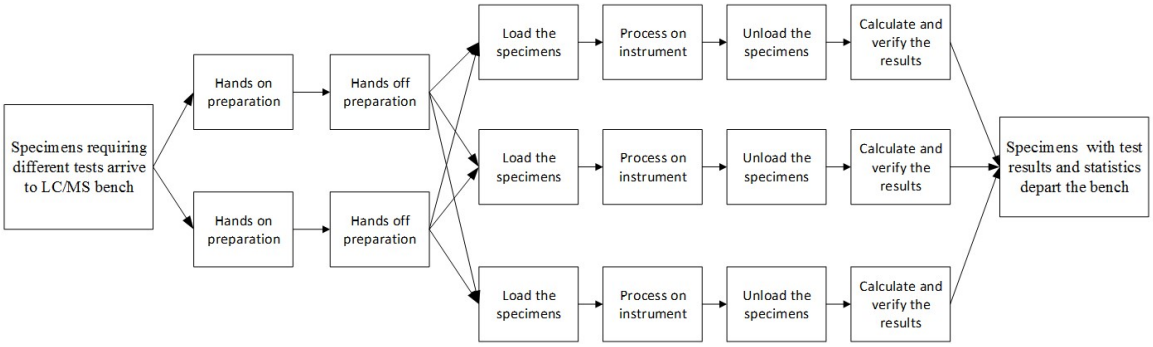

Figure 5.1: Case 1 model of an LC/MS bench constructed without using the high-level LC/MS and specimen preparation objects

Figure 5.1 shows a model constructed without the high-level LC/MS and specimen preparation objects. In this model each step of specimen preparation and testing is modeled individually. In comparison, Figure 5.2 shows an equivalent model constructed with the developed specimen preparation and LC/MS objects. The alternative model contains fewer instances of model constructs, which in turn means that the alternative model takes less time to build. The fact that the objects in the model are mapped to real world equipment and processes help domain experts understand the model. With many functions pre-defined in the objects, less time is required to validate the model.

Several performance metrics (e.g., TAT, resource utilization) are collected to evaluate different scheduling and staffing strategies. These performance metrics are not collected automatically in the objects. Model builders must define the performance metrics themselves.

Simulation on a small scale is often difficult to justify since the outcome may not be significant enough when compared to the cost of developing the simulation. When the model objects are available, however, many domain experts can build adequate models without starting from scratch and incurring the costs that result from involving

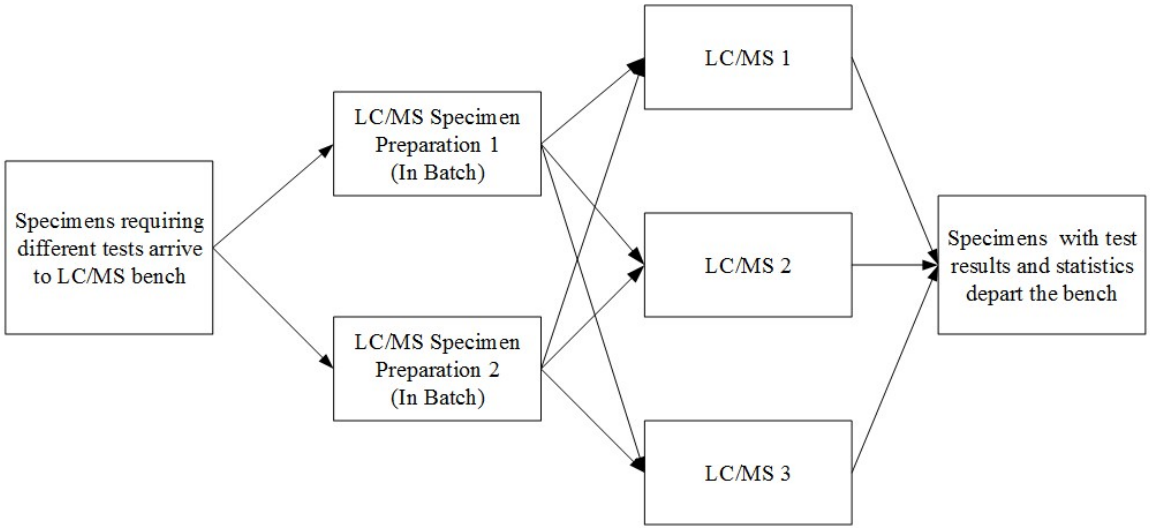

Figure 5.2: Alternative Case 1 model of an LC/MS bench using high-level LC/MS and specimen preparation objects

IT and modeling experts.

5.2 Case 2: Laboratory Model

The SCH chemistry laboratory is modeled with the clinical lab simulation objects developed in this research. The model is shown in Figure 5.3. When specimens arrive, they are assigned testing information from the database, including their route in the lab. They are then placed in a refrigerated storage facility. The specimens will not be processed until their scheduled day. At the appropriate time, an order entity is sent to storage with information on which specific tests to process. The specimens requiring these tests are removed from storage and move through the lab based on their particular route (obtained from the lab process database object). The model developed in Case 1 is embedded inside Case 2 as part of the lab model. Case 2 is used in a number of ways to explore the capacity and scheduling of the chemistry laboratory, as well as examine the consequences of changes in reference client demand.

Different performance metrics can be used to determine the performance of the lab and evaluate operation policies, staffing levels, and service levels. As in Case 1, performance metrics are defined by the model builder. Three metrics used in Case 2 include: throughput of the lab, TAT for the tests, and LT utilization.

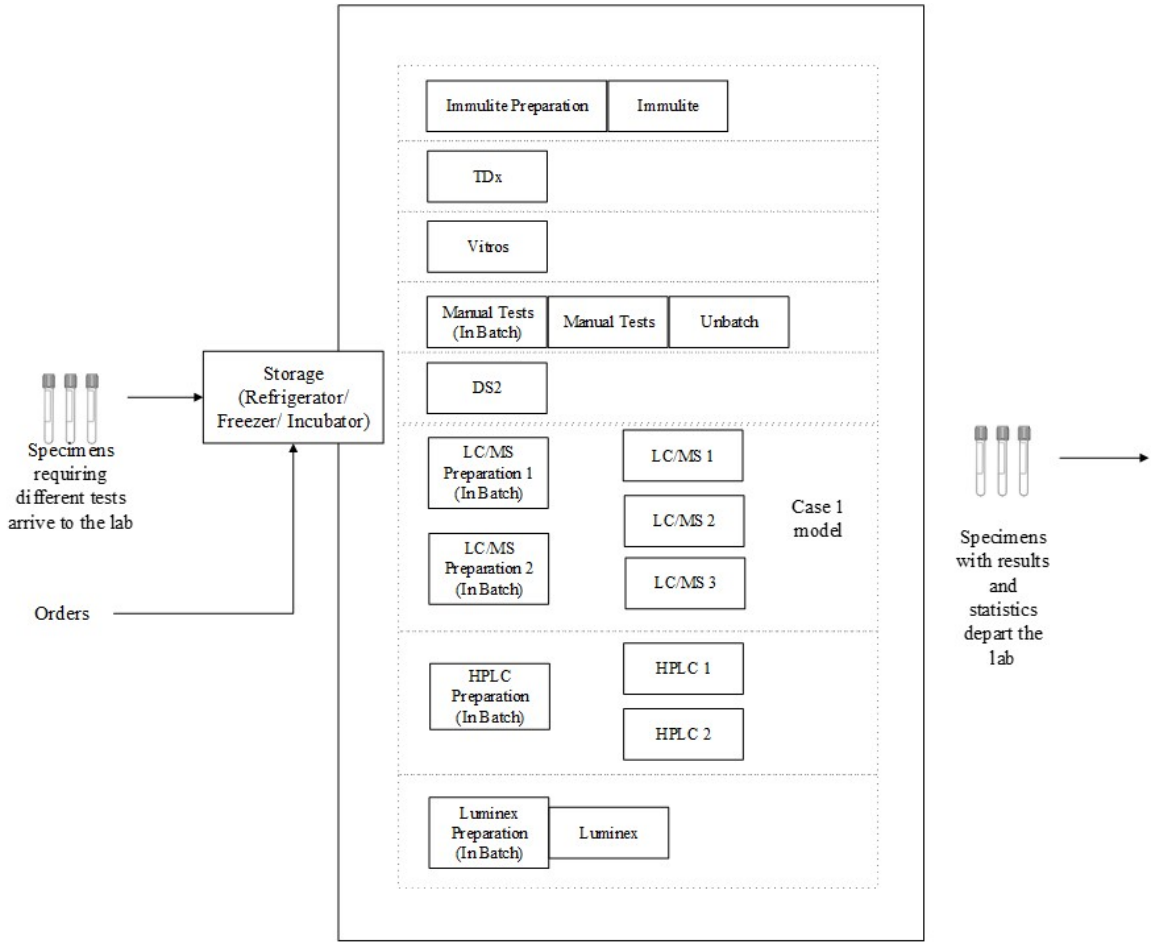

Figure 5.3: Case 2 model of the chemistry laboratory in SCH.

The model in Case 2 is more complicated in terms of the number of objects and tests involved compared to Case 1. Objects that represent instruments and processes are used in constructing the model which make it easier for the domain experts to map to the real world. If a method similar to the one used to construct the model in Figure

5.1 is applied to build this whole lab model, it is not only time consuming and difficult for model builders to construct, but also hard for domain experts to understand and validate the model because listing out each step affects readability and usability of the model. Therefore, there is a higher possibility of making mistakes in the construction and application of the model. Furthermore, constructing the model without using developed objects impedes the identification of different parts of the model.

5.3 Case 3: Occupational Health Services (OHS) Clinic and Laboratory Medicine

The final case illustrates the value of the developed clinical lab objects by quickly constructing simulation models and answering questions concerning the impact of one functional unit on the performance of another unit in the same organization. In 2011, SCH adopted a creative method for combining their annual flu immunization campaign with the tuberculosis (TB) screening required of each hospital worker (employees, students and volunteers). Instead of visiting the SCH Occupational Health Services Clinic twice during the year, the healthcare workers would visit only once to have their flu immunization shot and a blood draw for TB screening. The model is shown in Figure 5.4. It contains two primary objects: the OHS clinic and the chemistry laboratory. Patients and healthcare workers arrive at the OHS clinic for flu shots. Healthcare workers also have a blood sample taken for the TB screen; the blood specimens are transported in batches to the chemistry lab several times during the day. The analytical instrument used for analysis is DS2. The TB specimens will impact the workload on DS2 and could potentially have an impact on the overall performance of the chemistry lab. The arrival of patients and healthcare workers is predicted in advance. SCH wants to know how many nurses and phlebotomists will be needed to perform the operations in the OHS clinic as well as how the campaign will impact the chemistry laboratory. The chemistry laboratory object in Figure 5.4 is simply the Case 2 model shown earlier. With this model, different resource allocation

strategies can be tested.

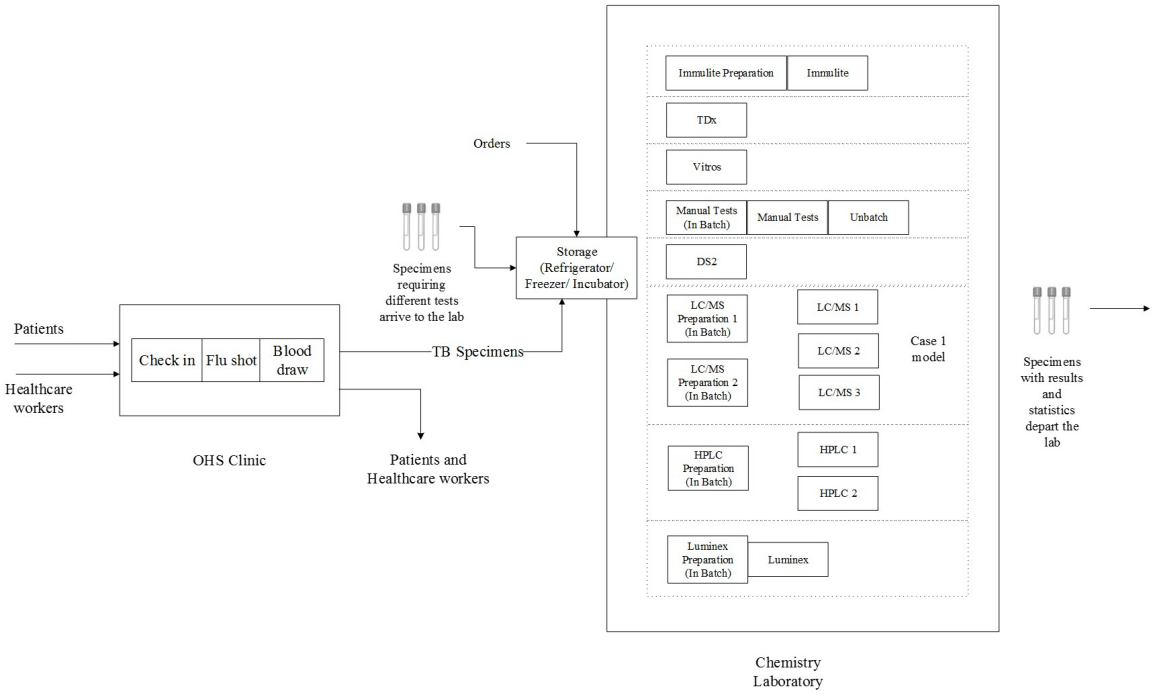

Figure 5.4: Case 3 model of occupational health services and chemistry laboratory.

This case demonstrates that the developed objects can be used to construct models of a complex system of systems. With Case 2 embedded in Case 3 as a submodel, no changes to an embedded Case 2 model can be made from the outside, therefore protecting the assumptions made with the embedded Case 2. By retaining Case 2 model's validity, the clinical lab object structure developed in this thesis allows Case 3 to employ a Case 2 model without needing to re-validate it. This, in turn, simplifies and shortens the validation process for Case 3.

The same approach used to develop domain-specific simulation objects has also been applied to the core lab at SCH. The core lab is a much higher volume lab with concerns about reducing TAT. Because of the nature of the tests performed in the core lab there is more pressure to get results out faster when compared to a chemistry

lab. The experience shows that the approach can be altered to be applied to different kinds of clinical laboratories.

Chapter 6
DISCUSSION

Laboratory professionals at SCH have employed clinical laboratory simulation objects constructed in this thesis to successfully build small models, such as Case 1. A brief introduction to simulation modeling and the Simio language was provided over a six-week period and laboratory professionals had the opportunity to have their questions answered and become familiar with using the objects. The objects were also provided to undergraduate industrial engineering students to test their ability to build models in a domain with which they have little experience; most have taken a course in simulation modeling. The feedback received from the students and the lab managers has demonstrated the value in having these high-level domain specific constructs readily available.

6.1 Summary

In this thesis, a framework for developing a collection of domain-specific simulation objects is introduced. The objects are developed based on the chemistry laboratory at SCH for analyzing clinical laboratory operations. The essential steps for defining and constructing the objects are presented. The structure for each object is discussed and practical applications using the objects are demonstrated to show their applicability.

6.2 Limitations

Though the objects constructed are beneficial to the domain experts and modelers, there are still limitations. One limitation is that the domain experts may not fully trust that the objects can accurately reflect reality. Valentin et al. (2003) conducted

an experiment to test the advantages and disadvantages of the building blocks they created. Their results showed that the model builders had a high conceptual mismatch between models and the real world, and therefore domain experts hesitated to use the building blocks. With similar construction it is reasonable to assume that the objects created in this research will have the same problem. Due to the objects being abstractions of the real world, they have certain limitations. How to balance the level of detail and have domain experts trust the objects' validity is an important issue.

Another limitation is that performance metrics and statistics are collected and analyzed outside the objects. Model builders must explicitly define the performance metrics and their interaction to the objects. Model builders must then analyze data to provide reliable results. This may be difficult for domain experts who may have a limited knowledge of statistics.

6.3 Future Work

This collection of simulation objects is developed based on the chemistry laboratory domain. With additional work, the framework introduced in this research makes it possible to expand this collection of objects to model different laboratory situations. This is done by updating the collection of objects and validating newly created objects. As mentioned in Section 6.2, the domain experts may hesitate to use the objects since they may not trust them in building models that accurately reflect the real world. This requires model developers to work very closely with domain experts and make sure the objects have an acceptable validity. This validation process may be continued until domain experts gain trust in the objects.

Future work could be done by defining performance metrics inside the objects. Analyzing the results provided by the simulation models requires a good understanding of statistics. Lab experts may have limited knowledge of data analysis and have difficulty defining performance metrics and interpreting the simulation results. Commonly used performance metrics can be built in the objects in the future. The statistical

results can then be calculated using simulation software or exported to a spreadsheet for further analysis. Also, data analysis objects should be created separately from others to make data analysis easier.

Furthermore, a training program for healthcare workers would facilitate the use of simulation for future projects. The program can help healthcare workers understand the value of simulation, as well as how to construct simulation models and interpret the results themselves.

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Appendix A

ANNOTATED FLOWCHARTS FOR CLINICAL LABORATORY TESTS AND EQUIPMENT

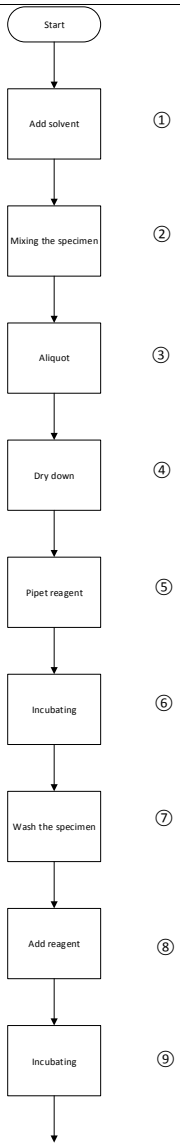
Figure A.1 to A.6 are the flowcharts for manual tests. Figure A.7 to A.16 are the flowcharts for processes that are done on the test essential equipment, and the flowcharts for the specimen preparation processes before loading the specimens onto the test essential equipment. There are no flowcharts for the lab technologist, specimens, or the clinical lab database because the flow is straight forward.

Figure A.1: 17aOH test, manual test.

Collected By: Penny (Shuainan) Hu Date:

Title: 17-α-OH Version: 1.0

Introduction: Manual test

Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
	①Add solvent to the specimens		Lab Technologist	1	
	② Mix the specimens using mixer and centrifuge.	Mixer : 5 min Centrifuge: 5 min	Mixer Centrifuge		
	③ Aliquot the specimens		Lab Technologist	1	
	④ Set the specimens to try	20-30 min			
	⑤Add the reagent into the specimens	45 min	Lab Technologist	1	
	⑥ Put the specimens to incubate for the first time	1 hour			
	⑦ Washing the specimens	Couple of minutes			
	⑧ Add another type of reagent to the specimen	5-10 min	Lab Technologist	1	
	⑨Put the specimens to incubate for the second time	39 min			

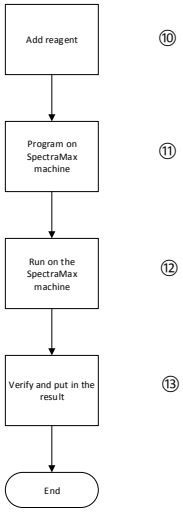
	⑩Add another type of reagent	5-10 min			
	⑪ Program it on the SpectraMax instrument, prepare for the specimens to run on the machine.	20 min	Lab Technologist	1	
	⑫ The specimens are run on SpectraMax instrument	5 min			
	⑬Verify the results and manually put them into the computer	30 min	Lab Technologist	1	

Figure A.2: Breath tolerance test, manual test.

Collected By: Penny (Shuainan) Hu Date: 11/2013

Title: Breath tolerance Version: 1.0

Introduction: Glucose/Lactulose/Fructose/Lactose/Sucrose

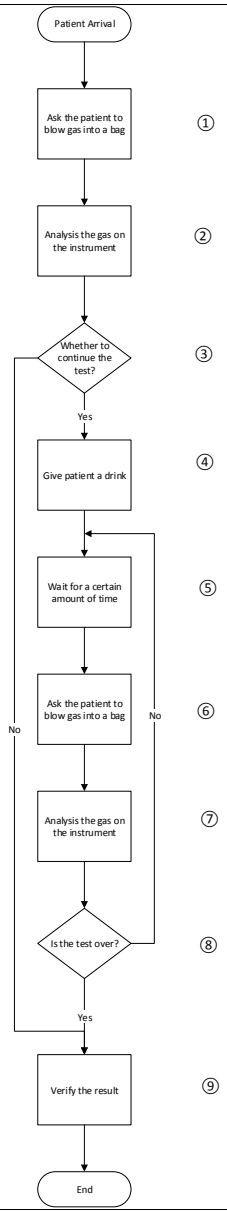
Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
	① Explain the procedure and ask the patient to blow gas into a bag.	A couple of minutes	Lab technologist	1	The time duration for this test is based on the assay type. Glucose: 20 minutes for 2 hours. Lactulose: 20 minutes for 3 hours. Fructose/Lactose/Sucrose: 30 minutes for 2 hours. Patients may be asked to stay for extra 20 or 30 minutes to make sure the test result is correct.
	② Put the specimen collected onto Breathtrack and wait for the result. Write down the result.	A couple of minutes	Lab technologist	1	
	③ The result is used for draw the baseline. If the result is too high, the test cannot be performed. The patient may be asked to blow the gas again after a certain amount of time to determine whether he/she is eligible to do the test.				
	④ Give the patient a cup of drink. The amount of drink is calculated based on the weight of the patient. And the type of the drink is based on the assay type.		Lab technologist	1	
	⑤ Patient wait for a certain amount of time.	This is determined by the assay type. Some are 30 minutes, some are 20 minutes.			
	⑥ After certain amount of time, the patient is asked to blow gas into the bag.		Lab technologist	1	
	⑦ Put the specimen collected onto Breathtrack and wait for the result. Write down the result.	A couple of minutes	Lab technologist	1	
	⑧ Steps 5 to 7 are repeated until the test is done.				
	⑨ Verify the result.		Lab technologist	1	

Figure A.3: Plasma Hemoglobin test, manual test.

Collected By: Penny (Shuainan) Hu Date:

Title: Plasma Hemoglobin Version: 1.0

Introduction: It's a manual process mainly performed by the Lab technologist

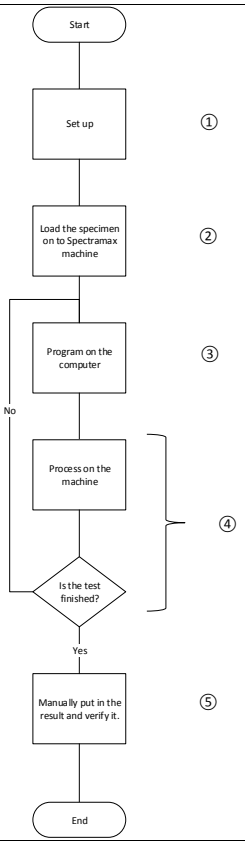
Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
	① Set up the test. The dark color specimens are diluted in case the machine cannot get accurate result. Usually, one specimen will take 4 wells on the tray. Two for controls and two for the tests. If the specimen is diluted, then additional 2 wells are need. The reason why is to reduce variability.		Lab Technologist Little tray	1	The little tray has a capacity.
	② Load the specimen on to the SpectraMax instrument.		Lab Technologist	1	
	③Program the test on the computer		Lab Technologist	1	
	④ Process the specimens on the machine. They usually do 3 times of the tests based on different standard. After one test, the lab technologist needs to reprogram it to do the next test.	A couple of minutes			
	⑤ Manually put in the result and verify the result. This result needs to be verified by another person as well.		Lab Technologist	1	

Figure A.4: Sweat Chloride test, manual test.

Collected By: Penny (Shuainan) Hu Date: 11/2013

Title: Sweat Chloride test Version: 1.0

Introduction:

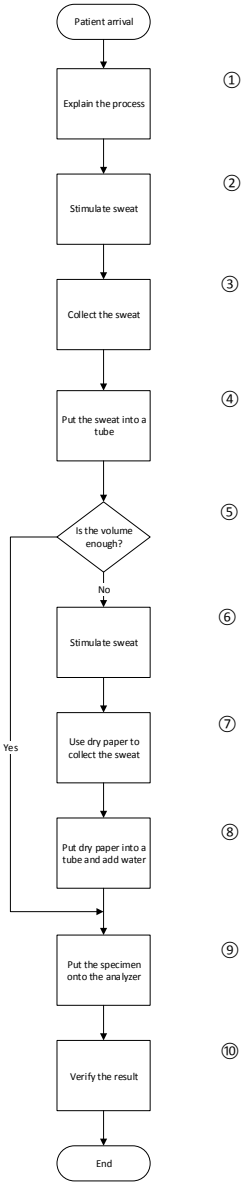
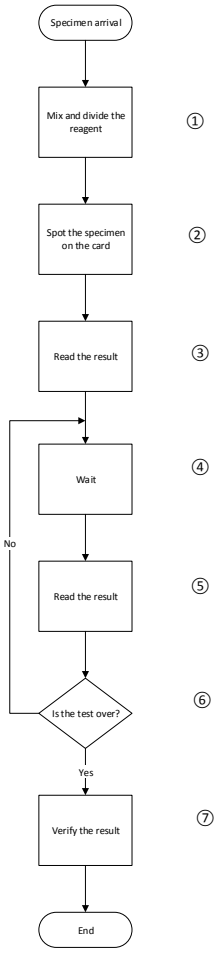
Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
	① Explain the procedure to the patient.		Lab technologist	1	Controls and standards are run before processing any specimens on the analyzer. The specimens for this type of test usually performed at the end of the day.
	② Setup and stimulate sweat using stimulator.	Setup time: Stimulating time: 6 minutes	Lab technologist	1	
	③ Setup and collect the sweat.	Setup time: Collecting time: 30 minutes			
	④ Put the sweat collected into a tube.		Lab technologist	1	
	⑤ Decide whether the volume is enough for the test. Otherwise, sweat needs to be collected using another method.				
	⑥ Setup and stimulate sweat again using another instrument.				
	⑦ Setup and use dry paper to collect sweat.	Step 6 and 7 together will take about an hour.			
	⑧ Put the dry paper into a tube and add water in to get washed out.		Lab technologist	1	
	⑨ Put the specimen collected onto the analyzer. Specimens are processed one by one.	30 seconds per specimen			
	⑩ Verify the result.		Lab technologist	1	

Figure A.5: Other manual tests in the chemistry lab on 8th floor.

Collected By: Penny (Shuainan) Hu Date: 11/2013

Title: Manual processes on 8th floor Version: 1.0

Introduction: G-6-PD/ Stretozyme

Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
G-6-PD: 	① Mix and divide the reagent into 9 tubes. Every 3 tubes per specimens. There are two controls. So there're total 9 tubes.		Lab technologist	1	The reagent is made every other time. This test has high priority. The result needs to be read right away.
	② Spot the specimen on the card.		Lab technologist	1	
	③ Read the result under black light.		Lab technologist	1	
	④ Wait for a certain amount of time.	5 minutes			
	⑤ Read the result under black light.		Lab technologist	1	
	⑥ The result is read at 0 minutes, 5 minutes and 10 minutes. So step 4 and 5 are repeated.				
	⑦ Verify the result.		Lab technologist	1	

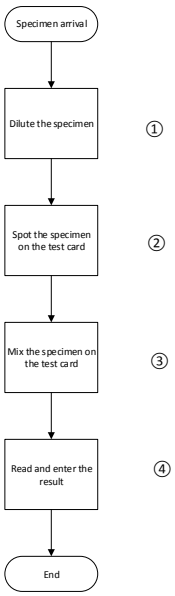
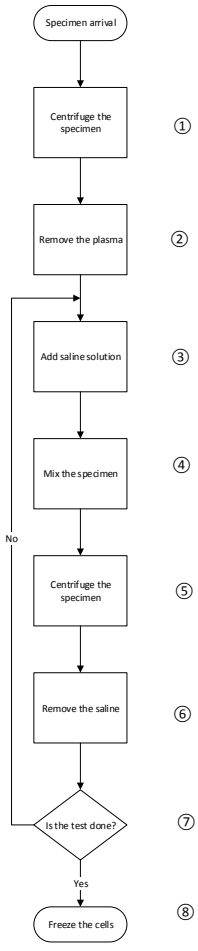
Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
Streptozyme:  	① Dilute the specimen with sodium.		Lab technologist	1	The specimens need to be at room temperature. Usually specimens are set aside for an hour before getting processed. The whole procedure takes less than 10 minutes.
	② Spot the specimen on the test card		Lab technologist	1	
	③ Mix the specimen. Hold the test card and rock it. The specimen may need further dilution.	2 minutes	Lab technologist	1	
	④ Read and manually enter the result.		Lab technologist	1	

Figure A.6: Other manual tests in the chemistry lab on 10th floor.

Collected By: Penny (Shuainan) Hu Date: 11/2013

Title: Manual process on 10th floor Version: 1.0

Introduction: Red Cell Enzymes/ WBS Enzymes

Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
Red Cell Enzymes(Gal-1-PD)  	① Centrifuge the specimen	10 minutes			This test is always performed on weekends for Bio lab. Since there's no one working there at that time and the specimens need to be processed within 24 hours.
	② Remove the upper layer (plasma).		Lab technologist	1	
	③ Fill up the tube with saline solution.		Lab technologist	1	
	④ Mix the specimen.		Lab technologist	1	
	⑤ Centrifuge the specimen.	10 minutes			
	⑥ Remove the upper layer (saline).		Lab technologist	1	
	⑦ Step 3, 4, 5, 6 is repeated 2 to 3 times.				
	⑧ Freeze the specimen after the test is done.				

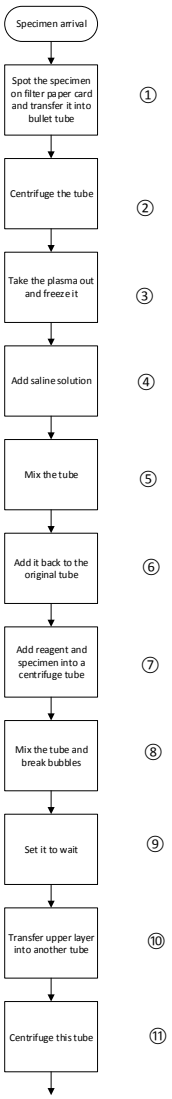
Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
WBC Enzymes:  	① Take the specimen and spot it on filter paper card. Transfer the filtered specimen into a bullet tube.		Lab technologist	1	This test is always performed on weekends for Bio lab. Since there's no one working there at that time and the specimens need to be processed within 24 hours.
	② Centrifuge the tube	5 minutes			
	③ Take out the clear top (plasma). Freeze the plasma.		Lab technologist	1	
	④ Fill the tube with saline solution.		Lab technologist	1	
	⑤ Hand mix the tube for 10 times.		Lab technologist	1	
	⑥ Add it back to the original tube.		Lab technologist	1	
	⑦ Add reagent into a centrifuge tube and add specimen into this tube.		Lab technologist	1	
	⑧ Hand mix the tube for 2 to 3 times and break the bubbles in the tube.		Lab technologist	1	
	⑨ Set the specimen aside to wait for 30-40 minutes at room temperature.	30-40 minutes			
	⑩ Transfer the upper layer into another tube.		Lab technologist	1	
	⑪ Centrifuge this tube	10 minutes			

Figure A.7: Process flow on the DCA instrument, test-essential equipment, type 1.

Collected By: Penny (Shuainan) Hu Date: 11/2013

Title: DCA Version: 1.0

Introduction: Perform HBA1C and MA/CRE tests

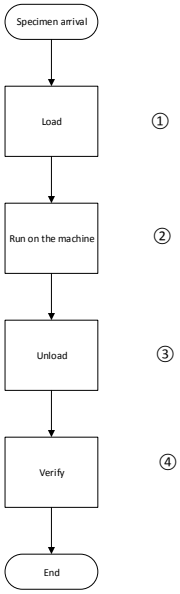
Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
	① Load the specimen onto DCA. This includes transferring the specimen onto a test kit, scanning the barcode and put the kit into DCA.		Lab technologist	1	The DCA instrument takes less than 5 minutes to warm up. Specimens are run on the instrument one by one.
	② Specimen is run on the DCA	HBA1C: 6 min/ea. MA/CRE: 7 min/ea.			
	③ Take the kit out.		Lab technologist	1	
	④ The result will be shown on the screen. Verify the result.		Lab technologist	1	

Figure A.8: Process flow on the Immulite instrument, test-essential equipment, type 2.

Collected By: Penny (Shuainan) Hu Date: 10/21/2013

Title: Immulite instrument Version: 1.0

Introduction:

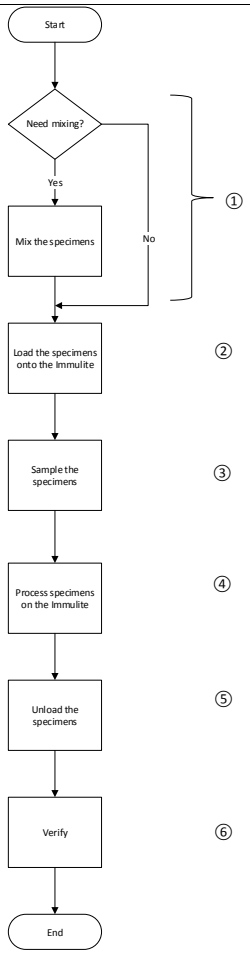
Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
	① Determine whether the specimens need mixing. If they are taken out of the freezer, then they need to be mixed. If they were just received from CPA, then they don't need to.	15 minutes	Lab Technologist	1	The daily maintenance lasts 45minutes to an hour. Controls need to be run every day to make sure the machine is working properly. When the reagents are running low and need refill, calibrations must be performed. Controls are run for one hour and a half. Once a control for a specific test is run, the specimens for that tests can be loaded onto the machine and be processed. Monday morning, there's 30 minutes extra maintenance time. And at least half an hour per week for aliquot the controls.
	② Load the specimens onto the Immulite		Lab Technologist	1	
	③ Each specimen is sampled. The times one specimen get sampled is based on the number of assays associated with the specimen.	18 seconds			
	④ Process the specimens on the Immulite. Each assay is processed individually.	Based on the assay type.	Cups inside Immulite		
	⑤ Unload the specimen from the Immulite		Lab Technologist	1	
	⑥ After all the assays finish, the result is verified.		Lab Technologist	1	

Figure A.9: Process flow on the Vitros3600 instrument, test-essential equipment, type 2.

Collected By: Penny (Shuainan) Hu Date:

Title: Vitros 3600 Version: 1.0

Introduction:

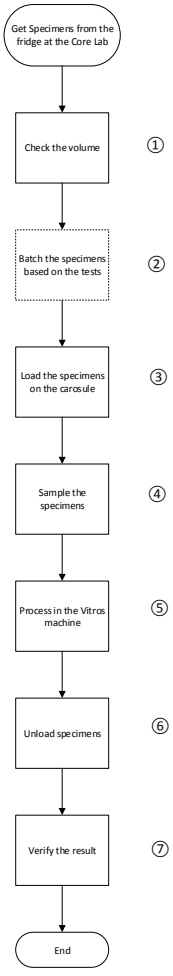
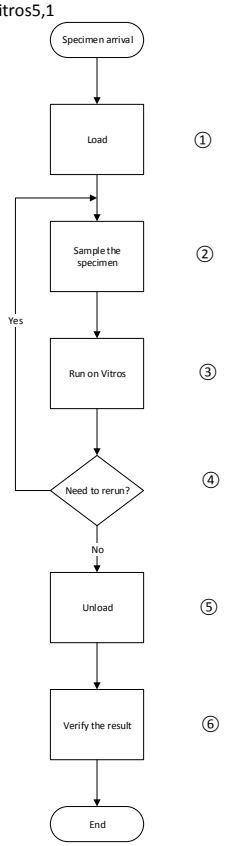
Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
	① Check the volume for each specimens, make sure they can be processes on the Vitros machine.		Lab technologist	1	The Vitros 3600 machine perform maintenance tasks every day. First, the lab technologist check the reagents and decide which tests need to be calibrated. Then, the lab technologist cleans the instrument (5 minutes). After cleaning, he/she will do calibrations and run the controls for the tests that needs to be performed on this machine on this day to check whether the instrument is running correctly (Running the controls should take about an hour. And the calibrations will be based on the tests and numbers of calibrations, usually one will take 25 minutes). The specimens can be loaded on the instrument once the control of the tests which need to be performed on these specimens are finished running. Some lab technologists like to batch the specimens which have the same tests together, so the specimens can come out at the same time, some don't.
	② (Optional) Batch the specimens based on the tests		Lab technologist	1	
	③ Load the specimens on to the carousel, and load the carousel on to the Vitros machine.		①Lab technologist ②Carousel slot (One carousel can load 8 tubes)	①1 ②1	
	④ Each specimen will be sampled. The number of time one specimen get sampled is based on the assays on the specimen.				
	⑤ Process the specimens in the Vitros instrument. Each assay is processed individually. The specimen finishes processing when the last assay on it is done.		Vitros machine		
	⑥ Unload the specimens from the Vitros instrument.		Lab technologist	1	
	⑦ Verify the result on the computer.		Lab technologist	1	

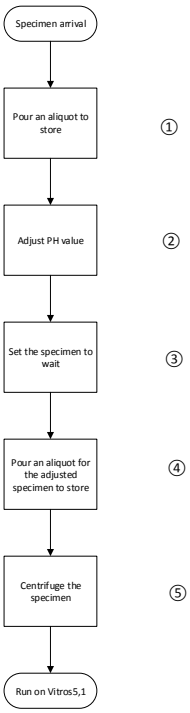
Figure A.10: Process flow on the Vitros5,1 instrument, test-essential equipment, type 2; preparation process flows for the tests on Vitros5,1.

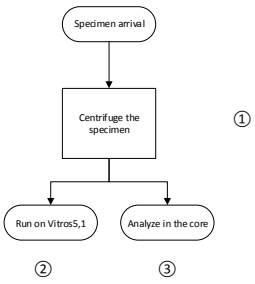
Collected By: Penny (Shuainan) Hu Date:

Instrument: Vitros5,1 Version: 1.0

Introduction: Calcium/ Magnesium/ Phosphorus/ Amolase/ Creatinine/ Glucose/ Protein/ Urea Nitrogen/ Potassium/ Sodium/ Homocysteine/ MPA

Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
Vitros5,1 	① Load the specimens onto a carousel, and load the carousel onto Vitros.		Lab technologist	1	Maintenance is not done by the chemistry staff. Control for a certain type of test needs to run first before performing this test. The lab technologist will write down what kind of controls have been run. Then other lab technologists don't need to run this kind of controls again on this shift.
	② Vitros instrument will sample the specimens one by one.				
	③ Specimens are run in the Vitros instrument. Specimens can be run simultaneously. But there's a capacity for running the specimens. The capacity one specimen needs is based on the numbers of assays. New specimens will queue up when the number of specimens running in the Vitros reach the capacity.	Processing time depends on the test type.			
	④ Vitros can only read the result for a certain range. If the result for a specimen exceed this range, this specimen needs to be diluted and run again. Vitros will automatically make a dilution and rerun the specimen.				
	⑤ Unload the specimen from Vitros.		Lab technologist	1	
	⑥ Verify the result.		Lab technologist	1	

Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
Calcium/Magnesium/ Phosphorus/Urine Acid preparation:  	① Pour an aliquot to store. Since the PH for this specimen needs to be adjusted, so the original specimen needs to be stored.		Lab technologist	1	A worksheet needs to be created before the test. Urine Acid test needs to be programed independently.
	② Adjust the PH to the required range.		Lab technologist	1	
	③ Set the specimens to wait for an hour.	1 hour			
	④ Pour an aliquot to store the adjusted specimen.		Lab technologist	1	
	⑤ Centrifuge the specimen				

Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
Amolase/Creatinine/Glucose/Protein/Urea/Potassium/ Sodium preparation:  	① Centrifuge the specimen				A worksheet needs to be created before the test.
	② For those tests below, the specimen is run on Vitros5,1 instrument. (Amolase/Creatinine/Glucose/Protein/Urea)				
	③ For those tests below, the specimen is analyzed in the core lab. (Potassium/Sodium)				

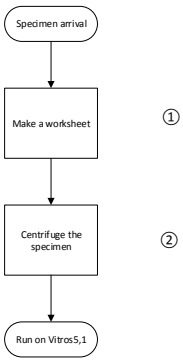
Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
User defined tests: Homocysteine/MPA  	① Make a worksheet		Lab technologist	1	Processing time on Vitros depends on the test type. For the Homocysteine test, it takes 10 minutes and 10 seconds per specimen, 12 minutes for 4 specimens.
	② Spin the specimen	5 minutes			

Figure A.11: Process flow on the ProSpec instrument, test-essential equipment, type 2.

Collected By: Penny (Shuainan) Hu Date:

Title: ProSpec Version: 1.0

Introduction:

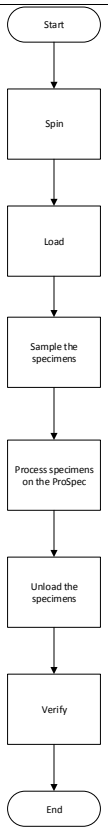
Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
	① Spin the specimens on centrifuge.	5 minutes	Lab Technologist Centrifuge (Capacity 20)	1 1	Every morning, the lab technologist need to check the instrument for 10 minutes. Checking and refilling the reagents takes about 15 minutes. Then the controls of all the tests are run on the instrument. A test can be run as long as the control for this test is running correctly. The wells in the instrument need to be replenished once they used up. The instrument will stop processing when the wells used up.
	② Load the specimens on the machine		Lab Technologist Carousel (3 carousels and 15 spots per each)	1 1	
	③ The instrument will sample the specimens one by one.	Sampling: less than 1 minutes			
	④ All the specimens can be run at the same time after finishing the sampling process. Each specimen will take up multiple wells. The number of wells one specimen takes depends on how many assays are on it.	Running time is about 7 minutes per specimen. Say, 43 minutes for 45 specimens.			
	⑤ Unload the specimens from the instrument		Lab Technologist	1	
	⑥ Verify the result		Lab Technologist	1	

Figure A.12: Process flow on the DS2 instrument, test-essential equipment, type 3.

Collected By: Penny (Shuainan) Hu Date:

Machine: DS2 Version: 1.0

Introduction: Perform TB/IGF-1/TTG-IgA tests

TB tests

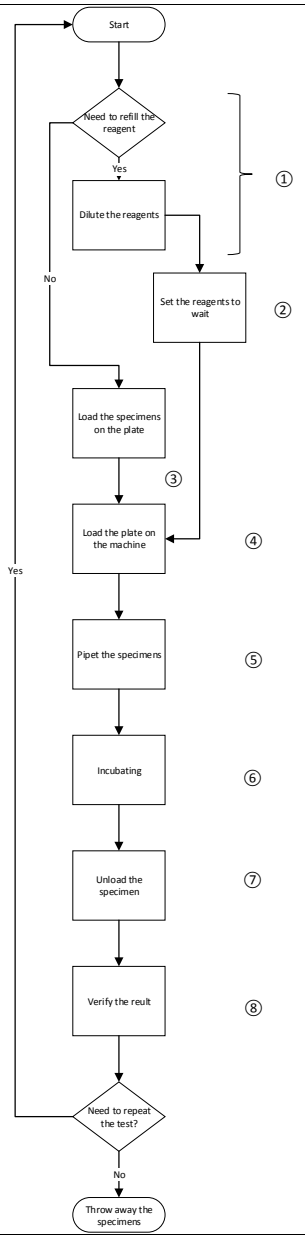
Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
	① Check the reagents. If the reagents need to be refilled, then dilute the reagents. If the reagents are fine, then it goes straight to process 3.		Lab technologist	1	The maintenance takes about 4 minutes a day. There are 96 wells for the tray. 8 are standard, so there are 88 wells left for specimens. For the TB tests, every specimen has 3 tubes. So one plate can run 29 specimens, 87 tubes, and leaving one well empty. Usually for the first plate of the day, two controls are run to make sure the machine is working correctly. So the first plate only carries 27 specimens.
	② Set the reagents to wait for a certain amount of time.	15-20 minutes			
	③Load the specimens on the plate. Make sure that the tubes are in order, and the bar codes are in the right positions so that the instrument can read them. Take out the tops of the tubes.		Lab technologist	1	
	④ Load the plate on to the instrument. Program it on the computer and then manually scan the bar codes. This step can only be done when we have both the reagents and the specimens ready.		Lab technologist	1	
	⑤ The instrument will pipet the specimens and the reagents on to a little tray. While the instrument is doing that, the lab technologist needs to hang around in case something is happening. And another plate cannot be loaded before it finish pipetting.	20 minutes. Based on the number of tubes on the plate	Pipet	1	
	⑥ The little tray is put into the incubator and then the test is performed.	About 3 hours	DS2 machine	1	
	⑦ Unload the specimens from the machine		Lab technologist	1	
	⑧Verify the result on the computer, print a hard copy. And marked the specimens that need to be rerun. After the tests, the specimens are thrown away, since they cannot be used for other tests		Lab technologist	1	

Figure A.13: Process flow on the TDx instrument, test-essential equipment, type 3.

Collected By: Penny (Shuainan) Hu Date:

Title: TDx Chemistry Analyzer Version: 1.0

Introduction: Perform Methotrexate test

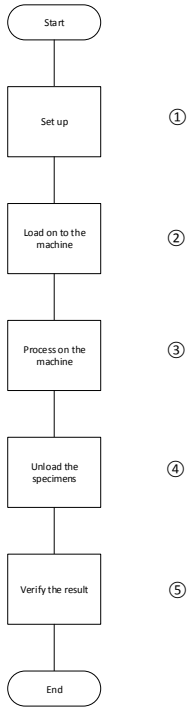
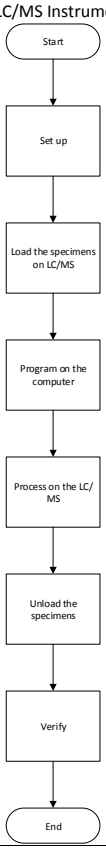
Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
	① Set up the test. Put the specimens into sample cup.		Lab Technologist	1	The maintenance of the machine usually takes about 5 minutes. And it's done in the morning before any tests are run. Sometimes the lab technologists need to refill the reagents.
	② Load the sample on to the machine. Load the reagents on to the machine. Program the machine.		Lab Technologist	1	
	③Process the specimens on the machine	15-20 minutes	TDx machine		
	④ Unload the specimens		Lab Technologist	1	
	⑤Verify the result		Lab Technologist	1	

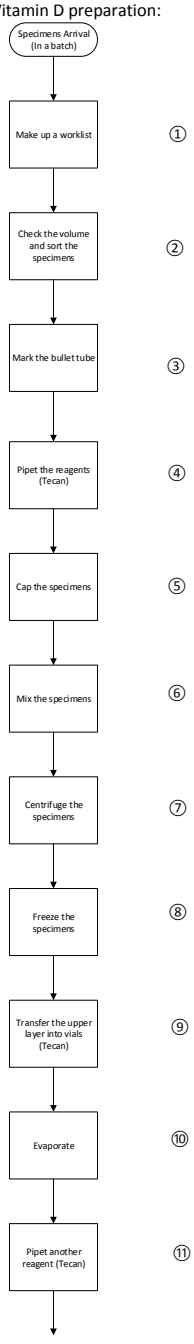
Figure A.14: Process flow on the LC/MS instrument, test-essential equipment, type 4; preparation process flows for the tests on LC/MS.

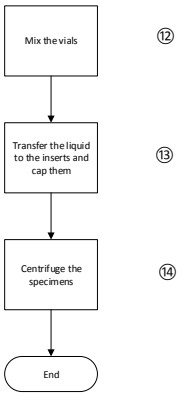
Collected By: Penny (Shuainan) Hu Date: 10/17/2013

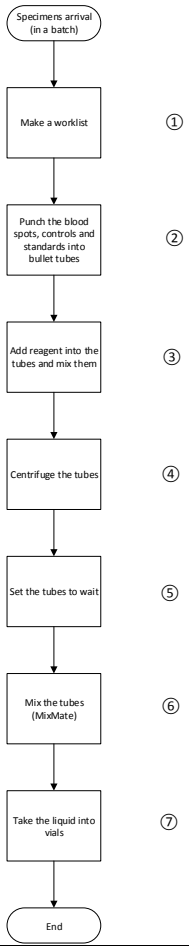
Title: LC/MS instrument Version: 1.0

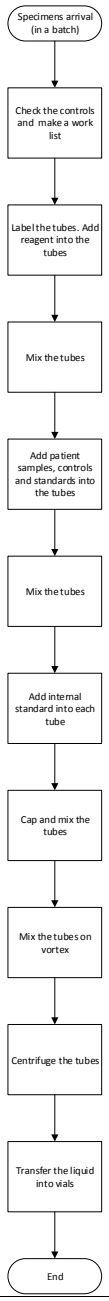
Introduction:

Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
LC/MS Instrument:  	① Specimens need to be pretreated. Different tests require different treatments.		Lab Technologist	1	LC/MS1 has one plate. The plate has 96 wells. LC/MS2 has 4 plates, and each has 48 wells. Xevo(LC/MS 3) has 2 plates. There is 1 blank, 6 standard and controls to be run on the first plate. The number of controls is based on the test type. One blank is run between standards, controls and actual specimens. Some tests can queue up since they have the same collision gas and column. If we want to run a test whose collision gas and column is different than the previous one, there's some adjustments needed to be done on the instrument. Specimens are processed one by one. The later specimen cannot be processed until the previous specimen pass the pipetting process. The test time may be different when performed by different LC/MS instrument.
	② Load the specimens on the LC/MS instrument.		Lab Technologist	1	
	③ Program the process on the computer		Lab Technologist	1	
	④ Process the specimens on the instrument. Specimens are processing individually.	IMS: 5 minutes per piece AED: 6 minutes per piece	LC/MS		
	⑤ Unload the specimens		Lab Technologist	1	
	⑥ Verify the result. 2 people verification.		Lab Technologist	1	

Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
Vitamin D preparation: 	① Make up a work-list.		Lab technologist	1	
	② Check the volume for each specimen and sort the specimens to make sure that they are in the same order as on the list. Different kinds of tube may be used to those specimens that don't have enough volume.	About 45 minutes for 61 specimens	Lab technologist	1	
	③ Mark the bullet tubes.		Lab technologist	1	
	④ Program on the Tecan, and use Tecan to pipet the reagents and specimens into the marked bullet tubes. Sometimes, Lab technologists do it manually.		Program on the Tecan need Lab technologist. While pipetting on the Tecan doesn't	1	
	⑤ Cap all the specimens		Lab technologist	1	
	⑥ Mix the specimens on the Vortexe.	4 minutes 30 seconds			
	⑦ Centrifuge the specimens	5 minutes			
	⑧ Freeze the specimens	At least 30 minutes	Lab technologist	1	
	⑨ Transfer the upper layer into the vials using Tecan.		Program on Tecan need Lab technologist, while pipetting doesn't	1	
	⑩ Evaporate the specimens		Lab technologist	1	
	⑪ Pipet another reagent using Tecan.		Program on Tecan need Lab technologist, while pipetting doesn't	1	

Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
Vitamin D preparation: 	⑫ Mix the vials		Lab technologist	1	
	⑬ Transfer the liquid to the inserts and cap all the vials		Lab technologist	1	
	⑭ Spin the specimens on the centrifuge	10 minutes			

Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
IMS spots preparation:  	① Make a work list and make sure there's no specimen missing.		Lab technologist	1	Immunosuppressant can be performed using blood spots or whole blood.
	② Label the tubes. Punch the blood spots, controls and standards into bullet tubes. There're usually 3 controls, 6 standards, and 2-3 patient controls.		Lab technologist	1	
	③ Add internal standard (reagent) into the tube. And mix each tube.	3 seconds to mix each tube.	Lab technologist	1	
	④ Spin the tubes in centrifuge.	2 minutes			
	⑤ Set the tubes to wait.	10 minutes			
	⑥ Mix the tubes on MixMate instrument.	20 minutes			
	⑦ Take the upper layer liquid out and transfer it into vials. Make sure the liquid doesn't contain anything from the bottom of the tube.		Lab technologist	1	

Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
IMS (whole blood) : 	① Check the controls and make a work list. Usually, there're usually 6 standards, 3 controls and 1 blank.		Lab technologist	1	Specimens, controls and standards need to be at room temperature. Usually allow at least 2 hours or longer for patient samples to be at room temperature. Specimens, controls and standards will be rocked for more than 15 minutes before getting processed.
	② Label the tubes and pipet the reagent into the tubes.		Lab technologist	1	
	③ Mix the tubes.				
	④ Add patient samples and controls to the tubes.		Lab technologist	1	
	⑤ Mix the tubes.				
	⑥ Add internal standard into each tube.		Lab technologist	1	
	⑦ Cap and mix the tubes.		Lab technologist	1	
	⑧ Mix the tubes on vortex.	30 seconds on vortex with the highest setting. 5 minutes on Tomy multi-tube mixer with the highest setting.			
	⑨ Spin the tubes in centrifuge.	5 minutes			
	⑩ Transfer the liquid into vials.		Lab technologist	1	

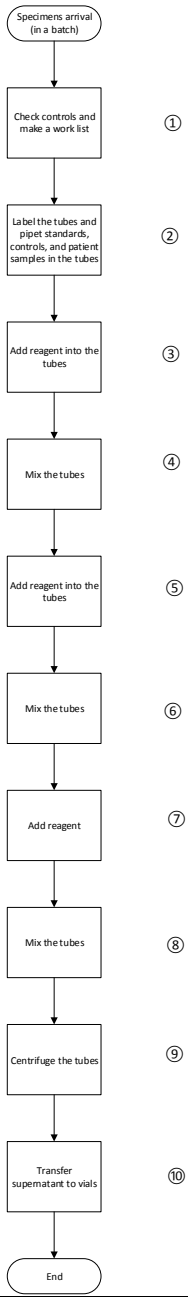
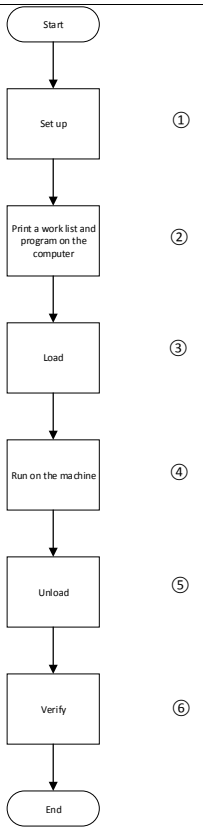
Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
AED preparation : 	① Check the controls and make a work list. Usually, there're usually 6 standards, 2 controls and 1 blank.		Lab technologist	1	
	② Label the tubes and pipet patient samples and controls into the tubes.		Lab technologist	1	
	③ Add reagent into the tubes.		Lab technologist	1	
	④ Mix the tubes.	1 minutes – Tomy mixer 30 seconds-single tube vortex.			
	⑤ Add reagent into the tubes.		Lab technologist	1	
	⑥ Mix the tubes on vortex.	30 seconds			
	⑦Add reagent into the tubes.		Lab technologist	1	
	⑧ Mix the tubes on vortex.	5-10 seconds			
	⑨ Spin the tubes in centrifuge.	5 minutes			
	⑩ Transfer the liquid into vials.		Lab technologist	1	

Figure A.15: Process flow on the HPLC instrument, test-essential equipment, type 4; preparation process flows for the tests on HPLC.

Collected By: Penny (Shuainan) Hu Date:

Machine: HPLC Version: 1.0

Introduction:

Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
	① Set up the test. The setup process is different based on the test type. The specimens need to be at the room temperature.		Lab Technologist	1	When the lab technologist turn on the instrument, it takes about 5-6 minutes to warm up. A set of controls are run before running specimens. If the test type changes, the controls for that test need to be run. The number of controls and standards are different based on the test type. The reagent (mobile phase) is made every 2-3 weeks. It takes about 2-3minutes to make the reagent. Run the mobile phase (the reagent) through the instrument. A reference is run before running any test to make sure the mobile phase is running correctly.
	② Print a work list and check every specimens on the list to make sure all the specimens are there. Program the test on the computer.		Lab Technologist	1	
	③ Load the specimens onto the instrument		Lab Technologist	1	
	④ Specimens are run on the instrument	18 minutes per specimen			
	⑤ Unload the specimen from the instrument		Lab Technologist	1	
	⑥ Calculate the result and manually input the result onto the computer		Lab Technologist	1	

Vitamin A & E setup

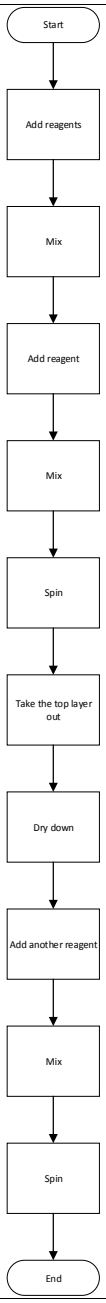
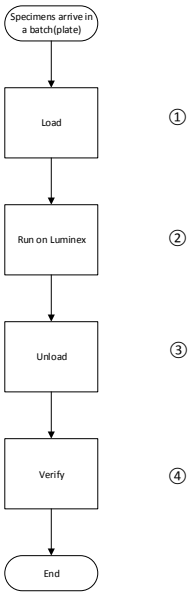
Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
	① Prepare little bullet tubes and pipet the specimens into these bullet tubes. Add 3 kinds of reagents.		Lab Technologist	1	
	② Mix the specimens	1 minutes			
	③ Add another kind of reagent		Lab Technologist	1	
	④ Mix the specimens	3 minutes			
	⑤ Spin the specimens on centrifuge	5 minutes	Centrifuge		
	⑥ Pipet the top layer out		Lab Technologist	1	
	⑦ Set the specimens aside to try	15 minutes			
	⑧ Add another kind of reagent		Lab Technologist	1	
	⑨ Mix the specimens	Couple of minutes			
	⑩ Spin the specimens	2 minutes	Centrifuge		

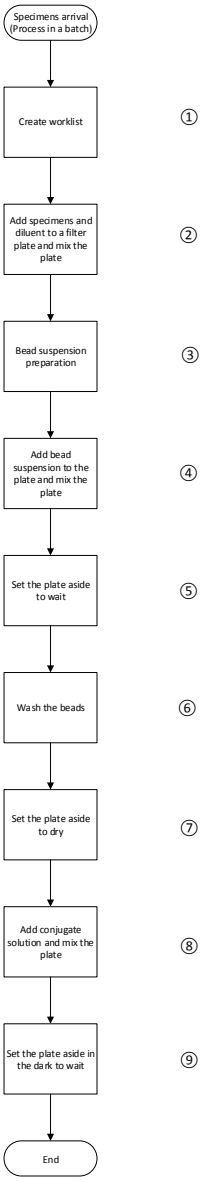
Figure A.16: Process flow on the Luminex instrument, test-essential equipment, type 4; preparation process flows for the tests on Luminex.

Collected By: Penny (Shuainan) Hu Date: 11/2013

Title: Luminex Version: 1.0

Introduction: Perform EBV and MMRV(Meals, Mumps, Rubella, Varicella) tests

Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
Luminex:  	① Program and load the plate onto Luminex.		Lab technologist	1	There's daily startup and daily shutdown. (20minutes) Also, there's different maintenance needs to be done weekly, monthly, every six months and yearly(as needed). For MMRV test, it only needs to run one kit. For EBV test, it needs to run 2 kits.
	② Run the whole plate on Luminex. Specimens are run one by one.	(15 minutes for the whole plate.)			
	③ Unload the plate from Luminex.		Lab technologist	1	
	④ Verify the result.		Lab technologist	1	

Process Flow	Description	Processing Time	Resource Requirement		Additional Information
			Name	Units	
Luminex specimens preparation: 	① Program on the computer and create a work list. Determine the controls that are used for the test.		Lab technologist	1	The filter plate has 96 wells. One specimen takes one well. A negative and a positive control are run per each plate.
	② Add specimens and diluent to a filter plate. Mix the specimens.		Lab technologist	1	
	③ Mix and sonicate bead suspension. Put it into a tray. Mix it again.		Lab technologist	1	
	④ Transfer it into the plate. Mix the plate.		Lab technologist	1	
	⑤ Set the plate to wait in the dark.	30±10 minutes			
	⑥ Use the vacuum to suck it through. Add diluted wash buffer, use vacuum to suck it through again. Repeat this step 3 times to wash the beads.		Lab technologist	1	
	⑦ Set the plate to dry	5 minutes			
	⑧ Add conjugate solution to the plate and mix the plate (shake the plate).	Shake 15 seconds	Lab technologist	1	
	⑨ Set the plate to wait in the dark.	30±10 minutes			

Appendix B

HIGH-LEVEL FLOWCHARTS FOR EACH ANALYTICAL INSTRUMENT

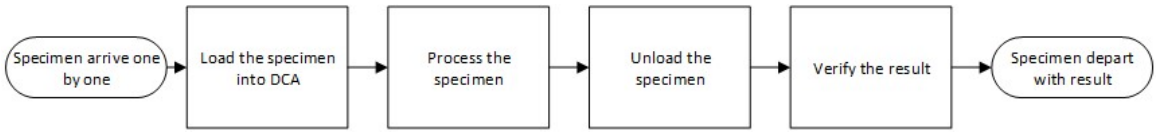


Figure B.1: Flowchart of analytical process on a DCA instrument.

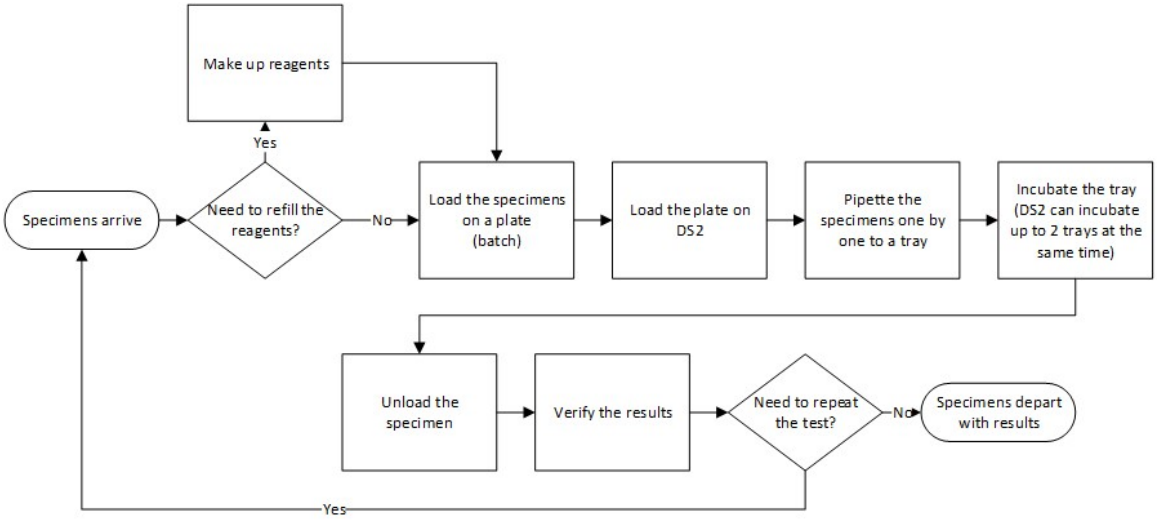


Figure B.2: Flowchart of analytical process on a DS2 instrument.

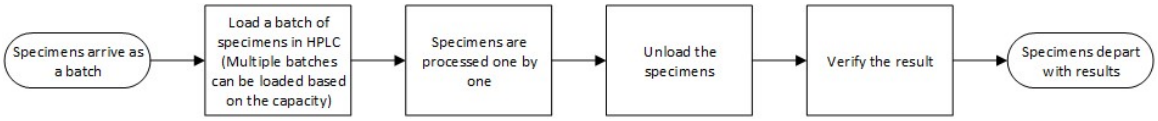


Figure B.3: Flowchart of analytical process on an HPLC instrument.

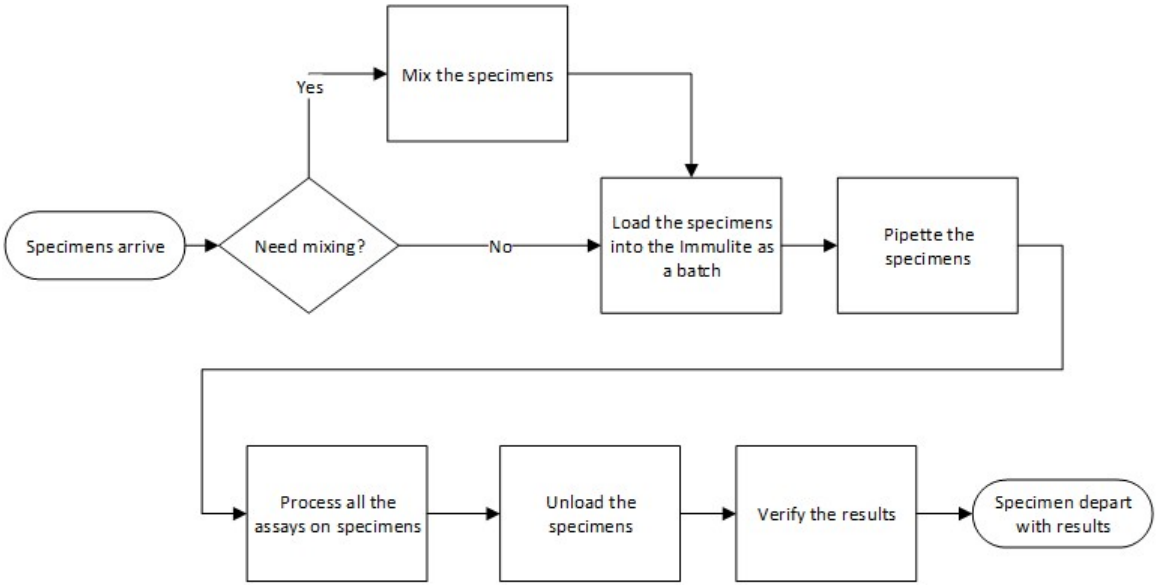


Figure B.4: Flowchart of analytical process on an Immulite instrument.

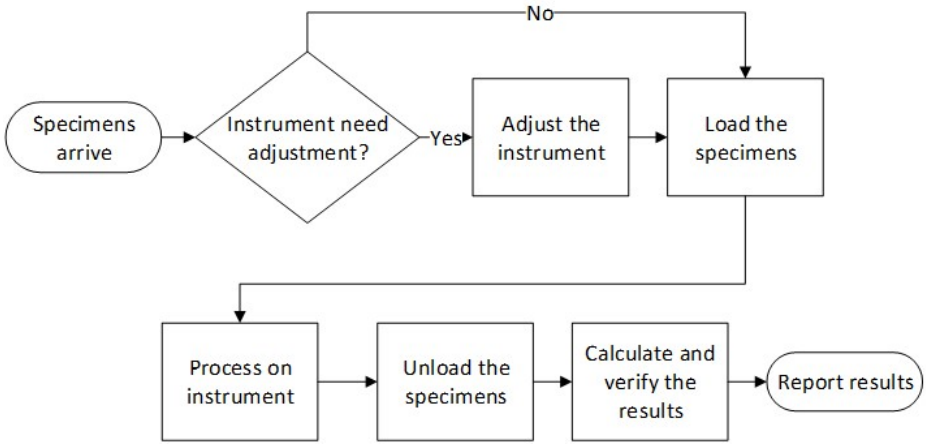


Figure B.5: Flowchart of analytical process on an LC/MS instrument.

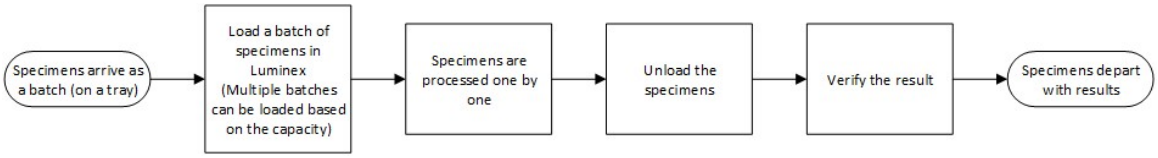


Figure B.6: Flowchart of analytical process on a Luminex instrument.

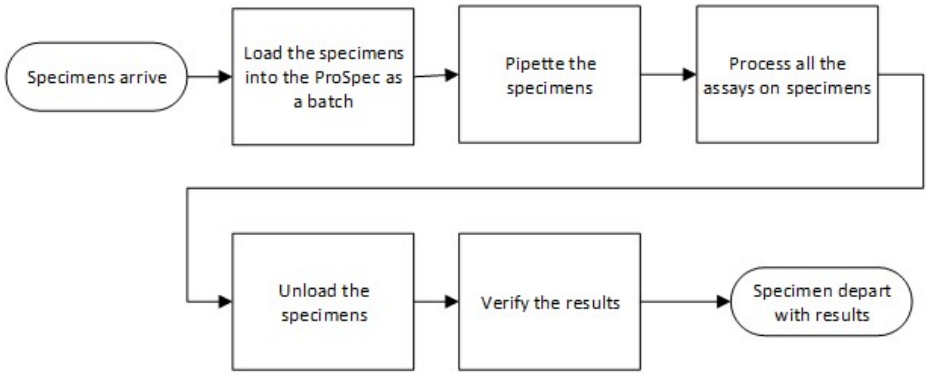


Figure B.7: Flowchart of analytical process on a ProSpec instrument. The instrument will stop processing when the trays in the instrument are used up. The trays need to be replaced for the instrument to continue processing.

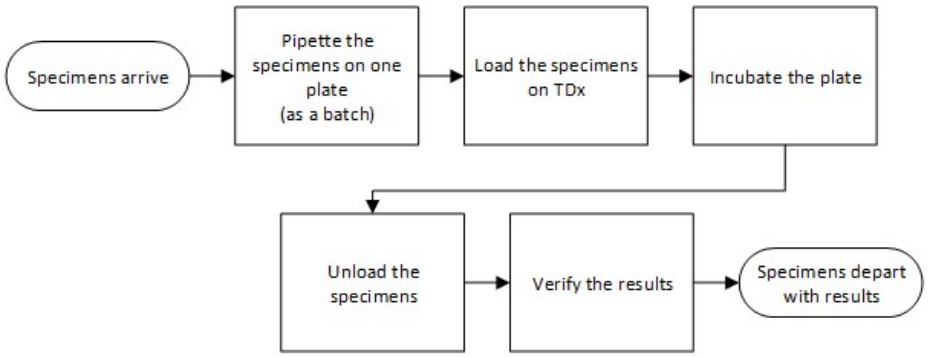


Figure B.8: Flowchart of analytical process on a TDx instrument.

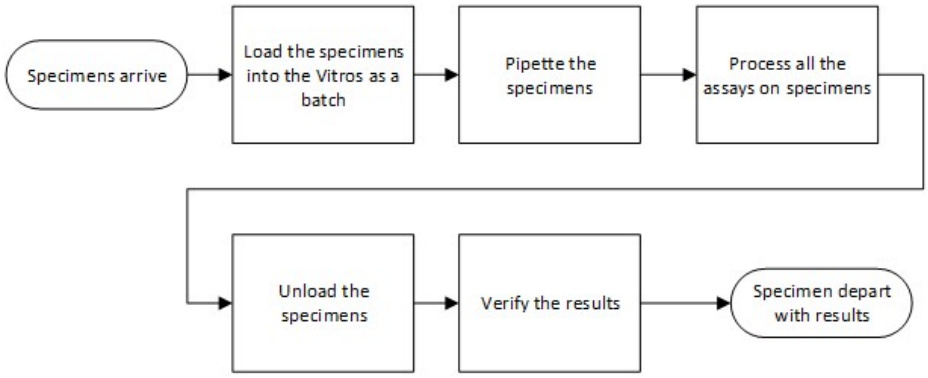


Figure B.9: Flowchart of analytical process on a Vitros instrument.

Appendix C

PARAMETER FIELDS FOR EACH OF THE OBJECTS

Appendix C contains the parameter fields for all of the objects:

1. Lab technologist
2. Specimen
3. Specimen preparation (in batch)
4. Manual test (in batch)
5. Specimen preparation (individual)
6. Manual test (individual)
7. DCA
8. Immulite
9. Vitros
10. ProSpec
11. Centrifuge
12. DS2
13. TDx
14. LC/MS
15. HPLC
16. Luminex
17. Storage

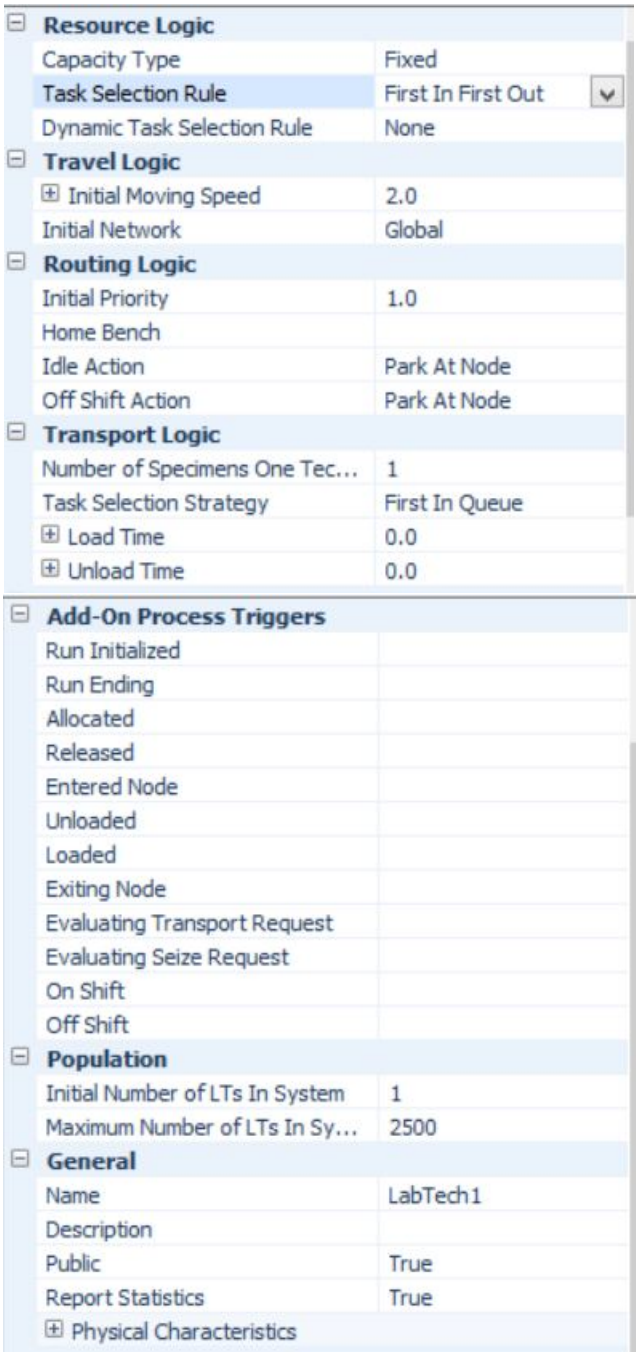


Figure C.1: Parameter fields of an LT object.

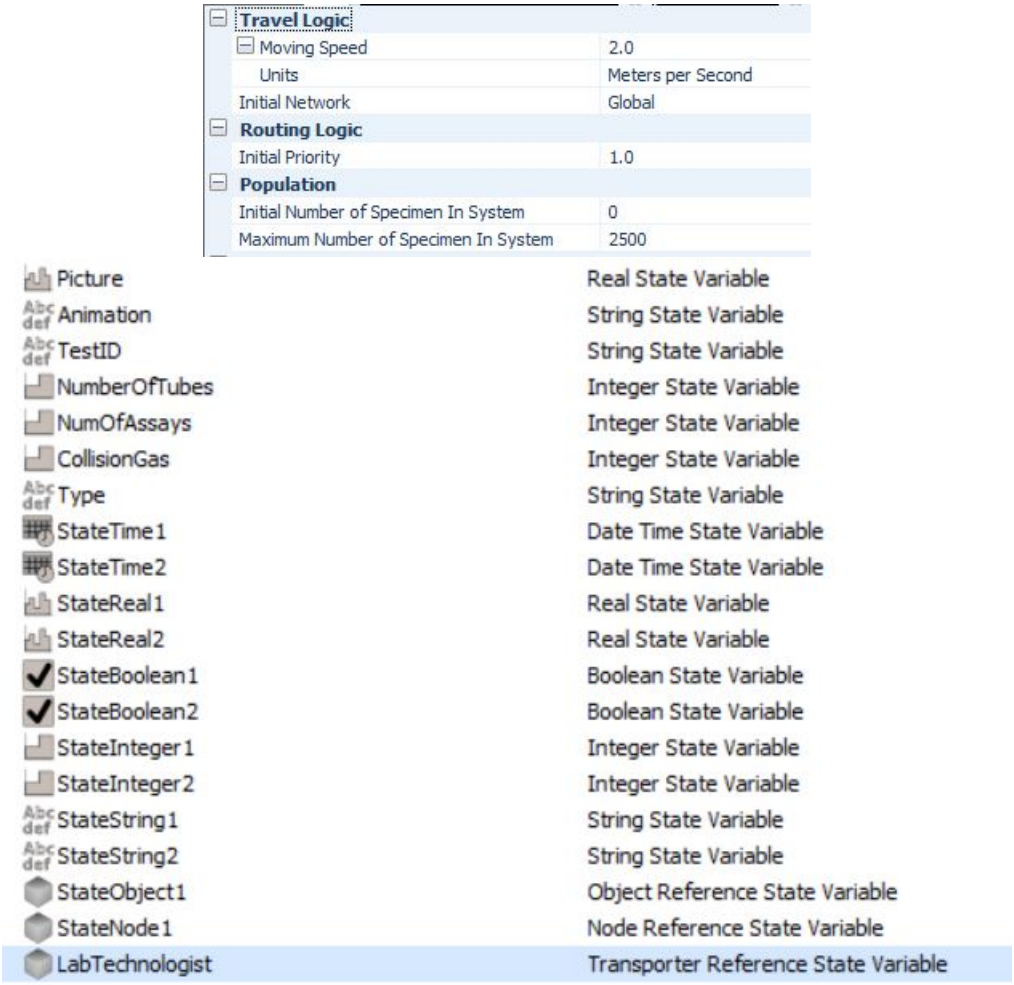
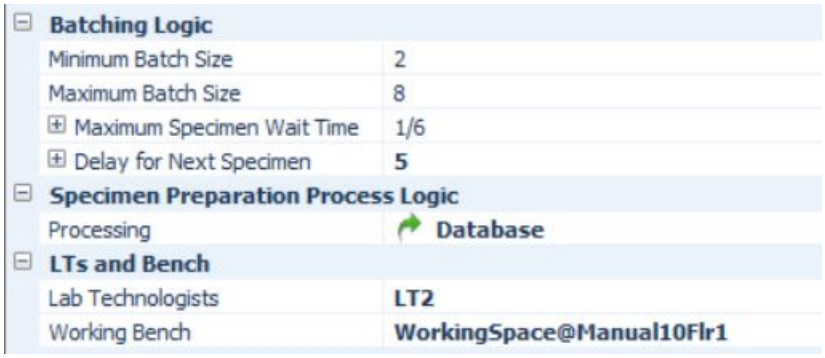
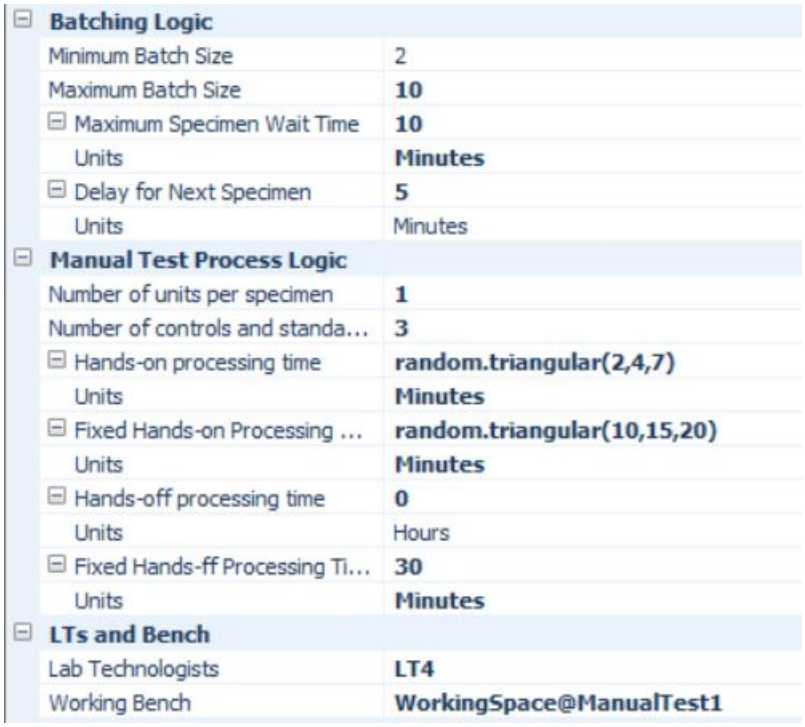


Figure C.2: Parameter fields and state variables of a specimen object. The state variables can be used in the model to record different information about a specimen.



Batching Logic	
Minimum Batch Size	2
Maximum Batch Size	8
⊞ Maximum Specimen Wait Time	1/6
⊞ Delay for Next Specimen	**5**
Specimen Preparation Process Logic	
Processing	**Database**
LTs and Bench	
Lab Technologists	**LT2**
Working Bench	**WorkingSpace@Manual10Flr1**

Figure C.3: Parameter fields of a specimen preparation (in batch) object.



Batching Logic	
Minimum Batch Size	2
Maximum Batch Size	**10**
⊟ Maximum Specimen Wait Time	**10**
Units	**Minutes**
⊟ Delay for Next Specimen	**5**
Units	Minutes
Manual Test Process Logic	
Number of units per specimen	**1**
Number of controls and standa...	**3**
⊟ Hands-on processing time	**random.triangular(2,4,7)**
Units	**Minutes**
⊟ Fixed Hands-on Processing ...	**random.triangular(10,15,20)**
Units	**Minutes**
⊟ Hands-off processing time	**0**
Units	Hours
⊟ Fixed Hands-ff Processing Ti...	**30**
Units	**Minutes**
LTs and Bench	
Lab Technologists	**LT4**
Working Bench	**WorkingSpace@ManualTest1**

Figure C.4: Parameter fields of a manual test (in batch) object.

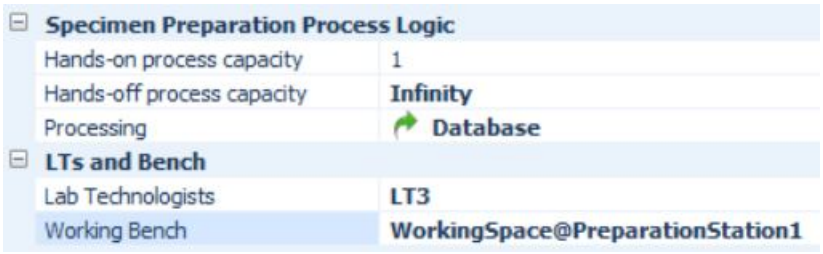


Figure C.5: Parameter fields of a specimen preparation (individual) object.

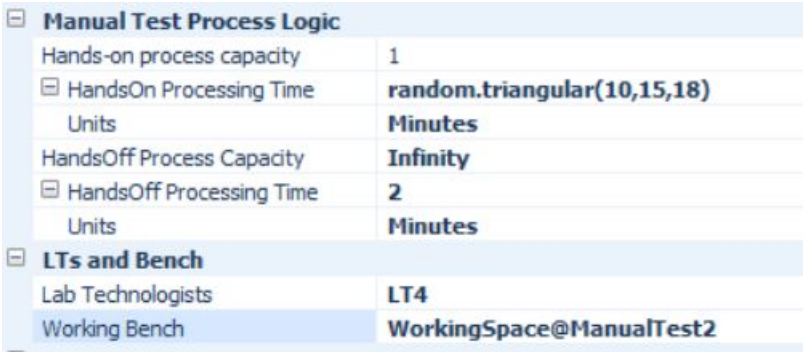


Figure C.6: Parameter fields of a manual test (individual) object.

Figure C.7: Parameter fields of a DCA object.

Batching Logic	
Minimum Batch Size	2
Maximum Batch Size	8
Maximum Specimen Wait Time	**10**
Units	**Minutes**
Delay for Next Specimen	**2**
Units	**Minutes**
Immulite Process Logic	
Immulite Capacity	**75**
Processing Capacity	**120**
Sampling Time	**18**
Units	**Seconds**
Processing	**Database**
Maintenance and running controls	**True**
Time Off-set	**8**
Time Interval	**24**
Maintenance Time	**random.triangular(0.3,0.5,0.7)**
Running Controls Time	**random.triangular(1,1.3,1.5)**
LTs and Bench	
Lab Technologists	**LT1**
Working Bench	**WorkingSpace@Immulite1**

Figure C.8: Parameter fields of an Immulite object.

Batching Logic	
Minimum Batch Size	2
Maximum Batch Size	**80**
Maximum Specimen Wait Time	**10**
Units	**Minutes**
Delay for Next Specimen	**5**
Units	**Minutes**
Vitros Process Logic	
Vitros Loading Capacity	**80**
Vitros Processing Capacity	**100**
Processing	**Database**
Sampling Time	**18**
Units	**Seconds**
Rerun Ratio	**0.1**
Maintenance and running co…	**True**
Time offset	**8**
Time Interval	**24**
Maintenance Time	**0.5**
Running Controls Time	**random.triangular(30,60,90)**
Units	**Minutes**
LTs and Bench	
Lab Technologists	**LT2**
Working Bench	**WorkingSpace@Vitros3600**

Figure C.9: Parameter fields of a Vitros object.

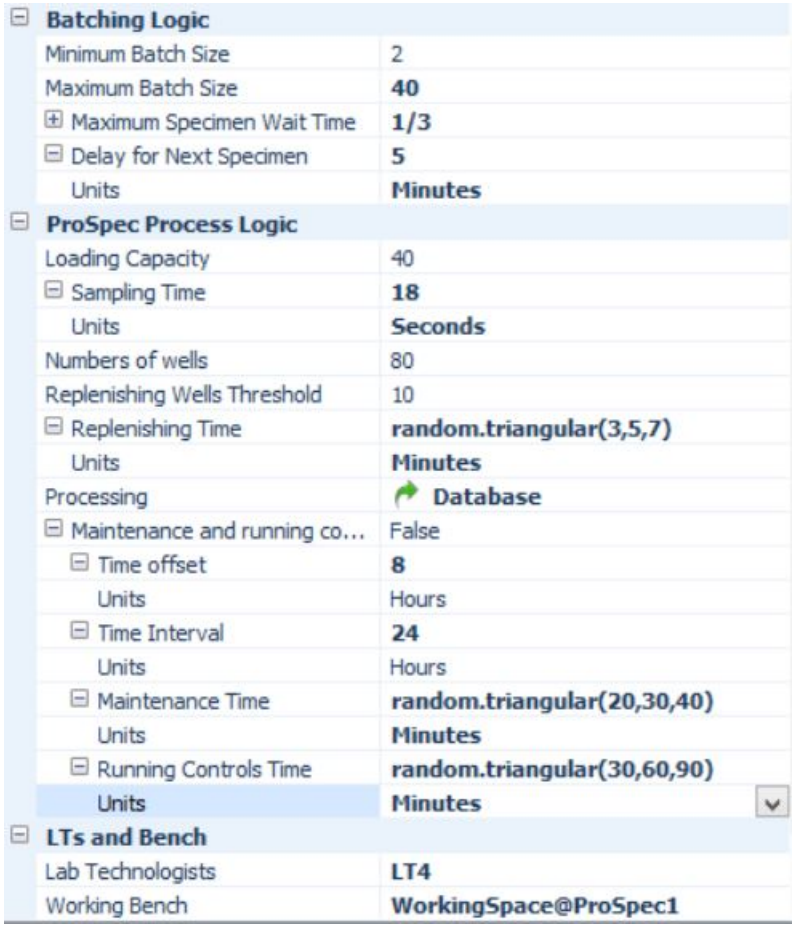


Figure C.10: Parameter fields of a ProSpec object.

Batching Logic	
Minimum Batch Size	**1**
Maximum Batch Size	**20**
Maximum Specimen Wait Time	**10**
Units	**Minutes**
Delay for Next Specimen	**5**
Centrifuge Process Logic	
Loading Time	**2**
Units	**Seconds**
Spinning Time	**5**
Unloading Time	**2**
Units	**Minutes**
LTs and Bench	
Lab Technologists	**LT2**
Working Bench	**WorkingSpace@Centrifuge1**

Figure C.11: Parameter fields of a Centrifuge object.

Batching Logic	
Minimum Batch Size	**1**
Maximum Batch Size	**96**
Maximum Specimen Wait Time	**1**
Units	Hours
Delay for Next Specimen	**10**
Units	**Minutes**
DS2 Process Logic	
Number of plates	2
Processing	**Database**
Fixed Hands-on Preparation Time	**0.2**
PipettingTime	**18**
Units	**Seconds**
LTs and Bench	
Lab Technologists	**LT1**
Working Bench	**WorkingSpace@DS2_1**

Figure C.12: Parameter fields of a DS2 object.

Figure C.13: Parameter fields of a TDx object.

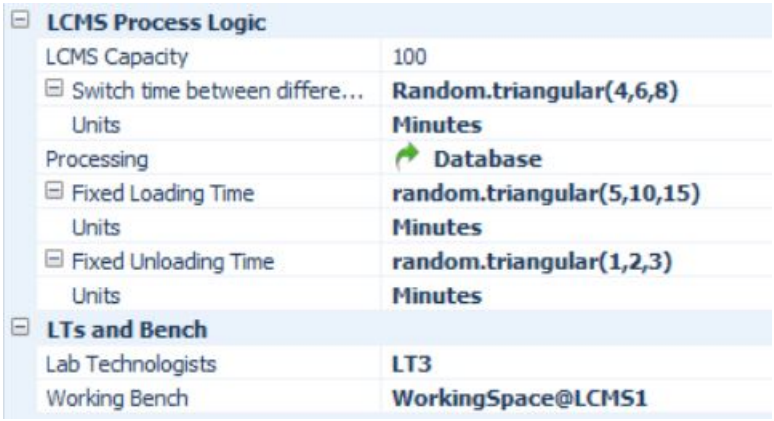


Figure C.14: Parameter fields of an LC/MS object.

Figure C.15: Parameter fields of an HPLC object.

Figure C.16: Parameter fields of a Luminex object.

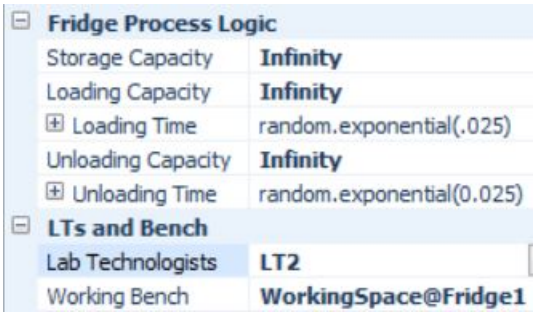


Figure C.17: Parameter fields of a storage object.

VITA

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