CLINICAL LABORATORY PERFORMANCE ANALYSIS: A SYSTEM DYNAMICS APPROACH

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CLINICAL LABORATORY PERFORMANCE ANALYSIS: A SYSTEM DYNAMICS APPROACH

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ABSTRACT

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While maintaining an organization, managers must think about both profitability and quality. Especially in healthcare systems, the service should be delivered with acceptable quality and it must be affordable for all patients. Studies show that clinical laboratories are one of the most critical parts in healthcare systems in terms of demand and expenditures. Thus, clinical laboratory systems should be delivered with acceptable quality and affordable price. Whether public or private, clinical laboratories must create value in their performance while meeting time, quality, resource, and cost constraints.

System dynamics is a sophisticated simulation modeling approach to understand and analyze the dynamics of complex systems in both business and social environment. This approach enables the modelers to make better judgments about their decision using the inner dynamics of the model in question. In this research, system dynamics approach is preferred for model development because it enables modelers to understand and discuss complex problems by illuminating the relationships among the variables involved.

The purpose of this study is to present a system dynamics model that is used to simulate the dynamics of various factors that impact the clinical laboratory performance. Facing a staff capacity constraint, a clinical laboratory can undertake a number of strategies: hiring new staff, working overtime, or doing both. Developed model is used to analyze the impact of various factors on main productivity parameters for these strategies. Model is run for one year and laboratory performance behavior is analyzed over this time period.

ÖZET

KLİNİK LABORATUVARLARDA PERFORMANS ANALİZİ: BİR SİSTEM DİNAMİĞİ YAKLAŞIMI

Bir organizasyonda karar vericiler karlılık ve kaliteyi bir arada düşünmelidirler. Özellikle sağlık sistemlerinde hizmet, kabul edilebilir bir kalite ile teslim edilmelidir ve tüm hastalar için uygun fiyatlı olmalıdır. Çalışmalar, klinik laboratuvarların sağlık sistemi talep ve harcamaları açısından en kritik bölümlerinden biri olduğunu göstermektedir. Bu nedenle, klinik laboratuvar sistemleri de makul bir fiyatla uygun bir kalitede olmalıdır. Yüksek kaliteli laboratuvar hizmeti, yüksek fiyatlarla sağlanırsa, etkinlik ve verimlilik kaybolacaktır. İster kamu ister özel bir laboratuvarda performans, zaman, kalite ve maliyet kriterleri açısından incelenmelidir.

Sistem dinamiği, hem iş hem de sosyal hayattaki karmaşık sistemlerin dinamiklerini anlamak ve analiz etmek için geliştirilmiş bir modelleme yaklaşımıdır. Bu yaklaşım, söz konusu modelin iç dinamiklerini kullanarak kronik problmelerin çözüm yollarının ne tür yeni sorunlar getireceğini göstermek ve görünürde olmayan problemleri fark etmek açısından oldukça yararlıdır.

Bu çalışma, klinik laboratuvarların performansını etkileyen çeşitli faktörlerin dinamiklerini simüle etmek için kullanılanılabilecek bir sistem dinamiği modeli kurmayı hedeflemiştir. Personel kapasitesi kısıtlaması ile karşı karşıya olan bir klinik laboratuvar, bir dizi stratejiyi yürütebilir: yeni personel alımı, fazla mesai yapmak veya her ikisini birden yapmak. Bu modelde, geliştirilen dinamik model, klinik laboratuvarlardaki kaynakları yönetmek için çeşitli seçenekler sunar. Çalışmada sistem dinamiği yaklaşımı kullanılmıştır çünkü bu yöntem, modelcilerin karmaşık değişkenleri anlayabilmeleri ve tartışabilmeleri için ilgili değişkenler arasındaki ilişkileri aydınlatabilir. Geliştirilen model “kalite”, “üretkenlik”, “test karmaşıklığı”, “test hata oranı”, “yapılacak testlerin değeri” nin ana üretkenlik parametreleri olan “teslimi gerçekleştirme zamanı”, “maliyet” ve “personel sayısı” üzerindeki etkilerini analiz etmek için kullanılır. Model bir yıllık periyot için çalıştırılmakta ve bu süre zarfındaki laboratuvar performans davranışı analiz edilmektedir.

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LIST OF SYMBOLS/ABBREVIATIONS

AHP	Analytic hierarchy process
AIDS	Acquired immune deficiency syndrome
ANP	Analytic network process
BS	Base strategy
CL	Clinical laboratory
CLD	Causal loop diagram
DES	Discrete event simulation
GDP	Gross domestic product
JCAHO	Joint Commission on Accreditation of HealthCare Organizations
MCDM	Multi-criteria decision making
OECD	Organization for Economic Co-operation and Development
OT	Overtime
PC	Percentage completed
SD	System dynamics
SERVQUAL	Service quality model
STEMI	Segment elevation myocardial infarction
TAT	Turnaround time
TURKSTAT	Turkish Statistical Institute
UK	United Kingdom
US	United States
WHO	World Health Organization

1. INTRODUCTION

A clinical laboratory (CL) is defined as a place where some physical, chemical and biochemical techniques are applied to pre-diagnose or diagnose patients' health problems [1]. The main task of a CL is to gather information and providing results for medical doctors on biological samples taken from patients.

CL's contribution to public health is fundamental in the prevention, diagnosis, and treatment processes [1]. CLs are necessary organs as an integral component of healthcare systems. Studies claim that laboratory services consume a significant portion of the hospital's budget and that reports prepared in the CLs are 60-70 per cent effective in making critical decision [1]. This means that critical decisions, such as treatment plan and permission to be discharged from hospitals, are made based on laboratory test results. For this reason, all of the applied tests must meet certain performance criteria based on a predetermined procedure. To deliver reliable and qualified healthcare services within specified time limits, it is important to carry out the correct procedures.

Progresses on medicine and technology directly create developmental effects on laboratory medicine. Especially information technology and automated equipment are the major factors for advances in CLs. While the laboratories are broadening their scope by such developments, economical aspects produce sharp limitations [2, 3]. This means economic trends create pressure on healthcare organizations to provide a service or product with minimum cost, within limited time, and required quality. In other words, CL managers are enforced to use up-to-date technology and enhance the laboratory service quality with a cost effective strategy. Additionally, to accommodate the service with above mentioned constraints, healthcare managers must handle fluctuated demand curve with their limited supplies. Langlois and Wallemacq (2009) state that CLs are handicapped to perform their services with imbalance on supply (capacity of supplies in CL equipment, labor, etc.) and demand (test request), and this instability brings out problems on quality, productivity and cost of CL services even in many European countries.

According to Organization for Economic Co-operation and Development (OECD), a healthcare service must provide a defined quality and quality of service to meet the main policy objectives approved [4]. However; quality, speed or price does not make sense

individually in terms of performance in healthcare industry. Assessment of CL performance can be carried out by identifying/prioritizing all needs of patients and other stakeholders under limited resources constraints. An organization must think about profitability while maintaining service quality. As a result, healthcare managers are enforced to deliver service by considering the aspects of quality, speed and price as a whole.

To summarize, 'resource management' has become a focal point for CL managers for a few decades. While utilizing the resources, a cost efficient procedure must be applied without compromising the other objectives of CL. Thus, a proper CL performance management system is required.

1.1. BACKGROUND

The development of CLs has been started two centuries ago [5, 6]. According to Büttner's study (1992), there are two prerequisite actions in history for the birth of laboratory medicine; the first one is "revolution of chemistry" and the second one is usage of "clinic" in medicine terminology. In Greek literature, "clinic" means "teaching at the sick bed". After these pre-requisite actions for the birth of CLs, researchers also agree on progressive events of CL has three breakthrough phases along these two centuries [6-8].

French revolution has a great impact on not only political point of view, but also science issues. After the revolution, usage of chemical signs and trying to cluster disease in diagnose become a requirement in medicine. In 18^{th} century could be accepted as the origin of CLs with the notion of using chemical sign to diagnose the disease and clustering the diseases rather than investigating each patient as a new case. The structure of CLs is mainly established on handling physical and chemical variations to diagnose the health problems. Thus, the diagnose phase of disease became a relevant issue, and this new goal namely required the CLs [9].

The second period is triggered by the Industrial Revolution, in 1840. In this case, CLs were transformed to the institutions and accepted as a part of medical science. Thus, the existence of CLs gradually increased. As a result of this trend, mathematical approaches were applied to test results and clinical tool kits were extended and improved. From this

period on, laboratory medicine was accepted as a discipline under medicine, and various documents were written in this field. However, the laboratories were limited in terms of space and volume, and could not reach the necessary popularity in medicine [6, 10].

In 19th century, this time span also referred as the third section, the successful studies on experimental physiology provoked the interest and popularity on applications of chemical methods in medicine [7]. By the discovery of blood groups and progressive acts on analysis of body fluids, in early 1900s, the demand for laboratory tests propagated the necessity on full time CL scientists in hospitals [11]. In time, CL became a relevant part of modern medicine because of the perception on applications in medicine could not be applicable without professional laboratory services [12]. After this period, CLs were accepted as part of the hospitals officially.

In 20th and 21st centuries, improvements in medicine were accelerated by invention of new technological devices. Additionally, ongoing developments in information technologies and electronics resulted in improvements on test techniques and equipment used in medical processes. However, this sophisticated equipment could be purchased with high price. This rapid escalation in the cost of health care leads a necessity to investigate new alternatives to manage budgeting problems. Especially in developing countries, managing the cost of medical services becomes mostly inconvenient due to high rate of imported materials consumption (equipment, one-time consumables, etc.). Subsequently, the term ‘resource management’ turned out to be a focal point in healthcare. Hospital costs become a significant issue not only in developing countries. The hospital managements (also in EU countries) are handicapped to perform services with imbalance on supply and demand. This imbalance brings out quality, productivity and cost problems in healthcare services. As result, quality and cost control issues have become critical interests in all divisions of healthcare systems all over the world [4]. Thus, these problems generated critical concerns on all divisions of healthcare systems all over the world. Consequently, CL practice is also affected from these modifications [13]. Test production has to be faster and more reliable. Quality, turnaround times, and cost come in prominence by the agency of computer integrated machines and smart equipment.

1.2. CLINICAL LABORATORIES IN TURKEY

Based on "World Health Report" published by World Health Organization (WHO), many governments have lack of knowledge on health service delivery in their own country [14]. To overcome this problem, a central institution is recommended to monitor the delivered health services. On the contrary, in Turkey, a national institution was not available to evaluate, monitor or ensure service quality until 2011. Although CLs are evaluated and regulated in Turkey under the legislation of the law 992 which is accepted in 1927, criteria on this law are considered "inadequate" by medicine communities. In addition, any national standardization on CL establishment and procurement were not available. Thus, the lack of national standardization caused a variation in laboratory service quality in Turkey. In 2011, Turkish government took an action on monitoring and standardization of CLs.

According to Deloitte "Turkey Health Sector Report" in 2012, nearly all public, university, and private hospitals provide CL service. Over the last fifteen years, the number of medical institutions has been on the rise. In 2006, based on the official statistics of Turkish Statistical Institute (TURKSTAT), more than a thousand medical institutions existed. This number is evolved to approximately 31,000 in 2016 [16]. However, these organizations are significantly interfered due to price regulations on health expenses implemented by Turkish government in 2007.

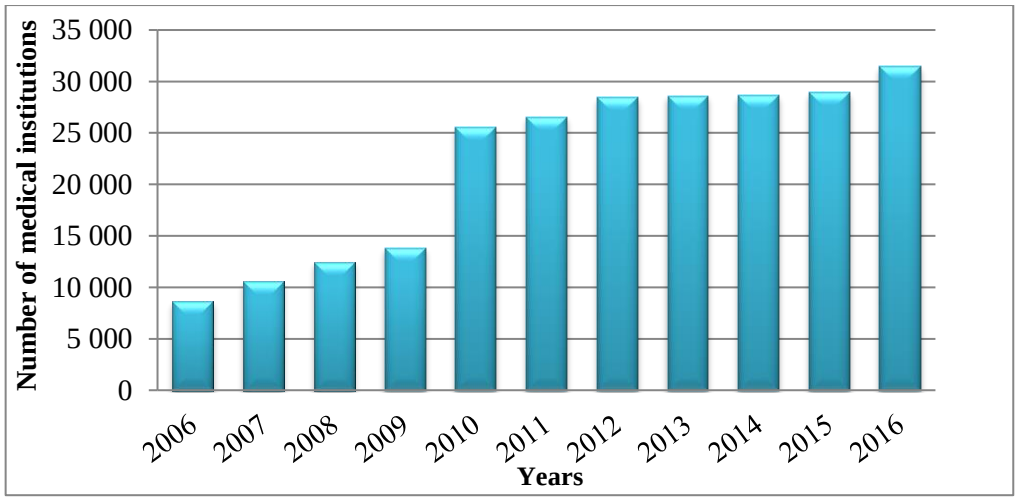


Figure 1.1. Number of medical institutions in Turkey [16]

Thus, while an exponential increase in the number of medical institutions is observed, total health expenditure is also expanded. As shown in the following figure, total health care expenditure expanded from nearly 44 billion in 2006 to 120 million Turkish Liras in 2016 [17].

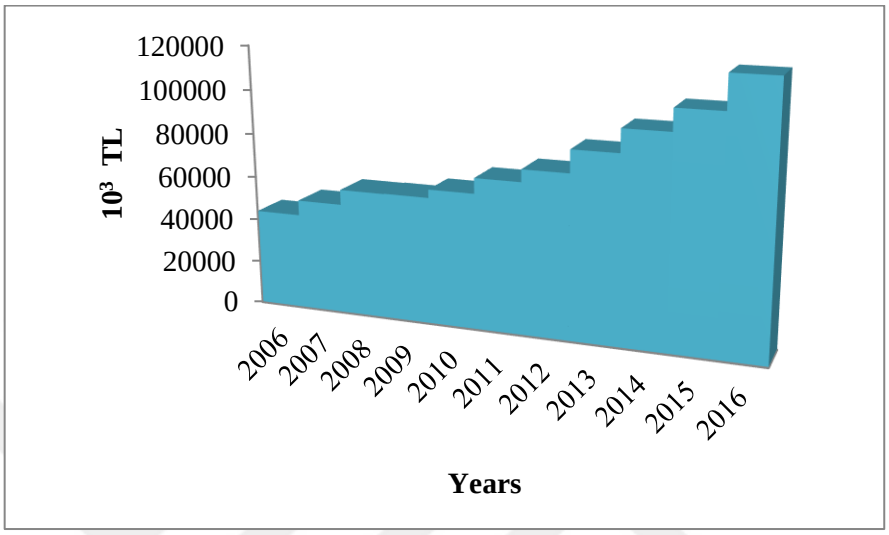


Figure 1.2. Total health expenditure changes in Turkey [17]

However, the number of medical institutions and total health expenditure over years should not be considered separately. Hence, the changes on percentage of total health expenditure to gross domestic product over last decade could give an idea about current healthcare consumption [18].

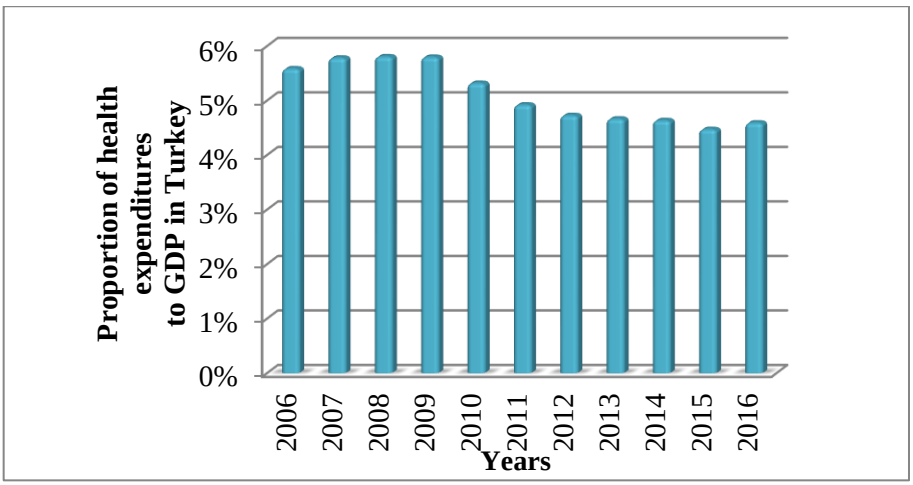


Figure 1.3. Change in rate of health expenditure to gross domestic product in Turkey

As seen on Figure 1.3, between 2006 and 2016, relative amount of health expenditures to gross domestic product has decreased from 5.5 to nearly 4.5 per cents. Except slight fluctuations, the proportion of total health expenditure to Gross Domestic Product (GDP) has a stable pattern over the years. That means; while the prices of healthcare services are increasing, Turkish people cannot afford healthcare expenditures easily.

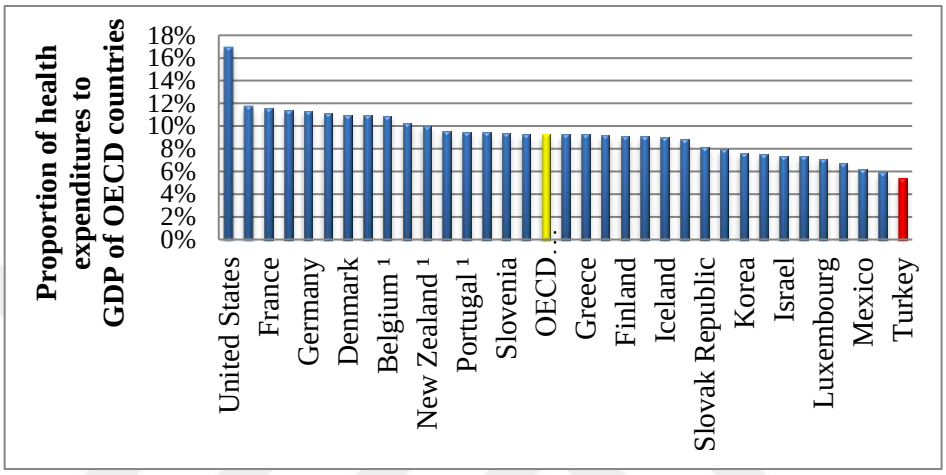


Figure 1.4. Percentage of health expenditures in OECD countries [17]

Figure 1.4 is prepared by the published data by OECD health statistics (2014), and it shows that Turkey is the last country in ranking based on proportion of health expenditure to gross domestic product. While the average of OECD countries is 9 per cent, Turkey follows Mexico and Estonia with 5.39 per cent, having the lowest value [19].

In Turkey, medical equipment and test kits are imported from developed countries. Thus, cost in healthcare is fluctuating day by day as a consequence of exchange rates. Health care services become more and more expensive because of the inflated costs of resources. That means healthcare expenditures are not affordable for most Turkish citizens.

There is no statistics available on demographics and scope of CLs in Turkey. Thus, exact number of CLs in Turkey cannot be determined exactly. However, based on the assumption that every public hospital has at least one type of CL (hematology, biochemistry, etc.), total number of CLs in hospitals is assumed to be about 2000. On the other hand, the predicted number of private CLs in Turkey is approximately 130. This

number is relatively low given the fact that they cannot afford high resource costs in healthcare services.

Based on a research conducted at Cumhuriyet University Hospital Faculty of Medicine, total income for each department and money outflow is recorded for one month and departments are ranked based on their profits [20]. Following table is developed according to this study.

Table 1.1. Income and profit relation in a hospital and CL

Department of Hospital	**Monetary Value (Turkish Liras)**
Total Income of Laboratories	1,322,594.86
Profit of Laboratories	301,238.92
Total Income of Hospital	5,353,289.63
Profit of Hospital	1,219,284.35

Biochemical, hematology, blood center, microbiology, pathology, radiology, parasitology laboratories are combined under one item in this study. Results show that approximately 22 per cent of total income remains as profit in CLs. In addition, 25 per cent of total profit of a hospital is provided by CLs. Thus, CLs have a great impact on hospital profits. However, the lack of performance monitoring and controlling in Turkish hospitals, hospital resources could not be managed properly. That means delivering CL service is one of the most critical and promising industry in healthcare services in Turkey.

Currently in Turkey, Ministry of Health manages the pricing policy by using pre-determined price plans, rather than using cost of the delivered service to the hospital. Due to unrealistic pricing policy developed by Turkish government, the funds do not correspond to the real expenditures of hospitals. The funding problems bring out a new matter; resource shortages. Consequently, hospital management should handle the problems originated from high costs of medical resources and try to survive in competitive environment [21]. Therefore, while utilizing the resources, a cost efficient procedure must be applied without compromising the other indicators of CL performance.

Another study was conducted on an aortic valve replacement surgery cost analysis [22]. The total cost of this surgery to hospital is found and; CL tests are classified as the second most expensive process based on the ranked cost types.

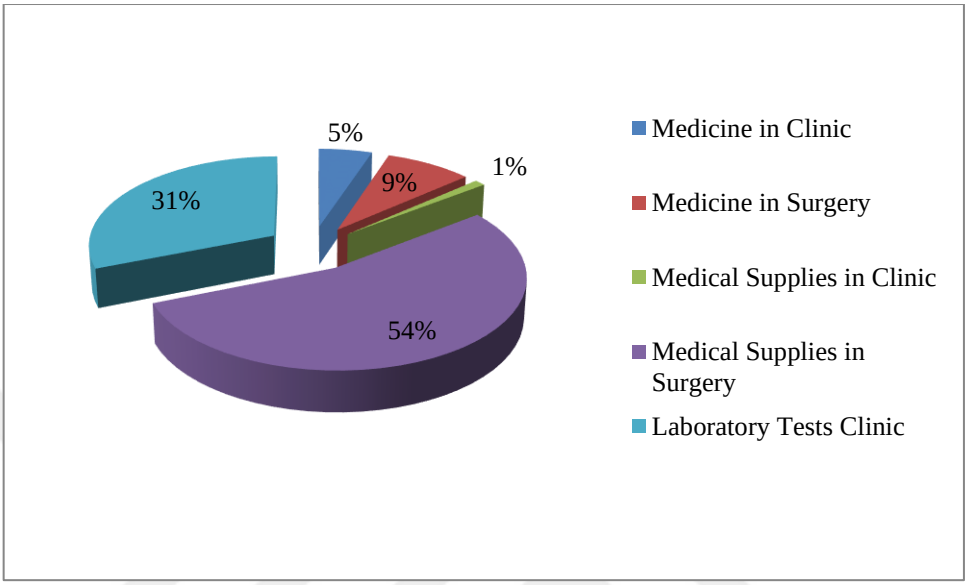


Figure 1.5. The percentage of cost types and values in a typical surgery [22]

A typical surgery includes five main cost types; cost of medicines used in clinic and used in surgery, cost of medical supplies in clinic and surgery, and finally cost of laboratory tests [22]. Figure 1.5 shows the percentages of these costs in a pie chart. Based on the figure, 31 per cent of medicines and medical supplies cost is expended as laboratory cost [22]. As seen in literature about history of CL, medical tests are essential and one of the important stages on medicine. Thus, not only cost control side must be improved, but also service quality must be considered as a complex and critical part of healthcare system. When the population growth rate is considered in Turkey, a need on healthcare service is expected to increase significantly over the years. In order to utilize limited resources and to ensure equal access to healthcare services by all patients, a great emphasis must be given to create efficient action plans for these institutions.

In summary, demand on healthcare services has been increasing and it is expected to continue in the following decades. However, importing medical technologies like testing equipment and test-kits created two serious problems on CL expenditures. The first one is imported medical elements create dependency to foreign companies on laboratory tools

manufacturers, and sensitivity to exchange rates is the second problem. In other words, the root causes of inflation in resource prices are the dependency to manufacturers and sensitivity to exchange rate. The difference in resource prices has a direct effect on cost of healthcare service. As shown in Figure 1.3, despite the fact that GDP of Turkey has increased in last decade, proportion of GDP that is allocated to healthcare expenditures remained in a tight range. This means, Turkish citizens could not benefit from healthcare systems easily. Although, every citizen has to have equal benefits from healthcare services, it is not affordable for everyone because of high resource costs. A proper resource management strategy should be utilized to decrease this high cost.

As indicated in the research by [22], nearly one quarter of healthcare cost per patient is originated from CL tests in diagnose or curing processes. Thus, a proper resource management strategy is crucial to overcome cost problems in CLs.

1.3. RESEARCH MOTIVATION

The core motivation of this research is to develop a system dynamics (SD) model that enables the decision makers to analyze and understand the overall CL performance. In healthcare literature, performance problems are handled by including limited number of dimensions. Generally, models are utilized to minimize time or optimize the staff levels. However, in this study, performance of CL is managed covering all critical dimensions that take place in literature (time, resource, quality and cost). Based on the literature review, this is the first study developed with SD approach to analyze CL performance. Also, our SD model generates an opportunity to reflect interrelations among all model indicators, and analyze their further impacts on performance.

The other motivating factor is developing a multi-methodology framework that can be used for structural validity of the SD model. In this framework, boundary adequacy, structural, and parameter assessment stages of structural validity are conducted with Analytic Network Process (ANP) model.

Finally, this thesis covers a technical comparison of two important and frequently used simulation techniques; discrete event simulation (DES) and SD. This technical comparison

discusses strengths and weaknesses of these methods, supported by healthcare systems literature.

1.4. RESEARCH OBJECTIVES

Although, productivity, quality, cost, and time are major clinical performance indicators, many of the studies about healthcare performance use only one of these indicators [23, 24]. As a consequence of this, performance in healthcare systems has been expressed in a narrow sense, and it is unrealistic.

If a high quality laboratory service is provided at a high price, it is believed that efficiency and effectiveness are impaired. A deficit in pricing policy diminishes the right of equity in health care [14]. CLs must create a value in their performance. If not, adapting new economic trends and technological developments will be difficult for CLs. This means, new strategies must be developed to ensure health care services are available for everyone.

Clearly, laboratory service processes generate most of the costs of a hospital budget, so improving efficiency in a healthcare organization requires improving these processes. Such processes also have strong influences on the satisfaction of the customer, which is of fundamental importance.

To this extend, in addition to making contribution to healthcare literature; the main objectives of this research can be listed as follows;

- Developing an SD model that can be used to simulate the dynamics of various factors that impact CL performance.
- Developing a framework for dynamic model construction and to support conceptual model development and structural validity by using a multi-methodology approach.
- Employing a dynamic model to study the impact of overtime work, and change on labor quantity (hiring) on productivity, and other performance indicators.
- Employing the dynamic model to make decisions about various laboratory management actions.
    i. Overtime strategy
    ii. Hiring strategy

iii. Overtime with hiring strategy

- Obtaining investment strategies in the laboratory.

In other words, this study could highlight new strategies for planning the capacities on the newly established hospitals, and help to determine the number of human resources needed such as number of qualified personnel for different levels of healthcare system to eliminate the inflation of unemployment. The model results will be helpful for new policy development in a CL.

Such a study could be remedy for wrong investments and also is a reference for further demand analysis in human, equipment and delivered service while discovering the triggering relations among each other.

1.5. RESEARCH QUESTIONS

The following thesis question is constructed to satisfy the research objectives, *"How to design a laboratory management strategy for optimum laboratory performance?"* The decomposition of this major question is given below (sub questions):

- How is a laboratory system modeled?
- What are the endogenous and exogenous variables which affect the main performance criteria of a laboratory?
- How do these variables affect each other?
- How should the resources planned and controlled in a laboratory?
- What are the longitudinal strategies (such as extra investment, recruitment) to improve the performance criteria of a laboratory?

Based on the questions given above, the aim of this research is to model a CL system by SD approach. This model will be used to develop longitudinal strategies for cost, quality and labor performance, by utilizing time and resources.

In literature, various approaches have been developed to manage and control laboratory service processes [25-28]. The strength of this study is using feedback relationships in SD approach. Feedback compares the current level of a variable to a desired level, and generates a behavior based on differences between actual and desired states [29, 30].

The main goal of this study is to develop a model to describe a CL service process. In addition, it helps to decision makers to analyze system behavior regarding various CL performance indicators. The model also includes different perspectives of CL experts. This is, the model covers real processes and offers a chance to analyze this realistic model under different policies and scenarios. By examining the relationships of CL performance indicators, managerial actions can be analyzed in this model.

1.6. OVERVIEW OF THE METHODOLOGY

This section explains how to use SD for modeling in the research by comparing two simulation modeling technique.

1.6.1. Comparison of Modeling Techniques

Modeling is the major necessity to enhance the existing systems. Healthcare systems also need to be modeled for improving delivered services without compromising any other objectives. Simulation techniques are frequently preferred to model healthcare problems. As it is expected, simulation has various applications which yield different results in different perspectives. For more realistic and efficient modeling, modelers need to simulation software with quantitative methodologies. This study compares two popular simulation techniques; Discrete Event Simulation (DES) and System Dynamics (SD).

The ability of reflecting behaviors of a real system as a simulation is fundamental process for simulation techniques. The main concern starts after satisfying this condition. All types of simulation models serve the same purpose: to analyze the system responses under different conditions within a certain period of time. Modelers try to interpret the results under different scenarios, then they prepare course of actions based on these circumstances and make decisions.

Although both DES and SD are simulation tools, SD approach provides a wide point of view to catch system as a combination of inner and outer dynamics of system. However in DES studies, research focuses on specific problems generated by service delays and tries to eliminating these problems. In other words, SD approach provides not only the reflections

of factors influences on objective(s) all together but also exposes the behaviors of factors on each other.

If the concerned problems are in operational or a tactical level, the system can be fully interpreted in discrete event simulation. SD is applicable for strategic level of concerns. In SD, models reflect the causal interactions and feedback effects in closed-loops where in DES models are in open loop structures and the effects of feedback is considerably low. The modeling philosophy is the main issue in system representation. DES has an analytical approach to a specified part of the system. As a result of this, the concerned problem is handled in a great concentration and detail. The inputs and results of these approaches are also different. In DES, system input and output data have to be quantitative whereas in SD the input and output data could be quantitative or qualitative. These two approaches also diverge in validation phase of modeling. In DES, a specified given input should be transformed into a certain output. There is no need to understand inner dynamics of this transformation process. On the other hand, SD validation phase concern is slipped from "what" the modeler gets from system to "how" it gets this output from the system. In addition to these seven dimensions, the purposes of these two studies also differ from each other. While DES models aim to make "decisions" like optimization, prediction and/or comparison of alternatives, the goal of SD models is to understand the relations and generate policies based on these interactions [31]. Hence, SD is applied in this research. While if the modeler needs to design a complex system or who wants to get long-term consequences of his solution, SD should be a better choice. The following table illustrates the summary of aspects compared above between DES and SD simulation techniques namely; nature of problem, feedback effects, representation of system, complexity and results handled from the model.

Table 1.2. Comparison for DES and SD (Revised version from [32])

Aspects Compared	**DES**	**SD**	**Author(s)**
Nature of problem	Tactical/operational	Strategic	[33, 34]

Feedback effects	Open loop structure	Closed-loop structure	[31, 33]
System representation	Analytic view	Holistic view	[34]
Complexity	Great complexity & detail	General & abstract systems	[34]
Model results	Statistically valid estimates of system performance	Full picture (qualitative & quantitative) of system performance	[32]

Based on literature review, researchers concern various departments and sides of healthcare services. Hence, the core critical issue in healthcare problems is managing the resources while meeting the demand in service within specified objectives. As mentioned in previous paragraphs, boundaries of the handled problems in some cases are extended by using the advantage of applied method. For this case, the SD approach creates an opportunity to model and simulate the system as various case studies to analyze the longitudinal effects among variables. As mentioned, system-thinking is utilized for strategy development phase for any system to overcome the problems caused by factor relations in the long run.

Tailoring multilevel healthcare problems by DES is generally problematic. Therefore, DES is preferred for short-term decisions and analysis on specific processes. As a result, short-term problems in patient flow and resource management problems are modeled using this technique. If the modeler needs to understand causes of a phenomena or wants to get long-term consequences of his decisions, SD could be a better choice. Thus, forecasting, causal relations and long-term consequences of actions could be represented better with this technique. Recalling the research objectives and questions, to analyze the CL performance with time, cost, resource, and quality indicators, and relation among these

indicators, SD modeling generates a great opportunity. Hence, SD modeling technique is preferred to develop a simulation model for CL performance analysis in this research.

1.7. ORGANIZATION OF THESIS

The thesis consists of six chapters; first chapter is introduction to research. Literature background of SD, why SD is preferred for this thesis, and resource management issues are presented in Chapter 2. Chapter 3 explains the methodological basis and procedures of SD and ANP. Actual system development is conducted in Chapter 4. Credibility of developed model is checked with verification and validation analysis in Chapter 5. SD simulation results, sensitivity analysis, and lessons learned from the model are located in Chapter 6. Final chapter includes conclusion of the study and proposes future research issues.

2. LITERATURE REVIEW

Healthcare systems are considered part of service systems, and are considered as complex systems [35-38]. Complex healthcare systems are defined as independently operable [35]. Wickramasinghe et al. (2007) considers healthcare as a complex system that is a collection of general and dispersed systems. Such systems have many components that are self-organizing, and adapt to their environment as they grow [37]. Faezipour and Ferreira (2011) add that healthcare systems can be managed within their own subsystems.

Healthcare as a complex systems include interacted elements. Thus, the most frequently used approach for healthcare systems is simulation for more than four decades [3]. Managing the system with regarding all stakeholders is main purpose of all healthcare services. Many applications in healthcare literature, proposed models propose solutions to chronic problems by altering some parameters and variables. However, this solution may generate a new bottleneck on analyzed process or generate a new or unknown problem. In many cases, analyzing the influences of proposed solutions in real systems may be expensive, time consuming and inefficient [39-41]. Thus, to overcome such problems, simulation models are preferred.

The healthcare simulation models have large spectrum from mental models to mathematical models [42-44]. These models propose many solutions for design improvements. DES modeling technique has significant dominance over the SD method in healthcare applications. DES is a stochastic modeling approach used for queuing models. It is a flexible modeling approach and has been used to improve healthcare services [45-47]. DES has been used for scheduling systems [47-50], patient waiting time reduction [51-54], operational performance improvement [55-64] and critical resource and capacity management problems [55, 56, 65-71].

Despite these examples of DES applications in healthcare, some researchers claim that there is a significant difficulty to study complex or multistage systems with DES [44, 72]. The limitations of DES as its inability to show the feedback dynamics which is related with full picture representation, and detail data requirements [44]. It concludes to simulate such models multiple replications need to be run with long runtimes [44]. Gönül-Sezer and

Ocak (2016) concludes that due to the nature of the method, altering the scope requires new restrictions in data analysis stage, thus generating additional challenges to the process.

On the other hand, SD offers a simulation modeling methodology that can assist decision makers develop and analyze strategies by modeling feedback systems, and manage multi stage, complex systems.

There are some studies that compared DES and SD modeling techniques [31-33, 72-74]. One of these studies conducted a comparison between SD and DES by using key concepts of SD [33]. Another one compared SD and DES in terms of modeling process steps [72]. They used problem definition, model design, data collection and model validation as criteria for comparison. Additionally they compared two methods based on nature of problems they handle. They concluded that DES is preferred to analyze systems with great detail of process flows whereas analysis on forecasting, causal relationships, and long-term consequences are easily represented in SD.

In another study two healthcare problems are illustrated using both SD and DES techniques [31]. The study concluded that the advantage of SD is in data collection procedure, and both quantitative and qualitative data can be used in SD modeling without any restriction which is not possible in DES modeling.

Morecroft and Robinson (2005) used SD and DES techniques for the same fishery problem and compared these models based on dissimilarities between representation and interpretation approaches. They concluded that DES is more suitable to model ‘constrained randomness’ and SD is better to model ‘deterministic complexity’. The key differences between these two methods were investigated under three dimensions; methodology, concerned system, and problem in this specific system [75-76]. They concluded that SD is more suitable when long-term scenarios are investigated.

It is suggested that both DES and SD serve to mimic a real system [74]. However, level of the system is the distinctive factor in modeling with these methods. They conclude SD is more suitable in tactical level, whereas DES is preferred for operational level problems.

As indicated before, although DES applications on healthcare have significant dominance over the SD method [31], however researchers support SD models in addressing the dynamic complexity in healthcare issues [31, 77-80]. The extensive characteristics of

healthcare systems can be generated with accumulation, delay and feedback loops. These generate dynamic complexity due to fact that various elements interact and have impact on each other, and such interactions are often difficult to capture, and to measure. The existence of nonlinear relationships makes it difficult to predict healthcare systems' behavior accurately. Thus, complicating the decision-making processes. Therefore, system dynamics methodology is supported as a framework to be used in various healthcare studies. SD literature for healthcare includes both quantitative (hard) and qualitative (soft) approaches to modeling.

A soft perspective, which is based on qualitative perspective, involves the use of CLD's to describe the system in detail to understand the feedback structure of the system [81-82]. For this method, input data is obtained through interviews, focus group meetings or review of reports and theories for the main output. On the other hand the objective of the hard perspective (quantitative perspective) is to test hypothesis about the model structure, to confirm that the structure is able to replicate system behavior, and provide time series showing performance over time. Additionally, models are employed for testing policy alternatives [83, 84].

In the remaining of this section, SD developments in healthcare will be evaluated under the areas of: resource planning, process analysis and improvement, and capacity management.

Stochastic systems and queuing models could be interpreted as DES models with a preliminary condition. Under these circumstances, entities should be represented by discrete states over time [73, 85, 86]. In this technique, modeler needs a clear event list of the system and input data must be collected. The data must be statistically appropriate. These requirements are generally seen as weaknesses of DES method [87]. The strength of DES is the ability to incorporate system details, time dependent behavior, and system constraints. DES generates various outputs about system performance parameters by considering altered conditions [88]. DES models are appropriate to manage resources efficiently while reducing the waiting times and costs. Hence, the method convinces decision makers who are involved in healthcare systems [89].

2.1. SD STUDIES IN HEALTHCARE

Based on the literature, healthcare problems that have solved by using SD approach are divided into three sections in this study. These are resource planning, capacity planning, and process improvement and analysis.

2.1.1. SD and Resource Planning

Resource planning with SD can be divided into two groups: workforce (human resources) planning, and materials and equipment planning including facilities. Both are evaluated for short term and long term strategies.

SD is rarely used for managing the workforce. An interactive system dynamics simulation model has been developed for workforce planning in healthcare [90]. SD modeling is applied to understand clinical workforce requirements. Their model helped management to improve their decision-making process [91].

Grössler and Zock (2010) developed an SD model to understand the recruitment and training period of new hires for healthcare decision makers. They evaluated the impact of hiring, and training in healthcare services.

Kunc (2008) built an SD model to determine the requirements of workforce skills, the results indicated that the volume and complexity of workload must be captured correctly. His objective was to determine policies for organizations to manage unbalanced workforce strategies.

In another study, researchers try to portrait differentiating pediatric workforce as a reaction to altering demand [93]. The study proposes projections for short-term demand and supply changes.

As shown in given examples, SD models are used for resource management problems. However, nature of method encourages the modelers to make further analysis on capacity management problems as well.

2.1.2. SD and Capacity Management

Geranmayeh and Iyer (2008) analyze the capacity planning for critical resources such as critical services and procedures, required equipment in an emergency department. They try to develop an economic justification for investment on laboratory and diagnostic facilities, and physicians.

In another study, a model for chronic disease prevention is developed and projections for this disease are given for 50 simulated years by using population health and healthcare delivery system. The model policies helped decision makers on long term capacity planning for disease prevention [95]. Chen (2003) handled the non-acute care, home-based health services for elders, and built a dynamic model on patient actions as a supplementary study to plan longitudinal budget and capacity strategies in Norway. In another study to estimate the medical specialist demand and resource capacity requirements in Spain, SD modeling approach is chosen [97]. Another model is developed to execute policies on electronic health information exchange reports for a regional health information department. SD model policies are used to overcome the gap between resulted demand and supply. Finally, model results are used to estimations on demand analysis and capacity management [98].

2.1.3. SD and Process Improvement and Analysis

System dynamics has been also used to map patient flows, and test alternative policies for process improvements such as cycle time reduction, patient waiting time reduction, etc. For example; Lane and Husemann (2007) used the method to suggest alternative improvements for patient check-out time reduction. In another study a waiting list dynamics model for cardiac surgery process is developed [100]. The main objective of this study was to understand dynamics of waiting list process and to reduce patient waiting times. Quinn et al. (2005) develop a causal model for delays on laboratory cycle time and captured operational monetary burdens for the hospital. In a recent study to reduce waiting times in segment elevation myocardial infarction (STEMI) patients care unit, a SD model is developed [102]. The researchers suggest that the bureaucratic system should be

transformed into a much more pleasing procedure for STEMI patients to minimize the waiting times.

Maliapen and Dangerfield (2010) developed a model to study clinical pathways in a hospital based on an empiric data. The SD model assisted decision makers by testing various scenarios to improve bottlenecks in hospital process flow. Smits (2010) proposed a model to support policy makers to solve and process management problems in the treatment process during work process redesign by using SD approach.

There are multiple SD studies conducted for emergency departments as well. Lane, Monefeldt, and Rosenhead (2000) applied an SD model to examine bottleneck in an emergency department workflow. Another study was conducted by [34] for an emergency department in United Kingdom. They utilized a dynamic model to analyze the reasons of delays in the department [34]. Also in another study, a system dynamics model has been developed for the emergency department to evaluate proposed design improvements for emergency service [106].

In a more recent study the urgent care unit is modeled with SD, and five alternatives are proposed to eliminate bottleneck of the process [107].

In summary, resource planning, capacity management issues in healthcare systems require an approach to manage complexity to improve process performance and patient satisfaction. SD method helps decision makers design strategies, assess the performance of these strategies over time, and determine the required actions to improve system performance. Thus, although SD is rather an underutilized methodology in healthcare systems research, literature supports SD models to be used to manage the issues in healthcare research. However, most of the models in health context are found to be at unit and/or hospital operations and are managed by including limited number of dimensions of the problem rather than managing multiple dimensions simultaneously. Thus, our study contributes to the literature in this aspect. In our study, CL performance is managed covering all critical performance indicators, and our model will be accounted for the demand and critical resources such as consumables and workforce and their respective costs.

2.2. ANALYTIC NETWORK PROCESS

Multi-Criteria Decision Making (MCDM) is a commonly used approach in literature. Many researchers from different fields have used multi objective decision making methods to determine which alternative is the most suitable for their goal or problem. MCDM has various approaches for prioritizing multiple factors to make decisions. Analytic Network Process (ANP) is a known technique in MCDM.

The healthcare systems are classified as organizations with distributed decision making structures [108]. Also, there are various studies that used ANP approach for decision making in healthcare systems.

To find the most appropriate location for health center considering the population density, parcel area, distance to other hospital and arterial roads in Shiraz, ANP method is applied [109]. Another ANP model is constructed to analyze and predict the negative effects of information technologies applications on healthcare management system at implementation stage [110]. Also hospital service quality is measured using ANP according to service quality model (SERVQUAL) dimensions (tangibility, responsiveness, reliability, assurance and empathy) in İstanbul [111]. Five most frequently used approach in hospital waste treatment alternatives in Turkey are compared based on risks, costs and benefits using the same approach [112]. Jamalizadeh et al (2013) suggested a fuzzy ANP model to find the factors that are effective on satisfaction of dialysis patients in an Iranian hospital. They handled patient satisfaction under four major branches; employee, management, physicians, and nurses. A hybrid method is developed using Interpretive Structural Modeling and ANP to find key performance indicators in healthcare system [114]. These indicators assisted financial analysis on their research.

Using SD and MCDM methodologies together is rarely used in literature. Also, these models are not classified as combination of methods because the methods are used independently and for their classical aims mainly in these studies. For example, a fuzzy logic MCDM method and an SD model are proposed together to generate solutions for sustainable supplier selection for manufacturing industry [115]. SD model in that study was utilized to check the reliability of MCDM method results in the long-run. Another study combined SD with ANP. Here, researchers developed an ANP model to find out the

most important criteria to evaluate business processes and activities on a re-engineering process. Based on the model results, four criteria were found as significantly important among twelve variables. After that, an SD model was developed that covers only these four most important factors [116].

3. METHODOLOGY

In this research, a multi-methodology approach using SD and ANP is employed to develop a dynamic model. Therefore, the methodology section consists of these two parts: methodology of SD modeling and methodology of ANP.

3.1. OVERVIEW

In this research, SD method is used to model performance management system indicators of CL. The main purpose of using SD is that we can simulate all the variables in a laboratory and analyze the results based on the relationship among the variables. Also, developed model can be used to discuss different scenarios with new strategies.

Modelers can interpret a system in various ways. These ways are summarized by expressions. If these expressions are composition of words, it is called qualitative model. If the modeler creates a prototype at the end, this would be a physical model. If mathematical equations are used widely; such models are called as quantitative models. Problems analyzed by engineering aspects are mostly generated by quantitative models. These models are classified by system characteristics. Thus, a system could be classified as *(a) static vs. dynamic, (b) descriptive vs. prescriptive, (c) continuous vs. discrete* [117].

In *static* systems, behaviors maintain same values due to the fact that variables are assumed to be constant over time. However, variables in *dynamic* systems change over time and generate new system behaviors [118].

If the focus of a study is to reflect the interactions among variables, *descriptive* models are suitable for modeling technique. But if a specific objective is chosen and analyses are employed to optimize the focused objective, in this case, *prescriptive* models are needed [118].

Change of time is an important factor to classify a system. In *continuous* systems, variables of the model can change at any instant in time [118]. If changes in states are occurred at pre-defined time intervals, these are called *discrete* models [118].

Revisiting the main purposes of this study, the problem could be modeled as a dynamic, descriptive and continuous system. In literature, the problems on quality, productivity, and cost in healthcare system are handled by modeling the specific sub-systems using DES or some other optimization techniques. However, analysis could only solve the problems in a limited scope, and are weak for complex systems. In this manner, solutions may create new and unpredictable problems in the long-run. To overcome such struggles, a system must be handled with systems thinking approach. The policy resistance may diminish and policy makers can create efficient and effective solutions for organizations and/or communities. The ability to see long-term behavior of the internal dynamics that underlie system thinking plays an important role in ensuring compliance with the goals and objectives of decision makers [119].

By using the iterative complexities, SD creates a chance to modelers to understand the problems in a holistic view. It enables the modeler to capture the effects of complex feedbacks, delays and non-linearity. As expected, it is difficult to understand and solve by using straight techniques. It is stated that for SD approach, alternative scenarios can be easily generated in a simulation model, so it can be used to visualize the results so that they can be used to test and explain the effects of various policies developed to share the results with decision makers and cope with the problem [96].

3.2. METHODOLOGY OF SYSTEM DYNAMICS

System Dynamics (SD) methodology has mainly six stages initiated with originating the problem, and finalized to implement the suggested ways into the real system. First, the modeler should choose a problem which is dynamic and eligible to feedback nature. Next step is a clear definition of problem including statements, time units, beneficial aspects of the problem, and a list of the key variables as components of the model. A thorough literature survey would be considerably conducive to handle the problem. This step is tracked by developing a list of variables that affect the dynamic behavior of the problem. To verify the model boundary, modelers should control key variables and behavior of these variables over time. The behaviors of key variables are generally obtained by data collection.

Based on these variables, initial and crude cause and effect diagram is constructed. In the long-run, some of these initial variables can be discarded and new ones can be added to the model. Relationships among key variables are identified in that stage, and these relationships are called as dynamics hypothesis. After dynamic hypothesis are built, main variables in dynamics hypothesis are classified as stock and flow variables. Stock and flow variables are the main building blocks of an SD simulation model. Using these variables, the formal simulation model is constructed. In addition, mathematical relationships of stock and flow variables are identified at that stage. Another matter on formal model construction process is designating the initial conditions for parameters and stocks. Before running the model, initial conditions and values of parameters must be set. If initial conditions of stock variables and parameter involved in any type of simulation (DES, SD etc.) are not similar to the real system's nature, the simulation model cannot reveal the expected solutions. Sometimes, such a problem can cause initialization bias or obtain totally different state of the system. The model credibility is one of the most important issues in simulation modeling. When simulation model is compared with real system, if the model did not generate similar behaviors, the model cannot be accepted as a mimic of reality. To model credibility, verification and validation is required. In verification and validation phase, model must satisfy two main objectives; structural and behavioral validity. In other words, dynamic relations that are included in the model must be meaningful in real world situations. Next, model behavior and real system must be suiting each other over time. The model must mimic the real problem. After ensuring the validity of the model, various scenarios and policies will be tested to eliminate the potential problems. Hence, policies must be reasonable and robust. If policies do not have these properties, it could not be applicable to the real system. Eventually, implementation of suggested policies/scenarios to generate a strategy is the last step of SD modeling. The main concern of that stage is providing a roadmap for managers to analyze the dynamics affecting their business. It captures the range of possibilities and organizes them for future actions and decisions. Policies and scenarios help decision makers obtain the results of alternatives that are developed by them. In Figure 3.1, the steps of SD modeling technique is explained in detail.

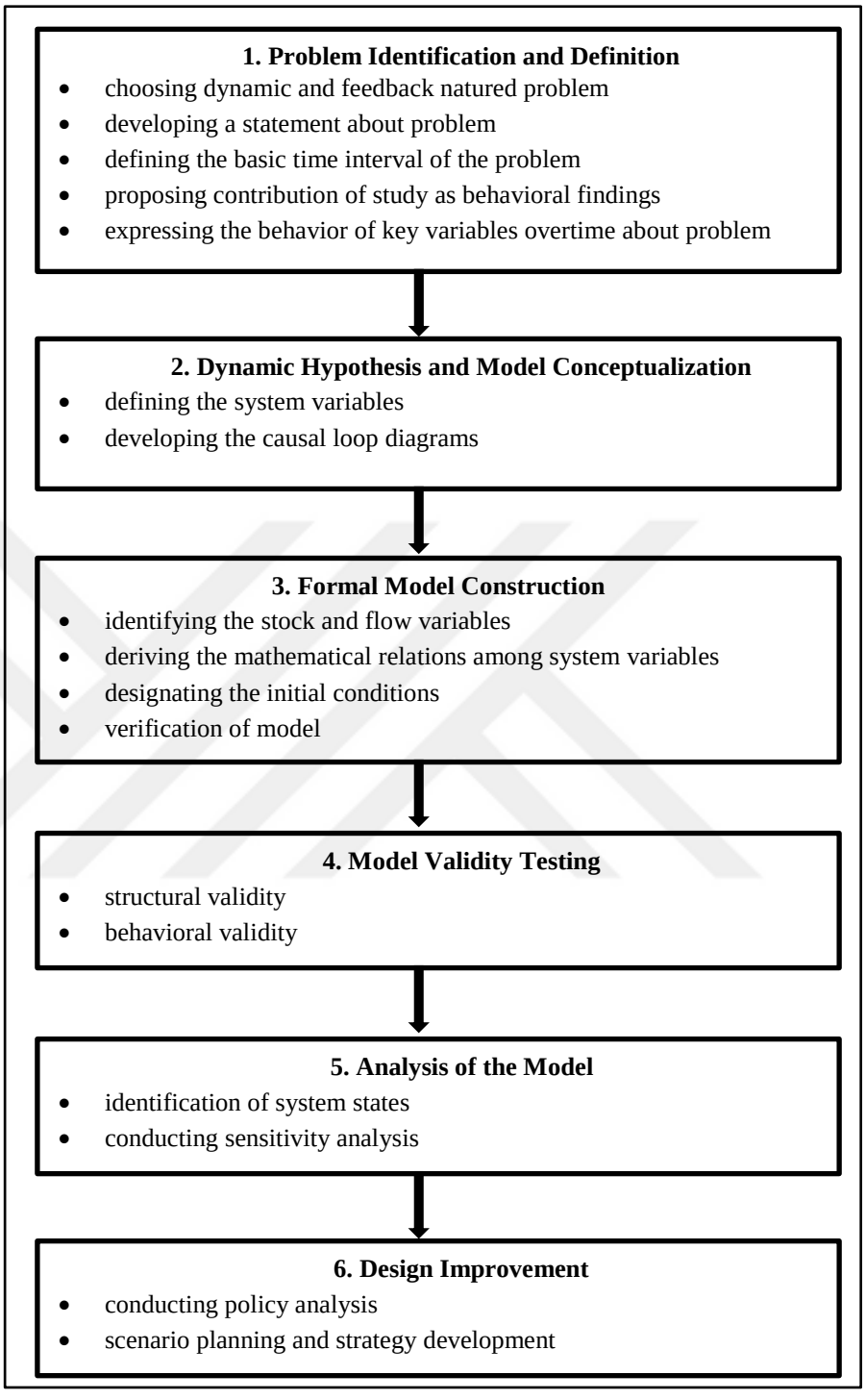


Figure 3.1. Steps of SD modeling [30]

3.2.1. Problem Identification and Definition

Problem definition and identification stage has five main processes. These are: choosing dynamic and feedback natured problem, and developing problem statement, defining the basic time unit of developed problem, proposing how the study will contribute to the solution of problem, and expressing the behavior pattern of key variables in the future by using historical data or hypothesize pattern.

Defining a problem in a suitable structure is the first issue in modeling. The model structure should be created as an illustration of determined aspects of the real system based on defined problem [118]. When the model is operated with a common scientific method, it produces behavior of the model [118]. Due to the fact that nature of systems thinking, one of the aims of an SD study will be observing the system within a given time period. Thus, the basic time unit of the problem must be determined in problem identification stage. Accordingly, behavioral findings from solution within this time period can be interpreted as proposing contribution of the study.

Finally, determining the preliminary key variables is essential to control and verify the scope of the study. Also, the behavior of key variables over time should be obtained by using the historical data about these variables. If there is no available data on the key variables, the modeler should conduct hypothesis about the patterns of them over time by using his opinions.

3.2.2. Dynamic Hypothesis and Model Conceptualization

Making an extended literature survey is accepted as one of the milestones for any type of research. Also, in SD approach, strong literature survey background is crucial to enrich the knowledge about problem and evaluate it widely. By conducting this background, the variables which are effective on dynamic behavior of the system are determined and listed. After the definition of system variables, causal relations among these variables are identified. Later, main causal loop or influence diagrams for variables are constructed. This section continues with presenting the methodology and constructing a causal loop diagram (CLD).

- *Causal Loop Diagram Construction:* A causal loop is a mental representation of a system's inner dynamics which is developed corresponding to interactions with external system [120].

In other words, causal loop is a diagramming approach that helps to draw the relationships among various variables. This technique creates an opportunity to illustrate the interacting feedback loop structures before deriving the mathematical equations of the system. It should be noted that, CLD has a great impact on SD modeling. In introductory level, the diagrams could be named as preliminary causal hypotheses. Modelers can easily adapt and comprehend the model using CLDs. In CLD, variables are related by "causal links" that are shown by arrows. Then, to each causal link a polarity is assigned, either positive (+) or negative (-) to show how a change in affected variable when the influencer variable changes. Link polarities describe the structure of a system. There are two types of feedback structures in a system:

- *Positive Feedback:* "Vicious" or "virtous" circles are alternative expressions for positive feedback structure. In such a structure, increase in one variable continually feeds itself to strengthen grow its own progress [121]. In other words, the variables in a positive feedback loop create a mutual effect and stimulate each other in same direction.

For example, there is a relation between productivity and average test time in laboratory. If the test time for each test is decreased, productivity will increase. This chain is followed by the average test time increase, thus the productivity of the CL will decrease. Due to the fact that, each variable encourages the other one in the same direction, relation between productivity and average test time can be interpreted as a positive feedback loop. Figure 5 illustrates the both CLD for productivity and average test time.

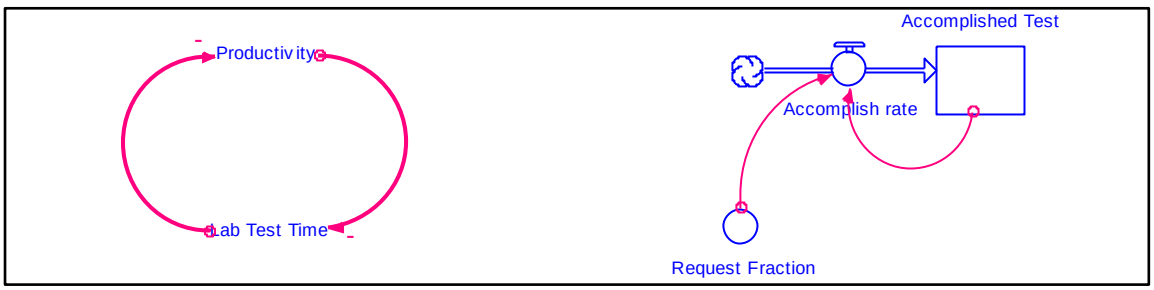


Figure 3.2. A sample causal loop and stock-flow diagram for positive feedback

As illustrated in Figure 3.2, request fraction and number of accomplished tests affect accomplish rate and this rate feeds into the accomplished test number. In this relation, accomplish rate reinforces accomplished tests. As expected, accomplish rate creates an escalation in number of accomplished tests over time. Following figure shows the system behavior of a positive feedback loop.

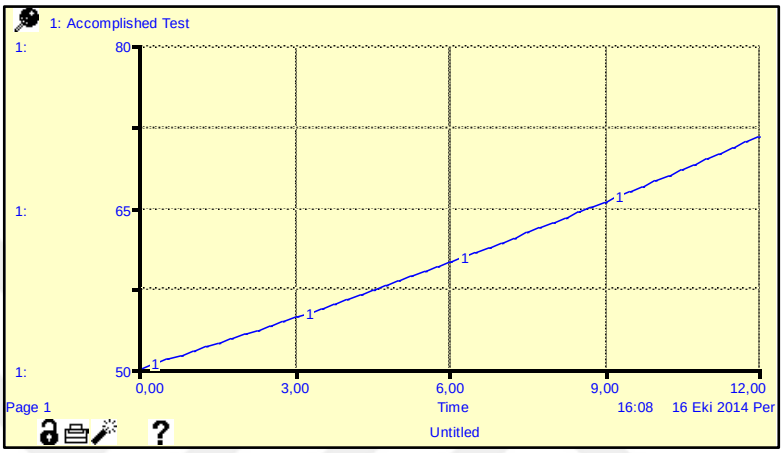


Figure 3.3. Behavior over time for a sample positive feedback system

In positive feedback loops, dependent variables display an exponential growth over time as shown in the figure. The number of accomplished tests increases from the stated initial condition exponentially as seen in the graphical output.

- *Negative Feedback:* "Self-regulating" and "adaptive" terms are frequently used for negative feedback systems or balancing loops. Negative feedback systems focus on a specified value, point or behavior. This means that such systems always seek the definite target. Taking an action to achieve the target, system continually needs its present output, position or situation. Hence, negative feedback brings stability or stubbornness to a system.

Test kits and one-time use materials are commonly used in laboratory testing. Stocked level of these materials in a laboratory will decrease when the tests are completed, but as we complete more tests, the stock level of specified resources will decrease. While these resources are decreasing, until new orders arrive to laboratory, managers may stop testing.

The following figure is obtained by using the above mention narrative. On the left hand side, relationship between variables is illustrated by using the CLD. Based on the given events; there is a negative feedback structure in this system.

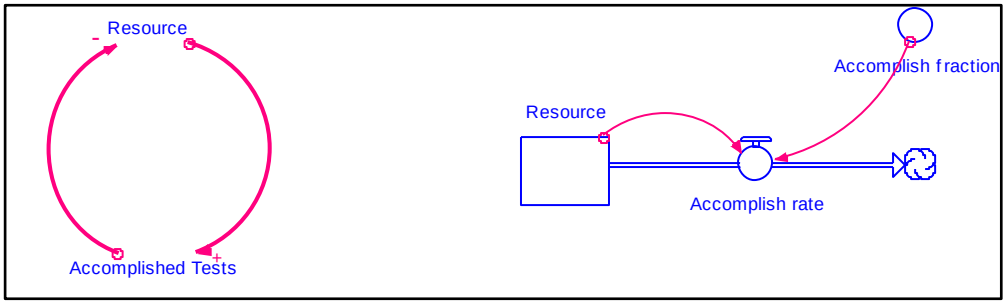


Figure 3.4. A sample causal loop and stock-flow diagram for negative feedback

Figure 3.5 is obtained from the simulation model of the given negative feedback loop system. As expected, consumption creates a reduction in resource level over time.

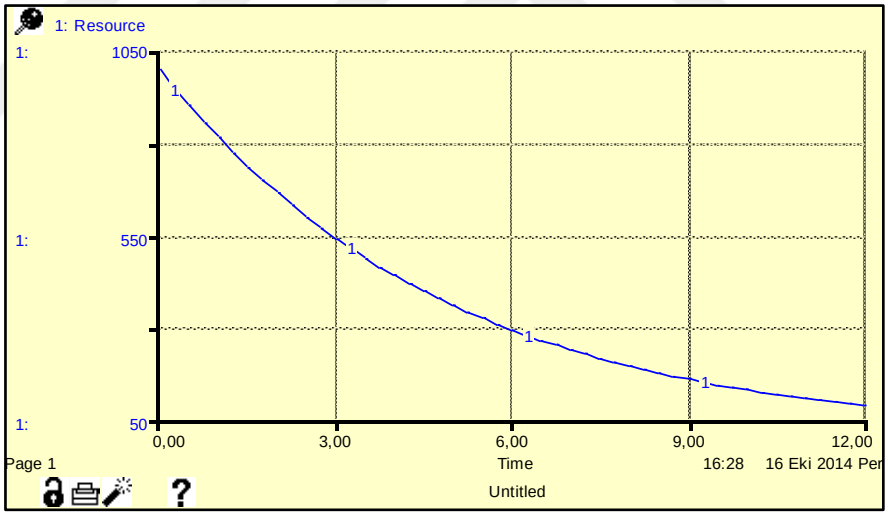


Figure 3.5. Behavior over time of a sample negative feedback system

In negative feedback loops, dependent variable displays an exponential reduction over time. As shown in the figure, the resource level in stock decreases exponentially over time, and it will come to an end.

3.2.3. Formal Model Construction

SD modeling is a simulation approach that conducts feedback mechanisms and relationship diagramming for both exogenous and endogenous variables. This modeling technique encourages the researchers to understand a complex system's inner dynamics [122].

In this stage, the variables on CLD of the model are classified as stock and flow variables. Stocks show accumulations over time in a system. They represent the state of the system at any time interval. Flows directly manipulate the stocks and change their values. They indicate the speed of change of stocks and its quantity is regulated.

Another matter on formal model construction process is designating the initial conditions for parameters and stocks. As known, every differential equation has a homogenous and particular solution. And, the particular solution could be acquired only by information of initial condition. Initial conditions are directly affecting the system behavior over time. Thus, determining the initial conditions is critical.

The last part of the constructing a formal model is verification. Before analyzing the outputs, modeler should focus his concern to verification of the model. In verification, the first issue which must be handled is to establish a correlation between requirements and problem statement. The next analysis must be done on model proposed deliverables that should correspond to all questions of problem statement. After checking the proposed deliverables, the conceptual model must be reviewed according to the system requirements. Hence, modeler can ensure that the simulation model is correct [123].

Overall, formal model construction phase starts with developing the stock-flow diagrams, and it is followed by deriving the mathematical model. Modeler should check and determine the values of initial conditions. After designating the initial conditions, verification of the model should be done.

3.2.4. Model Validity Testing

Validation of an SD model is complicated because estimating the validity of the model structure is philosophically and technically difficult [124]. Hence the literature suggests

that ensuring structural validity and behavioral validity [29, 30, 118]. Validation procedure of SD models is differentiating from other simulation techniques. In addition, there are various studies on validation of such systems.

Checking the structural credibility of the model is the first part of the validation in SD approach. In other words, the general structure and parameters of real system must be correctly transferred to the model. Additionally, units of parameters, stocks, and flows must be reviewed for dimensional consistency. If modeler can ensure that structure of developed model is valid, the next phase starts; behavioral credibility of the model. In behavioral validity, the values that are produced from the model output should be realistic and reasonable.

In structural validity, model is subjected to some specific tests. At first, model is analyzed for its conceptual boundary under *boundary adequacy test*. In this test, model is checked whether the model covers all relevant aspects for the handled problem or not. Next phase is *structure assessment* of the model. In this test, each relation that place in conceptual model should be checked and verified. *Parameter assessment* is also another important structural validity test. In this test, modelers examine all model parameters in terms of descriptive and numerical basis. After parameters are found reasonable, the next issue is *dimensional consistency*. Units of variables on the right-hand side of the equation should be equal to the dimensions on the left-hand side of the equation [30]. Final test under structural validity is *extreme conditions test*. In this test, model inputs are subjected to extreme values to check whether the model equations make sense under these extreme conditions.

The concern of behavioral validity test is accuracy of the model behavior. This test is conducted only after the modeler has confidence in model structure. To ensure the behavioral validity of the model, *behavior reproduction test* and *behavior anomaly test* are applied. Model results are compared with real system results in behavior reproduction test. For anomaly analysis, main purpose is to see whether the model generates anomalous behavior when a certain relation is neglected or modified. Model consistency and confidence will increase if it is not affected by parameter variations. Thus, parameters are subjected to small changes (±10 per cent) in sensitivity analysis, and model results are examined for these slight changes. If changes generate dramatic outcomes to a parameter, more effort is needed to estimate the value of it. Sensitivity analysis is the most critical part

of this stage. The purpose is to design a model which minimizes sensitivity on parameters. Designing robust systems generally is not possible especially in social systems. Therefore, sensitivity analysis gives advice on how to monitor them carefully [30].

3.2.5. Analysis of the Model

In this phase, the main objective is observing the behaviors of validated model under initial conditions. It is called identification of system states. States of a system could be described as the representation of system according to conditions of inputs and inner dynamics. The modeler interprets the simulation results by referring the initial conditions and given inputs.

3.2.6. Design Improvement

Design improvement phase includes scenario planning. Scenario planning provides a framework for managers to determine the forces affecting their business. It captures the range of possibilities and organizes them for future actions and decisions. They help decision makers develop their own feel for the future of the system. In scenario planning, the model is subjected to various conditions using policies and strategies. ‘Policy’ means changing single model variable. Strategy on the other hand deals with combination of set of policies and controlling their changes.

Schoemaker (1995) suggested that scenarios should be selected to represent either optimistic or pessimistic outcomes, or the potential theme of the future environment. According to him, key drivers of change together with uncertainties and factors that may have an impact on the decisions should be evaluated. Then optimistic and pessimistic scenarios should be created to check the internal consistency of the model. Finally, these scenarios should be modified to design the final scenarios.

3.3. METHODOLOGY OF ANALYTIC NETWORK PROCESS

Many researchers in different fields have used decision making methods to clarify which alternative is the best for their goal or problem. Multi-criteria decision making has various approaches utilized for divergent decision problems prioritizing multiple factors. Analytic Hierarchy Process (AHP) can be named as the most famous decision making approach, invented by Saaty [126, 127]. Although this method is well known and frequently used, for some cases it is not sufficient. AHP approach generates solutions for goals by comparing criteria for alternatives. Based on the method's nature, criteria relations are not considered. To overcome this problem, Saaty invented a modified process called as Analytic Network Process (ANP). In contrast with AHP, ANP approach utilizes relations among various criteria in the model. Additionally, ANP enables the researchers find the weights of variables for any objective utilizing expert opinion [128, 129].

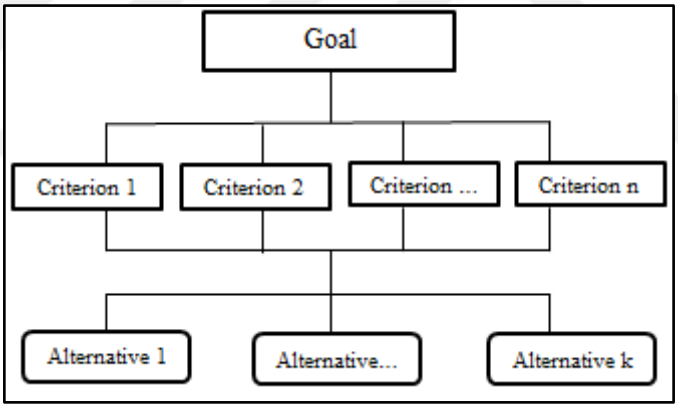


Figure 3.6. The relations among elements in AHP

ANP gives an advantage to identify inner and outer relations among criteria and this property is expressed as *'feedback'* relation. This feedback relation eliminates the one-way relation between criteria. Thinking relation among elements generates a more efficient and realistic way for problems.

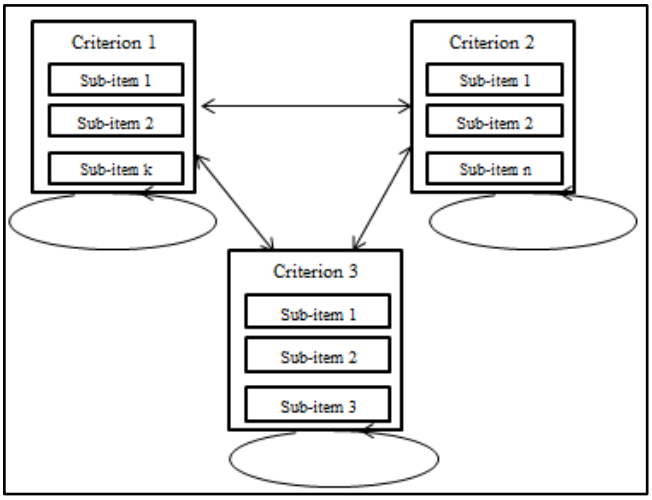


Figure 3.7. The relations among elements in ANP

ANP was developed at the beginning of 2000's, and it is accepted as a tool for both qualitative and quantitative decision analysis as a generalization of Analytic Hierarchy Process (AHP) [126, 130]. The technique aims to analyze the influence of variables (criteria) with pairwise comparison matrices judged by the experts. Similar to AHP method, the scale of judgment in pairwise comparison matrix has nine decision points for linguistic values. The corresponded numbers for these linguistic judgments are given in Table 3.1.

Table 3.1. Values of linguistic judgments [130]

Scale Value	**Meaning**
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance
Even Numbers (2,4,6,8)	Intermediate Values

The generalization property of ANP comes from pairwise relation matrix. This matrix enables decision maker to capture inner and outer relations between the clusters and among the criteria (variables). Thus, networks and links are accepted as important elements in ANP approach. In this study, ANP process is examined under three stages:

- **Stage 1** (Model construction): All variables that affect the laboratory performance are determined and grouped into clusters for the network. These variables are defined under Chapter 4. These influential variables are named as criteria and grouped based on their similarities to form a cluster.
- **Stage 2** (Pairwise relation and comparison among key variables): In the network, the outer dependencies (between clusters) and inner dependencies (among variables) are indicated by links. To do so, the following paired comparisons are performed, and supermatrix is formed.
    i. Cluster comparison: Paired comparisons are performed on the clusters with respect to the goal. Weights found in analysis are used to calculate values of factors in the columns.
    ii. Comparison of variables: Paired comparisons are performed on the variables within the clusters. Each variable in a cluster is compared based on its influence on a variable in its own cluster or on another variable in another cluster. The geometric means is calculated by using all paired-comparison judgments to find out the overall group judgments. For further analysis, all necessary calculations are done on Super Decisions (developed by Saaty).
- **Stage 3** (Overall weights of key variables): Stage 2 generates an unweighted super-matrix, where its columns contain pairwise comparison results. In order to obtain a weighted super-matrix, the blocks of the unweighted super-matrix and the corresponding cluster priority are used.

Networks and links are the preliminary elements used in this approach. In ANP, the networks are used to define affective elements about the problem. Karpak and Topcu (2010) states that the influence networks indicate the factors of and these networks are decomposed into clusters. The linkages are used to illustrate relations or dependencies among networks or within a network. These dependencies are classified as *'inner'* and *'outer'* dependencies. If the link indicates a relation between the elements under same parent, it is called as *'inner dependency'*. If this link is used to reflect a relation between elements of different parents, it is named as *'outer dependency'*. The feedback relation can be examined under the condition of outer dependency. According to literature, ANP approach is accomplished by four main steps. However, in this study, the aim of choosing

this method is not comparing the alternatives for a goal. The aim is found out elements that have an effect on the problem. Thus, first three steps will be completed.

- Problem must be defined for a general goal. Then the factors assumed as effective on goal are determined, and decomposed into sub-items. These main items are named as criteria and sub-items are sub-criteria.
- The dependencies (outer and inner) are indicated by links. The comparisons of clusters, and elements should be done, respectively. Constructed model is utilized for creating pairwise comparison matrix between the criteria.
- Utilizing the pairwise comparisons, a super-matrix is generated. After some mathematical arrangements, the priority matrix could be handled and interpreted for the problem. To express the mathematical background of ANP approach, the following figure is given. In Figure 3.8, the clusters of a decision system is denoted by C_h, h = 1, 2, . . . , n, and each cluster h has n_h elements, denoted c_{h1}, c_{h2}, . . . , c_{hnh}, then the super-matrix of such a network will be like Figure 3.8 [131, 132].

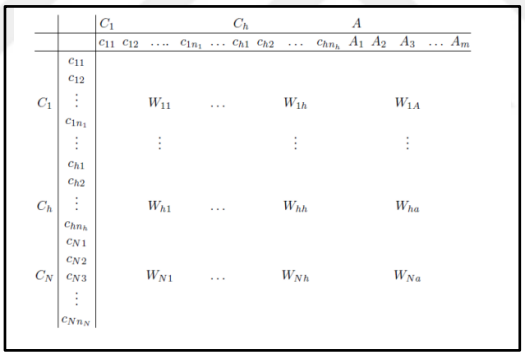


Figure 3.8. A super-matrix of a network [132]

The weights given to each relation is combined in a single matrix that is named as super-matrix. A super-matrix is developed by the eigenvectors of each cluster under the objective. Figure 3.9 illustrates a sample super-matrix network among clusters.

$$W_{ij} = \begin{vmatrix} W_{i1}^{j1} & W_{i1}^{j2} & \dots & W_{i1}^{jn_j} \\ W_{i2}^{j1} & W_{i2}^{j2} & \dots & W_{i2}^{jn_j} \\ \vdots & \vdots & \vdots\vdots & \vdots \\ W_{in_i}^{j1} & W_{in_i}^{j2} & \dots & W_{in_i}^{jn_j} \end{vmatrix}$$

Figure 3.9. i, j block of a network's super-matrix [132]

4. MODEL DEVELOPMENT

4.1. CLINICAL LABORATORY PERFORMANCE

4.1.1. Process

Laboratory operations are divided into three sections [133-136]. These are:

- Pre-analytic Phase
- Analytic Phase
- Post-analytic Phase

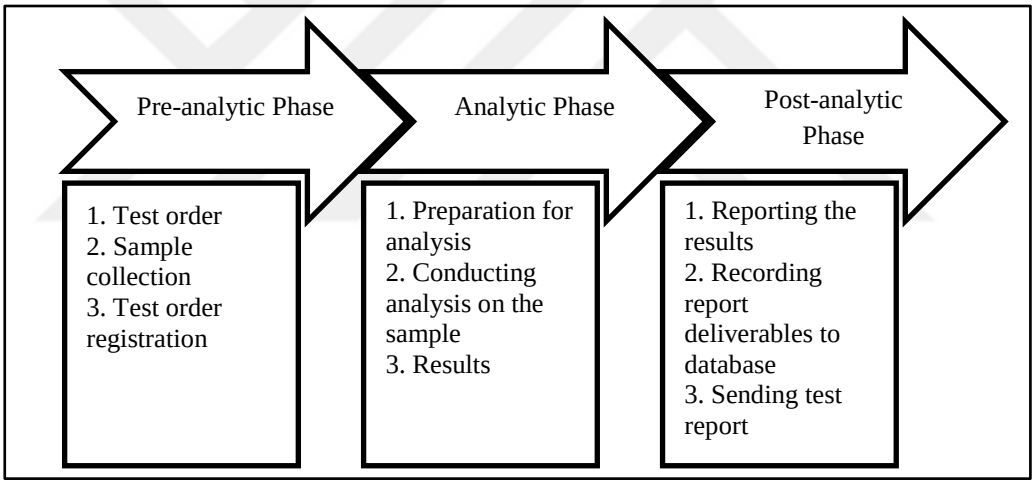


Figure 4.1. Steps of CL process

The pre-analytic phase begins with a test order request and ends with registration of the sample for analysis.

The analytic phase involves performing the required tests. In this case, well-defined steps are necessary to fully complete a test. Additionally, these steps are prerequisites for accurate reporting.

During the post-analytic phase, the results are summarized and recorded in a report by clinicians. This phase is closed by saving the results to a laboratory database and sharing a

hard or soft copy of the report with the patient. Reporting, archiving, and delivering the test results are the main deliverables of the post-analytic phase in a CL.

4.1.2. Performance Measurement

In literature, CL performance is measured under two main indicators; effectiveness and efficiency [137].

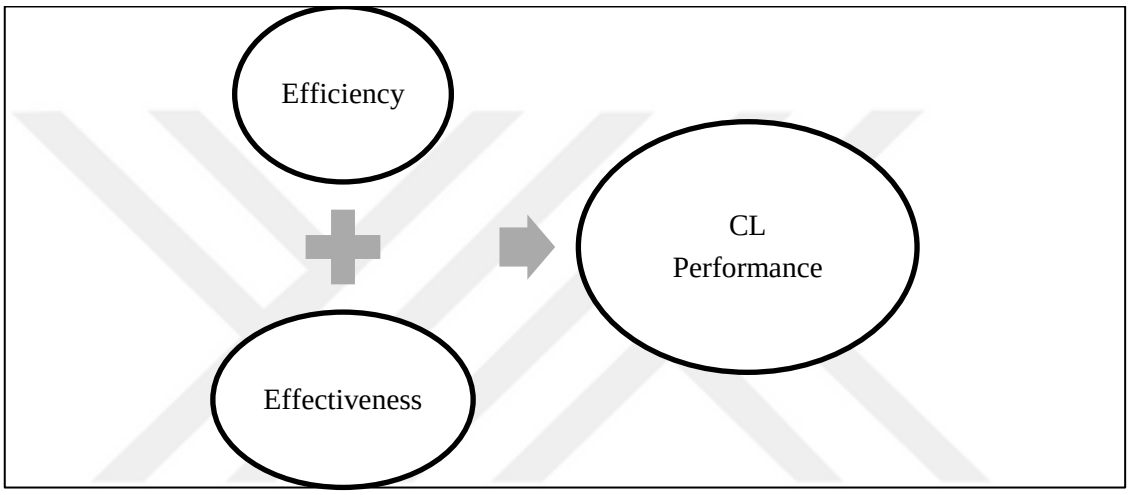


Figure 4.2. Main indicators of CL performance

Effectiveness of a laboratory service is defined as delivering the accurate information in a given time period. Effectiveness of the health care service is expressed as accomplishing planned outcome by following correct procedures accurately [138, 139]. This accuracy does not mean test results' reliability; it means meeting the specific purposes of patients and conducting the right procedure to attain the service [23, 27, 140]. The main goal of effectiveness is performing requested tests and delivering the results according to standards and correct process [141, 142]. Based on this definition, rework and test turnaround time are the major indicators of effectiveness.

In general, efficiency is targeting to get necessary output with minimum input. Efficiency is the level of resources to satisfy the healthcare service objectives [141]. Correspondingly, efficiency in a CL is completing maximum number of tests within a specified time interval while utilizing minimum resources. Therefore, resource utilization should be interpreted as

indicators of efficiency. Indicators of efficiency are determined as; labor, equipment, supplied materials, and their related costs [141, 143].

In this thesis, a dynamics model is constructed to analyze CL performance management system. The performance indicators included in the model are: labor and overtime level, test turnaround time, accomplished test request, and cost.

4.2. PROPOSED FRAMEWORK for MODEL CONSTRUCTION

In this research, a multi-methodology approach is employed to develop a dynamic model. Collaboration with experts and decision makers will create more realistic solutions and group decision making is a commonly used method during SD model development. To ensure this collaboration, ANP provides a structured approach to collect expert opinions and to ensure all given inputs are considered and weighted properly.

Additionally, the use of the ANP method creates an opportunity to reflect interrelations among various criteria (variables) and can accommodate to ensure complex interdependencies, and feedbacks among system variables for conceptual model validation are captured. Thus, ANP provides completeness and deeper insights to the SD simulation validation.

Therefore, a framework is proposed to capture the benefits of ANP and SD modeling methodologies (Figure 4.3). This framework generates an opportunity to enrich and validate the model. The strength of this combination is that proposed framework presents ANP approach to be used to validate conceptual model in an SD simulation model. ANP method is used to ensure boundary adequacy, structure and parameter verification of the model by capturing the judgments/viewpoints of different stakeholders about the system indicators.

This is a pioneer study that utilized ANP approach to conduct structural validity for an SD model, to prioritize CL performance indicators, and capture their relations. Also, prioritized indicators are utilized for policy analysis and strategy development purposes.

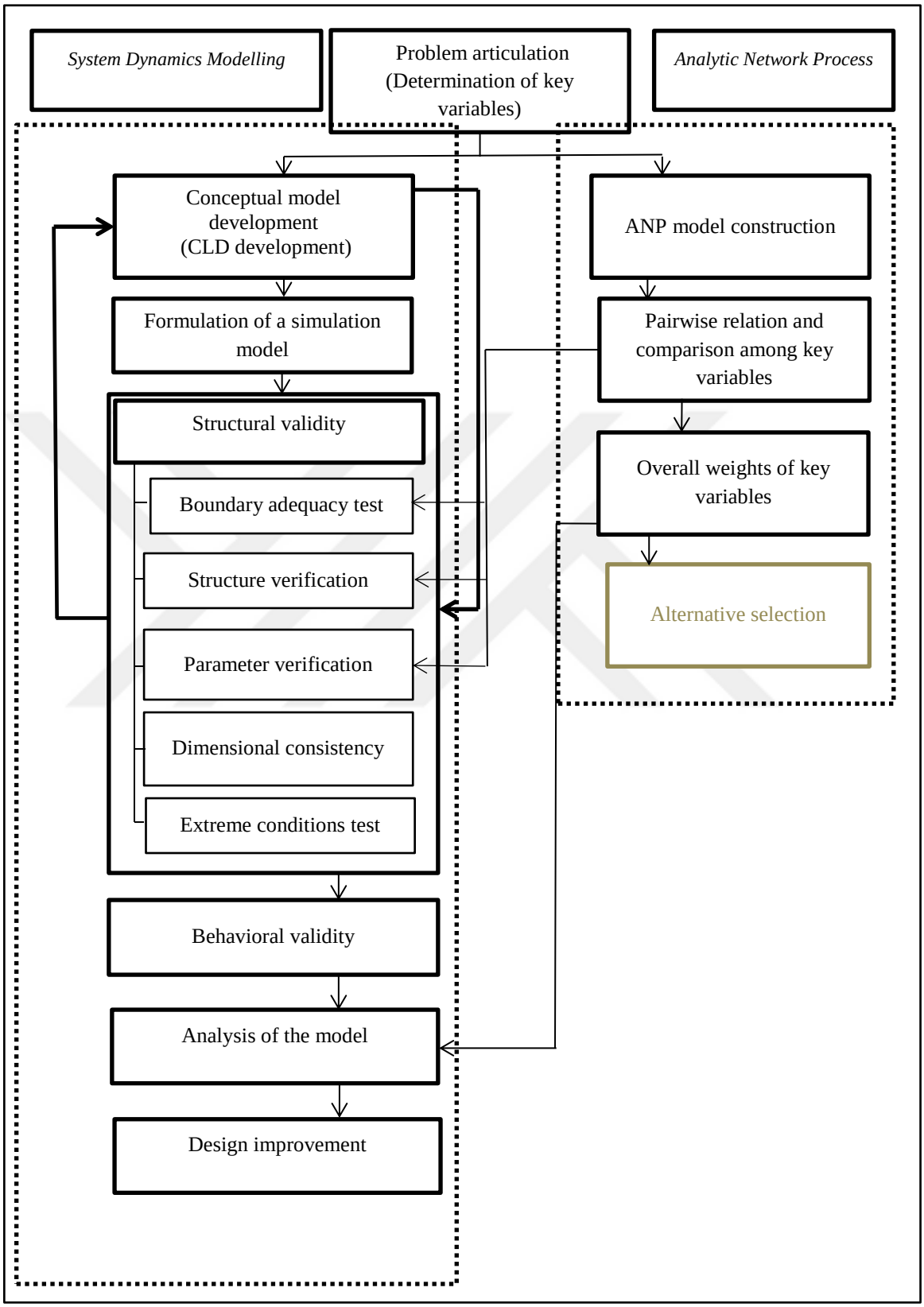


Figure 4.3. Proposed framework for model construction

4.3. PROBLEM ARTICULATION

Cost, test turnaround time, resource shortages, and quality defects are generally observed problems in a typical CL process [27, 144-149]. These problems generate drawbacks on performance of CLs. Performance degradation impairs the value of institution and causes a decline in the number of clients (patients) in the long run. To survive in healthcare industry, each institution must create a valuable and sustainable performance. Thus, performance management is essential in CL.

4.3.1. Key Variables

Based on the problem definition, the concepts represents the key variables are identified influential on CL performance. The following four variables are used as key concepts to develop overall model. These are the performance indicators for the CL performance management.

4.3.1.1. Cost

Estimation of total monetary burden of testing process is essential to make a judgment about cost efficiency in CL. Cost of testing is handled under variable and fixed cost accounting approach. These costs can be analyzed in four levels. These are: workstation prime cost (depreciation costs, maintenance, cost of time and errors), direct labor cost, test material cost (cost of used reagents, kits and other instruments), and overhead costs [144]. As part of the workstation cost, cost of exceeding the tolerable cycle time per test, and rework cost can be considered. Overhead costs (rent of building, cost of heating, legal fees, taxes, utilities, etc.) vary depending on the country; even CLs in different cities in the same country may have different overhead costs. Since the aim of this research is to develop a general model for CL performance, overhead costs are not included in this study.

4.3.1.2. Quality

CLs are an integrated part of healthcare organizations. Produced test results in CLs are used in pre-diagnose, diagnose, monitoring and controlling phases of health problems. Thus, errors occurred in any stage may lead to wrong decisions on patients' health problem. Quality indicators are needed to assess the gap between delivered service and stakeholders' needs [145]. Therefore, detected and undetected errors during pre-analytic, analytic, and post analytic stages, accidents during testing, late delivery of test results are listed as the indicators for CLs quality measurement [146].

4.3.1.3. Resource management

Based on the specifications of Joint Commission on Accreditation of HealthCare Organizations (JCAHO), laboratory managers are responsible for planning and providing that the resource utilization is properly arranged and meet the goals of the organization [26]. These specifications also include providing available and trained staff, and materials (reagents, equipment, consumables and all analytic systems) for testing procedure. Therefore, deciding on the staff level, type and duration of training program for new hires, ordering consumables for testing equipment, and equipment maintenance periods are variables of resource utilization in a CL. Inventory control: ordering and consumption of reagents and kits, mean time between failures (MTBF), maintenance and workload on machines (equipment), and workload on staff are selected as resource management performance indicators.

4.3.1.4. Time

Total elapsed time required to complete a test request, from the time that the test is received until the time the test result is reported, is called test turnaround time (TAT) [147]. Each type of test has different but standard cycle time, and patients are informed about expected report delivery time based on the testing procedure's standard time. In many CLs, having a delay on test delivery time is a major issue [148]. Delay in required/standard TAT is accepted as a major issue leading performance inadequacy [149].

Bottlenecks must be found to overcome this performance problem. Time related variables in this part are listed as order entry process time, specimen collection and delivery time, testing process time, reporting process time, and accession (recording of report deliverables) time.

4.3.2. Data Collection

Two different data sets are collected for this study. The first set of data was from ANP study. In ANP study expert opinions are collected. In ANP study, expert opinions are collected from five different CL experts. One of these experts works as a private pathology laboratory. The second expert is a documentation expert, and another works as laboratory quality manager in the same private hospital. The last two experts are bio-chemical laboratory experts in two different private hospitals.

The second set of data is base case parameters to run and analyze simulation model. This data is collected from a bio-chemical laboratory of a private hospital in Haznedar, İstanbul. Interviewed expert from this hospital, is a medical specialist on bio-chemical laboratory analysis. In addition to collecting the base case data, the expert was also consulted for assessing the revised conceptual model.

4.3.3. Assumptions of the model

The following assumptions were made to avoid unnecessary complexity. It should be noted that all assumptions are discussed and upon with the experts during the modeling sessions.

- In bio-chemical laboratories, due to the fact that no medium or high severity accidents occur, accidents are omitted in the simulation model. However, low severity accidents are taken into consideration in reference quality variable.
- Outsourcing is not defined as part of the system.
- Layoff decision is not part of the model.
- If resource for work is available, requested test is pushed through the testing procedure.
- The staff level changes in discrete numbers.

- Utility (electric, water supply, etc.) costs are omitted.

4.4. CONCEPTUAL MODEL DEVELOPMENT

A strong and correct conceptual model will generate the basis of a reliable model. Many researchers emphasize the importance of conceptual model development on validation of SD simulation models [150]. Conceptual models formalize a system designer's idea as a step to generate final dynamic model. It helps stakeholders to understand how objectives can be achieved based on strategically linked measures (variables). Conceptual models should include all main factors that have an effect on system performance [151]. Therefore, verification of boundary and validity of the conceptual model are critical issues before it is used any further. Especially, conceptual model has a great impact on structure assessment, parameter assessment, and boundary adequacy tests involved under structural validity.

The indicators that are mentioned in problem articulation stage are used for initial conceptual model development. Initial conceptual model of a CL performance management system is shown in Figure 4.4.

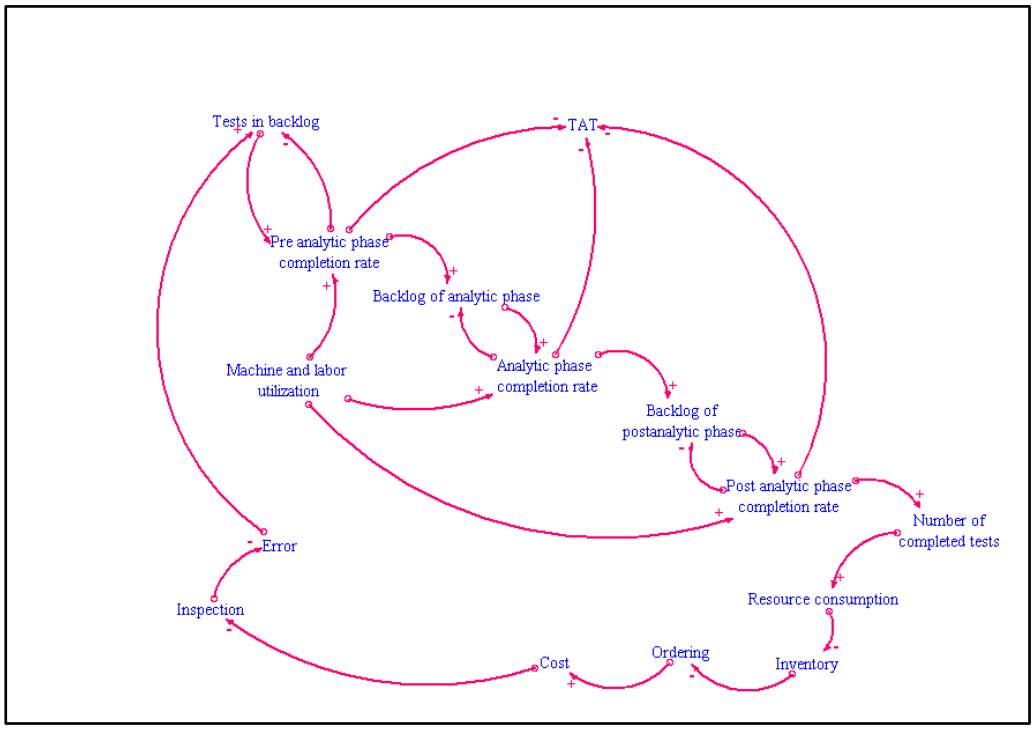


Figure 4.4. Initial conceptual model of CL performance system

In this initial conceptual model, test production is analyzed for three phases (pre-analytic, analytic, and post-analytic phases). Test requests accumulate the tests in backlog and these tests in backlog increase the pre-analytic phase completion rate if it is less than the laboratory machine and labor capacity. If pre-analytic phase completion rate increases, tests in backlog in pre-analytic phase will decrease while analytic phase backlog increases. This backlog value is reduced through the analytic phase completion rate. After analytic phase is completed, tests will wait for post-analytic phase in backlog of post-analytic phase. When post-analytic phase is completed, the number of completed tests will increase. It should be noted that, similar to pre-analytic phase completion rate, analytic and post-analytic phase completion rates increase if machine and labor capacity of CL is more than or equal to their individual backlog levels. When tests are performed, resource consumption will increase, and it reduces the inventory. To satisfy the level of inventory, new order of material is needed. This order will generate cost. The inspection (level of calibration) may decrease due to the fact that resource cost when cost of CL increase. In this case, errors will increase and it accumulates the tests in backlog.

The main variables that are influential on CL performance were defined in previous section as cost, quality, time, and resource management. These variables are captured as clusters for ANP model. Each one of these clusters is broken down into criteria (variable) to develop a network for our goal. The list and definition of variables under each cluster are given in Table 4.1. ANP survey questions are given in APPENDIX A.

To generate the network, relations between clusters and between variables are identified by the experts. These refined relations are transformed into a pairwise relation matrix (combined pairwise relation matrix) to obtain cluster and criteria weights and then into a network model in SuperDecisions Software. Refined relations among criteria are shown in Table 4.2. In order to develop the network model, each cluster and criterion under these clusters are created. Then, relation paths are mapped for each criterion, and finally overall network of the model is generated. Figure 4.5 illustrates the generic network view of the study.

Table 4.1. Names and explanations of criteria

Purpose	Main Performance Objectives (Clusters)	Sub-items for Each Main Objective (Criteria)	Explanation
Performance of a CL	**COST**	Cost of consumables (C1)	The monetary value of consumables such as test kits, injectors, and other components that have to use in testing procedure.
		Cost of quality (C2)	The total amount of expenses to procure quality management strategies.
		Cost of labor (C3)	Self explanatory
		Cost of equipment (C4)	The expenses related with maintainability, utilization and availability of test machineries.
		Penalty cost (C5)	Intangible or tangible cost of late or wrong test result delivery to the patients.
	QUALITY	Accidents (Q1)	Self explanatory
		Inspection (Q2)	The method used to satisfy quality control of tests
		TAT (Q3)	The cycle times of tests exceed feasible test time determined by laboratory management.
		Errors during testing procedure (Q4)	Errors occurred pre-analytic, analytic or post-analytic phases, for instance; writing wrong name or code on sample, wrong test applications, wrong result explanation in reporting, etc.
	RESOURCE MANAGEMENT	Inventory Control (RM1)	Accepted inventory or stock management strategy for all components used in any phase of testing procedure.
		Ordering (RM2)	Accepted ordering strategy for consumables that used in CL.
		Consumption (RM3)	Accepted consumption strategy of consumables and components needed in any phase of testing procedure
		MTBF (RM4)	Mean time between failures of testing equipment
		Workload of machine (RM5)	Capacity rate of equipment or testing machines
		Workload of staff (RM6)	Capacity rate of labor
		Maintenance of machine (RM7)	Accepted maintainability standards for testing machines
	TIME	Order entry process time (T1)	The spent time identify new test request to laboratory management system.
		Specimen collection and delivery time (T2)	The spent time to collect sample from patient and deliver laboratory.
		Testing process time (T3)	The spent time to accomplish a test based on the procedures
		Reporting process time (T4)	The spent time to prepare the folder or report about findings based on the test results.
		Accession time (T5)	The spent to deliver a report to the patient.

Table 4.2. Pairwise relation matrix

	C1	C2	C3	C4	C5	Q1	Q2	Q3	Q4	RM1	RM2	RM3	RM4	RM5	RM6	RM7	T1	T2	T3	T4	T5
C1		*								*	*										
C2	*		*	*	*		*			*		*	*		*	*					
C3					*																
C4	*	*					*	*	*				*	*		*					
C5	*	*		*			*	*	*					*	*						
Q1	*	*		*	*			*	*				*	*	*	*					
Q2	*	*		*	*			*	*						*	*		*	*	*	*
Q3							*						*	*	*			*	*	*	*
Q4															*					*	*
RM1	*	*									*								*		
RM2	*	*								*		*							*		
RM3	*									*	*										
RM4	*	*		*	*			*								*			*	*	*
RM5	*							*				*	*		*	*			*	*	*
RM6	*	*	*					*	*				*					*	*	*	*
RM7		*				*	*	*	*				*						*		
T1																			*	*	
T2	*														*				*		
T3	*	*		*	*	*	*	*	*		*				*	*		*		*	*
T4								*						*				*	*		*
T5																			*	*	

SuperDecisions software permits the modelers to define only one pairwise comparison matrix. In this case, opinions of different experts are aggregated in one comparison matrix which is developed by taking the geometric mean of each judgment point given in pairwise relation matrix (pairwise relation and comparison matrix answers of each expert are given in APPENDIX B).

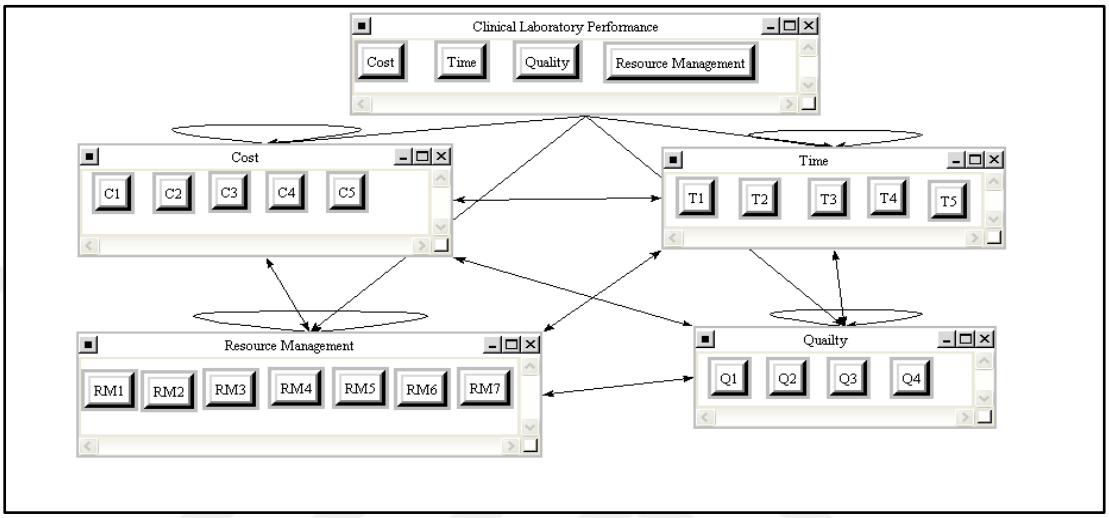


Figure 4.5. Obtained model view on SuperDecisions

Combined pairwise relation matrix and aggregated pairwise comparison matrix are utilized and un-weighted, weighted, and limiting matrices are calculated (see APPENDIX C). Table 4.3 shows the relative importance results on clusters (cost, quality, resource management, and time) for CL performance.

Table 4.3. Importance weights of clusters

Criterion Name	**Importance Weights**
Quality	0.459
Time	0.219
Cost	0.200
Resource Management	0.119

The results of Table 4.3 show that quality and time are the most influential variables on CL performance. Although cost and resource management are effective, their weights are less

than quality and time as main indicators. The impact of each criterion is important to prioritize the CL performance indicators. The overall importance of influential variables (criteria) on the goal can be calculated by normalizing the overall importance of clusters and importance of each criterion under these clusters. Individual weights of these variables are not needed for structural validity of the simulation model. Therefore, they are not included in this paper. However, they would be useful to generate strategies on an SD simulation model. The output of pairwise relation matrix verifies causal relations among the CL performance variables.

In Figure 4.6, CL procedure is again divided into three phases; pre-analytic, analytic, and post-analytic phases. Resource, quality and time indicators are also included. During the ANP study, experts emphasize on the importance of labor especially in pre-analytic and post-analytic phases. Based on their feedbacks, conceptual model is revised. In first prior design, quality was only associated with errors during the testing procedure. However, experts state that qualified sample rate is also an important variable during the procedures. Although the rate and severity of accidents are very low, experts state that it can be used as an exogenous variable for the analysis. Another concern of experts was about inventory. They stated that the desired level of inventory should be set by the CL management. While one-month stock level was accepted as adequate for private CLs, public CLs preferred two-month stock level. In our case, developed model is used to analyze the dynamics of a biochemical laboratory, and coagulation tests, blood tests, and urinalysis are applied in this CL. Thus, each test type needs different desired level of inventory based on their test request characteristics which was included in the revised model. In addition, experts emphasized the importance of a training period for new hires, which is nearly three months. Although each new hire has a license to perform tests, they are not permitted to be involved in the testing process until their training time is over. Initial conceptual model was enriched and revised including this information.

Based on the results of ANP model and modelers' observations in the CLs the initial conceptual model is enriched and revised. Following figure shows the final conceptual model of our study.

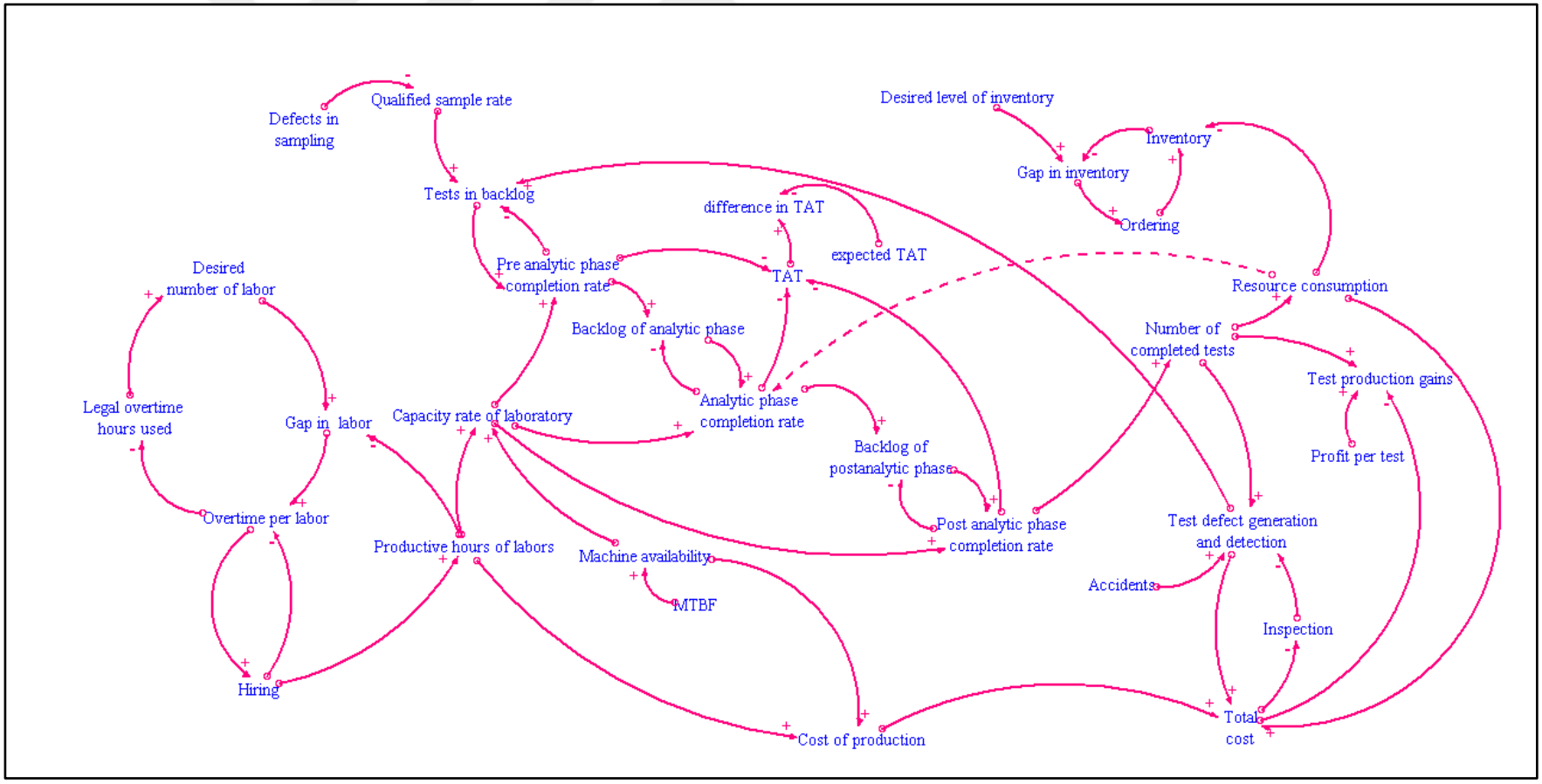


Figure 4.6. Finalized conceptual model

4.5. FORMULATION OF SIMULATION MODEL

4.5.1. Overall Model

Since data is gathered from a bio-chemical laboratory, blood, urine, and coagulation tests are considered in the model. The section covering blood, urine, and coagulation testing procedures are called as “test production sector”. The aim of this sector is to represent a typical test procedure seen in any type of CL by covering the pre-analytic phase, the analytic phase, and the post-analytic phases. This sector gives the process flow of the CL.

Similarly, other key variables and interrelations among these variables are identified. To develop the model based on these key variables some other sections are generated. These sections are called as “inventory control”, “overtime”, “hiring”, and “cost” sectors. The aim of “inventory control” sector is to regulate actual inventory levels based on desired inventory levels. In “overtime” and “hiring” sectors, labor level is managed and controlled by considering the backlog levels. The “cost” sector is used to calculate the total cost of CL regarding regular labor cost, overtime cost of labor, cost of inventory, and penalty cost. Penalty cost is generated if percentage completed (total number of completed tests over total number of test request) is less than one for daily basis. To analyze individual test types (blood, urine, and coagulation tests) behavior for inventory, cost, these variables are defined as one-dimensional arrays. Likewise, TAT and percentage completed (PC) variables are calculated dynamically, using array defined for each test type. For simulation modeling, STELLA® version 9.1.2 was used as an interface to interpret the problem and as a tool of solution. Figure 4.7 illustrates overall simulation model to analyze CL performance, and each equation of the model is given in APPENDIX D. The sections (sectors of the simulation model) involved in the model are explained in Section 4.4.2.

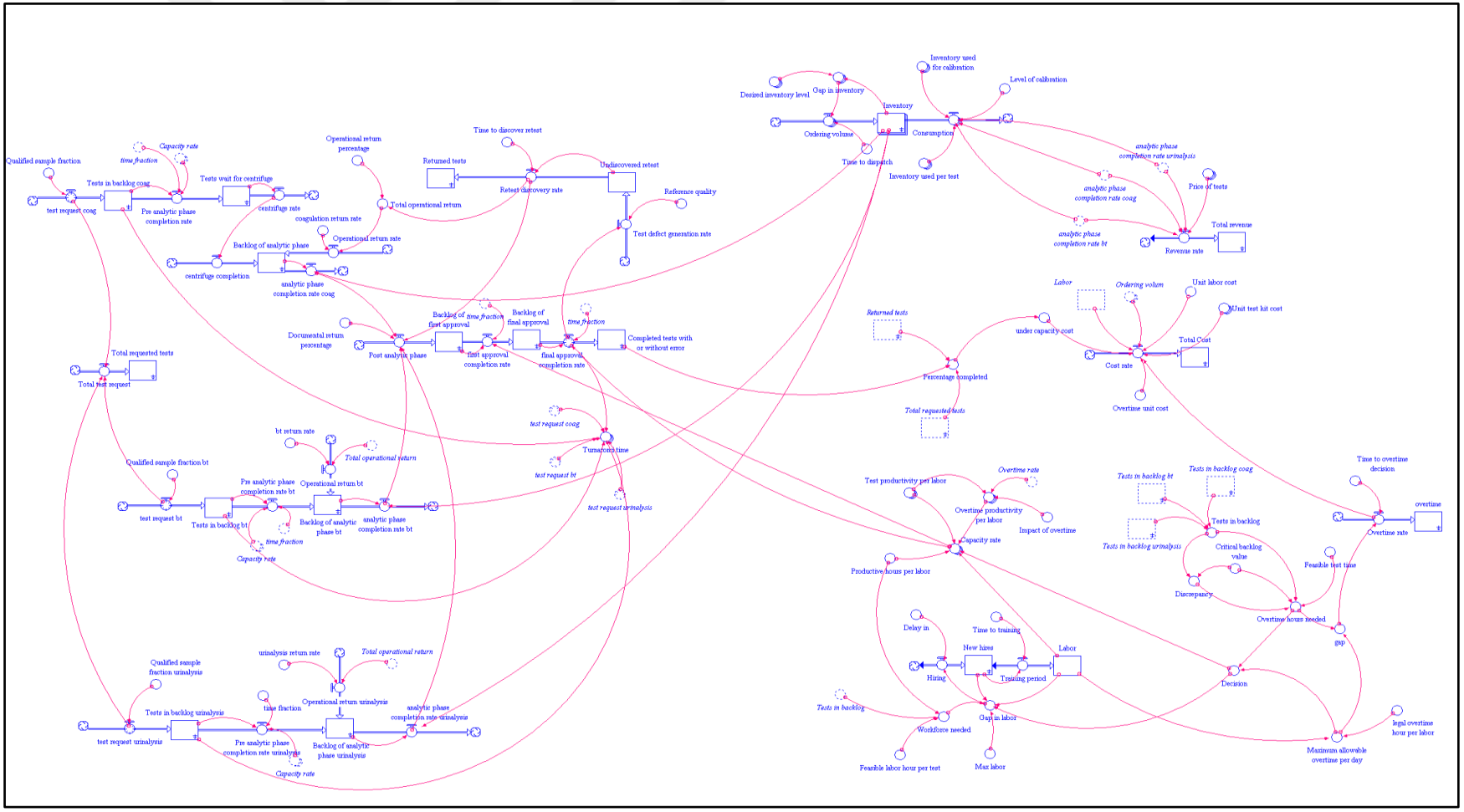


Figure 4.7. Simulation model overview on Stella

4.5.2. Sectors in the Model

Overall model is introduced under five sectors. CL performance SD model is composed of test production, inventory control, hiring, overtime, and cost sectors.

4.5.2.1. Test Production Sector

This sector represents a typical test procedure seen in any type of CL. The CL work process is divided into three phases: the pre-analytic phase, the analytic phase, and the post-analytic phase, as explained in Section 4.1.1. In addition, three different types of tests are examined in the model; coagulation, blood, and urine test. Test orders arrive according to demand behavior defined in *'test request coag'*, *'test request blood test (bt)'*, and *'test request urinalysis'* variables. Arriving orders accumulate in their backlog variables. The processes are serially connected. Work should not be released to the following phase unless the previous phase has been completed. Different test types have different time requirements. Thus, each of these phases is modeled with different completion rates rather than a total test completion rate. The completion rate variables of a given phase and test type are restricted by the minimum value of *'Capacity rate'* or *'Tests in Backlog'*. The *'Capacity rate'* for the laboratory is calculated as the regular productive hours per labor resource plus overtime hours (if utilized). These variables generate the total number of productive hours available per labor resource for pre-analytic and post-analytic phases of the tests. This total available time is divided by the *'Feasible test time'* (the expected time to complete a test under normal conditions) to calculate the total number of tests completed daily by technicians. If all waiting tests can be completed with the current capacity, there is no need to increase the work force in the CL. However, *'analytic phase completion rate'* variables are not related with labor force in the CL. These variables only depend on the capacity and the number of the testing machines. In the model, the analytic and pre-analytic phases are defined separately for each test type. However, in the post analytic phase, the machine test results are transmitted to the computer they are connected to and are checked by the laboratory officer and approved by the doctor or reprocessed according to the error type. For this reason, it is not needed to define the post-analytic phase separately for each test type.

Errors can occur during any of the three phases, and they must be considered when calculating the value of 'Tests in Backlog' variables for each test type. The number of errors and their type is taken from the CL reports prepared for the hospital quality department. *'Reference quality'* is defined as the percentage of tests with errors, i.e., not conforming to test specifications. If an error occurs during the pre-analytic or the analytic phase, rework is called the *'Operational return rate'*; it increases the number of tests in backlog. If an error occurs during the post-analytic phase, it is referred to as the *'Documental return rate'*, and it affects the number of tests waiting in the post-analytic phase. *'Completed test with or without error'* is a level variable that indicates the total number of tests accomplished and delivered to the patient with or without error.

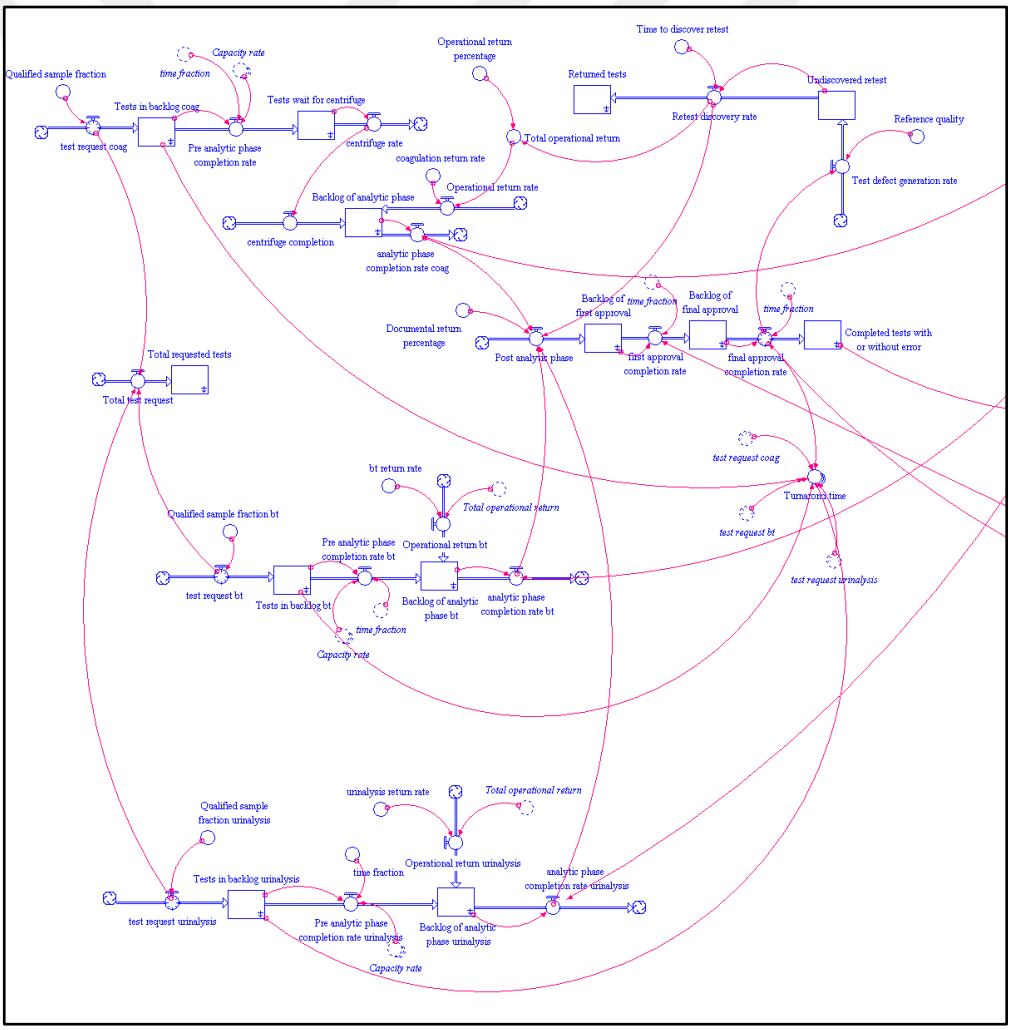


Figure 4.8. Test production sector

The test arrival rate directly affects the backlog level, which regulates one of the main performance parameters in the CL, test turnaround time (TAT). The model generates TAT for urine, blood, and coagulation tests separately because machine capacities and analysis times spent for tests are different.

4.5.2.2. Inventory Control Sector

Main building block to generate dynamic behavior in inventory control sector is a negative feedback loop. In this loop, *'Desired inventory level'* which is determined level of resources for coagulation, blood test, and urinalysis, are compared with *'Inventory'* real-time level of resources for each test type. Levels of '*Inventory'* change over time with 'analytic phase completion rates of coagulation, blood test, and urinalysis. The materials used during calibration are also spent on *'Inventory'*. Samples with known results are re-analyzed for calibration. Equipment used in coagulation, blood test, and urinalysis should be calibrated every day. Calibration is applied for each test type under coagulation, blood test and urinalysis. The number of repetition of analysis during calibration is *'level of calibration'*, and this is an exogenous variable given by quality department of the hospital. If there is a *'gap in inventory'*, the rate of *'ordering volume'* is calculated considering delivery time of ordered material which is labeled as '*time to dispatch'* and difference between actual and desired inventory levels.

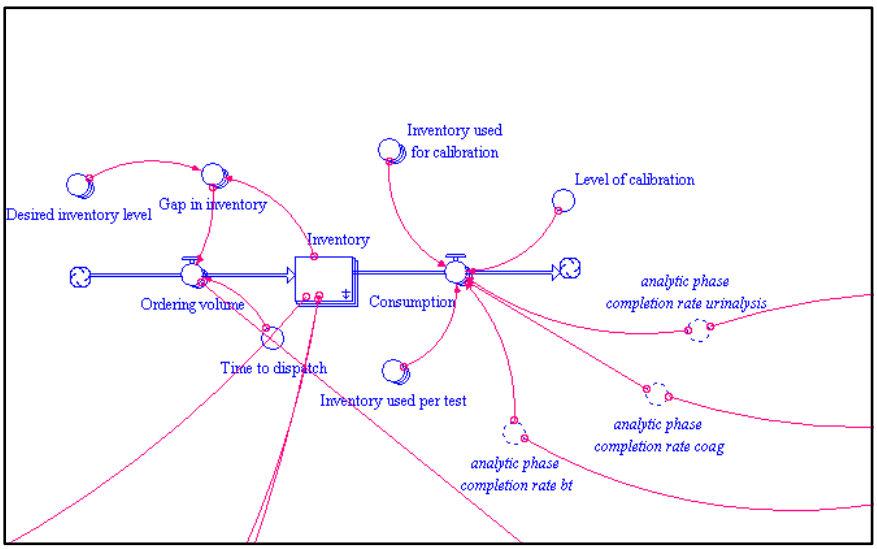


Figure 4.9. Inventory control sector

4.5.2.3. Overtime Sector

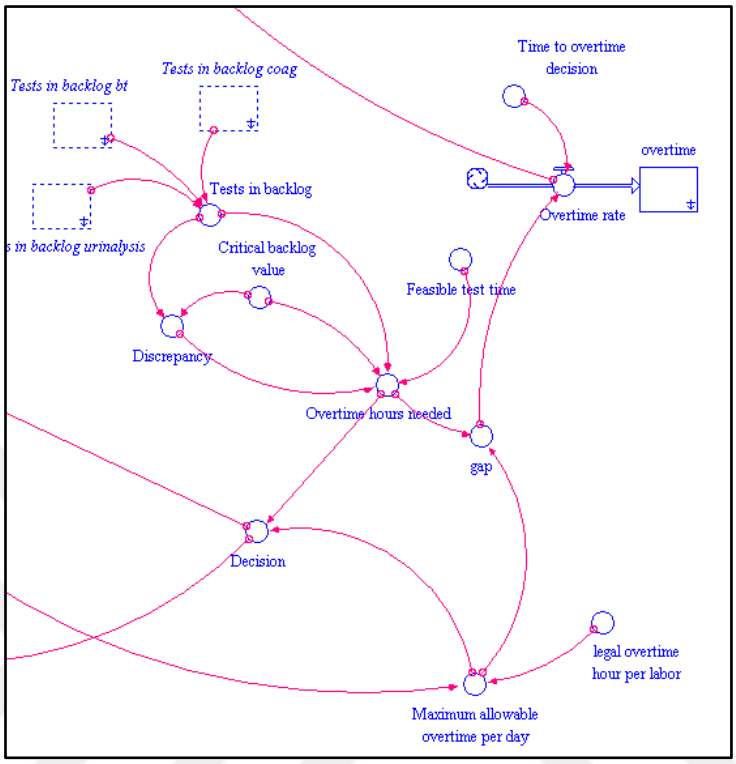


Figure 4.10. Overtime sector

The '*Overtime'* decision is made if the number of '*tests in backlog'* exceeds the '*critical backlog value*' (the maximum number of tests allowed in backlog), which is determined exogenously. This means that if the number of tests waiting reaches the critical backlog value, and if *'Overtime hours needed'* is smaller than the *'maximum allowable overtime'* (defined by law), then technicians will work overtime to decrease the number of tests in backlog until this number falls below the critical backlog value. However, as indicated in the section on the hiring sector, if the value of *'overtime hours needed'* exceeds the *'maximum allowable overtime'* (defined by law), hiring is performed. Detection of overtime hours exceeding the legal limits is achieved using a decision variable.

4.5.2.4. Hiring Sector

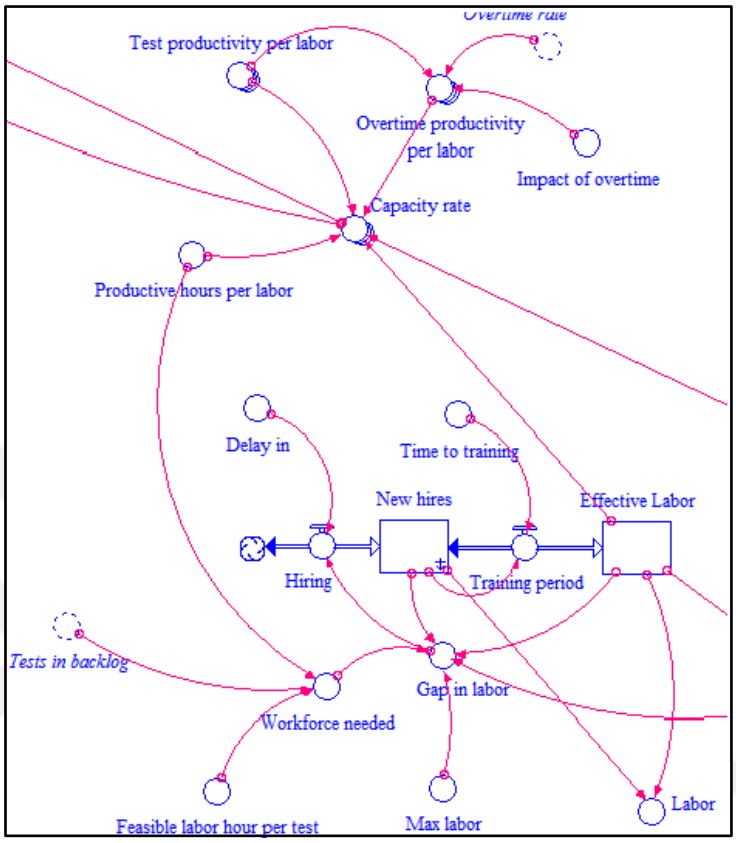


Figure 4.11. Hiring sector

When the backlog levels of tests increase (*'tests in backlog'* in Figure 4.11), management must make a tactical decision with regard to the labor force: whether to allow technicians to work overtime or hire new technicians. The decision is strategic, because when a technician is hired, he or she will receive permanent employment and cannot be laid off if the backlog level is reduced. Therefore, the costs associated with hiring a new technician over the long-term must be considered when making this decision. New hires cannot involve testing process during their training period. Thus, labor level is captured individually for effective labor who can involve testing process and total labor level (total number of workers hired and effective ones). In contrast, there are some restrictions in opting to allow overtime work. One restriction is the law that limits overtime hours per labor resource. Additionally, there are costs associated with staff working overtime. Thus,

managers should select a solution that does not infringe on labor rights or jeopardize productivity and cost.

'Effective Labor' is the total number of clinical staff (technicians) involved in any part of the testing procedure (including the pre-analytic and post-analytic phases of blood, urine, and coagulation tests). *'Labor'* shows the total number of clinical staff omitting the training restriction. This stock variable is controlled by the '*Hiring rate'* and is restricted by a constraint on the maximum number of technicians, '*Max labor'*. In other words, a CL manager cannot hire more technicians than the *'Max labor'*. A labor resource will be hired if the organization exceeds the legal limits of overtime, and overtime hours are calculated in the overtime sector.

4.5.2.5. Cost Sector

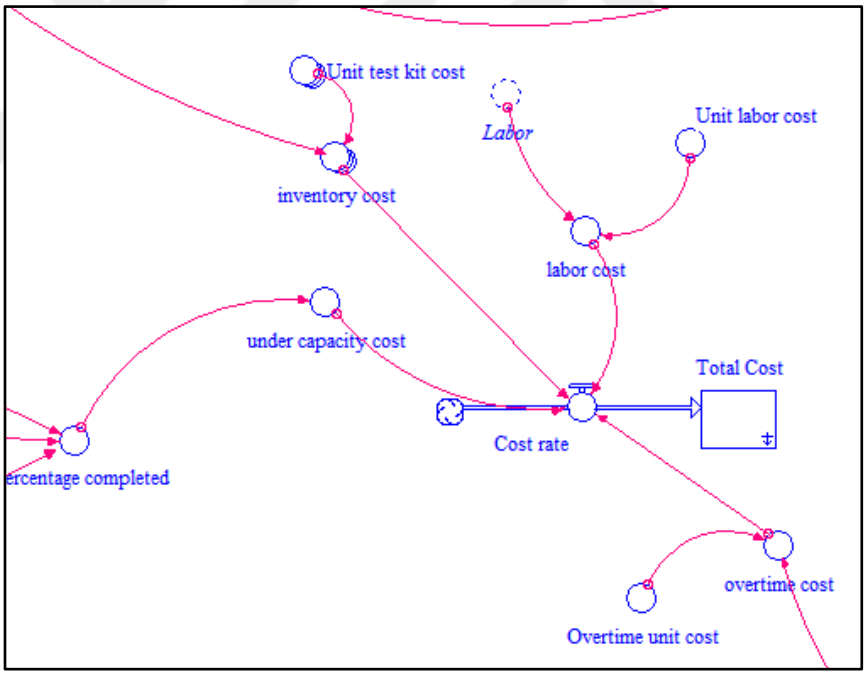


Figure 4.12. Cost sector

Cost analysis of CL is done under this sector. Total cost is calculated with regular labor cost, overtime cost of labor, cost of inventory, and penalty cost. Penalty cost is included in '*under capacity cost'* and it is generated if the daily test demand is not met. To detect the days on which the test demand is not met, *'Percentage completed'* variable is used. It

calculates percentage difference between *'Total test request'* and *'Completed tests without error'*. Cost of inventory is detected with *'ordering volume'* inventory rate of coagulation, blood test, and urinalysis.

In the model, *'Revenue'* is directly associated with the number of *'completed tests'* and the *'price of test'*. *'Completed tests'* are not calculated separately for each test type (blood tests, urinalysis, and coagulation tests), although there are different average selling prices of each type of test. For this reason, analytic phase completion ratios are used to calculate the *'Total revenue'* of CL.

5. VERIFICATION AND VALIDATION

Validation of an SD model is complicated because estimating the validity of the model structure is philosophically and technically difficult [124]. To a valid SD model, both structure of the model and behavior of model outputs should close to real system structure and behaviors. To ensure the model validity, a set of tests should be applied to SD models.

5.1. BASE CASE

The simulation was run with the following initial values. These values are specific to the bio-chemical laboratory where base case and performance parameters are gathered. In addition, some of them are defined based on governmental regulations, and opinions of CL experts. Listed below are the base case parameters.

Table 5.1. Base case simulation parameter values

Name of Parameter	**Value (unit)**
bt_return_rate	0.33 (percentage)
coagulation_return_rate	0.33 (percentage)
Critical_backlog__value	710 tests
Delay_in_hiring	45 days
Desired_inventory_level[1]	4200 units
Desired_inventory_level[2]	12480 units
Desired_inventory_level[3]	7680 units
Documental_return__percentage	0.90
Feasible_test_time	4.5 hours
Impact_of_overtime	0.75 percentage
Inventory_used_for_calibration[1]	17 units
Inventory_used_for_calibration[2]	22 units
Inventory_used_for_calibration[3]	10 units
Level_of_calibration	2 (unitless)
Max_labor	12 employee

Labor	6 employee
Operational_return_percentage	0.10 percentage
Overtime_unit_cost	12 ($/(employee.day))
Price_of_tests[1]	2 ($/test)
Price_of_tests[2]	3.5 ($/test)
Price_of_tests[3]	5 ($/test)
Productive_hours_per_labor	6.8 (hours/(employee.day)
Reference_quality	0.0006 (percentage)
Test_productivity_per_labor[1]	75 (tests/hour.employee)
Test_productivity_per_labor[2]	150 (tests/(hour.employee))
Time_to_discover_retest	3 days
Time_to_dispatch	7 days
Time_to_overtime__decision	1 day
Time_to_training	90 days
Unit_labor_cost	45 ($/employee.day)

The system initiated in the equilibrium with 6 technicians, no backlog, and new test requests arriving, and run for one year. The analysis are done by using base case parameters and explore three strategies: (1) working overtime only (OT only), (2) hiring new staff (hiring only), and (3) hiring new staff and working overtime (hiring with OT). The effects of these strategies are analyzed for *PC*, *TAT*, *cost*, overtime hours spent (*OT*) and the total number of technicians (*labor*) in the CL, In Table 5.2, simulation results for each strategy ('OT only', 'Hiring only', and 'Hiring with OT') are summarized.

Table 5.2. Comparison of the impact of the strategies on performance (year-end results)

OT only		**Hiring only**		**Hiring with OT**	
OT (hrs.)	292	**OT (hrs.)**	0	**OT (hrs.)**	292
Labor(emp.)	6	**Labor (emp.)**	11	**Labor (emp.)**	6
PC (%)	100%	**PC (%)**	100%	**PC (%)**	100%
TAT (coag.) (hours)	1.408	**TAT (coag.) (hours)**	1.408	**TAT (coag.) (hours)**	1.408

TAT (bt) (hours)	4.072	**TAT (bt) (hours)**	4.072	**TAT (bt) (hours)**	4.072
TAT (urine) (hours)	2.512	**TAT (urine) (hours)**	2.512	**TAT (urine) (hours)**	2.512
Cost ($)	469.397	**Cost ($)**	622.187	**Cost ($)**	469.397

When the model is run for three different strategies using base case parameters, it is seen that TAT and PC values are satisfied for end of year-end results. 'Hiring with OT' and 'OT only' strategies can be chosen for base case conditions because the values of all performance indicators are same, and within acceptable range for the decision makers.

5.2. STRUCTURAL VALIDITY OF THE MODEL

SD simulation models are often used for developing system operating policies and to understand system behaviors. However before a model is used for analysis or any other use, the decision makers would like to have sufficient confidence in the model, that is they can rely on the model (output). There is not one single test that validates an SD model. Rather, the model must pass various tests before confidence is built. The process to generate confidence is called validation. There are two types of validation in SD: structural validation and behavioral validation. Structural validation includes verifications tests, which are conducted to verify that the key variables of the real system have been properly transferred into developed model. Thus, in this research structure verification and parameter verification tests are conducted for structural validation. Additionally, boundary adequacy and dimensional consistency checks are also performed to validate the structure.

5.2.1. Boundary Adequacy Test

The constructed model should be checked for its boundary. One of the major concerns in this stage is to confirm that the model covers all relevant aspects for the handled problem. The modelers should think whether there are any important issues that are not included in the model, and they seek if any changes (especially extending) on boundary assumptions can generate dramatic changes on model behavior. If any additional important concept

(issue) is captured for the model, the model should be revised and these issues should be added to the model.

In our study, boundary of the model is determined by literature review on CL performance and during ANP study. Main key concepts (resource, time, quality and cost management) are found to be acceptable by the experts for the model purpose. These main concepts are decomposed into sub-items in ANP study. During pairwise relation and comparison matrix preparations, experts had a chance to evaluate each sub-item of the main instruments. The results of the pairwise comparison matrix show which individual items are more important than the others.

5.2.2. Structure Verification of the Model

To conduct the structure verification of an SD model, each individual relation in the model should be verified whether they are applicable in the real system. After relations are accepted, it must be ensured that these relations are converted into mathematical equations accordingly. In other words, the level of aggregation should be checked for appropriateness.

Main concern in structure verification is to confirm whether the model structure and real-world system correspond to each other or not. This descriptive knowledge should cover interrelations among the key variables proposed in conceptual model. In our study, consistency and adequacy of the model structure is ensured by ANP model results. Our initial conceptual model is also shown to the experts and their opinions are used to enrich and modify our model as mentioned in Proposed Framework section.

During the ANP study, experts emphasized the importance of labor especially in pre-analytic and post-analytic phases. Based on their feedbacks, conceptual model is revised. In the prior design, quality was only associated with errors during the testing procedure. However, experts stated that qualified sample rate is also an important variable for completing testing procedures. Although the rate and severity of accidents are very low, experts stated that they can be used as exogenous variables for the analysis and should be included. Thus, the initial conceptual model is enriched and revised by using the results of

ANP model and modelers' observations in the CLs (see section 4.4 Conceptual Model Development).

5.2.3. Parameter Verification of the Model

In parameter assessment stage, main concern of the modeler is that whether the parameter values are consistent and realistic or not. In other words, parameters included in the model should be controlled whether or not they are consistent with real life and their values should represent reality.

In our study, each of the parameter values is gathered from the CL that we are in contact with. During ANP model development, conceptual model is also shown to the experts and procedures are explained in detail.

5.2.4. Dimensional Consistency Test

All model equations should be checked for dimensional consistency. In other words, unit of each variable in the mathematical model of the simulation should be checked for consistency with the derived equations. The balance between units of right and left-hand side of the equations is checked [122]. But this is just a part of dimensional consistency. Parameters utilized in the equations must be reasonable for real world meaning. To be reasonable, the model should not have dummy parameters that have used to satisfy unit consistency of the equations [152]. In our model, unit consistency checks are performed with the dimensional analysis tool of the software. Also units of variables are analyzed to confirm that they are meaningful in real world.

5.2.5. Extreme Conditions Test for the Model

Some critical equation in the simulation model should be checked with inputs that have extreme values. It is expected that model generates reasonable responses and confirm basic physical laws when it is subjected to extreme conditions [30]. The extreme conditions that

are generally applied in SD models are: no available input, no production, and no available resource [30].

In that stage, model inputs are subjected to extreme values to test whether the model equations make sense for these extreme conditions or not. In some cases, model should generate a plausibility response to extreme conditions and shocks. It is expected that model and real-world system generates the same behavior for designated extreme-condition [30].

In our study, the model is observed for a set of extreme conditions. These conditions can be listed as no available inventory, no available labor, and no available test request.

5.2.5.1. Extreme Condition Case I: No available inventory

The model is subjected to "no available inventory" case to observe the model behavior under this condition. The expected behavior for such a condition is that model cannot respond to the test demand of CL. When running this case, 'time to dispatch' parameter must be also taken into consideration because model will generate a response to close the gap, and after a while inventory will be available. To do so, 'time to dispatch' is taken as a sufficiently greater number (1000 days).

As expected, no test could be accomplished without available test kits inventory. Due to the fact that test requests are in normal parameter values, analytic phase backlog values for each test (coagulation tests, blood test, and urine analysis) are accumulated as shown in Figure 5.1. However, number of *'completed tests with/out error'*, *'backlog of first approval'*, and *'backlog of final approval'* values are found to be zero throughout the year (Figure 5.2).

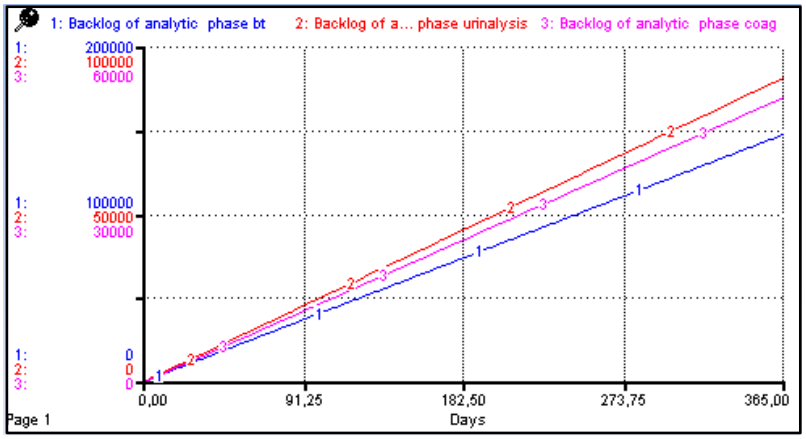


Figure 5.1. Analytic phase backlog values for three test types

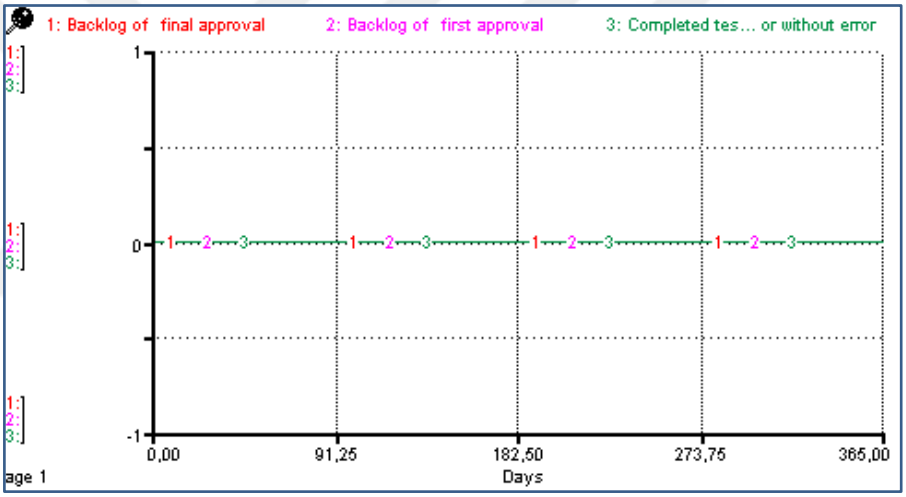


Figure 5.2. Post analytic and total number of completed tests values

5.2.5.2. Extreme Condition Case II: No available labor

In this case, CL will be simulated with no available labor. This means CL has no labor initially and 'maximum labor' number is set as zero. It should be noted that 'level of calibration' is set as zero in this case, because calibration cannot be done without labor force. The behavior of 'labor' stock variable is as shown in Figure 5.3 throughout simulation runtime.

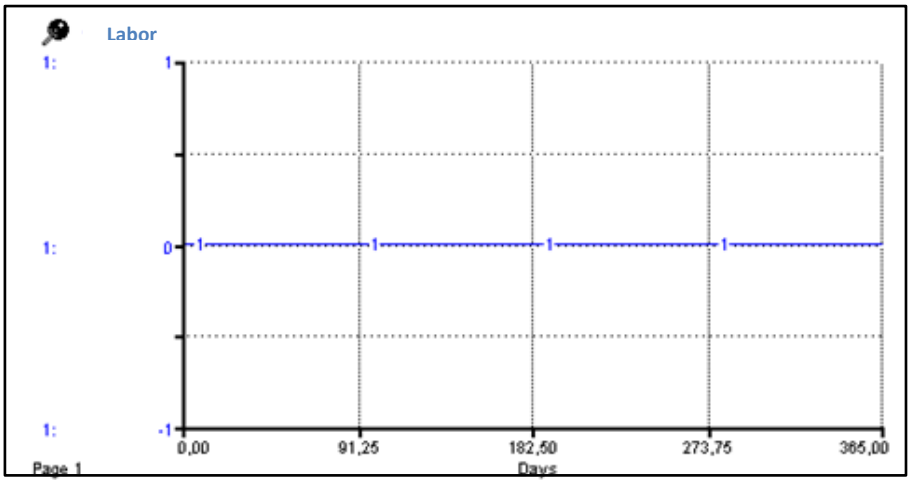


Figure 5.3. Number of available workforce for extreme case II

The technicians are involved to work from pre-analytic phase to post-analytic phase in a CL. Thus, it is expected that backlog of pre-analytic phases are accumulated, and there is no waiting work on analytic and post-analytic phase due to this bottleneck. Following figures show us the behavior of backlog stocks for pre-analytic phases, analytic, and post-analytic phases respectively for coagulation test, blood test, and urine analysis.

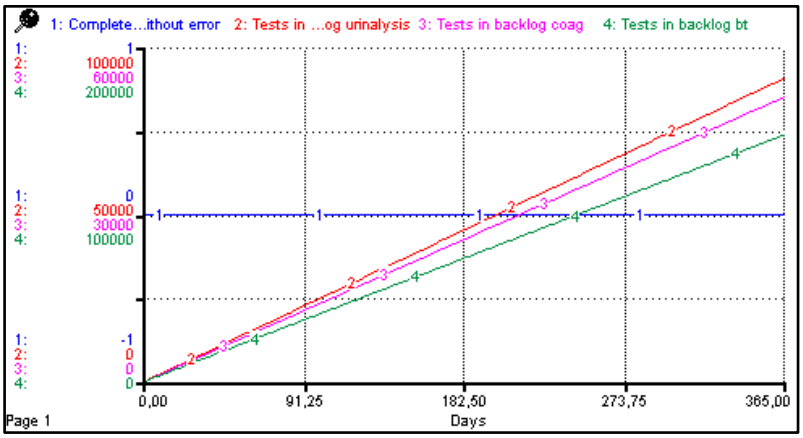


Figure 5.4. Backlog in pre-analytic phase values for three test types

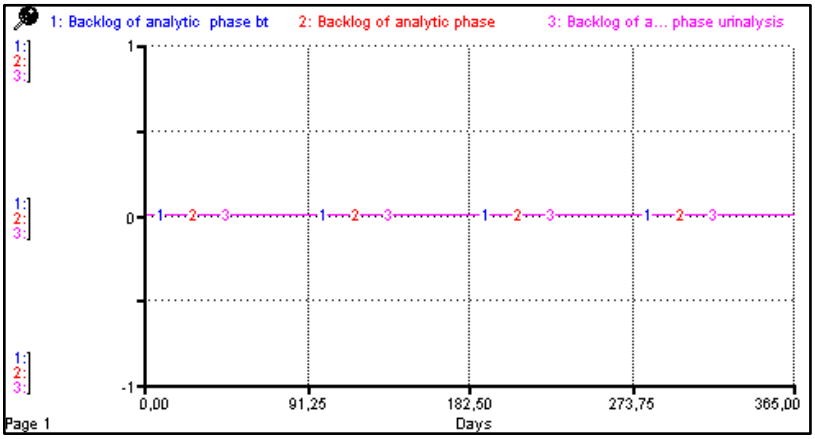


Figure 5.5. Analytic phase backlog values for extreme case II

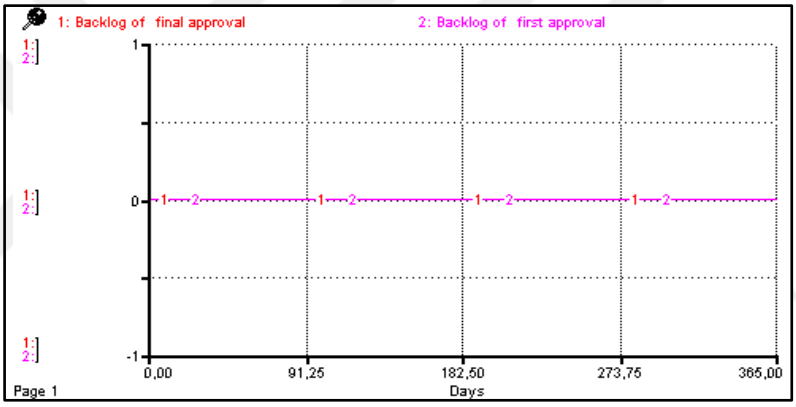


Figure 5.6. Post-analytic phase backlog values for extreme cases II

As seen in given figures above, tests cannot be processed without labor force. Thus, inventory consumption is also expected and found to be zero under this condition. . In Figure 5.7, Consumption [1], Consumption [2], and Consumption [3] are the consumed inventory for coagulation tests, blood tests, and urinalysis, respectively.

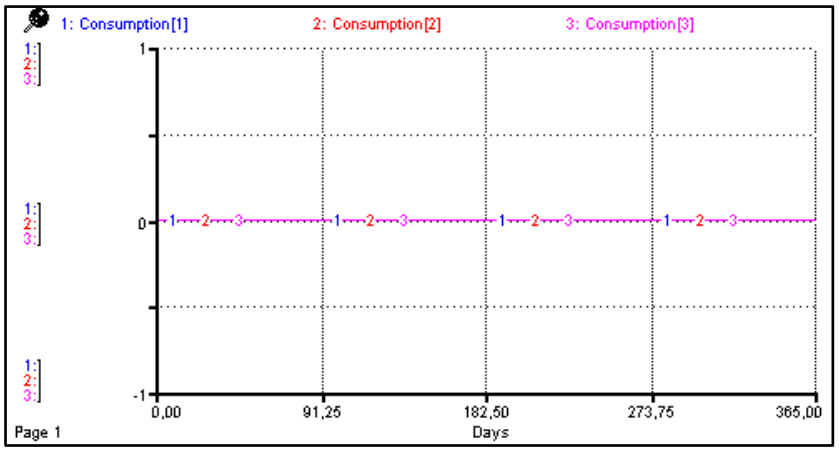


Figure 5.7. Inventory consumption rates for three test types under extreme case II

5.2.5.3. Extreme Condition Case III: No test request

In a CL with no test request, technicians have no workload. It means total number of tests processed and completed will be zero. Thus, CL will only generate cost of labor and inventory for calibration while there will be no revenue for CL.

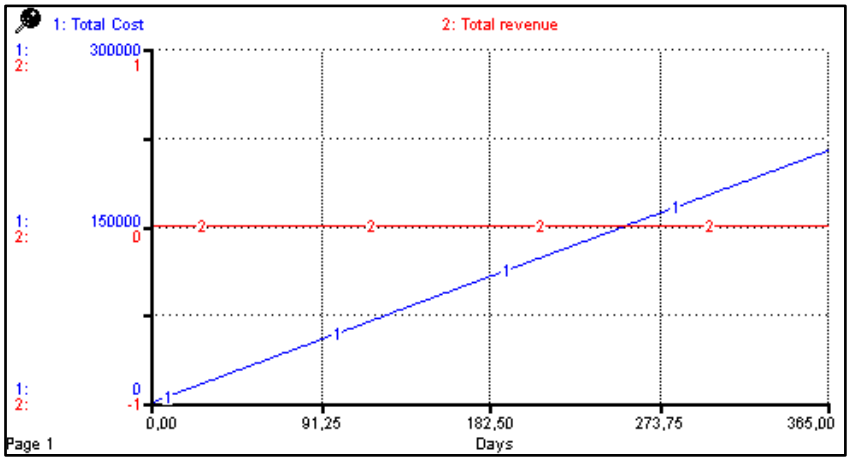


Figure 5.8. Revenue and cost behavior under extreme case III

Figure 5.8 shows the simulation model behavior under no test request extreme case. As expected, CL has no revenue but cost of labor and inventory cost for calibration is generated. Likewise, absence of test request does not generate any test production. Thus,

number of tests in backlog and completed tests will be zero throughout the year. Figure 5.9 shows that the model generates the expected behavior.

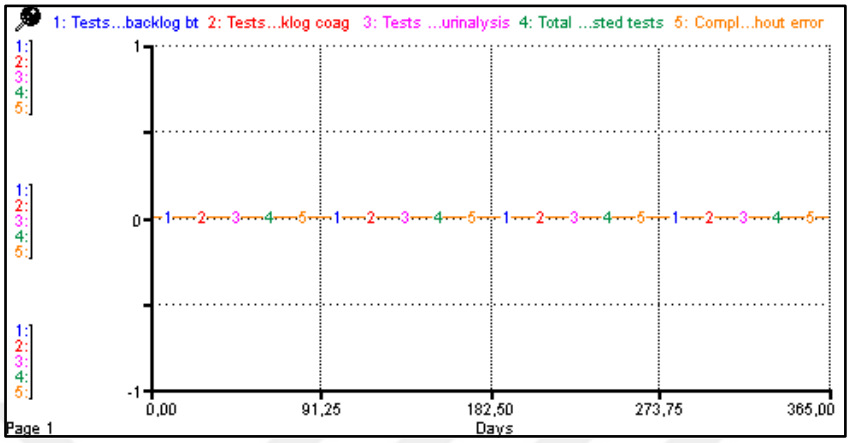


Figure 5.9. Tests in backlog behavior for three test types under extreme case III

5.3. BEHAVIORAL VALIDITY OF THE MODEL

Even if a model is structurally accepted, its validity cannot be fully proven without behavioral validity. Thus, the model should be subjected to behavioral analysis. Although structural validity tests are essential, they have a common disadvantage of being qualitative by their nature [124]. Thus, modelers need some quantifiable and numerical methods to complete the model validation procedure. In this study, behavior reproduction test and behavior anomaly are conducted on the model.

5.3.1. Behavior Reproduction Test for the Model

It is expected that the model reproduce real-life system behavior both qualitatively and quantitatively. Statistical methods should be preferred to compute statistical measures to compare the model with real-life results. There are multiple ways to measure the fit of simulation output to historical data. The analysis can include trend, period and mean comparisons [153]. In trend analysis, the model output will be compared with historical data, and type of trend is estimated. To compare the periods, generally autocorrelation tests are applied. In mean comparison method, percent errors in means of the outputs are

calculated. The comparison results will show whether model is overlapping with reality or not.

In this study, due to lack of data for trend and period comparison methods cannot be carried out. Instead of these methods, comparison of means is used. Following table shows real mean values of some key outputs and simulation results for these outputs. These outputs are total number of overtime hours within a year, total number of completed tests within a year, average turnaround time (TAT) for coagulation test, average TAT for blood tests, average TAT for urine analysis.

Table 5.3. Summary of analyzed simulation outputs

Analyzed Variable	**Real Output**	**Simulation Output**	**Percentage Error**
overtime hours	300 hours/year	292 hours/year	0.026
completed tests	300,000 tests/year	286,740 tests/year	0.042
TAT for coagulation	1.5 hours	1.408 hours	0.061
TAT for blood test	4 hours	4.072 hours	0.018
TAT for urine test	2.5 hours	2.512 hours	0.004
Labor	6 employees	6 employees	0.000

In this study, tolerable percentage error is taken as 0.05 [154]. Based on the results on given table above, percentage errors of the outputs are less than the tolerable percentage error, except *TAT for coagulation*. However, when the unit of *TAT for coagulation* parameter is considered in terms of minutes, the difference between real and simulation outputs is nearly five minutes which the experts find it to be negligible. Thus, all of the analyzed simulation outputs are acceptable when they are compared with real data taken from the CL.

5.3.2. Behavior Anomaly Test for the Model

In some cases, conducting statistical tests are not due to the fact that data limitations. Behavior anomaly tests offer a chance to examine such cases. The main purpose is to see whether the model generates anomalous behavior when a certain relation is neglected or

modified. When a modeler neglects a relation among variables, it is expected that new behavior clearly shows the effect of this relation in the model, thus the importance of the relation. To detect behavior anomaly, **loop knockout analysis** is used as a common method in literature [30].

A negative feedback relation loop is selected to zero out the target relation in 'loop knockout analysis'. Due to the fact that negative feedback loops always try to reach a target value, the adjustment time in the loop is set at a very greater value [30].

5.3.2.1. Inventory dispatched time

In behavior anomaly test, inventory loop is the first loop that is examined. 'Time to dispatch' variable is set as an infinite number, and then model is run under this condition. Until the initial inventory is emptied, the model generates test production. After initial inventory value reached to zero for each of three test types, consumption and backlog values of first and final approval became zero as well (Figure 5.10). However, waiting tests in analytic phase backlog for three test types were accumulated (Figure 5.11).

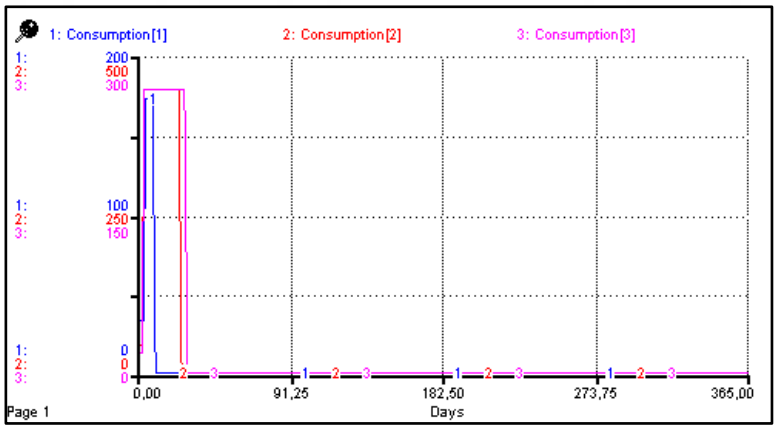


Figure 5.10. Consumption rates under infinite dispatching time condition

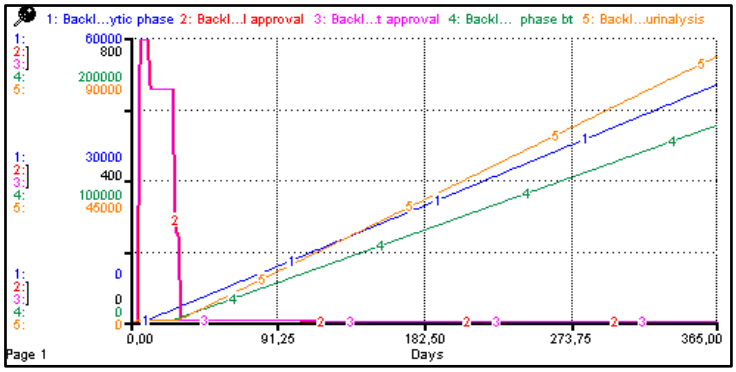


Figure 5.11. Backlog behaviors under infinite dispatching time condition

5.3.2.2. Time to Decide Overtime

Model detects overtime decision with a gap analysis. If 'maximum allowable overtime hours' is greater than 'overtime hours needed', then needed overtime hours are satisfied with overtime decision. In the loop, adjustment time to this corrective action is named as 'time to overtime decision'. This variable is set to an infinite value, and model is run for this case.

Without allowable overtime, it is expected that model is pushed to make hiring decision. Although the same behavior is observed in our simulation model, it should be noted that hiring only 2 new employees is a bizarre decision for 292 overtime hours in a year. For such conditions (bizarre or physically impossible behavior) in behavior anomaly tests, modelers realize that examined relation is important for the model, and it must be included [30]. Figure 5.12 shows that without overtime decision, model needs more two technicians to hire.

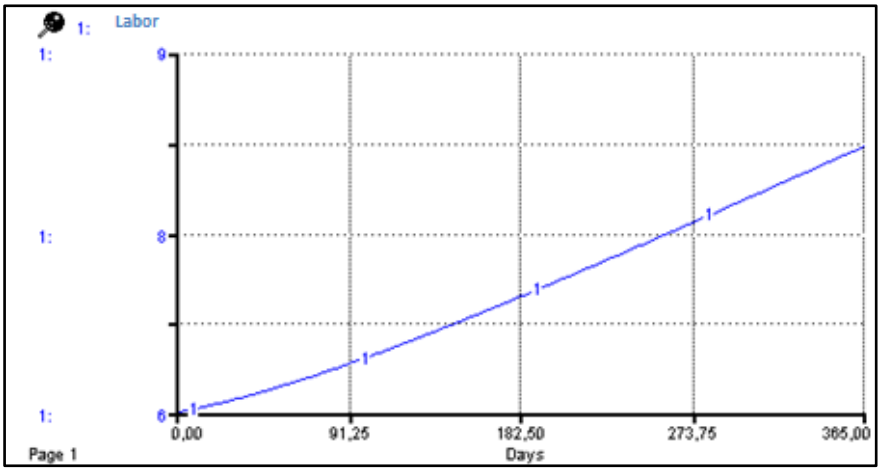


Figure 5.12. Number of employees under infinite time to decide overtime condition

6. ANALYSIS OF MODEL

Most of real systems are stable. When some small changes are made in a model parameter value, it is expected that model behavior does not response to these changes with dramatic outcomes. Thus, model consistency and confidence will increase if it is not affected by parameter variations. The purpose of sensitivity analysis is to determine the changes in model behavior if certain parameter values are altered in a definite range [124]. If changes in some parameter generate great changes in model behavior, then modelers conclude that more effort is needed to estimate the value of such parameters.

In this study, we changed some critical model parameters and model outputs are examined for these changes. Here, effect of changes in *critical backlog*, *test productivity*, and *test request* on *TAT*, *percentage completed (PC)*, *overtime (OT)*, *cost*, and *labor* are analyzed.

6.1. SENSITIVITY ANALYSIS FOR 'CRITICAL BACKLOG VALUE'

In the first sensitivity analysis, '*critical backlog value'* is decreased and increased by per cent. Table 6.1 illustrates the summary of sensitivity analysis results of CL performance parameters under 'OT only', 'Hiring only', and 'Hiring with OT' strategies for different *critical backlog values*.

Table 6.1. Effect of 'critical backlog value' on performance outputs

	OT only			**Hiring only**			**Hiring with OT**			
Critical Backlog	**Cost ($K)**	**Change in Cost (%)**	**OT (hours)**	**Cost ($K)**	**Change in Cost (%)**	**Effective / Labor**	**Cost ($K)**	**Change in Cost (%)**	**OT (hours)**	**Effective / Labor**
710	492		2184	622		11/12	492		2184	6/6
790	469	-4	292	622	0	11/12	469	-4	292	6/6
870	465	< -1	0	622	0	11/12	465	< -1	0	6/6

Decreasing the '*critical backlog value*' leads to a more repressive working system in the CL. For this reason, the model is pushed to more overtime and hiring conditions. Thus, in all strategies, *'cost'* increases as *'critical backlog value'* decreases (Table 6.1). The results suggest that for the 'OT only' and 'OT with hiring' strategies, *TAT* and *PC* are insensitive,

where *cost* values generate a slight sensitivity to changes in the *'critical backlog value'*. Conversely, for the 'hiring only' strategy, *'cost'* is sensitive to variations in the *'critical backlog value'*.

6.2. SENSITIVITY ANALYSIS FOR 'TEST PRODUCTIVITY'

In this research, test productivity is defined as a one-dimensional array. *'Test productivity 1'* defines technicians' productivity during pre-analytic phase, and *'test productivity 2'* is used for productivity of doctor and supervisor during post-analytic phase. In base case, pre-analytic phase productivity per technician is set as 75 (tests/hour) and post-analytic phase productivity is set as 150 (tests/hour). Again, parameter values are decreased and increased by 10 per cent for sensitivity analysis. Simulation results for different productivity levels under 'OT only', 'Hiring only', and 'Hiring with OT' strategies are given in Table 6.2.

Table 6.2. Effect of 'test productivity per labor' on system performance outputs

	OT only			**Hiring only**			**Hiring with OT**			
Test Productivity	**PC (%)**	**Cost ($K)**	**OT (hours)**	**PC (%)**	**Cost ($K)**	**Effective/ Labor**	**PC (%)**	**Cost ($K)**	**OT (hours)**	**Effective/ Labor**
-10 (%)	100	469	292	100	622	11/12	100	469	292	6
Base case	100	469	292	100	622	11/12	100	469	292	6
+10 (%)	100	469	292	100	622	11/12	100	469	292	6

Although the number of technicians and overtime hours are same for 'OT only' and 'Hiring with OT' strategies, *'cost'* of these strategies are different. The reason of the difference is delays in daily assessments. When strategies are examined within themselves, the altered parameter does not change the year-end simulation results. It means model performance outputs have no sensitivity to *'test productivity'* when it is changed in a reasonable range.

Despite the test productivity is an important indicator for the model, a change in ten per cents of the number of tests accomplished by the labor during pre-analytic phase did not generate a significant difference. The reason behind this is probably the bottleneck that exists in post-analytic phase. As mentioned in CL process (section 4.1.1), post-analytic phase consists of two serial processes in which, a supervisor and a laboratory doctor execute first approval and final approval of the test results respectively. To eliminate the existing bottleneck, one would have to increase productivity however this would cause lack of awareness detecting errors during the process. Moreover if we tried to overcome this bottleneck, we would be forced to employ an additional supervisor and laboratory doctor, then again this would cause a new problem for the hospital management since these positions require people with special set of skills meaning that the cost of wage would increase dramatically.

6.3. SENSITIVITY ANALYSIS FOR 'TEST REQUEST'

The parameter value, *test request*, is decreased and increased by 10 per cent for sensitivity analysis. Table 6.3 summarizes the sensitivity analysis results for altering *'test request'* values.

Table 6.3. Effect of 'test request' on system performance outputs

	OT only			**Hiring only**			**Hiring with OT**			
Test Request	**Cost ($K)**	**Change in Cost (%)**	**OT (hours)**	**Cost ($K)**	**Change in Cost (%)**	**Effective / Labor**	**Cost ($K)**	**Change in Cost (%)**	**OT (hours)**	**Effective/ Labor**
-10 (%)	442		0	566		10/11	442		0	6/6
Base case	469	6	292	622	10	11/12	469	6	292	6/6
+10 (%)	494	5	331	661	6	12/12	494	5	331	6/6

In all strategies, an increase in *'test request'* (demand) generates more *'cost'*, while *'PC'* and *'TAT'* are not affected in the year-end values. In addition, the results show that, in terms of *'cost'*, 'Hiring only' strategies are more sensitive than 'OT only' and 'Hiring with OT' strategies. It is obvious that the model can satisfy yearly test demand without using all

available overtime hours. Consequently, model does not need to increase labor level in ‘OT only’ and ‘Hiring with OT’ strategies. Whilst the process, this method offers stable functioning features even if we are to face a change of ten per cents in test demand. The reason behind that the machine capacity is never utilized fully.

7. DESIGN IMPROVEMENT

7.1. POLICY DEVELOPMENT

To make further analysis, a number of structural changes will be undertaken to the policies in the base case. The changes to be made are found from importance weights of key performance variables gathered from ANP study. The first policy is selected as "increasing machine capacity" and second policy is "increasing training period after hiring". Additionally, desired workforce is also considered as a policy to satisfy time requirement in this study. Then, these policies are introduced to three scenarios: "base case" scenario, "increase in test demand" scenario, and "redesigned labor workforce" scenario. Applied policies are summarized in the following table.

Table 7.1. Descriptions of policy interventions

Policy	Policy Type	Description
Policy 1	Flow Intervention	In base case, centrifuge capacity is 192 tests/hour, coagulation is 40 tests/hour, blood test machine 100 tests/hour, and urine analyzer capacity is taken as 200 tests/hour. In this policy analysis, CL decision makers could change by renting their machines with higher capacity ones or duplicate their machines. In the case of duplicating the machines, if test demand is under 50.000 tests/year, it generates a cost of renting for each machine. Otherwise, CL only pays the test kit demand cost. When yearly test demands are analyzed for base case, only blood test analyzer can be duplicated without rent cost.
Policy 2	Flow Intervention	This policy intervention is focused on labor force of CL. Every new staff should be subjected to a training period, and during this period they do not involved in any testing procedure as workforce. In base case, this training period is three months. In this policy, training

		period is extended to 4.5 months. It is implemented in the model by altering time to training parameter.
Policy 3	Stock & Flow Intervention	In base case, desired workforce is found based on tests in backlog and available overtime hours of labor. In this policy, desired workforce is calculated based on test requests directly.
Policy 4	Flow Intervention	A Combination of Policy 1 & 2
Policy 5	Stock & Flow Intervention	A Combination of Policy 1, 2 & 3

Developed policies are analyzed for base strategy (BS) and two different scenarios (Scenario 1 and Scenario 2). New scenarios are explained in the following section in detail.

7.1.1. Scenario 1: Base Strategy

Above mentioned policies are examined for base case strategy. The model is run for one year, and the year-end results of each policy are given in the following table.

Table 7.2. Policy analysis results for scenario 1

	OT (hrs.)	**Labor (emp.)**		**PC (%)**	**TAT (coag.) (hrs.)**	**TAT (bt) (hrs.)**	**TAT (urine) (hrs.)**	**Cost ($K)**
		Hired	**Effective**					
Policy 1 (increasing machine capacity)	292	0	6	100	1.408	4.072	2.512	469.397
Policy 2 (increasing training period)	292	0	6	100	1.408	4.072	2.512	473.004

Policy 3 (changing labor level based on daily test requests)	3594	6	12	100	1.408	4.072	2.512	693.845
Policy 4 (Policy1&2)	292	0	6	100	1.408	4.072	2.512	469.397
Policy 5 (Policy 1,2&3)	3403	6	12	100	1.408	4.072	2.512	691.553

Table 7.3. Cost indicator values for policies under scenario 1

	Labor Cost ($K)	**Inventory Cost ($K)**	**OT Cost ($K)**	**Penalty Cost ($)**	**Total Cost ($K)**
Policy 1 (increasing machine capacity)	188.856	275.773	3518	1250	469.397
Policy 2 (increasing training period)	189.372	278.613	3518	1500	473.004
Policy 3 (changing labor level based on daily test requests)	373.564	275.773	43.257	1250	693.845
Policy 4 (Policy1&2)	188.856	275.773	3518	1250	469.397
Policy 5 (Policy 1,2&3)	373.564	275.773	40.965	1250	691.553

Due to the fact that demand behavior did not change, in Policy 1, 2, and 4, the model performance data (overtime, labor, percentage completed, test turnaround time (TAT), and cost did not generate difference from the base case results given in the previous chapter. In Policy 3, desired workforce is redesigned based on daily test demand. If overtime limit is fulfilled, hiring decision is done based on daily test demand in CL. Based on this policy; number of employees increase from 6 to 12. Thus, total allowable overtime hours are increased to 3594 hours/year. As mentioned before daily test demand is not changed, so there is no difference in terms of TAT and cost of CL. However, due to new hires and increased overtime hours, and cost of CL increases under this policy. In Policy 5, blood test machine capacity and training period of new hires are increased, and desired workforce level in hiring decision is calculated based on daily test demand instead of daily backlog

level. In this case, labor need increases to 12 employees and overtime hours reach 3403 hours/year. Due to these reactions, cost of CL increases to $691.553.

It should be noted that Policy 1 and Policy 4 generate exactly the same behavior although Policy 4 also covers increasing the machine capacity condition. Accordingly, when the machine utilizations were checked; it is observed that duplicated blood analyzer is idle for 90 per cent of process time. For base case scenario, Policy 1, 2, and 4 should be chosen by the decision makers rather than Policy 3 and 5 because same performance can be achieved with less cost.

7.1.2. Scenario 2: Increase in Demand Environment

In scenario 2, test demand is increased by 20 per cent for each test type after sixth month, and each policy is run for this changing demand environment. Such an increase can be examined in simulation model by altering the demands of each test type based on the following equations.

Table 7.4. Altered equations for scenario 2

Variable name in simulation	Equation for the variable
Test request coag	(144+Step(30,180))*Qualified_sample_fraction
Test request bt	(416+STEP(84,180))*Qualified_sample_fraction_bt
Test request urinalysis	(256+Step(51,180))*Qualified_sample_fraction_urinalysis

Again, simulation time period is taken as one year, and Table 7.4 shows year-end results of performance parameters.

Table 7.5. Policy analysis results for scenario 2

	OT (hrs.)	Labor (emp.)		PC (%)	TAT (coag.) (hrs.)	TAT (bt) (hrs.)	TAT (urine) (hrs.)	Cost ($K)
		Hired	Effective					
Policy 1 (increasing machine capacity)	2485	6	11	100	1.408	4.072	2.512	610.129
Policy 2 (increasing training period)	2377	6	10	100	1.408	4.072	2.512	608.821
Policy 3 (changing labor level based on daily test requests)	3622	6	12	100	1.408	4.072	2.512	729.114
Policy 4 (Policy1&2)	2377	6	10	100	1.408	4.072	2.512	608.821
Policy 5 (Policy 1,2&3)	3436	6	12	100	1.408	4.072	2.512	726.870

Table 7.6. Cost indicator values for policies under scenario 2

	Labor Cost ($K)	Inventory Cost ($K)	OT Cost ($K)	Penalty Cost ($)	Total Cost ($K)
Policy 1 (increasing machine capacity)	272.942	304.735	29.952	2500	610.129
Policy 2 (increasing training period)	272.942	304.735	28.644	2500	608.821
Policy 3 (changing labor level based on daily test requests)	378.268	304.735	43.611	2500	729.114
Policy 4 (Policy1&2)	272.942	304.735	28.644	2500	608.821
Policy 5 (Policy 1,2&3)	378.268	304.735	41.367	2500	726.870

In Policy 2 and 4, need of labor reaches to maximum number and effective labor level reaches 10, and overtime hours are also affected from this change in labor level.

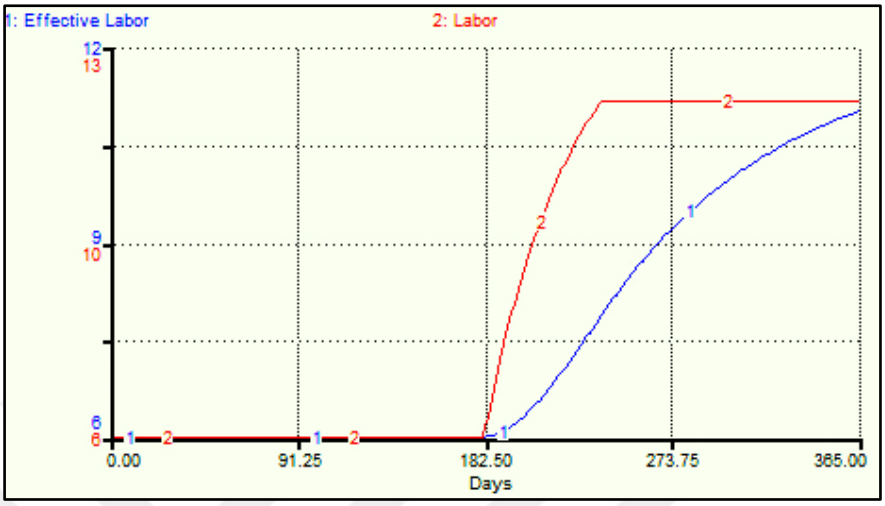


Figure 7.1. Labor and effective labor behavior under Scenario 2 for Policy 1

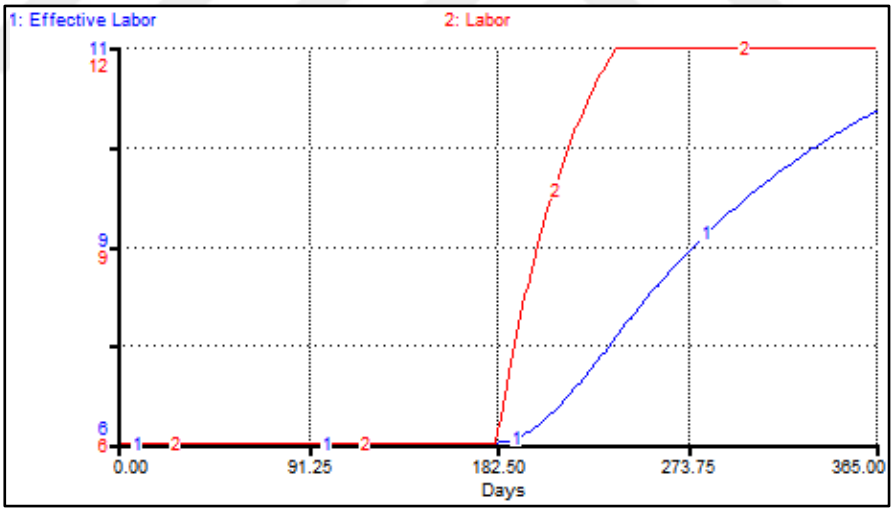


Figure 7.2. Labor and effective labor behavior under Scenario 2 for Policy 2

Cost of CL increases due to the fact that these changes (labor and overtime cost). Although TAT of blood test decreases, TAT of coagulation and urine analysis increase to 1.480 and 2.536 hours on the average, however, these values are still within feasible test times. Policy analysis results show that Policy 2, increased training time, and Policy 4, extending training period of new hires and increasing blood test machine capacity, yield the same performance results. It should be noted that Policy 4 is a combination of Policy 1 and 2, the

results show that if decision makers faced a demand increase in the second half of the year, only increasing the blood test machine capacity generates more cost than increasing machine capacity and training period of new hires. The difference between Policy 1 and Policy 2 or 4 is that they generate different overtime levels. Actually, increasing only machine capacity in an increased demand environment cannot capture all performance indicators directly. Consequently, increased machine capacity generates bottleneck in pre and post-analytic phases and it generates more overtime.

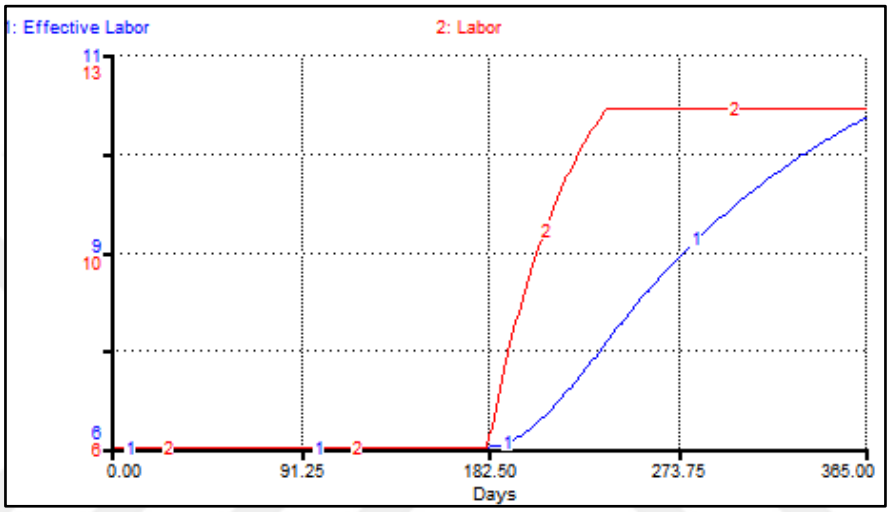


Figure 7.3. Labor and effective labor behavior under Scenario 2 for Policy 4

Although labor level reaches the maximum level in all policies, the cost of labor and overtime hours in Policy 3 and Policy 5 are greater than the others. Changing hiring and overtime decision technique based on the daily test requests, in Policy 3 and 5, this is because the rate of hiring more rapidly (Figure 7.4 and Figure 7.5).

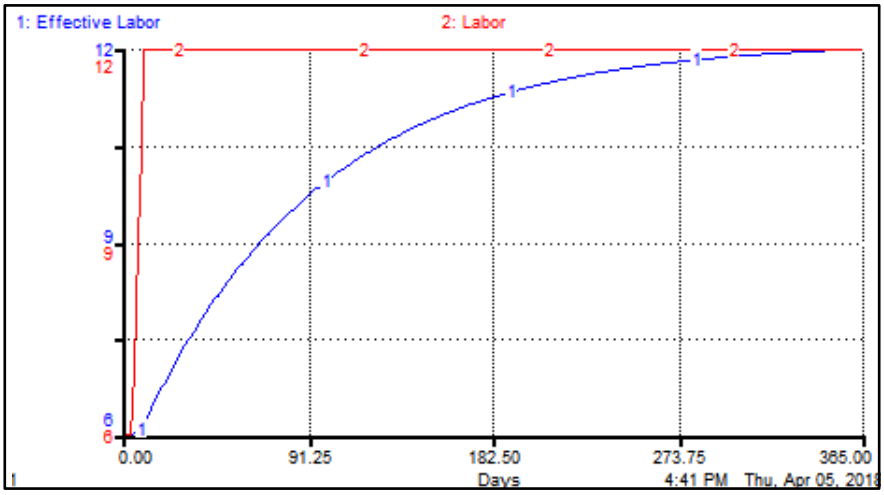


Figure 7.4. Labor and effective labor behavior under Scenario 2 for Policy 3

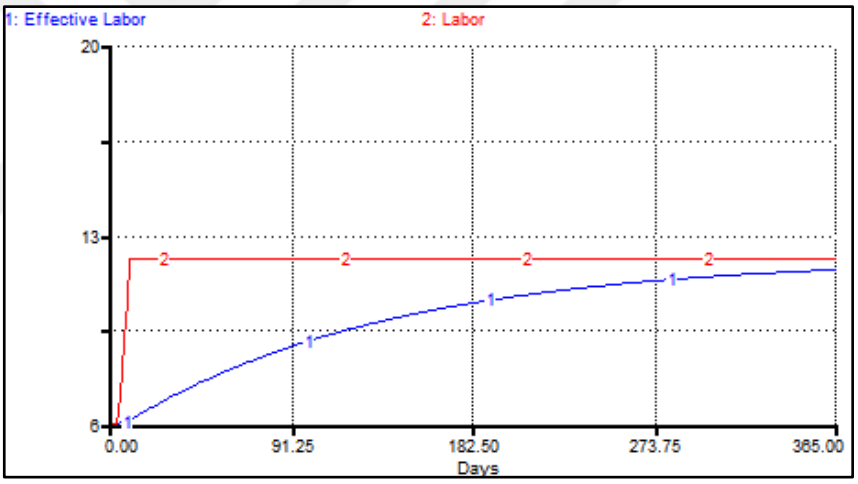


Figure 7.5. Labor and effective labor behavior under Scenario 2 for Policy 5

In other words, in Policy 3 and 5, model decides hiring decision earlier than other polices. Due to the fact that all test requests are satisfied, time related performance parameters do not change for any policies under this scenario. Thus, decision makers can make a judgment based on cost. In this case, it can be concluded that Policy 2, or 4 should be chosen by the decision makers.

7.1.3. Scenario 3: Rapid Market Shrinkage and Boost

In this scenario, for the first three quarters of the year, test demands drop 20 per cent from the previous year's demand, and a sudden increase occur after third quarter of the year by 30 per cent from the last year's demand. Simulation model is again run for one year, and year-end results of performance parameters are summarized for each policy.

Table 7.7. Policy analysis results for scenario 3

	OT (hrs.)	**Labor (emp.)**		**PC (%)**	**TAT (coag.) (hrs.)**	**TAT (bt) (hrs.)**	**TAT (urine) (hrs.)**	**Cost ($K)**
		Hired	**Effective**					
Policy 1 (increasing machine capacity)	668	6	9	100	1.432	4.062	2.5	495.839
Policy 2 (increasing training period)	630	6	8	100	1.432	4.062	2.5	495.371
Policy 3 (changing labor level based on daily test requests)	3597	6	12	100	1.432	4.062	2.5	678.775
Policy 4 (Policy1&2)	630	6	8	100	1.432	4.062	2.5	495.371
Policy 5 (Policy 1,2&3)	3413	6	12	100	1.432	4.062	2.5	676.567

Table 7.8. Cost indicator values for policies under scenario 3

	Labor Cost ($K)	**Inventory Cost ($K)**	**OT Cost ($K)**	**Penalty Cost ($)**	**Total Cost ($K)**
Policy 1 (increasing machine capacity)	227.653	257.561	8124	2500	495.839

Policy 2 (increasing training period)	227.653	257.561	7656	2500	495.371
Policy 3 (changing labor level based on daily test requests)	375.417	257.561	43296	2500	678.775
Policy 4 (Policy1&2)	227.653	257.561	7656	2500	495.371
Policy 5 (Policy 1,2&3)	375.417	257.561	41088	2500	676.567

In case of a sharp decrease and increase, the change in penalty costs show that although average value of percentage completed (PC) is 100 per cent; model cannot perform the total test requests for 10 days in a year thus under capacity cost (penalty cost) is generated. Also, blood test TAT increases, but still is within feasible test time. Policy analysis results show that Policy 2, increased training time, and Policy 4, extending training period of new hires and increasing blood test machine capacity, yield the same performance results. Accordingly, when the machine utilizations were checked; it is observed that duplicated blood analyzer is idle for nearly 50 per cent of process time. The total number of labor behaviors of all policies under a market shrinkage and boost are given in the following figures.

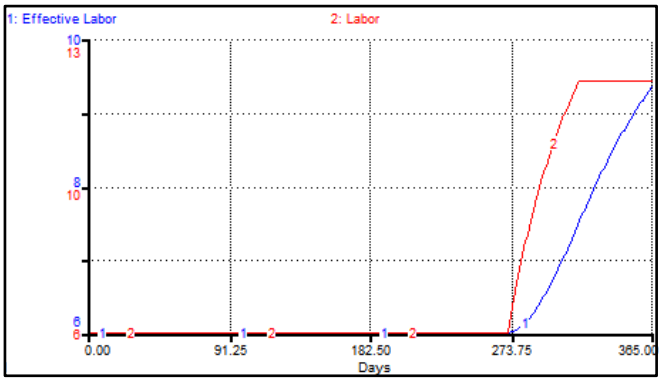


Figure 7.6. Labor and effective labor behavior under Scenario 3 Policy 1

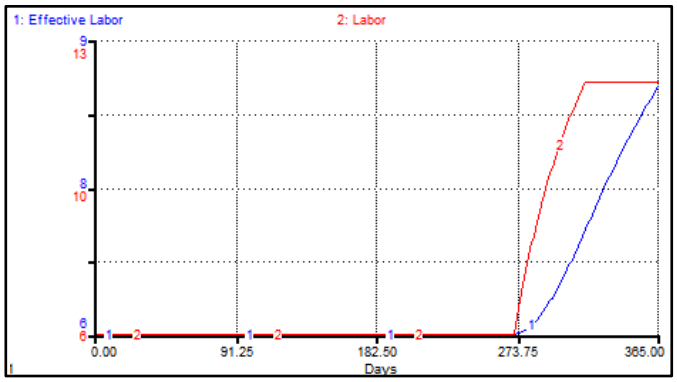


Figure 7.7. Labor and effective labor behavior under Scenario 3 Policy 2

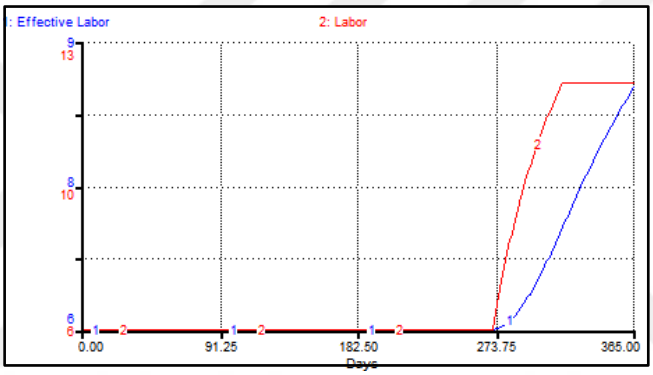


Figure 7.8. Labor and effective labor behavior under Scenario 3 Policy 4

Figure 7.6, 7.7, and 7.8 show that model hires new labor to catch up with the new demand behavior. End of the year, effective labor number is 9 for Policy 1 and 8 for Policy 2 and Policy 4.

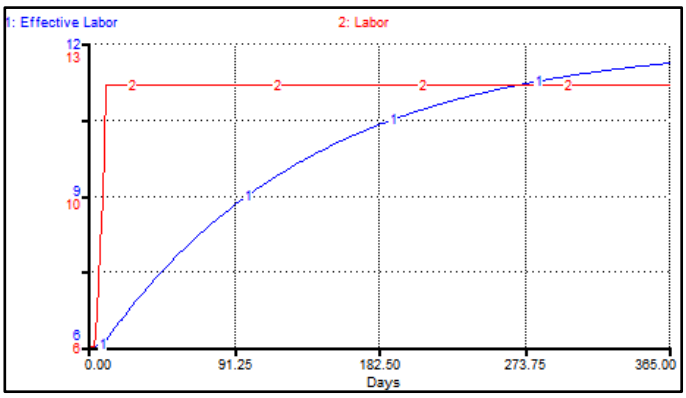


Figure 7.9. Labor and effective labor behavior under Scenario 3 Policy 3

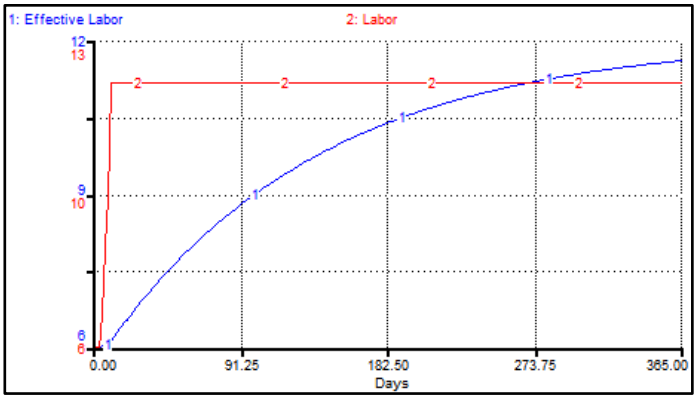


Figure 7.10. Labor and effective labor behavior under Scenario 3 Policy 5

As mentioned before, Policy 3 and Policy 5 have an aggressive hiring structure. This behavior is also shown in Figure 7.9 and 7.10, thus model starts to hiring in the first days of the simulation. Labor level reaches to maximum capacity when the CL faces a rapid increase in demand.

8. CONCLUSION

In this research, a multi-methodology approach was used to present a framework for dynamic model construction and to support the conceptual model development and structural validation phases of SD modeling.

In this study, first the working process of a CL was explained, and the performance indicators were outlined. Then, based on the definition of "performance" in Section 4.1.2, main variables of the conceptual model were determined. After that to illustrate the influence of variables on each other initial conceptual model was developed. At the same time, an ANP model was developed using pairwise relation and comparison matrices (see Section 4.2). Based on the ANP model results, initial conceptual model (CLD) was revised based.

Revised conceptual model was used to develop the dynamic model. Developed model was run for base case parameters taken from a CL. The results of the simulation model were used for verification and validation.

Structure verification, parameter verification, and boundary adequacy tests are conducted in a multi-methodology framework. In this framework, the results gathered from ANP method was used for structure and parameter verification, and boundary adequacy analysis. Thus, conceptual and simulation models were enriched to be more suitable for real-life conditions. Then, equations in the model were checked for dimensional consistency, and a set of extreme conditions tests were applied to the model for structural validity check. The results confirm the structural validity of the model. For behavioral validity; behavior reproduction and behavior anomaly tests were carried out. The model outputs: overtime hours, completed tests, TAT, and labor level were compared with real performance results for behavior reproduction test. Based on the compared results, all outputs were found to be within the tolerable error range. Additionally, inventory and overtime loops were subjected to 'loop knockout analyses' under behavior anomaly tests. Simulation model generated expected results for this analysis as well. Based on the results of examined tests (both structural and behavioral validity tests), the model credibility was found to be adequate. Thus, developed model to analyze CL performance management dynamics was verified and validated.

Sensitivity analysis was conducted to increase model consistency and confidence. '*Critical backlog value'*, '*test productivity'*, and '*test request'* variables were selected for this analysis. The sensitivity analysis show that model performance outputs are sensitive to changes in '*critical backlog value'* for 'OT only' and 'Hiring only' strategies. On the other hand, for 'Hiring with OT' strategy '*cost'* was not sensitive to changes in '*critical backlog value'*. For both three strategies, '*test productivity'* cannot generate sensitivity on model performance outputs. Last sensitivity analysis was done to analyze responses of model performance outputs for different '*test request'* values. The results indicate that '*cost'* was sensitive to '*test request'* under all strategies. 'OT only' and 'Hiring with OT' strategies generated same results for different values of *'test request'*. Under 'Hiring only' strategy, *'cost'* variable behaved more sensitive than other two strategies.

The overall results indicate that critical model parameters cannot generate dramatic changes in model behavior. This means that there was no more effort that had been needed to estimate the values of these critical parameters, and the model can be used for design improvement.

In design improvement section, a set of policies were developed to make some structural changes in the model. In Policy 1, machine capacities were increased by renting additional machines or replacing current machines with higher capacity ones. In policy 2, training period of new hires was increased. *'Desired workforce'* level was determined by *'a test in backlog' and 'available overtime hours',* but in Policy 3, *desired workforce* was calculated based on test requests. Policy 4 is the combination of Policy 1 and 2, and Policy 5 is the combination of Policy 1, 2, and 3. Developed policies were applied for three scenarios; scenario 1: base strategy, scenario 2: increase in demand environment, and scenario 3: rapid market shrinkage and boost. For base strategy, Policy 1 and Policy 4 were found as the most applicable ones. This means if the managers faced with base case scenario, increasing the machine capacity or more training for new hires and increasing machine capacity increase the productivity of the CL. If decision makers faced with an increase in test requests or rapid changes in market demand, Policy 1, 2 or 4 should be chosen to increase CL performance.

A significant value of this research is that it provides a rich literature review about simulation application in healthcare studies and comparison between two important simulation techniques; System Dynamics and Discrete-event simulation.

The major goal of this study was to constitute a system dynamics model to understand and evaluate overall performance of a clinical laboratory by considering the dynamics among cost, resource utilization, labor, quality, and time constraints. This study improved on existing model structures in the literature. The endogenous focus of our model and its ability to simulate the factors involved with multiple sectors (hiring, test production, cost, inventory, and overtime) to examine the dynamic behavior of a system improves the more common single sector models driven by external data.

In today's fast moving world CL's are facing a long term dynamic resource management problems that requires careful planning and decision making. System dynamics methodology attempts to address the structural root causes of continuing problems. Its "systems" perspective captures a holistic view, and aggregates various disciplines together. This approach of system dynamics is significant in handling multi-dimensional problems. This research provides a comprehensive outline of SD, including and suggesting a new conceptual framework, and capturing the technical aspects of SD analysis. Thus, this study improves the existing SD model development methodology suggested in the literature by Sterman [30]. A new SD model development framework is created using multi-methodology approach. This framework can be used to provide guidance to modelers during their model development process.

SD simulation models are mostly used for developing system operating strategies, and to understand system behaviors. The main concern of stakeholders is the model and generated outputs are correct for real system. This concern is addressed through model validation and verification. However, verification and validation in SD is a complex process because it has the difficulty of formalizing and quantifying results. This study provides a structured and strategic conversation with stakeholder to address this difficulty. Model conceptualization is another crucial part of SD since all the concepts that are going to be worked on will be linked to causal relationships among variables. Collaboration with experts and decision makers will create more realistic solutions for model conceptualization and structural validity is carried out through group decision making in

literature. In proposed framework, to be able to ensure this collaboration, ANP methodology is suggested. ANP provides a structured approach to collect expert opinions and to ensure all given inputs are considered and weighted properly. This framework captures the benefits of both ANP and SD modeling methodologies and generates a more structured (formalized) conversation with experts to quantify structural confirmation and model development. Thus, this study will complement existing literature by providing a multi-methodology framework that presents ANP approach to be used to initially generate and then validate the conceptual model and to ensure boundary adequacy, structure and parameter verification of the dynamic model. This can be classified as another significant contribution of this research to the literature.

Finally, the developed SD model can be used in CLs by designing an interface between model and the users. In this case, various conditions can be tested by the users, and what-if scenarios can be generated for managerial decisions and actions. The model can be altered with additional variables and scenarios if the conditions of a CL changes. Even though this study has not covered leave rate of labor, it is able to fully work out this case of implication in practice.

In current model, late deliveries affect the model in terms of penalty cost, and demand behavior of the model is independent of this phenomenon. For future work, model can be extended to function with endogenous demand behavior. In order to accomplish this, TAT will affect test demand behavior of the patients in cases of late deliveries. This way, the change in market could be much more easily demonstrated in the model. Moreover, test demand behavior can be forecasted with a non-linear regression model. In this forecast, penalty cost and late delivery variables can be included.

In conclusion, SD modeling technique has significant tools to offer as we enter the fast moving, complex new era. The problems in the real world cannot be isolated from social, economic, or technical aspects. They all interact in real world system. Thus, the interdisciplinary and systemic approach of SD is necessary to model complex problems that faced in reality.

REFERENCES

1. Forsman RW. Why is the laboratory an afterthought for managed care organizations? *Clinical Chemistry*. 1996; 42 (5): 813-816.

2. Bossuyt X, Verweire K, Blanckaert N. Laboratory medicine: challenges and opportunities. *Clinical Chemistry.* 2007; 53(10): 1730-1733.

3. Langlois MR, Wallemacq P. The future of hospital laboratories. Position statement from the Royal Belgian Society of Clinical Chemistry (RBSCC). *Clinical Chemistry and Laboratory Medicine*. 2009; 47(10): 1195-1201.

4. Anderson G, Hussey PS. Comparing health system performance in OECD countries. *Health Affairs*. 2001; 20(3): 219-232.

5. Büttner J. The origin of clinical laboratories. *Clinical Chemistry and Laboratory Medicine*. 1992; 30(10): 585-594.

6. Mindemark M. The Use of Laboratory Analyses in Sweden: Quality and Cost-Effectiveness in Test Utilization. Acta Universitatis Upsaliensis. Digital Comprehensive Summaries of Uppsala Dissertations form Faculty of Medicine. 2010.

7. Berger D. A brief history of medical diagnosis and the birth of the clinical laboratory. Part 1—Ancient times through the 19th century. *MLO Med Lab Obs*. 1999; 31(7): 28-30.

8. Rosenfeld L. Clinical chemistry since 1800: growth and development. *Clinical Chemistry*. 2000; 48(1): 186-197.

9. Mani N. The historical background of clinical chemistry. *Journal of Clinical Chemistry and Clinical Biochemistry*. 1981; 19: 311-322.

10. Rosenfeld L. Clinical chemistry since 1800: growth and development. *Clinical Chemistry*. 2002; 48(1): 186-197.

11. Rothstein WG. Pathology: the evolution of a specialty in American medicine. *Medical Care.* 1979; 17: 975-988.

12. Kirby BA. The future of clinical laboratory science: A Delphi study. West Virginia University, 2007.

13. Burke MD. Laboratory Medicine in the 21st Century. *American Society of Clinical Pathologists*. 2000; 114: 841-846.

14. World Health Organization. The world health report 2000: health systems: improving performance. 2000; World Health Organization.

15. Delloite, "Türkiye Sağlık Sektörü Raporu", [cited 2015 May 25]. Available from: http://www.deloitte.com/assets/DcomTurkey/Local%20Content/Articles/YASED_T%C3%BCrkiye%20Sa%C4%9Fl%C4%B1k%20Sekt%C3%B6r%C3%BC%20Raporu.pdf

16. TURKSTAT[a], "Sağlık İstatistikleri", [cited 2018 Jan 10]. Available from: http://www.tuik.gov.tr/PreIstatistikTablo.do?istab_id=1613

17. TURKSTAT[b], "Sağlık Harcamaları", [cited 2018 Jan 10]. Available from: http://www.tuik.gov.tr/VeriBilgi.do?alt_id=1084.

18. TURKSTAT[c], "Gayri Safi Yurtiçi Hasıla ve Kişi Başına Gayri Safi Yurtiçi Hasıla", [cited 2018 Jan 10]. Available from: http://www.tuik.gov.tr/PreIstatistikTablo.do?istab_id=2218.

19. OECD, "Health Statistics", [cited 2015 May 10]. Available from: http://www.oecd.org/els/health-systems/oecd-health-statistics-2014-frequently-requested-data.htm

20. Kısakürek MM. Hastane işletmelerinde bölüm maliyet analizi:Cumhuriyet Üniversitesi Tıp Fakültesi Hastanesinde bir uygulama. *Atatürk Üniversitesi İktisadi ve İdari Bilimler Dergisi*. 2010; 24 (3): 229-256.

21. Özkan A. Hastane işletmelerinde maliyet yaklaşımları. *Uludağ Üniversitesi İktisadi ve İdari Bilimler Fakültesi Dergisi*. 2003. 22(2): 113-130.

22. Erkol Ü, Ağırbağ İ. Hastanelerde Maliyet Analizi Ve Faaliyet Tabanlı Maliyetleme Yöntemine Dayalı Bir Uygulama. *Journal of Ankara University Faculty of Medicine*. 2011; 64(2): 87-95.

23. Minvielle E, Sicotte C, Champagne F, Contandriopoulos AP, Jeantet M, Préaubert N and Richard C. Hospital performance: Competing or shared values? *Health Policy*. 2008; 87(1): 8-19.

24. Leggat SG, Narine L, Lemieux-Charles L, Barnsley J, Baker GR, Sicotte C, Champagne F, Bilodeau H. A review of organizational performance assessment in health care. *Health Services Management Research*. 1998; 11(1): 3-18.

25. Andrade JM, McDowall RD. Management attitudes in laboratory automation projects and quality programmes. *Laboratory Automation & Information Management*. 1998; 33(3): 217-226.

26. Yenice S. Implementing a resource management program for accreditation process at the medical laboratory. *Clinical Biochemistry*. 2009; 42(4): 266-273.

27. Snozek C, Kaleta E, Hernandez JS. Management structure: Establishing a laboratory utilization program and tools for utilization management. *Clinica Chimica Acta*. 2014; 427: 118-122.

28. Sluss PM. Reference laboratory utilization management. *Clinica Chimica Acta*. 2014; 427(1): 167–172.

29. Forrester JW. *Industrial dynamics*. Portland: Productivity Press; 1961.

30. Sterman JD. *Business dynamics: systems thinking and modeling for a complex world*. Boston: Irwin McGraw-Hill; 2000.

31. Brailsford SC, Hilton NA. A comparison of discrete event simulation and SD for modelling health care systems. *In Riley J (ed). Proceedings from ORAHS*, Glasgow, 18–39; 2001: ORAHS.

32. Tako AA, Robinson S. Model development in discrete-event simulation and SD: An empirical study of expert modellers. *European Journal of Operational Research*. 2010; 207(2): 784-794.

33. Sweetser A. A comparison of SD (SD) and discrete event simulation (DES). *In 17th International Conference of the SD Society*, Wellington, 20-23; 1999: ISDC.

34. Lane DC, Monefeldt C, Rosenhead JV. Looking in the wrong place for healthcare improvements: A SD study of an accident and emergency department. *Journal of the Operational Research Society.* 2000; 51(5): 518-531.

35. Jamshidi M. *System of Systems Engineering: Innovations for the 21st Century*. Hoboken: John Wiley & Sons, Inc.; 2009.

36. Wickramasinghe N, Chalasani S, Boppana RV, Madni A. M. Healthcare system of systems. *IEEE International Conference on System of Systems Engineering on*; 2007: IEEE.

37. Sheard SA, Mostashari A. Principles of complex systems for systems engineering. *Systems Engineering*. 2009; *12*(4): 295-311.

38. Faezipour M, Ferreira S. Applying systems thinking to assess sustainability in healthcare system of systems. *International Journal of System of Systems Engineering*. 2011; 2(4): 290-308.

39. Slovensky DJ, Morin B. Learning through simulation: the next dimension in quality improvement. *Quality Management in Health Care*. 1997; 5(3): 72-79.

40. Sterman JD. Learning from evidence in a complex world. *American Journal of Public Health*. 2006; 96(3): 505-514.

41. Forsberg HH, Aronsson H, Keller C, Lindblad S. Managing health care decisions and improvement through simulation modeling. *Quality Management in Healthcare*. 2011; 20(1): 15-29.

42. Jeffrey P, Seaton R. The Use of Operational Research Tools: A Survey of Operational Research Practitioners in the UK. *Journal of the Operational Research Society*. 1995; 46 (7): 797-808.

43. Fildes R, Ranyard JC. Success and Survival of Operational Research Groups – A Review. *Journal of the Operational Research Society*. 1997; 48 (4): 336-360.

44. Bayer S, Brailsford S, Bolt T. Examining the role of simulation models in health planning. *Proceedings of the 27th International Conference of the SD Society on*; 2009: ISDC.

45. Brailsford SC, Harper PR, Patel B, Pitt M. An analysis of the academic literature on simulation and modelling in health care. *Journal of Simulation*. 2009; 3(3), 130-140.

46. Rohleder TR, Lewkonia P, Bischak DP, Duffy P, Hendijani R. Using simulation modeling to improve patient flow at an outpatient orthopedic clinic. *Health Care Management Science*. 2011; 14(2), 135-145.

47. Mielczarek B, Uziałko-Mydlikowska J. Application of computer simulation modeling in the health care sector: a survey. *Simulation*. 2012; 88(2), 197-216.

48. Klassen KJ, Yoogalingam R. Improving performance in outpatient appointment services with a simulation optimization approach. *Production and Operations Management*. 2009; 18(4), 447-458.

49. OgulataSN, Cetik MO, Koyuncu E and Koyuncu M. A simulation approach for scheduling patients in the department of radiation oncology. *Journal of Medical Systems*. 2009; 33(3), 233-239.

50. Alvarado MM, Cotton TG, Ntaimo L, Pérez E, Carpentier WR. Modeling and simulation of oncology clinic operations in discrete event system specification. *Simulation*. 2018; 94(2), 105-121.

51. Ahalt V, Argon NT, Ziya S, Strickler J, Mehrotra A. Comparison of emergency department crowding scores: a discrete-event simulation approach. *Health Care Management Science*. 2018; 21(1), 144-155.

52. Rohleder TR, Lewkonia P, Bischak DP, Duffy P, Hendijani R. Using simulation modeling to improve patient flow at an outpatient orthopedic clinic. *Health Care Management Science*. 2011; 14(2), 135-145.

53. White DL, Froehle CM, Klassen KJ. The effect of integrated scheduling and capacity policies on clinical efficiency. *Production and Operations Management*. 2011; 20(3), 442-455.

54. Brailsford SC, Harper PR, Sykes J. Incorporating human behavior in simulation models of screening for breast cancer. *European Journal of Operational Research*. 2012; 219(3): 491-507.

55. Steins K, Persson F, Holmer M. Increasing utilization in a hospital operating department using simulation modeling. *Simulation*. 2010; 86(8-9): 463-480.

56. Cochran KJ, Bharti A. A multi-stage stochastic methodology for whole hospital bed planning under peak loading. *International Journal of Industrial and Systems Engineering*. 2006; 1: 8-35.

57. Ballard SM, Kuhl ME. The Use of Simulation to Determine Maximum Capacity in the Surgical Suite Operating Room. *Proceedings of the 2006 Winter Simulation Conference on*; 2006: WSC.

58. Marjamaa R, Torkki P, Hirvensalo E, Kirvelä O. What is the best workflow for an operating room? A simulation study of five scenarios. *Health Care Management Science*. 2009; 12(2): 142 -146.

59. Denton BT, Miller AJ, Balasubramanian HJ, Huschka TR. Optimal allocation of surgery blocks to operating rooms under uncertainty. *Operations Research*. 2010; 58(4): 802-816.

60. Taheri J, Gellad Z, Burchfield D, Cooper K. A simulation study to reduce nurse overtime and improve patient flow time at a hospital endoscopy unit. *Proceedings of the 2012 Winter Simulation Conference on*; 2012: WSC.

61. Fryk P, Steins K. A modern process perspective, process mapping, and simulation in health care: Opportunities and IT infrastructural needs. *Health Care Management IEEE Workshop on*; 2010: (WHCM).

62. Kuhl ME. A simulation study of patient flow for day of surgery admission. *Simulation Conference (WSC), Proceedings of the 2012 Winter IEEE on*; 2012: IEEE.

63. Vincent DS, Berg BW, Ikegami K. Mass-casualty triage training for international healthcare workers in the Asia-Pacific Region using manikin-based simulations. *Prehospital and Disaster Medicine*. 2009; *24*(3): 206-213.

64. Griffiths JD, Jones M, Read MS, Williams JE. A simulation model of bed-occupancy in a critical care unit. *Journal of Simulation*. 2010; 4(1): 52-59.

65. Cote MJ. Patient flow and resource utilization in an outpatient clinic. *Socio-Economic Planning Sciences*. 1999; 33(3): 231-245.

66. Kim SC, Horowitz I, Young KK, Buckley TA. Analysis of capacity management of the intensive care unit in a hospital. *European Journal of Operational Research*. 1999; 115(1): 36-46.

67. Cayirli T, Veral E. Outpatient scheduling in health care: a review of literature. *Production Operations Management*. 2003; 12(4): 519–549.

68. Gupta D, Natarajanb MK, Gafnic A, Wangd L, Shiltonb D, Holderb D, Yusuf S. Capacity planning for cardiac catheterization: A case study. *Health Policy*. 2007; 82 (1): 1–11.

69. Ahmed MA, Alkhamis TM. Simulation optimization for an emergency department healthcare unit in Kuwait. *European Journal of Operational Research*. 2009; 198(3): 936–942.

70. Rado O, Lupia B, Leung JMY, Kuo Y-H, Graham CA. Using Simulation to Analyze Patient Flows in a Hospital Emergency Department. *Proceedings of the International Conference on Health Care Systems Engineering;* 2014, Springer.

71. Kadri F, Chaabane S, Tahon C. Simulation-based decision support system to prevent and predict strain situations in emergency department systems. S*imulation Modelling Practice and Theory*. 2014; 42: 32–52.

72. Gönül-Sezer ED, Ocak Z. Comparison of system dynamics and discrete event simulation approaches. *In: Obaidat M., Kacprzyk J., Ören T., Filipe J. (eds) Simulation and Modeling Methodologies, Technologies and Applications. Advances in Intelligent Systems and Computing*. 2016: 69-81.

73. Pidd M. *Tools for thinking: modelling in management science*. West Sussex: Wiley; 2003.

74. Viana J, Brailsford SC, Harindra V, Harper PR. Combining discrete-event simulation and system dynamics in a healthcare setting: A composite model for Chlamydia infection. *European Journal of Operational Research*. 2014; 237(1), 196-206.

75. Chahal K, Eldabi T. Applicability of hybrid simulation to different modes of governance in UK healthcare. Simulation Conference, Proceedings of the 2008 Winter IEEE on; 2008: IEEE.

76. Morecroft JDW, Robinson S. Explaining puzzling dynamics: comparing the use of SD and discrete-event simulation. *In Proceedings of the 23rd International Conference of the SD Society*; 2005: ISDC.

77. Taylor K, Lane D. Simulation applied to health services: opportunities for applying the system dynamics approach. *Journal of Health Services Research & Policy*. 1998; 3(4), 226-232.

78. Dangerfield BC. System dynamics applications to european health care issues. *Journal of the Operational Research Society*. 1999; 50(4), 345-353.

79. Coyle MA. Meeting the needs of the family: the role of the specialist nurse in the management of brain death. *Intensive and Critical Care Nursing*. 2000; 16(1), 45-50.

80. Homer JB, Hirsch GB. System dynamics modeling for public health: background and opportunities. *American Journal of Public Health*. 2006; 96(3), 452-458.

81. Homer J, Oliva R. Maps and models in system dynamics: a response to Coyle. *System Dynamics Review*. 2001; 17(4), 347-355.

82. Kunc M. System dynamics: A soft and hard approach to modelling. *Simulation Conference (WSC), Proceedings of the 2017 Winter IEEE on*; 2017: IEEE.

83. Kunc M. Achieving a balanced organizational structure in professional services firms: some lessons from a modeling project. *System Dynamics Review*. 2008; *24*(2), 119-143.

84. Kunc M. Teaching strategic thinking using system dynamics: lessons from a strategic development course. *System Dynamics Review*. 2012; 28(1), 28-45.

85. Ramwadhdoebe S, Buskens E, Sakkers RJB, Stahl JE. A tutorial on discrete event simulation for health policy design and decision making: Optimizing pediatric ultrasound screening for hip dysplasia as an illustration. *Health Policy*. 2009; 93:143-150.

86. Fialho AS, Oliveira MD, Sá AB. Using discrete event simulation to compare the performance of family health unit and primary health care centre organizational models in Portugal. *BMC Health Services Research*. 2011; 11(1): 274-285.

87. Heath SK, Brailsford SC, Buss A, Macal CM. Cross-Paradigm Simulation Modeling: Challenges and Successes. *Proceedings of the 2011 Winter Simulation Conference, Edited by S. Jain, R. R. Creasey, J. Himmelspach, K. P. White, and M. Fu*; 2011: IEEE.

88. Griffin J, Xia S, Peng S, Keskinocak P. Improving patient flow in an obstetric unit. *Health Care Management Science*. 2012; 15(1): 1-14.

89. Jun JB, Jacobson SH, Swisher JR. Application of discrete-event simulation in health care clinics: A survey. *Journal of the Operational Research Society*. 1999; 50: 109-123.

90. Duckett S, Bloom J, Robertson A. Planning to meet the care need challenge in Alberta, Canada. *The International Journal of Health Planning and Management*. 2012; *27*(3), 186-196.

91. Masnick K, McDonnell G. A model linking clinical workforce skill mix planning to health and health care dynamics. *Human Resources for Health*. 2010; 8(1), 1-10.

92. Größler A, Zock A. Supporting long-term workforce planning with a dynamic aging chain model: A case study from the service industry. *Human Resource Management*. 2010; 49 (5), 829–848.

93. Wu MH, Yu JY, Huang CH. Theoretical SD Modeling for Taiwan Pediatric Workforce in an Era of National Health Insurance and Low Birth Rates. *Pediatrics & Neonatology*. 2013; 54(6): 389-396.

94. Geranmayeh S, Iyer AS. Capacity Analysis of Critical Hospital Resources Using SD Approach. 2008.

95. Homer J, Jones A, Seville D, Essien J, Milstein B, Murphy D. The CDC's diabetes systems modeling project: Developing a new tool for chronic disease prevention and control. *22nd International Conference of the SD Society on*; 2004: ISDC.

96. Chen Y. A SD based study on elderly non-acute service in Norway. *Proceedings of the 21st International Conference of the SD Society on*, 2003: ISDC.

97. Barber P, López-Valcárcel BG. Forecasting the need for medical specialists in Spain: application of a SD model. *Human Resources for Health*. 2010; 8(1): 1-9.

98. Merrill JA, Deegan M, Wilson RV, Kaushal R, Fredericks K. A SD evaluation model: implementation of health information exchange for public health reporting. *Journal of the American Medical Informatics Association*. 2013; 20: 131-138.

99. Lane DC, Husemann E. System dynamics mapping of acute patient flows. *Journal of the Operational Research Society*. 2008; 59(2), 213-224.

100. Hilton NA. Exploration into the behavior of cardiac waiting lists. Doctoral dissertation, University of Southampton, England. 2001.

101. Quinn T, Rudolph JW, Fairchild DG. Lab Turnaround Time and Delayed Discharges: A Systems-Based Action Research Investigation. *Proceedings of the 2005 International SD Conference on*; 2005: ISDC.

102. De Andrade L, Lynch C, Carvalho E, Rodrigues CG, Vissoci JRN, Passos GF, de Barros Carvalho MD. SD modeling in the evaluation of delays of care in ST-segment elevation myocardial infarction patients within a tiered health system. *PloS ONE*. 2014; 9(7): 1-11.

103. Maliapen M, Dangerfield BC. A system dynamics-based simulation study for managing clinical governance and pathways in a hospital. *Journal of the Operational Research Society*. 2010; 61(2), 255-264.

104. Smits M. Impact of policy and process design on the performance of intake and treatment processes in mental health care: a system dynamics case study. *Journal of the Operational Research Society*. 2010; 61(10), 1437-1445.

105. Lane DC, Monefeldt C, Rosenhead JV. Looking in the wrong place for healthcare improvements: A system dynamics study of an accident and emergency department. *Journal of the Operational Research Society*. 2000; 51(5), 518-531.

106. Cook NL, Hicks LS, O'Malley AJ, Keegan T, Guadagnoli E, Landon BE. Access to specialty care and medical services in community health centers. *Health Affairs*. 2007; 26(5), 1459-1468.

107. Lattimer V, Brailsford SC, Turnbull J, Tarnaras P, Smith H, George S, Maslin-Prothero S. Reviewing emergency care systems I: insights from SD modelling. *Emergency Medicine Journal*. 2004; 21(6): 685-691.

108. Tako AA, Kotiadis K. PartiSim: A multi-methodology framework to support facilitated simulation modelling in healthcare. *European Journal of Operational Research*. 2015; 244(2), 555-564, 2015.

109. Soltani A, Marandi IZ. Hospital site selection using two-stage fuzzy multi-criteria decision making process. *Journal of Urban and Environmental Engineering*. 2011; 5(1): 455-462.

110. Yucel G, Cebi S, Hoege B, Ozok AF. A fuzzy risk assessment model for hospital information system implementation. *Expert Systems with Applications*. 2012; 39(1): 1211-1218.

111. Altuntas S, Dereli T, Yilmaz MK. Multi-criteria decision making methods based weighted SERVQUAL scales to measure perceived service quality in hospitals: A case study from Turkey. *Total Quality Management & Business Excellence*. 2012; 23(11-12): 1379-1395.

112. Ozkan A. Evaluation of healthcare waste treatment/disposal alternatives by using multi-criteria decision-making techniques. *Waste Management & Research*. 2013; 31(2): 141-149.

113. Jamalizadeh Z, Meshkani F, Naami A. A study on factors influencing customer satisfaction: A case study of hospital dialysis patients. *Management Science Letters*. 2013; 3(10): 2603-2608.

114. Meena K, Thakkar J. Development of Balanced Scorecard for healthcare using Interpretive Structural Modeling and Analytic Network Process. *Journal of Advances in Management Research*. 2014; 11(3): 232-256.

115. Orji IJ, Wei S. An innovative integration of fuzzy-logic and systems dynamics in sustainable supplier selection: A case on manufacturing industry. *Computers & Industrial Engineering*. 2015; 88: 1-12.

116. Ashayeri J, Keij R, Bröker A. Global business process re-engineering: a SD-based approach. *International Journal of Operations & Production Management*. 1998; 18(9/10): 817-831.

117. Buede MD. *The Engineering Design of Systems Models and Methods*. Hoboken: John Wiley & Sons, Inc.; 2000.

118. Barlas Y. System dynamics: systemic feedback modeling for policy analysis. *System*. 2007; 59: 1-29.

119. Richardson GP. *Feedback thought in social science and systems theory*. Waltham: Pegasus Communications, Inc.; 1991.

120. Doyle JK, Ford DN. Mental models concepts for SD research. *SD Review*. 1998; 14(1): 3-29.

121. Morecroft JD. *Strategic modelling and business dynamics: a feedback systems approach*. Hoboken: John Wiley & Sons, Inc.; 2015.

122. Maani KE, Cavana RY. *Systems thinking and modelling: understanding change and complexity*. Auckland: Prentice Hall; 2000.

123. Richmond B. *An introduction to systems thinking.* Hanover: High Performance Systems, Inc.; 2001.

124. Barlas Y. Formal aspects of model validity and validation in SD. *SD Review*. 1996; 12(3): 183-210.

125. Schoemaker PJ. Scenario planning: a tool for strategic thinking. *Sloan Management Review*. 1995; 36(2), 25.

126. Saaty TL, Peniwati K. *Group decision making: drawing out and reconciling differences*. Pittsburgh: RWS Publications; 2008.

127. Karpak B, Topcu I. Small medium manufacturing enterprises in Turkey: an analytic network process framework for prioritizing factors affecting success. *International Journal of Production Economics*. 2010; 125(1): 60–70.

128. Dikmen İ, Birgönül MT, Özorhon B, Eğilmezer Şapçı N. Using Analytic Network Process to Assess Business Failure Risks of Construction Firms. *Engineering, Construction and Architectural Management*. 2010; 17(4): 369-386.

129. Erdem D. Assessing real estate project success using the analytic network process. Master of Science Thesis. Boğaziçi University, İstanbul. 2010.

130. Saaty TL. Analytic network process. S.I. Gass and C.M. Harris (Eds.), *Encyclopedia of operations research and management* (100th ed.), Boston, 2001: 28–35.

131. Lee H, Lee S, Park Y. Selection of technology acquisition mode using the analytic network process. *Mathematical and Computer Modelling*. 2009; 49(5-6): 1274–1282.

132. Sadeghi M, Rashıdzadeh M, Soukhakian M. Using analytic network process in a group decision-making for supplier selection. *INFORMATICA*. 2012; 23(4): 621–643.

133. MacMillan D. Calculating cost savings in utilization management. *Clinica Chimica Acta*. 2014; 427: 123-126.

134. Kirchner TA, Markowski EP, Ford JB. Relationships among levels of government support, marketing activities, and financial health of nonprofit performing arts organizations. *International Journal of Nonprofit and Voluntary Sector Marketing*. 2007; 12(2): 95-116.

135. Shahangian S, Snyder SR. Laboratory Medicine Quality Indicators A Review of the Literature. *American Journal of Clinical Pathology*. 2009; 131(3): 418-431.

136. Chawla R, Goswami B, Singh B, Chawla A, Gupta VK, Mallika V. Evaluating laboratory performance with quality indicators. *Lab Medicine*. 2010; 41(5): 297-300.

137. Fottler MD. Health care organizational performance: Present and future research. *Journal of Management*. 1987; 13(2): 367-391.

138. Arah OA, Klazinga NS, Delnoij DMJ, Ten Asbroek AHA, Custers T. Conceptual frameworks for health systems performance: a quest for effectiveness, quality, and improvement. *International Journal for Quality in Health Care*. 2003; 15(5): 377-398.

139. Veillard J, Champagne F, Klazinga N, Kazandjian V, Arah OA, Guisset AL. A performance assessment framework for hospitals: the WHO regional office for Europe PATH project. *International Journal for Quality in Health Care*. 2005; 17(6): 487-496.

140. Zinn J, Zalokowski A, Hunter L. Identifying indicators of laboratory management performance: a multiple constituency approach. *Health Care Management Review*. 2001; 26(1): 40-53.

141. Arah OA, Westert GP, Hurst J, Klazinga NS. A conceptual framework for the OECD health care quality indicators project. *International Journal for Quality in Health Care*. 2006; 18 (1): 5-13.

142. Ancarani A, Di Mauro C, Giammanco MD. The impact of managerial and organizational aspects on hospital wards efficiency: Evidence from a case study. *European Journal of Operational Research*. 2009; 194(1): 280-293.

143. Li LX, Benton WC. Performance measurement criteria in health care organizations: review and future research directions. *European Journal of Operational Research*. 1996; 93(3): 449-468.

144. Scinto LD. *Product cost analysis in the clinical laboratory. Issues in cost accounting for health care organizations*. Gaithersburg: Aspen Publishers Inc.; 1994.

145. ISO 15189: Medical Laboratories - Particular Requirements for Quality and Competence, Geneva. 2003.

146. Plebani M. Errors in clinical laboratories or errors in laboratory medicine? *Clinical Chemistry and Laboratory Medicine*. 2006; 44(6): 750-759.

147. Lundberg GD. Acting on significant laboratory results. *Journal of the American Medical Association*. 1981; 245: 1762-1783.

148. Azadmanjir Z, Torabi M, Safdari R, Bayat M, Golmahi F. A map for clinical laboratories management indicators in the intelligent dashboard. *Acta Informatica Medica*. 2015; 23(4): 210-214.

149. Hawkins RC. Laboratory turnaround time. *The Clinical Biochemist Reviews*. 2007; 28(4): 179-194.

150. Balci O, Ormsby WF. Conceptual modelling for designing large-scale simulations. *Journal of Simulation*. 2007; 1(3), 175-186.

151. Chick SE. Six ways to improve a simulation analysis. *Journal of Simulation*. 2006; 1 (1): 21-28.

152. Sargent TJ, Glasow P, Kleijnen JP, Law AM, McGregor I, Youngblood S. Strategic directions in verification, validation and accreditation research. *Proceedings of the 2000 Winter Simulation Conference on; 2000: WSC.*

153. Back G, Love G, Falk J. The doing of model verification and validation: Balancing cost and theory. *Proceedings of the 18th International Conference of the SD Society on*; 2000: ISDC.

154. Barlas Y, Erdem A. Output behavior validation in system dynamics simulation. *Proceedings of the European Simulation Symposium on*; 1994: EES.

APPENDIX A: ANP SURVEY

Pairwise Comparison Questions

1. Based on your own opinion, which indicator do you consider more influential on clinical laboratory performance?

Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Quality
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Resource Management
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time
Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Resource Management
Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time
Resource Management	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time

2. Based on your own opinion, which indicator do you consider more influential on cost of a clinical laboratory?

C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C2
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C3
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C3
C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4
C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4
C3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5

3. Based on your own opinion, which indicator do you consider more influential on quality of a clinical laboratory?

Q1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q2
Q1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q3
Q1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q4
Q2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q3
Q2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q4
Q3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q4

4. Based on your own opinion, which indicator do you consider more influential on resource management of a clinical laboratory?

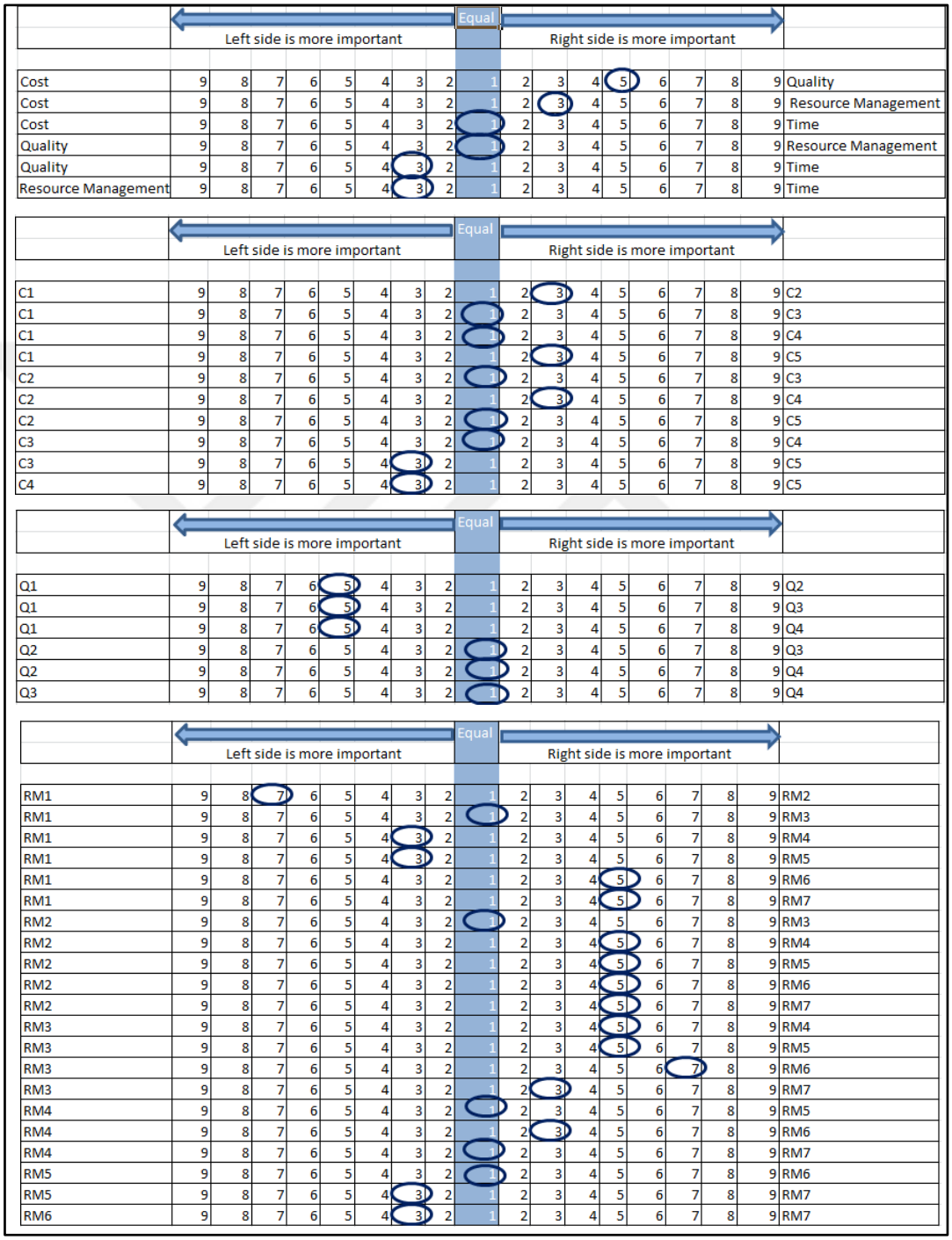
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM2
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM3
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM4

RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM3
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM4
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM4
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM6	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7

5. Based on your own opinion, which indicator do you consider more influential on time management of a clinical laboratory?

T1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**T2**
T1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**T3**
T1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**T4**
T1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**T5**
T2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**T3**
T2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**T4**
T2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**T5**
T3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**T4**
T3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**T5**
T4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**T5**

APPENDIX B: EXPERT OPINIONS



	Left side is more important								Equal	Right side is more important								
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Quality
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Resource Management
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time
Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Resource Management
Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time
Resource Management	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time

	Left side is more important								Equal	Right side is more important								
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C2
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C3
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C3
C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4
C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4
C3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5

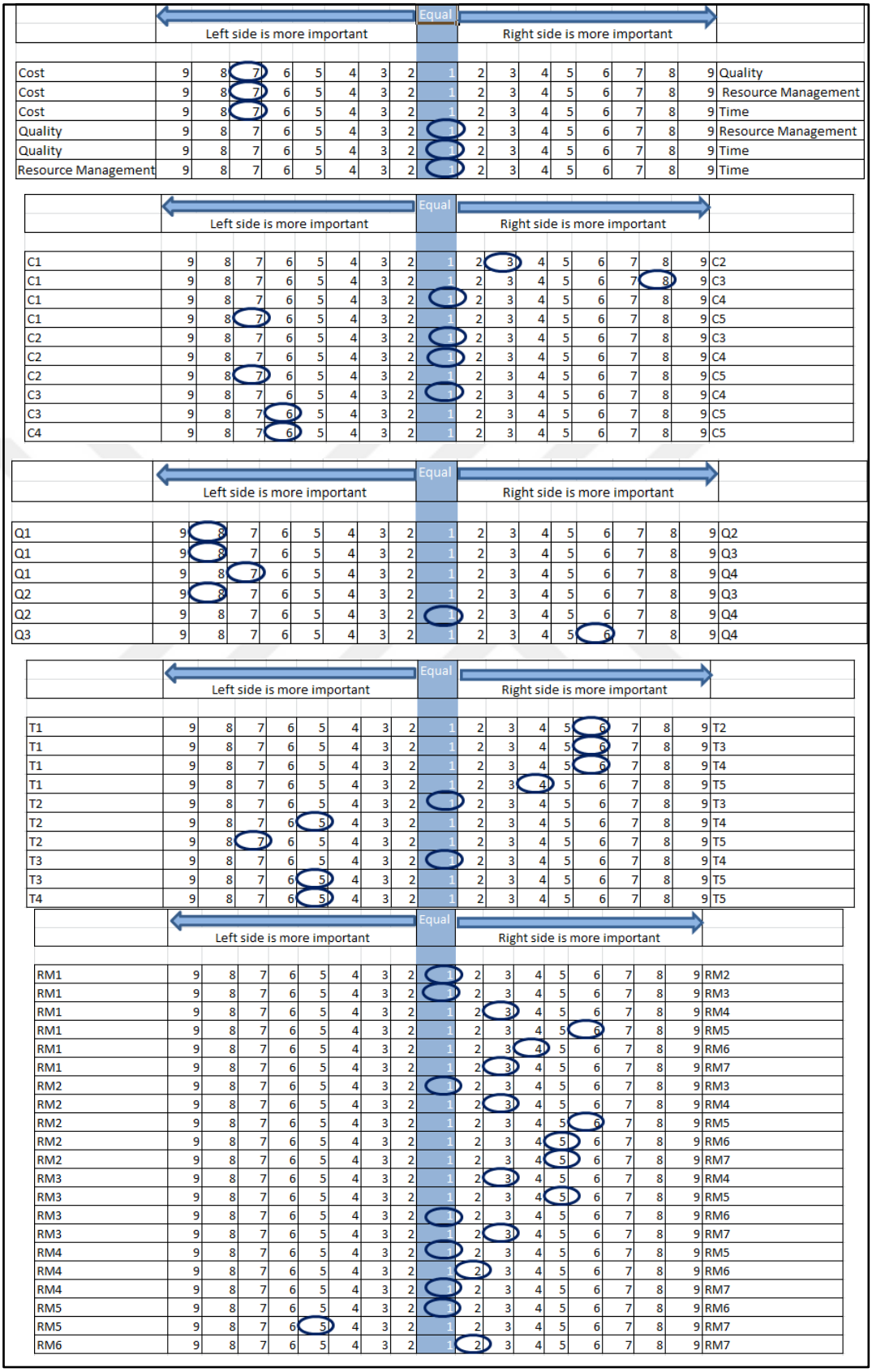
	Left side is more important								Equal	Right side is more important								
Q1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q2
Q1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q3
Q1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q4
Q2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q3
Q2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q4
Q3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q4

	Left side is more important								Equal	Right side is more important								
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM2
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM3
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM4
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM3
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM4
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM4
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM6	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7

Figure B. 1. ANP questionnaire results for Expert 1

Bilateral relations		Affected																			
		C1	C2	C3	C4	C5	Q1	Q2	Q3	Q4	RM1	RM2	RM3	RM4	RM5	RM6	RM7	T1	T2	T3	T4	T5
Affecting	C1		+		+						+	+	+				+					
	C2	+		+		+	+	+			+		+		+	+	+	+				
	C3					+								+	+							
	C4	+	+			+	+		+								+					
	C5		+		+			+	+	+									+	+	+	+
	Q1		+		+	+		+	+	+				+		+	+					
	Q2		+		+	+	+		+	+									+	+	+	+
	Q3		+			+	+	+						+	+	+		+	+	+	+	+
	Q4					+	+	+	+					+		+				+	+	+
	RM1	+						+	+			+	+		+	+				+		
	RM2	+	+		+				+		+		+		+					+		
	RM3	+			+						+	+			+	+	+		+	+		
	RM4		+		+	+	+	+	+				+		+	+	+			+	+	+
	RM5	+	+	+	+				+		+		+			+	+	+	+	+	+	+
	RM6	+	+			+		+	+	+			+	+	+		+		+	+	+	+
	RM7		+		+	+	+	+	+	+				+		+				+		
	T1				+						+		+		+		+		+	+	+	
	T2	+	+		+	+	+	+	+		+		+			+	+			+	+	+
	T3		+		+	+	+	+	+	+		+	+			+	+		+		+	+
	T4		+			+	+	+	+	+						+			+	+		+
	T5		+			+		+	+	+					+	+	+	+	+	+	+	

Figure B. 2. Pairwise comparison results of Expert 1



	Left side is more important								Equal	Right side is more important								
Cost	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Quality
Cost	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Resource Management
Cost	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time
Quality	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Resource Management
Quality	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Time
Resource Management	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Time

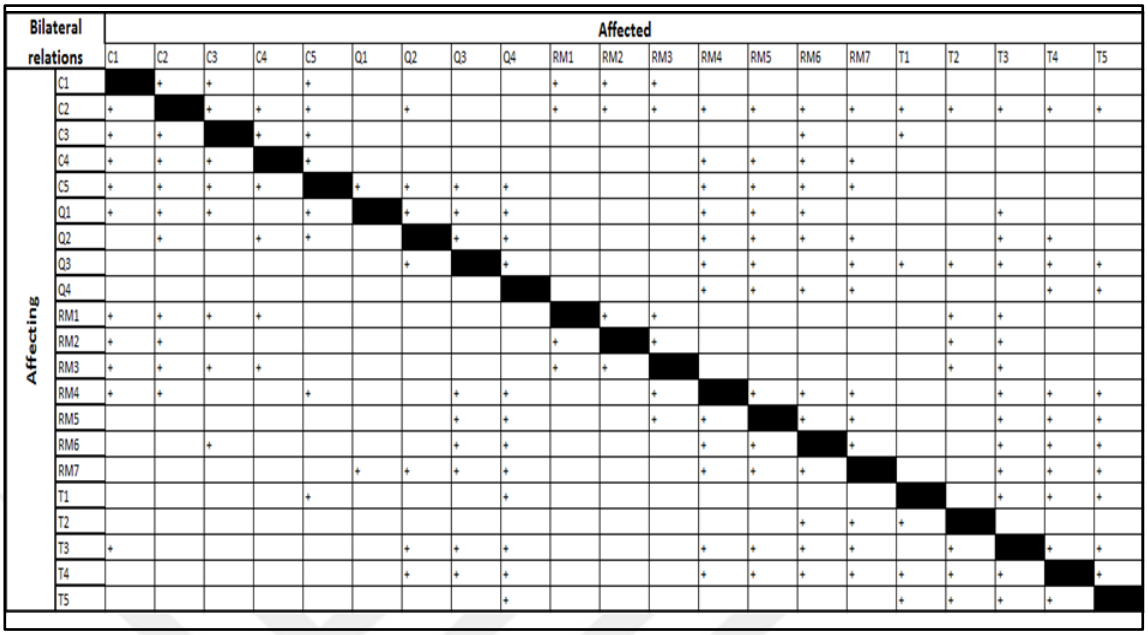
	Left side is more important								Equal	Right side is more important								
C1	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	C2
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	**8**	9	C3
C1	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	C4
C1	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C2	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	C3
C2	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	C4
C2	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C3	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	C4
C3	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C4	9	8	7	**6**	5	4	3	2	1	2	3	4	5	6	7	8	9	C5

	Left side is more important								Equal	Right side is more important								
Q1	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q2
Q1	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q3
Q1	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q4
Q2	9	**8**	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q3
Q2	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Q4
Q3	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	Q4

	Left side is more important								Equal	Right side is more important								
T1	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	T2
T1	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	T3
T1	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	T4
T1	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	T5
T2	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	T3
T2	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	T4
T2	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T5
T3	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	T4
T3	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	T5
T4	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	T5

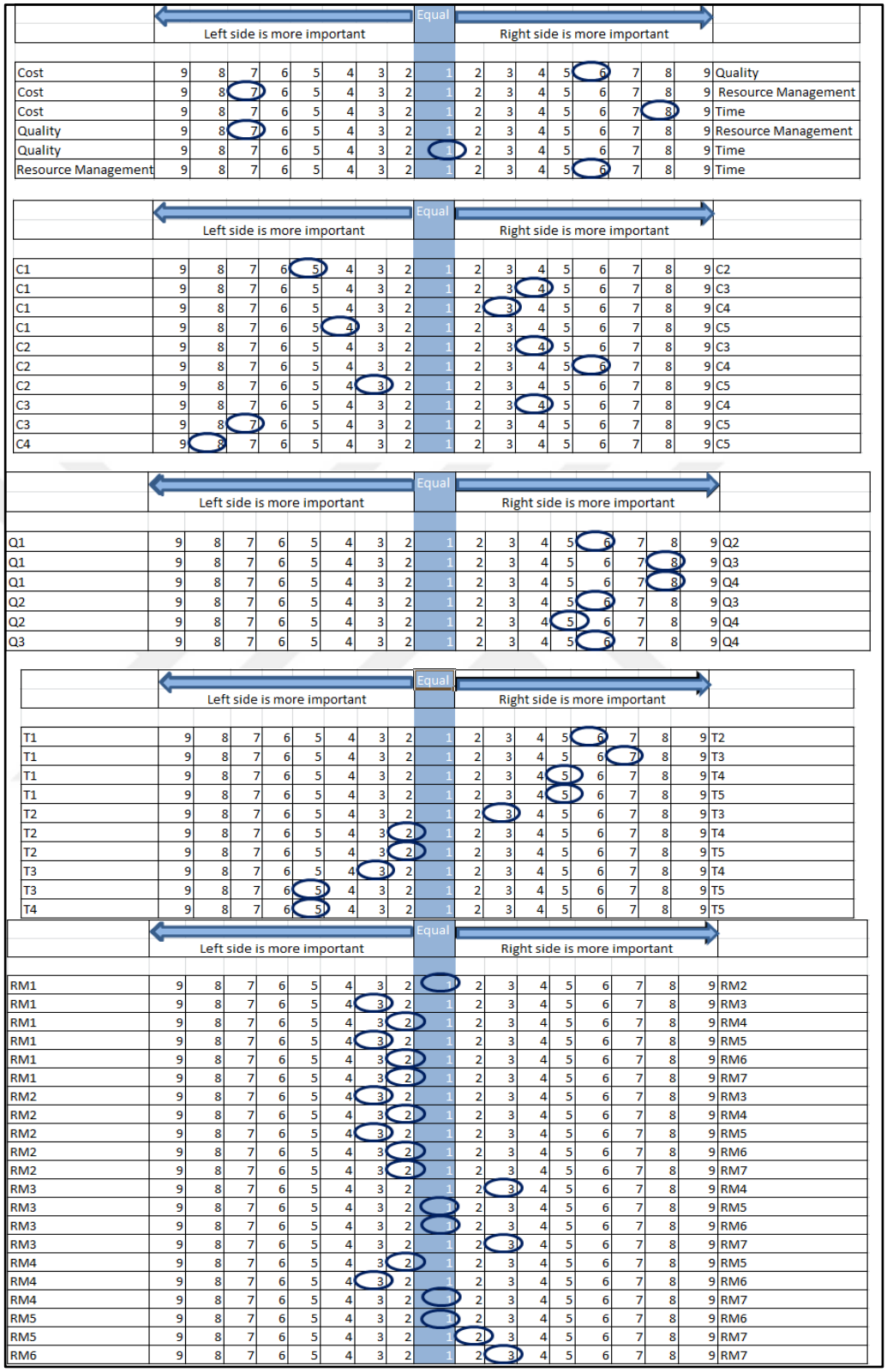
	Left side is more important								Equal	Right side is more important								
RM1	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RM2
RM1	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RM3
RM1	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	RM4
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	RM5
RM1	9	8	7	6	5	4	3	2	1	2	3	**4**	5	6	7	8	9	RM6
RM1	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	RM7
RM2	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RM3
RM2	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	RM4
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	**6**	7	8	9	RM5
RM2	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	RM6
RM2	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	RM7
RM3	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	RM4
RM3	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	RM5
RM3	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RM6
RM3	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	RM7
RM4	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RM5
RM4	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	RM6
RM4	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RM7
RM5	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	RM6
RM5	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM6	9	8	7	6	5	4	3	2	1	**2**	3	4	5	6	7	8	9	RM7

Figure B. 3 ANP questionnaire results for Expert 2



Bilateral relations		Affected																			
		C1	C2	C3	C4	C5	Q1	Q2	Q3	Q4	RM1	RM2	RM3	RM4	RM5	RM6	RM7	T1	T2	T3	T4	T5
Affecting	C1		+	+		+					+	+	+									
	C2	+		+	+	+		+			+	+	+	+	+	+	+	+	+	+	+	+
	C3	+	+		+	+										+		+				
	C4	+	+	+		+								+	+	+	+					
	C5	+	+	+	+		+	+	+	+				+	+	+	+					
	Q1	+	+	+		+		+	+	+				+	+	+				+		
	Q2		+		+	+			+	+				+	+	+	+			+	+	
	Q3							+		+				+	+		+	+	+	+	+	+
	Q4													+	+	+	+				+	+
	RM1	+	+	+	+							+	+						+	+		
	RM2	+	+								+		+						+	+		
	RM3	+	+	+	+						+	+							+	+		
	RM4	+	+			+			+	+			+		+	+	+			+	+	+
	RM5								+	+			+	+		+	+			+	+	+
	RM6			+					+	+				+	+		+			+	+	+
	RM7						+	+	+	+				+	+	+				+	+	+
	T1					+				+										+	+	+
	T2															+	+	+				
	T3	+						+	+	+				+	+	+	+		+		+	+
	T4							+	+	+				+	+	+	+	+	+	+		+
	T5									+								+	+	+	+	

Figure B. 4. Pairwise comparison results of Expert 2



	Left side is more important								Equal	Right side is more important								
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Quality
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Resource Management
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time
Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Resource Management
Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time
Resource Management	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time

	Left side is more important								Equal	Right side is more important								
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C2
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C3
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C3
C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4
C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4
C3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5

	Left side is more important								Equal	Right side is more important								
Q1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q2
Q1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q3
Q1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q4
Q2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q3
Q2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q4
Q3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q4

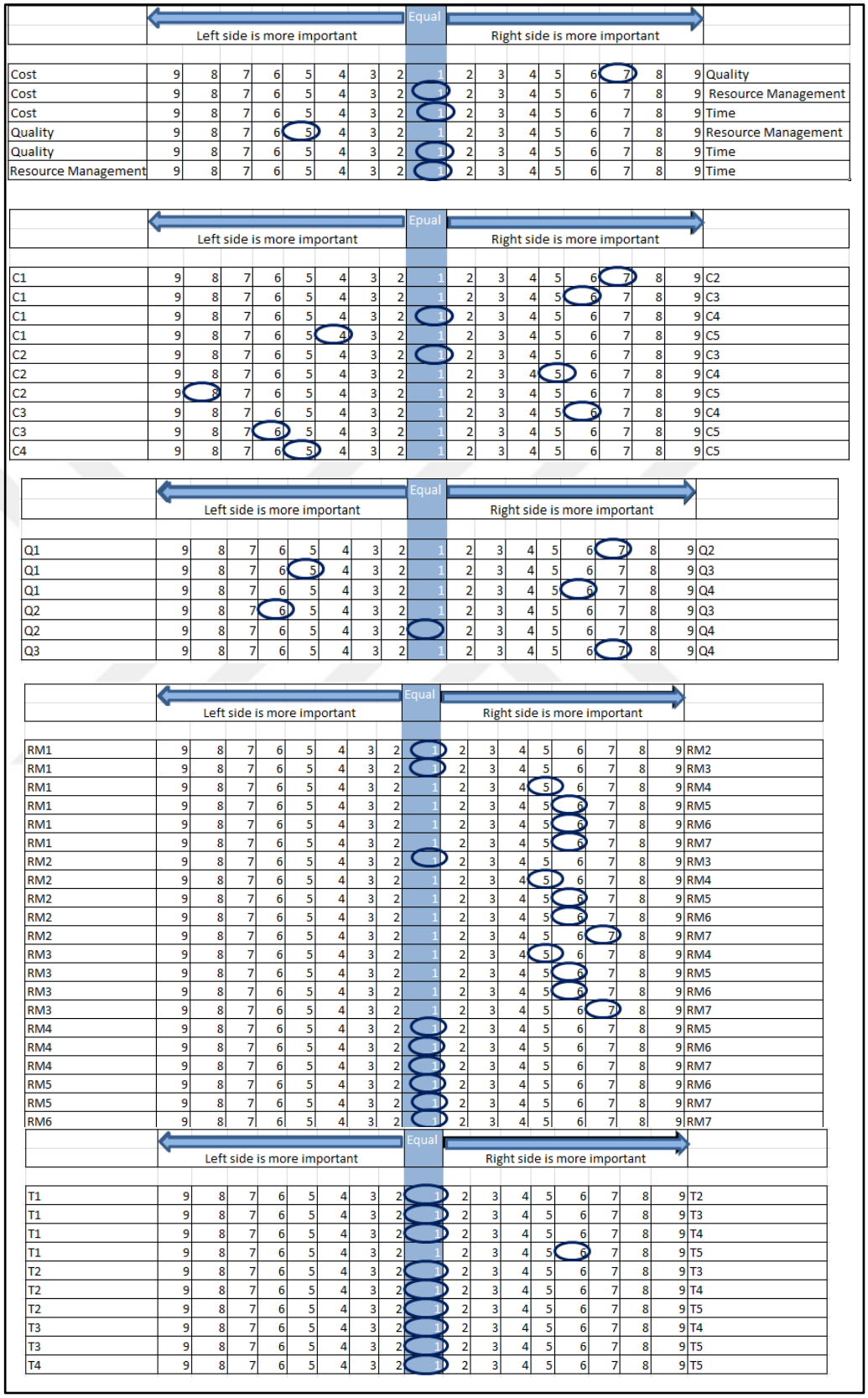
	Left side is more important								Equal	Right side is more important								
T1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T2
T1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T3
T1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T4
T1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T5
T2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T3
T2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T4
T2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T5
T3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T4
T3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T5
T4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T5

	Left side is more important								Equal	Right side is more important								
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM2
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM3
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM4
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM3
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM4
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM4
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM6	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7

Figure B. 5. ANP questionnaire results for Expert 3

Bilateral relations		Affected																			
		C1	C2	C3	C4	C5	Q1	Q2	Q3	Q4	RM1	RM2	RM3	RM4	RM5	RM6	RM7	T1	T2	T3	T4	T5
Affecting	C1		+			+	+	+	+	+	+	+	+									
	C2	+		+	+	+	+	+	+	+	+	+	+	+		+	+		+	+	+	+
	C3		+			+	+	+	+	+		+				+			+	+	+	+
	C4	+	+	+		+	+	+	+	+				+	+		+					
	C5	+	+	+	+			+	+	+	+	+	+		+	+	+	+	+	+	+	+
	Q1	+	+	+	+	+			+	+	+	+	+	+	+	+	+	+	+	+	+	+
	Q2	+	+	+	+	+			+	+	+	+	+			+			+	+	+	+
	Q3		+			+		+		+									+			+
	Q4	+	+	+	+	+			+		+	+	+		+	+			+	+	+	+
	RM1	+	+			+			+			+	+		+	+			+	+	+	+
	RM2	+	+			+			+		+		+						+	+	+	+
	RM3	+	+			+		+	+	+	+	+										
	RM4	+	+		+	+		+	+	+	+	+					+			+	+	+
	RM5	+	+	+	+	+	+	+	+	+	+	+	+	+			+			+	+	+
	RM6	+	+	+		+	+	+	+	+	+	+						+	+	+	+	+
	RM7		+		+	+	+	+	+	+	+	+		+	+					+	+	+
	T1			+		+			+		+	+				+			+	+	+	+
	T2			+		+			+			+				+				+	+	+
	T3	+	+	+	+	+	+	+	+	+		+				+	+		+		+	+
	T4		+	+		+			+							+						+
	T5		+	+		+			+													

Figure B. 6. Pairwise comparison results of Expert 3



	Left side is more important								Equal	Right side is more important								
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Quality
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Resource Management
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time
Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Resource Management
Quality	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time
Resource Management	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time

	Left side is more important								Equal	Right side is more important								
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C2
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C3
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4
C1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C3
C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4
C2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C4
C3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5
C4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	C5

	Left side is more important								Equal	Right side is more important								
Q1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q2
Q1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q3
Q1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q4
Q2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q3
Q2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q4
Q3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Q4

	Left side is more important								Equal	Right side is more important								
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM2
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM3
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM4
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM3
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM4
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM4
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM5
RM4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM6
RM5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7
RM6	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	RM7

	Left side is more important								Equal	Right side is more important								
T1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T2
T1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T3
T1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T4
T1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T5
T2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T3
T2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T4
T2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T5
T3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T4
T3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T5
T4	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T5

Figure B. 7. ANP questionnaire results for Expert 4

Bilateral relations		Affected																			
		C1	C2	C3	C4	C5	Q1	Q2	Q3	Q4	RM1	RM2	RM3	RM4	RM5	RM6	RM7	T1	T2	T3	T4	T5
Affecting	C1																					
	C2	+		+	+	+		+		+				+		+	+					
	C3																					
	C4	+												+	+		+					
	C5	+	+					+	+	+				+								
	Q1	+													+	+	+					
	Q2	+							+	+				+		+	+	+	+	+	+	+
	Q3	+									+	+	+	+		+				+	+	+
	Q4																					
	RM1	+										+	+									
	RM2	+																				
	RM3	+									+											
	RM4	+	+		+																	
	RM5	+												+		+						
	RM6	+	+	+										+								
	RM7	+																				
	T1	+	+																			
	T2	+																				
	T3	+	+	+	+	+	+	+	+	+	+	+	+	+		+	+	+	+			
	T4	+																	+	+		
	T5	+																				

Figure B. 8. Pairwise comparison results of Expert 4

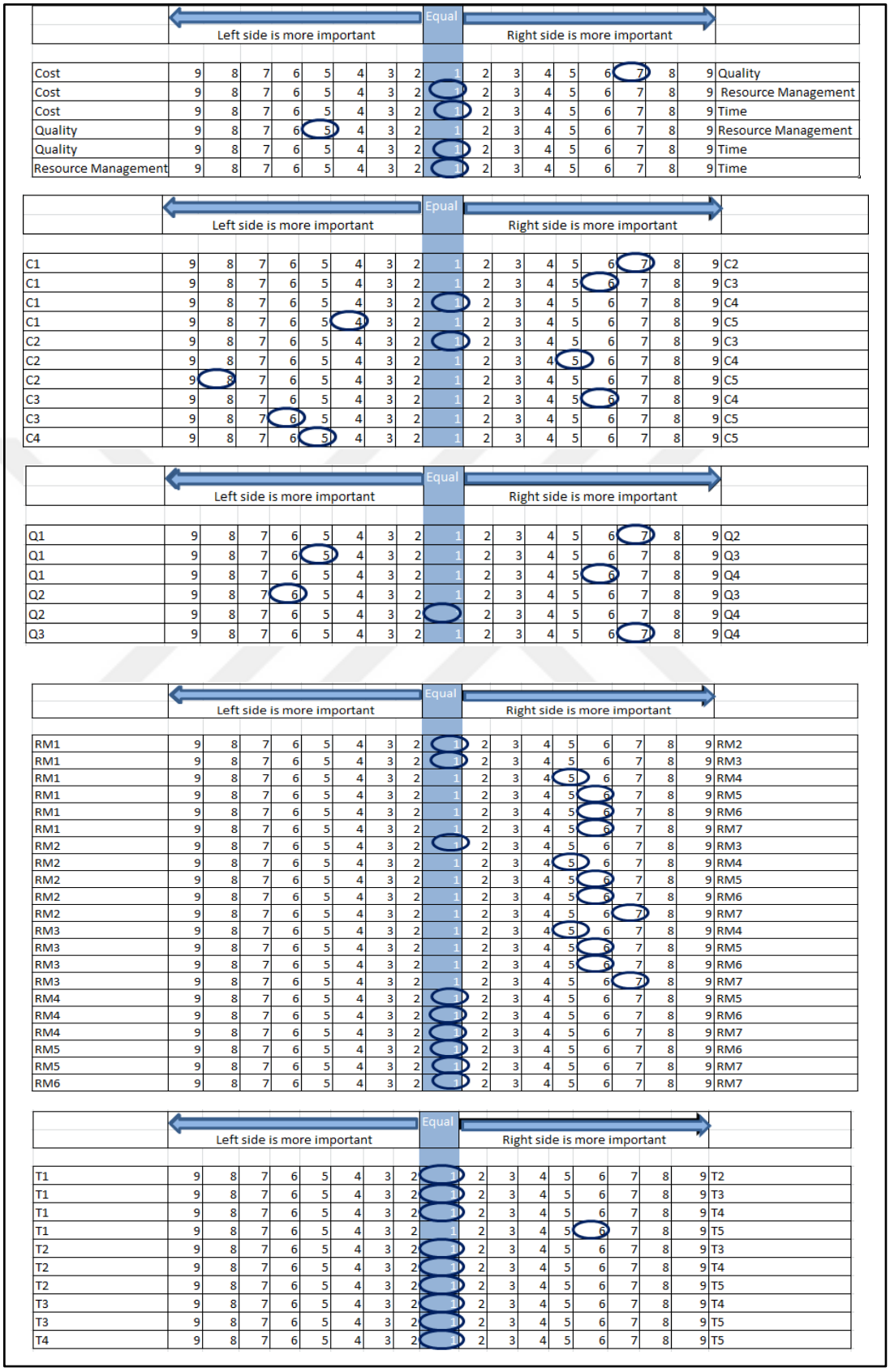


Figure B. 9. ANP questionnaire results for Expert 5

Bilateral relations	Affected																			
	C1	C2	C3	C4	C5	Q1	Q2	Q3	Q4	RM1	RM2	RM3	RM4	RM5	RM6	RM7	T1	T2	T3	T4	T5
Affecting C1				+					+	+	+	+						+	+		
C2																					
C3																					
C4	+				+					+	+	+		+	+		+				
C5								+						+	+						
Q1				+	+			+					+								
Q2	+							+								+					
Q3													+		+						
Q4							+											+		+	
RM1	+	+									+	+									
RM2										+		+									
RM3	+									+	+										
RM4						+										+					
RM5															+	+					
RM6														+			+	+	+	+	+
RM7	+																				
T1																			+	+	
T2	+														+				+		
T3															+						
T4																+	+				
T5															+				+	+	

Figure B.10. Pairwise comparison results of Expert 5

		Clinical Laboratory Performance				Cost					Quality				Resource Management							Time				
		Cost	Quality	Resourc	Time	C1	C2	C3	C4	C5	Q1	Q2	Q3	Q4	RM1	RM2	RM3	RM4	RM5	RM6	RM7	T1	T2	T3	T4	T5
Clinical Laboratory Performance	Cost	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Quality	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Resource Mar	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Time	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Cost	C1	0,12	0,00	0,00	0,00	0,00	0,25	0,00	0,33	0,33	0,25	0,25	0,00	0,00	0,50	0,50	1,00	0,25	1,00	0,33	0,00	0,00	1,00	0,25	0,00	0,00
	C2	0,19	0,00	0,00	0,00	1,00	0,00	0,00	0,33	0,33	0,25	0,25	0,00	0,00	0,50	0,50	0,00	0,25	0,00	0,33	0,00	0,00	0,00	0,25	0,00	0,00
	C3	0,29	0,00	0,00	0,00	0,00	0,25	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,33	0,00	0,00	0,00	0,00	0,00	0,00
	C4	0,34	0,00	0,00	0,00	0,00	0,25	0,00	0,00	0,33	0,25	0,25	0,00	0,00	0,00	0,00	0,00	0,25	0,00	0,00	0,00	0,00	0,00	0,25	0,00	0,00
	C5	0,07	0,00	0,00	0,00	0,00	0,25	1,00	0,33	0,00	0,25	0,25	0,00	0,00	0,00	0,00	0,00	0,25	0,00	0,00	0,00	0,00	0,00	0,25	0,00	0,00
Quality	Q1	0,00	0,21	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,25	0,00	0,00	0,25	0,00	0,00
	Q2	0,00	0,32	0,00	0,00	0,00	1,00	0,00	0,00	0,33	0,00	0,00	1,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,25	0,00	0,00	0,25	0,00	0,00
	Q3	0,00	0,10	0,00	0,00	0,00	0,00	0,00	0,00	0,33	0,50	0,50	0,00	0,00	0,00	0,00	0,00	1,00	1,00	0,50	0,25	0,00	0,00	0,25	1,00	0,00
	Q4	0,00	0,37	0,00	0,00	0,00	0,00	0,00	0,00	0,33	0,50	0,50	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,50	0,25	0,00	0,00	0,25	0,00	0,00
Resource Management	RM1	0,00	0,00	0,08	0,00	0,00	0,20	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,50	0,50	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	RM2	0,00	0,00	0,06	0,00	0,50	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	1,00	0,00	0,50	0,00	0,00	0,00	0,00	0,00	0,00	0,33	0,00	0,00
	RM3	0,00	0,00	0,06	0,00	0,50	0,20	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,50	0,00	0,00	0,25	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	RM4	0,00	0,00	0,19	0,00	0,00	0,20	0,00	0,33	0,00	0,25	0,00	0,33	0,00	0,00	0,00	0,00	0,00	0,25	1,00	1,00	0,00	0,00	0,00	0,00	0,00
	RM5	0,00	0,00	0,19	0,00	0,00	0,00	0,00	0,33	0,50	0,25	0,00	0,33	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	RM6	0,00	0,00	0,20	0,00	0,00	0,20	0,00	0,00	0,50	0,25	0,50	0,33	1,00	0,00	0,00	0,00	0,00	0,25	0,00	0,00	0,00	1,00	0,33	1,00	0,00
	RM7	0,00	0,00	0,21	0,00	0,00	0,20	0,00	0,33	0,00	0,25	0,50	0,00	0,00	0,00	0,00	0,00	1,00	0,25	0,00	0,00	0,00	0,00	0,33	0,00	0,00
Time	T1	0,00	0,00	0,00	0,09	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	T2	0,00	0,00	0,00	0,25	0,00	0,00	0,00	0,00	0,00	0,00	0,25	0,25	0,00	0,00	0,00	0,00	0,00	0,00	0,25	0,00	0,00	0,00	0,33	0,33	0,00
	T3	0,00	0,00	0,00	0,24	0,00	0,00	0,00	0,00	0,00	0,00	0,25	0,25	0,00	1,00	1,00	0,00	0,33	0,33	0,25	1,00	0,50	1,00	0,00	0,33	0,50
	T4	0,00	0,00	0,00	0,22	0,00	0,00	0,00	0,00	0,00	0,00	0,25	0,25	0,50	0,00	0,00	0,00	0,33	0,33	0,25	0,00	0,50	0,00	0,33	0,00	0,50
	T5	0,00	0,00	0,00	0,20	0,00	0,00	0,00	0,00	0,00	0,00	0,25	0,25	0,50	0,00	0,00	0,00	0,33	0,33	0,25	0,00	0,00	0,00	0,33	0,33	0,00

Figure C. 1. Unweighted super-matrix

		Clinical Laboratory Performance				Cost					Quality				Resource Management							Time				
		Cost	Quality	Resour	Time	C1	C2	C3	C4	C5	Q1	Q2	Q3	Q4	RM1	RM2	RM3	RM4	RM5	RM6	RM7	T1	T2	T3	T4	T5
	Cost	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Quality	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Resource Management	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	Time	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,25	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Cost	C1	0,12	0,00	0,00	0,00	0,00	0,08	0,00	0,17	0,11	0,08	0,06	0,00	0,00	0,13	0,17	0,50	0,06	0,25	0,08	0,00	0,00	0,33	0,06	0,00	0,00
	C2	0,19	0,00	0,00	0,00	0,50	0,00	0,00	0,17	0,11	0,08	0,06	0,00	0,00	0,13	0,17	0,00	0,06	0,00	0,08	0,00	0,00	0,00	0,06	0,00	0,00
	C3	0,29	0,00	0,00	0,00	0,00	0,08	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,08	0,00	0,00	0,00	0,00	0,00	0,00
	C4	0,34	0,00	0,00	0,00	0,00	0,08	0,00	0,00	0,11	0,08	0,06	0,00	0,00	0,00	0,00	0,00	0,06	0,00	0,00	0,00	0,00	0,00	0,06	0,00	0,00
	C5	0,07	0,00	0,00	0,00	0,00	0,08	1,00	0,17	0,00	0,08	0,06	0,00	0,00	0,00	0,00	0,00	0,06	0,00	0,00	0,00	0,00	0,00	0,06	0,00	0,00
Quality	Q1	0,00	0,21	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,08	0,00	0,00	0,06	0,00	0,00
	Q2	0,00	0,32	0,00	0,00	0,00	0,33	0,00	0,00	0,11	0,00	0,00	0,33	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,08	0,00	0,00	0,06	0,00	0,00
	Q3	0,00	0,10	0,00	0,00	0,00	0,00	0,00	0,00	0,11	0,17	0,13	0,00	0,00	0,00	0,00	0,00	0,25	0,25	0,13	0,08	0,00	0,00	0,06	0,33	0,00
	Q4	0,00	0,37	0,00	0,00	0,00	0,00	0,00	0,00	0,11	0,17	0,13	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,13	0,08	0,00	0,00	0,06	0,00	0,00
Resource Man	RM1	0,00	0,00	0,08	0,00	0,00	0,07	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,17	0,25	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	RM2	0,00	0,00	0,06	0,00	0,25	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,25	0,00	0,25	0,00	0,00	0,00	0,00	0,00	0,00	0,08	0,00	0,00
	RM3	0,00	0,00	0,06	0,00	0,25	0,07	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,17	0,00	0,00	0,06	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	RM4	0,00	0,00	0,19	0,00	0,00	0,07	0,00	0,17	0,00	0,08	0,00	0,11	0,00	0,00	0,00	0,00	0,00	0,06	0,25	0,33	0,00	0,00	0,00	0,00	0,00
	RM5	0,00	0,00	0,19	0,00	0,00	0,00	0,00	0,17	0,17	0,08	0,00	0,11	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	RM6	0,00	0,00	0,20	0,00	0,00	0,07	0,00	0,00	0,17	0,08	0,13	0,11	0,50	0,00	0,00	0,00	0,00	0,06	0,00	0,00	0,00	0,33	0,08	0,33	0,00
	RM7	0,00	0,00	0,21	0,00	0,00	0,07	0,00	0,17	0,00	0,08	0,13	0,00	0,00	0,00	0,00	0,00	0,25	0,06	0,00	0,00	0,00	0,00	0,08	0,00	0,00
Time	T1	0,00	0,00	0,00	0,09	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	T2	0,00	0,00	0,00	0,25	0,00	0,00	0,00	0,00	0,00	0,00	0,06	0,08	0,00	0,00	0,00	0,00	0,00	0,00	0,06	0,00	0,00	0,00	0,08	0,11	0,00
	T3	0,00	0,00	0,00	0,24	0,00	0,00	0,00	0,00	0,00	0,00	0,06	0,08	0,00	0,25	0,33	0,00	0,08	0,08	0,06	0,33	0,50	0,33	0,00	0,11	0,50
	T4	0,00	0,00	0,00	0,22	0,00	0,00	0,00	0,00	0,00	0,00	0,06	0,08	0,25	0,00	0,00	0,00	0,08	0,08	0,06	0,00	0,50	0,00	0,08	0,00	0,50
	T5	0,00	0,00	0,00	0,20	0,00	0,00	0,00	0,00	0,00	0,00	0,06	0,08	0,25	0,00	0,00	0,00	0,08	0,08	0,06	0,00	0,00	0,00	0,08	0,11	0,00

Figure C. 2. Weighted super-matrix

		Cost					Quality				Resource Management							Time				
		C1	C2	C3	C4	C5	Q1	Q2	Q3	Q4	RM1	RM2	RM3	RM4	RM5	RM6	RM7	T1	T2	T3	T4	T5
Cost	C1	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08
	C2	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08
	C3	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
	C4	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03
	C5	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04
Quality	Q1	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01
	Q2	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07
	Q3	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,08
	Q4	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04
Resource Management	RM1	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
	RM2	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04
	RM3	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03
	RM4	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06	0,06
	RM5	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
	RM6	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09
	RM7	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04
Time	T1	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	T2	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,03
	T3	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10
	T4	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07	0,07
	T5	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05

Figure C. 3. Limit matrix

APPENDIX D: SIMULATION MODEL EQUATIONS

Backlog_of_analytic_phase(t) = Backlog_of_analytic_phase(t - dt) +
(centrifuge_completion + Operational_return_rate -
analytic_phase__completion_rate_coag) * dt
INIT Backlog_of_analytic_phase = 0
INFLOWS:
centrifuge_completion = centrifuge_rate
Operational_return_rate = coagulation_return_rate*Total_operational_return
OUTFLOWS:
analytic_phase__completion_rate_coag = IF Inventory[1]>=320 THEN
MIN(Backlog_of_analytic_phase,320) ELSE
MIN(Inventory[1],Backlog_of_analytic_phase)
Backlog_of_analytic__phase_bt(t) = Backlog_of_analytic__phase_bt(t - dt) +
(Pre_analytic_phase__completion_rate_bt + Operational_return_bt -
analytic_phase__completion_rate_bt) * dt
INIT Backlog_of_analytic__phase_bt = 0
INFLOWS:
Pre_analytic_phase__completion_rate_bt =
MIN((Tests_in_backlog_bt/time_fraction),Capacity_rate[1])
Operational_return_bt = bt_return_rate*Total_operational_return
OUTFLOWS:
analytic_phase__completion_rate_bt = IF Inventory[2]>=800 THEN
MIN(Backlog_of_analytic__phase_bt,800) ELSE
MIN(Inventory[2],Backlog_of_analytic__phase_bt)
Backlog_of_analytic__phase_urinalysis(t) = Backlog_of_analytic__phase_urinalysis(t
- dt) + (Operational_return_urinalysis +
Pre_analytic_phase__completion_rate_urinalysis -
analytic_phase__completion_rate_urinalysis) * dt
INIT Backlog_of_analytic__phase_urinalysis = 0
INFLOWS:
Operational_return_urinalysis = Total_operational_return*urinalysis_return_rate

Pre_analytic_phase__completion_rate_urinalysis =
MIN((Tests_in_backlog_urinalysis/time_fraction),Capacity_rate[1])
OUTFLOWS:
analytic_phase__completion_rate_urinalysis = IF Inventory[3]>=1600 THEN
MIN(Backlog_of_analytic__phase_urinalysis,1600) ELSE
MIN(Inventory[3],Backlog_of_analytic__phase_urinalysis)
Backlog_of__final_approval(t) = Backlog_of__final_approval(t - dt) +
(first_approval__completion_rate - final_approval__completion_rate) * dt
INIT Backlog_of__final_approval = 0
INFLOWS:
first_approval__completion_rate =
MIN((Backlog_of__first_approval/time_fraction),Capacity_rate[2])
OUTFLOWS:
final_approval__completion_rate =
MIN((Backlog_of__final_approval/time_fraction),Capacity_rate[2])
TIMESTAMPED
Backlog_of__first_approval(t) = Backlog_of__first_approval(t - dt) +
(Post_analytic_phase - first_approval__completion_rate) * dt
INIT Backlog_of__first_approval = 0
INFLOWS:
Post_analytic_phase =
SUM(analytic_phase__completion_rate_bt,analytic_phase__completion_rate_coag,analytic_phase__completion_rate_urinalysis,(Retest_discovery_rate*Documental_return__percentage))
OUTFLOWS:
first_approval__completion_rate =
MIN((Backlog_of__first_approval/time_fraction),Capacity_rate[2])
Completed_tests_with_or_without_error(t) =
Completed_tests_with_or_without_error(t - dt) + (final_approval__completion_rate) * dt
INIT Completed_tests_with_or_without_error = 0
INFLOWS:

final_approval__completion_rate =
MIN((Backlog_of__final_approval/time_fraction),Capacity_rate[2])
TIMESTAMPED
Effective_Labor(t) = Effective_Labor(t - dt) + (Training_period) * dt
INIT Effective_Labor = 6
INFLOWS:
Training_period = New_hires/Time_to_training
Inventory[1](t) = Inventory[1](t - dt) + (Ordering_volume[1] - Consumption[1]) * dt
INIT Inventory[1] = 0
Inventory[2](t) = Inventory[2](t - dt) + (Ordering_volume[2] - Consumption[2]) * dt
INIT Inventory[2] = 0
Inventory[3](t) = Inventory[3](t - dt) + (Ordering_volume[3] - Consumption[3]) * dt
INIT Inventory[3] = 0
INFLOWS:
Ordering_volume[1] = Gap_in_inventory[1]/Time_to_dispatch
Ordering_volume[2] = Gap_in_inventory[2]/Time_to_dispatch
Ordering_volume[3] = Gap_in_inventory[3]/Time_to_dispatch
OUTFLOWS:
Consumption[1] =
(Inventory_used_per_test[1]*analytic_phase__completion_rate_coag)+(Inventory_used_for_calibration[1]*Level_of_calibration)
Consumption[2] =
(Inventory_used_per_test[2]*analytic_phase__completion_rate_bt)+(Inventory_used_for_calibration[2]*Level_of_calibration)
Consumption[3] =
(Inventory_used_per_test[3]*analytic_phase__completion_rate_urinalysis)+(Inventory_used_for_calibration[3]*Level_of_calibration)
New_hires(t) = New_hires(t - dt) + (Hiring - Training_period) * dt
INIT New_hires = 0
INFLOWS:
Hiring = Gap_in_labor/Delay_in
OUTFLOWS:
Training_period = New_hires/Time_to_training

overtime(t) = overtime(t - dt) + (Overtime_rate) * dt

INIT overtime = 0

INFLOWS:

Overtime_rate = gap/Time_to_overtime__decision

Returned_tests(t) = Returned_tests(t - dt) + (Retest_discovery_rate) * dt

INIT Returned_tests = 0

INFLOWS:

Retest_discovery_rate = Undiscovered_retest/Time_to_discover_retest

Tests_in_backlog_bt(t) = Tests_in_backlog_bt(t - dt) + (test_request_bt - Pre_analytic_phase__completion_rate_bt) * dt

INIT Tests_in_backlog_bt = 0

INFLOWS:

test_request_bt = MEAN(416)*Qualified_sample_fraction_bt

TIMESTAMPED

OUTFLOWS:

Pre_analytic_phase__completion_rate_bt = MIN((Tests_in_backlog_bt/time_fraction),Capacity_rate[1])

Tests_in_backlog_coag(t) = Tests_in_backlog_coag(t - dt) + (test_request_coag - Pre_analytic_phase__completion_rate) * dt

INIT Tests_in_backlog_coag = 0

INFLOWS:

test_request_coag = MEAN(144)*Qualified_sample_fraction

TIMESTAMPED

OUTFLOWS:

Pre_analytic_phase__completion_rate = MIN((Tests_in_backlog_coag/time_fraction),Capacity_rate[1])

Tests_in_backlog_urinalysis(t) = Tests_in_backlog_urinalysis(t - dt) + (test_request_urinalysis - Pre_analytic_phase__completion_rate_urinalysis) * dt

INIT Tests_in_backlog_urinalysis = 0

INFLOWS:

test_request_urinalysis = MEAN(256)*Qualified_sample_fraction_urinalysis

TIMESTAMPED

OUTFLOWS:

Pre_analytic_phase__completion_rate_urinalysis =
MIN((Tests_in_backlog_urinalysis/time_fraction),Capacity_rate[1])
Tests_wait_for_centrifuge(t) = Tests_wait_for_centrifuge(t - dt) +
(Pre_analytic_phase__completion_rate - centrifuge_rate) * dt
INIT Tests_wait_for_centrifuge = 0
INFLOWS:
Pre_analytic_phase__completion_rate =
MIN((Tests_in_backlog_coag/time_fraction),Capacity_rate[1])
OUTFLOWS:
centrifuge_rate = MIN(Tests_wait_for_centrifuge,1200)
Total_Cost(t) = Total_Cost(t - dt) + (Cost_rate) * dt
INIT Total_Cost = 0
INFLOWS:
Cost_rate =
inventory_cost[1]+inventory_cost[2]+inventory_cost[3]+labor_cost+overtime_cost+under_capacity_cost
Total_requested_tests(t) = Total_requested_tests(t - dt) + (Total_test_request) * dt
INIT Total_requested_tests = 0
INFLOWS:
Total_test_request = test_request_bt+test_request_coag+test_request_urinalysis
Total_revenue(t) = Total_revenue(t - dt) + (Revenue_rate) * dt
INIT Total_revenue = 0
INFLOWS:
Revenue_rate =
SUM((Price_of_tests[1]*analytic_phase__completion_rate_coag),(Price_of_tests[2]*analytic_phase__completion_rate_bt),(Price_of_tests[3]*analytic_phase__completion_rate_urinalysis))
Undiscovered_retest(t) = Undiscovered_retest(t - dt) + (Test_defect_generation_rate - Retest_discovery_rate) * dt
INIT Undiscovered_retest = 0
INFLOWS:
Test_defect_generation_rate = Reference_quality*final_approval__completion_rate
OUTFLOWS:

Retest_discovery_rate = Undiscovered_retest/Time_to_discover_retest

bt_return_rate = 1/3

Capacity_rate[1] = IF Decision=0 THEN

(0.7*Effective_Labor)*((Productive_hours_per_labor*Test_productivity_per_labor[1])+ Overtime_productivity_per_labor[1]*(0.7*Effective_Labor)) ELSE

(0.7*Effective_Labor)*(Productive_hours_per_labor*Test_productivity_per_labor[1])

Capacity_rate[2] = IF Decision=0 THEN

(0.3*Effective_Labor)*(Productive_hours_per_labor*Test_productivity_per_labor[2])+(Overtime_productivity_per_labor[2]*0.3*Effective_Labor) ELSE

(0.3*Effective_Labor)*(Productive_hours_per_labor*Test_productivity_per_labor[2])

coagulation_return_rate = 1/3

Critical_backlog__value = 791

Decision = IF Overtime_hours_needed >= Maximum_allowable_overtime_per_day THEN 1 ELSE 0

Delay_in = 45

Desired_inventory_level[1] = 4200

Desired_inventory_level[2] = 12480

Desired_inventory_level[3] = 7680

Discrepancy = IF Critical_backlog__value<=Tests_in_backlog THEN 1 ELSE 0

Documental_return__percentage = 0.90

Feasible_labor_hour_per_test = 0.1

Feasible_test_time = 4

gap = IF Overtime_hours_needed<Maximum_allowable_overtime_per_day THEN Overtime_hours_needed ELSE Maximum_allowable_overtime_per_day

Gap_in_inventory[1] = Desired_inventory_level[1]-Inventory[1]

Gap_in_inventory[2] = Desired_inventory_level[2]-Inventory[2]

Gap_in_inventory[3] = Desired_inventory_level[3]-Inventory[3]

Gap_in_labor = IF Decision=1 AND ((Effective_Labor+New_hires)<Max_labor) THEN (Workforce_needed-(New_hires+Effective_Labor)) ELSE 0

Impact_of_overtime = 0.75

inventory_cost[1] = Ordering_volume[1]*Unit_test_kit_cost[1]

inventory_cost[2] = Ordering_volume[2]*Unit_test_kit_cost[2]

inventory_cost[3] = Ordering_volume[3]*Unit_test_kit_cost[3]

Inventory_used_for_calibration[1] = 17

Inventory_used_for_calibration[2] = 22

Inventory_used_for_calibration[3] = 10

Inventory_used_per_test[1] = 1

Inventory_used_per_test[2] = 1

Inventory_used_per_test[3] = 1

Labor = Effective_Labor+New_hires

labor_cost = Labor*Unit_labor_cost

legal_overtime__hour_per_labor = 1

Level_of_calibration = 2

Maximum_allowable_overtime_per_day =

INT(legal_overtime__hour_per_labor*Effective_Labor)

Max_labor = 12

Operational_return_percentage = 0.10

overtime_cost = Overtime_rate*Overtime_unit_cost

Overtime_hours_needed = IF Discrepancy=1 THEN((Tests_in_backlog-

Critical_backlog__value)/Feasible_test_time) ELSE 0

Overtime_productivity_per_labor[1] =

Overtime_rate*Test_productivity_per_labor[1]*Impact_of_overtime

Overtime_productivity_per_labor[2] =

Overtime_rate*Test_productivity_per_labor[2]*Impact_of_overtime

Overtime_unit_cost = 12

Percentage_completed = ((final_approval__completion_rate-

Retest_discovery_rate)/Total_test_request)

Price_of_tests[1] = 1

Price_of_tests[2] = 3.5

Price_of_tests[3] = 5

Productive_hours_per_labor = 8*0.85

Qualified_sample_fraction = 0.9733

Qualified_sample_fraction_bt = 0.9733

Qualified_sample_fraction_urinalysis = 0.9733

Reference_quality = 0.0006

Tests_in_backlog =

SUM(Tests_in_backlog_bt,Tests_in_backlog_coag,Tests_in_backlog_urinalysis)

Test_productivity_per_labor[1] = 75

Test_productivity_per_labor[2] = 150

time_fraction = 1

Time_to_discover_retest = 3

Time_to_dispatch = 7

Time_to_overtime__decision = 1

Time_to_training = 90

Total_operational_return = Retest_discovery_rate*Operational_return_percentage

Turnarond_time[1] =

Tests_in_backlog_coag/CTFLOW(test_request_coag,final_approval__completion_rate)

Turnarond_time[2] =

Tests_in_backlog_bt/CTFLOW(test_request_bt,final_approval__completion_rate)

Turnarond_time[3] =

Tests_in_backlog_urinalysis/CTFLOW(test_request_urinalysis,final_approval__completion_rate)

under_capacity_cost = IF Percentage_completed<0.99 THEN 250 ELSE 0

Unit_labor_cost = 86

Unit_test_kit_cost[1] = 0.3

Unit_test_kit_cost[2] = 1

Unit_test_kit_cost[3] = 0.8

urinalysis_return_rate = 1/3

Workforce_needed =

Tests_in_backlog/(Productive_hours_per_labor/Feasible_labor_hour_per_test)