The Pennsylvania State University
The Graduate School
Harold and Inge Marcus Department of Industrial and Manufacturing Engineering

DATA VISUALIZATION IN MODELS
FOR HEALTHCARE WORKFLOW IMPROVEMENT

A Thesis in
Industrial Engineering and Operations Research

By

Yining Chen

© 2013 Yining Chen

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

August 2013
The thesis of Yining Chen was reviewed and approved* by the following:

Harriet Black Nembhard  
Professor of Industrial Engineering  
Thesis Adviser

Chia-Jung Chang  
Assistant Professor of Industrial Engineering

Saurabh Bansal  
Assistant Professor of Supply Chain Management

Paul Griffin  
Professor of Industrial Engineering  
Peter and Angela Dal Pezzo Department Head Chair

*Signatures are on file in the Graduate School.
Workflow optimization in the healthcare system has been analyzed and discussed by many researchers in recent years. The increasing difficulties in dealing with complex data and the increasing expectations from physicians and patients for more reliable information have necessitated improvements in the health care decision making process. Data visualization (DV) is a useful approach for dealing with multifaceted data and presenting information in a user-friendly way. Much research has been done to develop useful DV tools that have made information more accessible to patients as well as physicians. However, very little research has been done to implement the DV techniques effectively into the different stages of a healthcare delivery workflow.

In this thesis, we study the question domains that patients and physicians must address in the treatment encounter, followed by a possible solution set for each domain with the DV techniques that may be involved. The workflow is investigated and developed from the input stage to the treatment cycle stage, focusing on steps in the decision making process and their sequences in the workflow. The DV techniques are then analyzed in detail based on their characteristics, functions, and advantages. For each stage, the DV display is shown with a focus on how it may help patients and the physicians better communicate.

An optimization model is formulated based on the workflow to identify the DV technique for each stage so that the overall objectives of quality, efficiency, and cost are addressed. Goal programming is used to combine different criteria into one single overall criterion. In order to evaluate the workflow with DV interventions, a workflow model is built in Simio to simulate the current and proposed workflow. Analysis of the simulation results provides insight on comparisons of the performance of the workflow with DV intervention and without DV intervention. A case study is presented for tuberculosis (TB) to show how DV techniques can
help TB patients and the physicians better communicate, understand and use the information to make informed decisions. Based on this study, several future research opportunities are identified.
# TABLE OF CONTENTS

LIST OF FIGURES ............................................................................................................................ vii

LIST OF TABLES ............................................................................................................................... ix

ACKNOWLEDGEMENTS ...................................................................................................................... x

Chapter 1 Introduction ....................................................................................................................... 1

1.1 Problem Description and Background ...................................................................................... 1

1.2 Data Visualization ....................................................................................................................... 3

1.2.1 Brief Introduction of Data Visualization ............................................................................... 3

1.2.2 Data Visualization in the Healthcare System ...................................................................... 4

1.2.3 Improvement in Data Visualization .................................................................................... 5

1.3 Workflow in the Healthcare Delivery System .......................................................................... 5

1.3.1 Brief Introduction to Workflow ........................................................................................... 6

1.3.2 Data Visualization Intervention in Workflow .................................................................... 6

1.4 Research Motivation and Objective .......................................................................................... 6

Chapter 2 Literature Review: Data Visualization in the Healthcare System ......................... 9

2.1 Brief Introduction of Development in Data Visualization ....................................................... 9

2.1.1 Definition ............................................................................................................................ 9

2.1.2 Functions .......................................................................................................................... 10

2.1.3 Brief History of Data Visualization .................................................................................. 10

2.1.4 Data Visualization Techniques Today .............................................................................. 12

2.1.5 The DV Process ............................................................................................................... 12

2.1.6 Perception ......................................................................................................................... 13

2.1.7 Human Factors in Data Visualization .............................................................................. 14

2.2 Data Visualization in Healthcare Practice ............................................................................ 15

2.2.1 Objectives ......................................................................................................................... 15

2.2.2 Data Visualization Examples in Healthcare Practice ....................................................... 16

Chapter 3 Physician-Patient Encounter Workflow with Data Visualization Intervention .......... 27

3.1 Introduction and Background .................................................................................................. 27

3.2 Overall Methodology .............................................................................................................. 27

3.2.1 Situation .......................................................................................................................... 28
3.2.2 Problems

3.2.3 Goal

3.2.4 Problem Solving Phase I

3.2.5 Problem Solving Phase II

3.2.6 Problem Solving Phase III

3.2.7 Model Formulation

Chapter 4 Simulation of the Workflow Problem

4.1 Goal of Simulation

4.2 Model Assumptions and Development

4.3 Analysis and Discussion

Chapter 5 Case Study

5.1 Background on TB

5.2 TB Workflow

5.2.1 Questions and Tests

5.2.2 Diagnosis

5.2.3 Treatment

5.2.4 Patient Education

5.3 Data Visualization

5.4 Optimization

5.5 Results

5.6 Analysis and Discussion

Chapter 6 Conclusion and Future Research

6.1 Conclusion

6.2 Future Work

APPENDIX

REFERENCES
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Timeline in EMR (Bui et al., 2007)</td>
<td>5</td>
</tr>
<tr>
<td>1.2</td>
<td>Methodology</td>
<td>7</td>
</tr>
<tr>
<td>2.1</td>
<td>History of Data Visualization (Friendly, 2006)</td>
<td>11</td>
</tr>
<tr>
<td>2.2</td>
<td>Visualization Pipeline (Ward, 2010)</td>
<td>13</td>
</tr>
<tr>
<td>2.3</td>
<td>DV Process (Fry, 2004)</td>
<td>13</td>
</tr>
<tr>
<td>2.4</td>
<td>Comparison of Images with and without DV (Fry, 2004)</td>
<td>14</td>
</tr>
<tr>
<td>2.5</td>
<td>Visualization of Risk (Ancker et al., 2006)</td>
<td>16</td>
</tr>
<tr>
<td>2.6</td>
<td>Visualization of Scale (Ancker et al., 2006)</td>
<td>17</td>
</tr>
<tr>
<td>2.7</td>
<td>Visualization of Scale (Ancker et al., 2006)</td>
<td>18</td>
</tr>
<tr>
<td>2.8</td>
<td>Visualization of Frequency (Zheng et al., 2010)</td>
<td>20</td>
</tr>
<tr>
<td>2.9</td>
<td>Visualization of Workflow (Zheng et al., 2010)</td>
<td>21</td>
</tr>
<tr>
<td>2.10</td>
<td>Visualization of Period (Aigner et al., 2011)</td>
<td>22</td>
</tr>
<tr>
<td>2.11</td>
<td>Visualization of Time (Aigner et al., 2011)</td>
<td>23</td>
</tr>
<tr>
<td>2.12</td>
<td>Glyph (Nembhard et al., 2012)</td>
<td>24</td>
</tr>
<tr>
<td>2.13</td>
<td>Visualization of Overlap (Fairfield et al., 2013)</td>
<td>25</td>
</tr>
<tr>
<td>3.1</td>
<td>Overall Methodology</td>
<td>28</td>
</tr>
<tr>
<td>3.2</td>
<td>Expectations from Patients and Physicians</td>
<td>30</td>
</tr>
<tr>
<td>3.3</td>
<td>Uncertainty Visualization Techniques for 1D Datasets</td>
<td>32</td>
</tr>
<tr>
<td>3.4</td>
<td>Visualization of Uncertainty (Sanyal et al., 2009)</td>
<td>33</td>
</tr>
<tr>
<td>3.5</td>
<td>Normal Ranges for White Blood Cells (Häggström, 2008)</td>
<td>34</td>
</tr>
<tr>
<td>3.6</td>
<td>Healthcare Delivery Workflow</td>
<td>36</td>
</tr>
<tr>
<td>3.7</td>
<td>Display for Disease Severity</td>
<td>37</td>
</tr>
<tr>
<td>3.8</td>
<td>Disease Reasons</td>
<td>38</td>
</tr>
<tr>
<td>3.9</td>
<td>Display for Disease Reasons</td>
<td>39</td>
</tr>
<tr>
<td>3.10</td>
<td>Display for Treatment Plans</td>
<td>40</td>
</tr>
<tr>
<td>3.11</td>
<td>Patient Education</td>
<td>41</td>
</tr>
<tr>
<td>3.12</td>
<td>Conceptual Model</td>
<td>43</td>
</tr>
<tr>
<td>4.1</td>
<td>Model Logic</td>
<td>48</td>
</tr>
<tr>
<td>4.2</td>
<td>Simio Model</td>
<td>50</td>
</tr>
<tr>
<td>4.3</td>
<td>Workflow with Intervention of Data Visualization Techniques</td>
<td>52</td>
</tr>
<tr>
<td>4.4</td>
<td>Workflow without Intervention of Data Visualization Techniques</td>
<td>53</td>
</tr>
</tbody>
</table>
Figure 5.1 TB Question Sets .......................................................... 56
Figure 5.2 High Risk Groups.......................................................... 56
Figure 5.3 Test for Three Types of TB........................................... 57
Figure 5.4 Diagnosis.................................................................. 58
Figure 5.5 Treatment ................................................................. 60
Figure 5.6 Data Visualization Display for TB............................... 61
LIST OF TABLES

Table 3.1 Example of Uncertainty in Healthcare Practice (Skeels et al., 2010) ................................. 32
Table 3.2 Comparison Table for Disease Severity ............................................................................. 37
Table 3.3 Comparison Table for Reasons ......................................................................................... 39
Table 3.4 Comparison Table for Treatment Plans ............................................................................ 40
Table 3.5 Comparison Table for Patient Education ............................................................................ 42
Table 3.6 Coefficient Table ............................................................................................................. 45
Table 4.1 Input Table ....................................................................................................................... 49
Table 5.1 Coefficient Table ............................................................................................................. 64
Table 5.2 Optimization Result with P=(3, 2, 1) ............................................................................... 65
Table 5.3 Optimization Result with P=(1, 5, 7) ............................................................................... 65
Table 5.4 Highlighted Coefficient Table for P=(3, 2, 1) ................................................................. 66
Table 5.5 Highlighted Coefficient Table for P=(1, 5, 7) ................................................................. 67
ACKNOWLEDGEMENTS

I would like to express my utmost gratitude for my advisor Prof. Harriet Black Nembhard, for all her encouragement, support and valuable guidance throughout the course of my thesis.

Furthermore I would like to thank Dr. Chang for her help and valuable ideas. Last but not least I would like to thank my friends Long Jiang, Xington Wen, Yangshen He and Yang Jin for their help and support throughout the entire process.
Chapter 1

Introduction

1.1 Problem Description and Background

Issues and concerns around the state of the healthcare system have driven research to improve the overall quality and efficiency. Newly released healthcare reform acts and increasing expectations from patients contribute to a series of new challenges for physicians, technicians, and healthcare leaders who have to adapt to continuously more rigorous standards.

One part of the challenge comes from the increasing amount of information and data from patients’ records, new facilities and equipment. No field is exempt from the impact of this era of information explosion – including the healthcare field. The advantage of large amounts of information is that the physicians now are able to learn more about their patients and thus be enabled to make more accurate and informed decisions. However, it can also confuse the physicians and make it difficult for them to search for useful information and rule out unrelated data. Physicians need to identify the important information, compare, synthesize and process it. Based on the selected information for a certain patient, they need to combine their experiences and then make decisions about the patient’s disease and a series of follow-up treatment plans. Unnecessary and redundant data will not only waste physicians’ time, but also confuse patients when they read their test reports or treatment suggestions (Mechanic, 2003). The larger and more complex information and data systems in health care system requires a new, efficient and effective approach so that the physicians and the patients can understand the information easier, communicate better, and make decisions more wisely.

The other part of challenge is due to increasing expectations from the patients. Mechanic (2003) pointed out that patients’ exposure to mass media has provided them with knowledge and
information about various new technologies and applications in healthcare system, which in turn empowered them with higher demands and expectations from physicians and hospitals. In addition, professional organizations and the government set up goals for decreasing medical errors and improving the overall quality in health care decision making. Higher performance standards incorporate the efficiency of the overall workflow in healthcare system, including decreasing idle time and unnecessary procedures in the system, optimizing the utilization of time and information, and the simplification of the facilities as well as the processes (Mechanic, 2003).

In face of such high expectations from public, a more efficient workflow system needs to be designed for the purpose of saving time, decreasing cost, and improving utilization.

The problems and challenges in the healthcare systems also brought us with opportunities. The Patient-Centered Outcomes Research Institute (PCORI) has launched many funded projects aiming at helping physicians and patients to better communicate and make high-quality health care decisions. Customized treatment and decision making in healthcare has become an important aspect when dealing with workflow problems in decision making or process improvement.

According to PCORI, “patient-centric” means answering patients’ questions that matter to them, explaining the diagnosis or treatment plans from their point of view and incorporating patients’ preferences in decision making. This concept of incorporating patients into the decision making process and considering patients’ demands and different opinions reflects a trend from the general single standard to a customized and diverse type of design. Patients can be advised and counseled in ways that help them understand their disease more easily and more accurately. They can also participate in the decision making process in terms of the determination of their treatment plans, the types of medicine they are going to take, and even the self-care they are going to follow. Given different criteria by different patients, physicians and patients together can figure out a way to determine an optimal treatment plan for the patient based on his or her preferences and conditions. In order to incorporate this patient-centric concept into the healthcare
system, this thesis focuses on implementing the patient-centric concept into the methodology, modeling, and analysis.

The challenges and changes in healthcare systems provide researchers many opportunities to develop new methodologies or new applications of technologies to better facilitate the healthcare quality and efficiency. The development of new technologies has brought opportunities, some of which have already been put into practice. Information systems such as Electronic Medical Records (EMR) and Electronic Health Records (EHR) have been applied to help organize and manage the patient personal records and information (Bui et al, 2009). In this thesis, we focus on only a fraction of those technologies, and show that they can help achieve our goals in improving the healthcare workflow.

1.2 Data Visualization

1.2.1 Brief Introduction of Data Visualization

Data visualization (DV) has long been used in statistics and mathematics, but applied broadly only more recently. DV may be used on a series of data in a graphical manner, helping to communicate the information in a direct way (Dzemyda et al., 2013) or it can be used to integrate multi-dimensional data and present them in a lower dimensional space (one-dimension or two-dimensions).

No matter the type of DV, they all share the same purpose: to present the data and information in a way so that the users can grasp the meaning it conveys both accurately and quickly. Friedman (2008) defined the main goal of data visualization as “to communicate information clearly and effectively through graphical means.” According to him, DV should combine the form and function together and try to find balance between these two attributes.
In order to achieve this goal, there are many techniques to present and display data in a user friendly way. Based on different data types, from spatial data to multivariate data, visualization techniques can range from the simple bar chart to a complex tree graph, from the interaction to a glyph; these will be discussed in detail in Chapters 2 and 3.

DV has been applied to many aspects of our daily basis, including the results of a financial analysis, a weather forecasting graph presenting the movement of the storm, or a distribution of certain decease around the world (Ward, 2010). This wide application has proved the effectiveness of DV to help users achieve clear and integrated information. In this thesis, we investigate how DV can help the health care system become more efficient and effective when incorporated into the workflow.

1.2.2 Data Visualization in the Healthcare System

The implementation and intervention of DV in the healthcare system is no longer a novelty. In fact, many techniques have been applied in healthcare systems for years, such as the display of blood pressure, heart rate, and blood tests. These techniques help display the index in an expanded time line to show the results in a dynamic manner, which can help the patients and the physicians to easily identify the levels as well as the trends in each index and thus get a more reliable understanding and self-awareness. Recently, more advanced DV techniques have been developed. For example, the timeline technique, shown in Figure 1.1, is one of those innovations. This visualization technique uses the integration concept to summarize all the information in the same display and thus can help users to better grasp information, combine related information and make quick and high quality decisions in the end. According to Bui et al. (2007), this visualization is able to display data in a problem-oriented way, which is conducive to patient management and medical research.
1.2.3 Improvement in Data Visualization

Given the DV techniques that have been developed, there is a need to customize them and integrate them appropriately into the healthcare workflow. Although many techniques have proven to be effective and efficient, they may not naturally be appropriate for every field.

Therefore, based on the specific situation, selected DV techniques are modified to enhance their efficiency in this domain as detailed in Chapter 3.

1.3 Workflow in the Healthcare Delivery System
1.3.1 Brief Introduction to Workflow

Workflow is the process that patients and all the people or facilities they encounter during their stay in hospital. According to Karlsson (2010), “health care workflows manage physical resources such as patients and doctors and can help to standardize care process and support management decisions through workflow simulation.” Therefore, it is important to carefully analyze the current workflow before redesign any stages in workflow. According to Scichilone (2009), the current healthcare workflow has problems such as high complexity, high costs and is not sustainable. She also stated that “it is critical to pay attention to data flows and usability factors that save time, ensure accuracy, and facilitate compliance.” The redesigned workflow should incorporate the new technologies that can help save time and bring convenience. It should also be reliable and concise.

1.3.2 Data Visualization Intervention in Workflow

Substantial research has been conducted in the area of redesigning patient flow problems for the purpose of increasing efficiency and productivity as well as saving money. In this thesis, we also want to redesign the workflow in healthcare system, but the methodologies we applied are different from other researchers. Our purpose is to increase the efficiency and effectiveness of the workflow in healthcare using DV interventions. Accordingly, there is a need to assess whether the workflow is better when DV techniques are applied. Then, there is a need to select the most appropriate DV technique that can help patients and physicians make best decisions.

1.4 Research Motivation and Objective

The objective of this thesis is to implement DV techniques in the healthcare workflow to improve the overall quality and efficiency of the system. This thesis focuses on solving the problems stated in the first part of this chapter by using the DV techniques. The selection of DV techniques is a multi-criteria selection problem where a trade-off scenario is developed and
analyzed based on the workflow model. In addition to selecting the feasible and applicable DV techniques, some improvement and modification are also applied based on the specific use and situation where the techniques are implemented. Figure 1.2 represents the conceptual approach to this problem.

Figure 1.2 Methodology

Chapter 2 mainly discusses a detailed literature review from the following aspects: patients and physicians’ demand, DV and its application in healthcare, human factors in DV, workflow in healthcare system, and workflow problem solving methods. In Chapter 2, related definitions of these five parts are provided. The techniques are classified and summarized. The methods are explained in detail, followed by some specific applications.
In Chapter 3, the method to approach this problem is presented, followed by a detailed analysis of patients and physicians demands and characteristic analysis. A list of possible solutions based on the demands of both patients and physicians is developed as the guide to select and modify DV techniques. The data techniques are categorized into four aspects from statistical point of view. Then, the current workflow in healthcare system is presented, followed by an upgraded version of workflow which covers the patients and physicians’ demands. On the basis of this newly designed workflow, the stages where DV techniques can be intervened are identified and the corresponding techniques are developed accordingly.

Moreover, an optimization model is developed in order to find the best arrangement and selection of DV techniques to optimize the overall quality, efficiency and cost. The multi-criteria problem focuses on the trade-off based on the demand of patients and therefore, the goal programming is chosen to be the targeting approach in this model.

Chapter 4 focuses on the results of the intervention of DV techniques. Accordingly, a simulation study of two scenarios is generalized in Simio: workflow with DV and workflow without DV. An analysis is developed to compare and frame the results.

Chapter 5 presents a case study about the intervention of DV in tuberculosis (TB). A specific and detailed workflow for TB is provided. The methodology developed in Chapter 3 is then used to deal with this specific workflow in this chapter.

Chapter 6 mainly delivers the conclusion from the previous chapters, including the discussion and summary obtained from the simulations and case study. Potential future work is also identified.
Chapter 2

Literature Review: Data Visualization in the Healthcare System

In this chapter, the topic of DV is organized in a temporal way to show the development of the visualization techniques. In addition, some milestones in this field are highlighted to emphasize their significance in promoting the development of new ideas in visualization. The chapter addresses the steps to approach DV, some important factors in visualization design and a series of examples of DV practice in healthcare.

2.1 Brief Introduction of Development in Data Visualization

Definition

DV is a valuable tool in helping users to discover what otherwise would have remained hidden. It can also facilitate better understanding of massive and complex data set and communicate the meaning to others. Visualization can be defined as a collection of parts of graphical speech and should consist of a series of components such as data, coordinates, elements, statistics, aesthetics, faceting, guides, interactivity and styles (Wills, 2012).

“The ability to take data—to be able to understand it, to process it, to extract value from it, to visualize it, to communicate it—that’s going to be a hugely important skill in the next decades, …because now we really do have essentially free and ubiquitous data. So the complimentary scarce factor is the ability to understand that data and extract value from it.”

2.1.1 Functions

Visualization can explore data, summarize data and confirm hypothesis due to its ability in providing an overview of complex and massive data sets and identifying regions of the parameters of interest for further analysis (Grinstein, 2002).

2.1.2 Brief History of Data Visualization

The history of visualization goes back to 2nd century in Egypt, where some astronomical information was organized as a tool for better navigation (Few, 2007). But the common form of visualization didn’t arise until the 17th century, when Rene Descartes designed the innovative method to present data based on a system of coordinates. By the late 18th and early 19th centuries, more techniques, such as bar charts emerged and improved. In 1983, Edward Tufte, a pioneer in the field of DV, published his book The Visual Display of Quantitative Information, visually presenting many effective ways of displaying data (Few, 2007). With the spread of affordable computers, the 20th century witnessed the emergence of information explosion, along with a new research area called information visualization, which is what we now experience and study (Card, 1999).

There are so many advanced DV designs that only a few of them with great significance are presented here as the milestones in the field of DV. Friendly (2006) from York University conducted an expansive study, called the Milestone Project, focusing on the important developments in the history of DV. Based on his research, a visual display of the milestones in the history of DV is organized and presented in Figure 2.1.
Minard's depiction of the fate of Napoleon's army by Charles Minard
The graph shows the size of the army by the width of the band across the map of the campaign on its outward and return legs, with temperature on the retreat shown on the line graph at the bottom.

Nightingale's Coxcomb
is notable for its display of frequency by area, like the pie chart. The Coxcomb keeps angles constant and varies radius (proportional to square-root(frequency)).

Moseley's X-rays and the concept of atomic number
Mendeleev's table arranged the elements only by a serial number, denoting an atom's position in a list arranged by increasing atomic mass.

Playfair's charts by William Playfair
The area between two time-series curves was emphasized to show the difference between them, representing the balance of trade.

Dynamic graphics by Etienne-Jules Marey
The graphical representation of movement and dynamic phenomena. This image compares the time course of respiration of a person at rest and under exertion, using a pen-recording device to plot the traces over time.

Figure 2.1 History of Data Visualization (Friendly, 2006)
2.1.3 Data Visualization Techniques Today

The organization and classification of previous visualization techniques are essential for the design and application of new techniques. As Friendly (2000) stated, “The past is often the fountain of ideas, as rich as the future”. There are a number of ways to classify and organize the visualization techniques. They can be classified based on their dimensions, based on whether they are static or dynamic, or based on whether they are geometric or symbolic (Grinstein, 2002). Ward (2010) summarized and synthesized these techniques and developed eight ways to increase efficiency and effectiveness when designing or improving new techniques. The eight visual variables are position, shape, size, brightness, color, orientation, texture, and motion (Ward et al., 2010), which are fully described in Chapter 3.

According to Fry (2004), there are actually two main categories of visualization in healthcare practice. One category focuses on the primarily numeric or symbolic data, while another category of visualization concerns with the display of the physical nature of subjects. This thesis mainly considers the visualization techniques for numerical features rather than physical ones (i.e., the physical shape of a part, where the emphasis is on shape rather than numerical attributes) (Fry, 2004). Given the scope of DV, the next step to take is to figure out the process to approach it.

2.1.4 The DV Process

Several approaches to visualization techniques have been proposed. Although there are some differences among approaches, the general logic remains the same.

It starts with the analysis of the types of data we want to display, followed by the organization of data and visualization of data. For example, Bui et al. (2009) designed a new information clinical system to help improve the presentation of knowledge and simplify the structure, which incorporate three steps (i.e., information extraction, information organization and
information visualization). Ward (2010) developed the visualization pipeline, consisting of data modeling, data selection, data to visual mappings and scene parameter setting. Figure 2.2 is an example of the visualization pipeline proposed by Ward. Another process by Fry (2004) has a series of more detailed steps which are also nicely classified according to their subjects. Figure 2.3 shows the visualization process developed by Fry (2004).

Figure 2.2 Visualization Pipeline (Ward, 2010)

Figure 2.3 DV Process (Fry, 2004)

2.1.5 Perception

A good visualization not only requires the knowledge in statistics and mathematics, but also calls for careful studies of human perception and the information process mechanism (Ward, 2010). According to Ward, perception means “the process of recognizing (being aware of), organizing (gathering and storing), and interpreting (binding to knowledge) sensory information.” Without the external aids, the capacity of our cognition and mental power would be decreased
dramatically (Norman, 1993). Ware (2000) pointed out the human visual system is particularly good at seeking and recognizing patterns, and has a strong ability to process what is seen.

An example provided by Fry (2004) in Figure 6 from (Bertin, 1983) is presented below. The two images present a set of data from regions of France using two different methods.

The left-hand image contains quantity information which requires the viewer to search the numbers, compare the numbers and turn them into a more understandable meaning, while the right-hand image provides a qualitative understanding, where the meaning of the graph can be conveyed to the viewer immediately and clearly (Fry, 2004). Therefore, the right-hand image is much better than the left-hand one in terms of visualization.

2.1.6 Human Factors in Data Visualization

In recent years, more emphasis has been put into the customized design, delivering the concept of designing for targeted users rather than designing for all. This concept is extremely important in the practice of DV since the purpose of visualization is to help viewers to better grasp and understand information based on their demand. In order to incorporate human factors into the design of visualization, a general approach is recommended by many designers in the
process of the DV. This approach starts by classifying users, followed by the clarification of function and objectives. Then, a clear description is required to show further details. A good design should also provide effective guidance for viewers, create meaningful graphics and images when necessary, and choose proper color for each technique. Last but not least, the integration, organization and testing are always essential in determining whether it is a good customized design or not.

2.2 Data Visualization in Healthcare Practice

The prevalence of DV also found its way into healthcare practice. The high-volume of medical data and complex nature of the medical knowledge require a more efficient tool to help share and communicate these types of information between patients and physicians. The DV techniques can support the informed decision making in healthcare and reduce the cognitive burden for patients (Rajwan et al., 2010). Based on the demand, many DV techniques have been designed and customized for the purpose of improving the efficiency and quality of the communication between patients and physicians and thus enhancing the overall quality and efficiency in healthcare workflow.

2.2.1 Objectives

In the following chapter, 9 DV techniques are introduced with their application in healthcare practice. Each technique is discussed from seven aspects: name, category, purpose, description, image, advantages and patient-centric point of view.
2.2.2 Data Visualization Examples in Healthcare Practice

Example 1: Icon Arrays

Category: Risk analysis in healthcare

Purpose: To convey both the ‘numerator’ and the ‘denominator’ simultaneously using discrete level of measurement (Ancker et al., 2006).

Description: The icon arrays consist of part-to-whole relationship with sequential arrangement. Proportions are easy to judge in this icon array because the part-to-whole information is available visually (Ancker et al., 2006).

Image:

![Figure 2.5 Visualization of Risk (Ancker et al., 2006)](image_url)
Advantages: According to the research conducted by Ancker, patients tend to perform better when the data are displayed at the discrete level rather than as a number in proportion (Ancker et al., 2006).

Patient oriented: This visualization technique addresses patients’ understanding ability and the different education levels among them. Patients may better understand risks with the help of this technique.

Example 2: Magnifier Risk Scale

Category: Risk analysis in healthcare

Purpose: To elicit risk perceptions when the scale is at the low end (Ancker et al., 2006)

Description: A value \( x \) can be placed in the scale to allow the magnifier to describe the chance of each event that happens in the lower end (Ancker et al, 2006).

Image:

![Figure 2.6 Visualization of Scale (Ancker et al., 2006)](image)

Advantages: The magnifying lens at the low end allowed users to perceive and understand smaller values for very low risks and reduces the magnitude of higher risks (Ancker et al., 2006).
Disadvantages: May not be applied to large data sets.

Patient oriented: Allows the patient to identify his or her test results if the values are very small.

Example 3: Risk Scale

Category: Risk analysis in healthcare

Purpose: To depict a range of risks from very low to very high as context for an individual risk (Ancker et al, 2006)

Description: The risks from a blood transfusion with other hazards are displayed together in the horizontal scale (Ancker et al, 2006).

Image:

Figure 2.7 Visualization of Scale (Ancker et al., 2006)
Function:

1. Present unfamiliar concept with text and graphics (Ancker et al., 2006);

2. Improved peoples’ ability to notice the full range of possible risks (Ancker et al., 2006).

Advantages: This visualization technique is effective in increasing knowledge and reducing dread about rare hazards of transfusion. It can be also used for presenting unfamiliar concepts together with other familiar tasks (Ancker et al., 2006).

Disadvantages: The logarithmic scale may be unexpected for many people.

Patient oriented: Patient can compare their unfamiliar risks with familiar ones to get a better understanding of the risks of their deceases.

Example 4: Timeline Belt

Category: Workflow evaluation

Purpose: To exhibit the fragmentation of workflow in healthcare before and after the computerized provider order entry (CPOE) implementation (Zheng et al., 2010)

Description: Each row represents a time and motion (T&M) observation session (Zheng et al., 2010). The first 20 stripes indicate the pre-implementation T&M session, while the following 22 stripes represent the post-implementation session. Different colors designate different clinical tasks execution. Length of a colored stripe is proportional to how long the task lasted (Zheng et al., 2010).
Advantages: This visualization technique displays the difference between the post-CPOE representation and the pre-CPOE representation clearly and obviously. Thus it can help researchers to identify the problem within the workflow and then figure out a way to deal with it to decrease the frequencies of switching the tasks.

Example 5: Heatmap

Category: Workflow evaluation

Purpose: To exhibit task transition probabilities (Zheng et al., 2010)

Description: Different density of color represents the transition probabilities estimated from empirical data, with higher density of color meaning higher transition probabilities (Zheng et al., 2010).
Figure 2.9 Visualization of Workflow (Zheng et al., 2010)

**Advantages:** It can be easily observed which tasks are with the highest transitional probability from all the possibilities between different task pairs (Zheng et al., 2010).

**Example 6:** Kaleidomaps by Bale et al. (2007)

**Category:** Time-dependent

**Purpose:** To visualize multivariate time-series data using the curvature of a line to alter the detection of possible periodic patterns (Aigner et al., 2011).

**Description:** The following six kaleidomaps show the morphology of blood pressure and flow waves over two experimental phases (Aigner et al., 2011). A base circle is broken into segments of equal angles for different variables. Each circle segment has two axes representing time, one along the radius and one along the arc of the segment. The data values and categories are represented using color.
**Image:**

Figure 2.10 Visualization of Period (Aigner et al., 2011)

**Advantages:** The kaleidomaps provide an interactive way for viewers to explore both in time and frequency to have a better understanding of the relationships between time and waveform morphologies (Aigner et al., 2011).

**Disadvantages:** Since the kaleidomaps have the format of a circle, it can only have a maximum of six to eight variables within one circle (Aigner et al., 2011).

**Patient oriented:** Kaleidomaps can help patients follow their prescription accurately and on time (Aigner et al., 2011).
**Example 7:** Time Line Browser by Cousins and Kahn (1991)

**Category:** Time-dependent

**Purpose:** To develop the time line browser for visualizing heterogeneous time-oriented data.

**Description:** Intervals are displayed as labeled bars and events are displayed as icons. The small circles form a point plot that shows the patient’s blood glucose over time.

**Image:**

![Figure 2.11 Visualization of Time (Aigner et al., 2011)](image)

**Advantages:** The time line browser integrates qualitative and quantitative data as well as instant and interval data into a single coherent view.

**Patient oriented:** Distinguish simple events, complex events, and intervals. Simple events are represented as small circles; Complex events are shown as icons. Bars are used to indicate location and duration of intervals.
Example 8: Glyph

**Category:** Integration

**Purpose:** To help patients better understand their disease and track their health status for a chronic illnesses.

**Description:** Uses gestalt principles to create a “unified whole” for visual perception of multiple factors; the body shape forms a loci for recognizing and remembering important information.

**Image:**

![Figure 2.12 Glyph (Nembhard et al., 2012)](image)

**Advantages:** Help patients to follow the dietary approaches to stop hypertension and have a better understanding of complications of hypertension (Nembhard et al., 2012).
Patient oriented: Help patients have an integrated view of their current health status and assist their understanding and comprehension of the important information for their health issues (Nembhard et al., 2012).

Example 9: Overlaps and Interconnections

Category: Overlap

Purpose: To present the proportion of three diseases (Alzheimer’s disease, high blood pressure and heart disease), which have certain probability of overlapping.

Description: Different colors and numbers of icons present different overlapping groups of patients and the different proportions of the diseases respectively.

Image:

Figure 2.13 Visualization of Overlap (Fairfield et al., 2013)
Advantages: Able to visually present the individual proportion of the disease and the overlapping of the disease respectively.

Patient oriented: Since the number of patients who are diagnosed with one of these three diseases is expected to increase continuously, it is crucial to let people aware of the overlap of the three diseases so that they can take proper measurements to prevent them (Fairfield et al., 2013).
Chapter 3

Physician-Patient Encounter Workflow
with Data Visualization Intervention

3.1 Introduction and Background

In order to implement DV techniques into a healthcare system workflow, a suitable problem-solving methodology was followed. With this methodology, we investigate the structure of a physician-patient encounter workflow, focusing on information transfer points. DV techniques are then developed in relationship to this workflow. In particular, the techniques are designed to address disease severity, reasons and indicators for contracting the disease, treatment plans, and patient education.

3.2 Overall Methodology

The overall methodology of this work is shown in Figure 3.1 and summarized below. It resonates with traditional lean and six sigma methodologies in that it begins with a clear definition of the problem along with goal-setting to achieve the desired results. The scope of our work supported a three phase problem-solving approach. This remainder of this chapter addresses with step of the methodology in detail.
3.2.1 Situation

The current workflow is assessed for improvement opportunities.

3.2.2 Problems

Inefficient activities within the workflow and tasks with which physicians or patients are dissatisfied are identified. According to a study conducted by Lee (2010), the current workflow can involve physicians with little understanding of system data, poorly integrated interface, and difficulties in communication (Lee et al., 2010).

3.2.3 Goal

Our goal is to identify information transfer points in the workflow and use DV interventions to improve physicians and patients’ communication and shared informed decisions making.
3.2.4 Problem Solving Phase I

Improvement requires a precise definition which in turn requires learning about patients and physicians’ demands, their concerns, and what they want to know. From this information, a detailed work order can be developed across three domains of information about the patients and physicians: (i) knowledge requirements of the patients and physicians; (ii) characteristics of the patients and physicians; and (iii) possible solutions for the problem list. Based on the analysis of literature reviews and interviews conducted by researchers, a detailed problem list is presented in Figure 3.2.
Possible solutions  
- May not be able to describe clearly  
- May not remember some details that is important  
- May not be willing to tell something embarrassing

**Physician**  
Problem lists  
- What patients want to figure out?  
  1. Diagnosis of the patient. (What is going on with me?)  
  2. The severity of the disease. (How serious I am?)  
  3. What is the percentage of this kind of disease? (Is it rare?)  
  4. What are the treatment plans? (How to get cured?)  
  5. Duration of the treatment. (How long it will take to be cured?)  
  6. Is there an risk for treatment and for the case if not treated (e.g., Side effect of medicine risk may affect other organs or even bring in new disease)?  
  7. Cost of the treatment  
  8. Is there any relationship with my previous medical problem?  
  9. Anything I can do to help recovery besides medication (e.g., healthy food).
  
- Better know their patients  
  - Reasons to come  
    (what’s going on to their health)  
  - Historical record (what kinds of disease one have been diagnosed)  
  - Recent activities, events that may be the incentives to the problem (What did they eat, drink, and do? What happened both physically and mentally)  
  - Decision making  
    - Decide what tests one has to take  
    - Combine all the results together  
    - Make decisions  
    - Make treatment plans

**Patient**  
What patients want to figure out?  
1. Diagnosis (Am I better?)  
2. Duration of the treatment (How long it will take for me to be back in normal?)  
3. The recovery rate compared with other patients (Is it good compared with other patients with the same disease)  
4. Change of the treatment according to the patient current condition (e.g., quantity of the medicine, change of the medicine, etc.)

**Characteristics**  
**Characteristics of physicians:**  
1. Professional  
2. Full of experiences

**Characteristics of patients:**  
1. Lack of professional knowledge  
2. Do not trust physicians  
3. Have difficulty in telling from the right from the wrong

Possible solutions  
1 Awareness of their disease and the importance to get treatment  
2 Severity of the disease:  
  - If follow treatment  
  - If not follow treatment  
3 Frequency of the disease  
4 Provide treatment with uncertainty and risk for each  
  - Scoring method can be applied for each treatment  
    - Quality (e.g., possible results, time duration, side effect)  
    - Cost  
    - Efficiency  
5 Optimization method;  
6 Reasons for getting the disease (e.g., unhealthy life style, personal historical record)  
7 Suggestions (e.g., stay healthy, things need to pay attention to)

- Test result: display (confidence interval) display integratedly, dynamically; after entering safe area, still need to observe for a certain time, we need to determine the certain time  
- Forecasting  
- Tree graph (e.g., medication change based on time changing and certain appearance of symptoms)  
- Comparisons with other patients who are in the same condition (e.g., capture the trend & the level of the index)

**Figure 3.2 Expectations from Patients and Physicians**

### 3.2.5 Problem Solving Phase II

Based on concerns of both patients and physicians, a series of DV techniques is provided to help answer the questions in a manner that is easy to understand, efficient and accurate. In order to better incorporate DV techniques within the healthcare practice, a classification and analysis of DV techniques from a statistical point of view can be beneficial.
3.2.5.1 Incorporating DV Techniques

At the end of Chapter 2, some DV techniques in healthcare systems were presented. Based on concerns of both patient and physicians, a series of DV techniques is provided to help answer the questions in a manner that is easy to understand, and more efficient and accurate.

3.2.5.2 Classification of DV techniques

In order to better incorporate DV techniques within healthcare practices, a classification and analysis of DV techniques from statistical point of view is developed, focusing on displaying characteristics of healthcare data in an accessible way. The focus is on the display of healthcare data based on three categories: uncertainty, scale, and dynamic pattern.

Uncertainty

Uncertainty is one of the main characteristics of healthcare data, from test results, to diagnosis, and to treatment plans. It is also a characteristic that is difficult to understand and communicate. There are two types of uncertainty, one of which is called the Type A evaluation of standard uncertainty (e.g., standard deviation), and the other which is called the Type B evaluation of standard uncertainty (e.g., experience) (Sanyal et al., 2009). In the healthcare domain, both Type A and Type B have important roles. By incorporating uncertainty in the DV techniques, we can develop more accurate depictions of data sets so that patients can better understand the data and physicians can make more informed decisions without hiding uncertainty (Skeels et al., 2010).

According to Skeels, there are five main sources of uncertainty: measurement precision, completeness, inference, disagreement, and credibility. Table 3.1 describes each of these sources of uncertainty from the standpoint of the healthcare domain.
Table 3.1 Example of Uncertainty in Healthcare Practice (Skeels et al., 2010)

<table>
<thead>
<tr>
<th>Category</th>
<th>Healthcare domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inference</td>
<td>Signs and symptoms are used to infer diagnosis when often there is not a clear line between one set of signs and symptoms and one diagnosis</td>
</tr>
<tr>
<td>Completeness</td>
<td>Due to the cost and other reasons, decisions sometimes must be made with incomplete medical records or without running all possible tests</td>
</tr>
<tr>
<td>Measurement precision</td>
<td>Some diagnostic procedures are not precise and require further improvement</td>
</tr>
<tr>
<td>Credibility</td>
<td>Different opinions among experts</td>
</tr>
<tr>
<td>Disagreement</td>
<td>Two different tests’ results may contradict each other; Two doctors’ opinions may be different</td>
</tr>
</tbody>
</table>

Four commonly used techniques for visualizing uncertainty are traditional error bars, scaled size of glyphs, color-mapping on glyphs, and color mapping of uncertainty on the data surface (e.g., blurring of the glyphs and transparency) (Sanyal et al., 2009). A comparison study was conducted by Sanyal et al. to illustrate the idea of uncertainty visualization in Figure 3.3. It showed how scaling the size of glyphs, altering the color attribute of glyphs, color-mapping the surface of data with uncertainty, and using traditional error bars all contribute to the visualization goal.

![Figure 3.3 Uncertainty Visualization Techniques for 1D Datasets](image)

a) Scaling the size of glyphs b) Altering the color attribute of glyphs c) Color-mapping the surface of data with uncertainty, and d) Using the traditional error bars (Sanyal et al., 2009).
Scale

The problem of scale arises when a range of unfamiliar data (e.g., risk) spans from very low to very high. People often have difficulty in perceiving the meaning of the distance when the interval spans are so large and when there are no comparative reference system (Ancker et al., 2006). However, this problem can be solved if a series of proper comparative data set can be displayed together to help patients perceive the meaning of their test results or diagnosis report (Ancker et al., 2006).

The sources of scale come mostly from the probabilities, risks and other types of data that have large spans. For example, the number of white blood cells in the blood test result can vary from 4,500/mL to 10,000/mL or even to 100 thousand per mL if the white blood cell count is not in the normal range.

Some DV techniques for displaying scale problems have been proposed, such as the risk scale, which is also called the visual analog scale and magnifier risk scale, which have been displayed and described in the Chapter 2. These techniques illustrate unfamiliar concepts with text and graphics, thus improving peoples’ ability to understand the full range of the data. An insightful application has been developed for testing white blood cells in Figure 3.5.
Dynamic Pattern

Medical data in healthcare are often time related and they are often changing dynamically. Visualization techniques can help capture the trend of the data so that both patients and physicians are able to have an overview of their health status.

An example of this can be seen in a blood pressure table (American Heart Association, 2012). Traditionally, physicians will provide a blood pressure table with suggested ranges for each category and for both systolic and diastolic pressure (upper and lower blood pressure). In order to help patients understand a blood pressure table, the table assigns different colors for different categories based on their severities. However, the numerical values for the pressure do not have a clear and perceivable meaning for patients. They can only capture the level of the blood pressure without displaying the trend based on their historical data, which may lead to inaccurate diagnosis and decision making. A variation displays both the diastolic and systolic pressure in the same graph and incorporates the color and icon elements to show the severities of different ranges. Other examples include a display of the low and high blood pressures in a certain period of time, which captures not only the level but also the trend dynamically with time (My health software, 2013) and a combined chart of systolic and diastolic pressure (Bloodbeat.org, 2013).
3.2.6 Problem Solving Phase III

Modeling the physician-patient encounter workflow with DV techniques requires mapping a level of detail of the Inputs and Treatment Cycle as shown in Figure 3.6. Points in the model where DV techniques can be applied are indicated.

The workflow Input includes both factors from the Patient Interview (i.e., patient symptoms, medical history, emotions) and physical examination as well as those obtained from further Diagnostic Evaluation (i.e. laboratory tests, imaging studies, diagnostic procedures).

The Treatment Cycle begins with ordering diagnostic testing. The next step in the Cycle is the Diagnosis I stage, where physicians need to combine and synthesize the inputs from the patients, diagnostic testing and their clinical experience to appropriately diagnose the condition. The Diagnosis II stage involves the physicians and patients communicating to address the work order and education for the patient regarding the condition.

Following diagnosis, the Treatment I stage focuses on the physician-patient collaboration to develop an appropriate treatment plan. Treatment II stage focuses on the medication and therapeutic needs of the patient.

Based on the demands of patients and physicians presented in problem solving phase I, a set of possible solutions is displayed in accordance with the stages in the workflow. As we can see from the Figure 3.6, there are five stages where DV techniques can be intervened to meet the demands by patients and physicians. For each stage, the following five steps need to be considered: 1) Define purposes for this stage; 2) how to accomplish the purpose using DV; techniques: literature review; 3) integration and improvement; 4) display; and 5) compare with the previous techniques.
Patients have difficulty understanding the severity of their disease due to limited healthcare literacy and inefficient communication with their physicians. This difficulty may result in either under- or overestimation of disease severity. For example, patients may be uneasy or fearful about an unusual disease, which may in fact be curable and/or not very serious. On the other hand, if patients know that there are others with the same disease, they may feel relieved regardless of the severity of the disease itself. Accurately communicating disease severity can help patients understand their disease objectively and correctly.
According to research conducted by Ancker (2006), patients have a better understanding of percentages when the data are displayed using discrete values. Therefore, this design feature is introduced to present the percentage of the patient affected by the disease and disease outcomes with proper treatment.

Figure 3.7 Display for Disease Severity

The display showed in Figure 3.7 visually presents the part-to-whole information both in disease incidence and the cure rate, allowing patients have a more intuitive understanding of the disease and the severity of the disease. This visualization may help patients see their disease status more objectively and thus help the communication between physicians and patients. The comparison between the new display and the current display is presented in Table 3.2.

Table 3.2 Comparison Table for Disease Severity

<table>
<thead>
<tr>
<th>Display Content</th>
<th>Typical Approach</th>
<th>Data Visualization</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of patients with the disease</td>
<td>Numerical values; percentage</td>
<td>Percentage in graphs The severity (rare, mid, common)</td>
<td>Easy to interpret</td>
</tr>
<tr>
<td>Possible consequences</td>
<td>Numerical values</td>
<td>Cure rate if treatment applied</td>
<td>More intuitive</td>
</tr>
</tbody>
</table>
**DV Technique 2**

**Reasons for Getting the Disease**

Currently, physicians may tend to explain the disease in a technical way or may avoid discussion when they believe their patients cannot understand the technical terms. Disease conditions are difficult for patients to understand when the name of the disease is unfamiliar to them. In order to solve this problem, the disease name can actually be replaced or supplemented by the indicators of the disease followed by a series of possible disease mechanisms for each indicator. In this way, we turn meaningless terminology into a series of understandable and perceivable attributes, along with their respective disease mechanisms, building a relationship between what the patients observe and the true disease nature. The relationship is displayed in Figure 3.8.

![Figure 3.8 Disease Reasons](image)

In Figure 3.9, the new display shows the integrated version of disease indicators from test results with their comparative values and levels. In addition, a mapping from reasons to indicators is also presented to help patients have a better understanding of their conditions.
Figure 3.9 Display for Disease Reasons

In the new display in Figure 3.9, the upper-left image shows the reasons for getting a certain disease, with the different sizes representing different correlations; the bottom-right image shows the change of the four indicators over time. The corresponding level for each indicator and the trend of the indicator can be easily spotted. The comparison between the new display and the current display is presented in Table 3.3.

Table 3.3 Comparison Table for Reasons

<table>
<thead>
<tr>
<th>Display Content</th>
<th>Typical Approach</th>
<th>Data Visualization</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reasons for getting the disease</td>
<td>Official definition of the disease Text-based information about the disease</td>
<td>Display the correlations and levels of the reasons and indicators by using different colors and sizes; Show the relationships between the disease indicators and reasons</td>
<td>Simplify the information in an integrated view</td>
</tr>
</tbody>
</table>
DV Technique 3

Treatment Plans

Treatment plans are often provided with written descriptions and numerical results, making it difficult for patients to compare information and make informed decisions. This problem can be addressed using quantitative and qualitative techniques to simplify and clarify the treatment plan as shown in Figure 3.10.

The rating method (Ravindran, 2008) is applied in this display to determine a score for each criterion for each treatment plan. The first two criteria, namely quality and efficiency, are qualitative and require physicians and experts to provide corresponding scores from 1 to 10. The cost criterion is scaled to align with the other two criteria so that they can be displayed in the same scale.

![Figure 3.10 Display for Treatment Plans](image)

<table>
<thead>
<tr>
<th>Treatment Plans</th>
</tr>
</thead>
<tbody>
<tr>
<td>quality</td>
</tr>
<tr>
<td>Treatment plan 4</td>
</tr>
<tr>
<td>Treatment plan 3</td>
</tr>
<tr>
<td>Treatment plan 2</td>
</tr>
<tr>
<td>Treatment plan 1</td>
</tr>
</tbody>
</table>

Figure 3.10 Display for Treatment Plans

Table 3.4 Comparison Table for Treatment Plans

<table>
<thead>
<tr>
<th>Display Content</th>
<th>Typical Approach</th>
<th>Data Visualization</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three criteria for four treatment plans</td>
<td>Text-based written explanation of the treatment plans</td>
<td>Visualized version of qualitative and quantitative results</td>
<td>Integrate three criteria when making the decision</td>
</tr>
</tbody>
</table>
DV Technique 4

Patient Education

Patient education has become more important and popular with the advent of *self-care*. According to Vivian (2010), the self-management regimen and the self-control of medication may be one of the most difficult elements in chronic disease management (Fonseca, 2010). However, it also provides us with opportunities to strengthen the overall quality of patient education. DV techniques may be deployed to help achieve this goal by providing patients with visually friendly tools for their health status, medication plans and physicians’ recommendations.

![Patient Education Diagram]

Figure 3.11 Patient Education

The display in Figure 3.11 can help patients gain a better understanding of what kind of medical care is needed and when. The glyph on the left can provide patients with useful information about their health status. The colors green, yellow and blue represent good, low-level warning, and high-level warning respectively. The disk on the right shows time in the form of a
cycle to help patients to take their medicine on schedule. The use of a glyph may help improve patient adherence and better assess the impact of patient progress between treatments (Nembhard, 2012). The comparison between the new display and the current display is presented in Table 3.5.

Table 3.5 Comparison Table for Patient Education

<table>
<thead>
<tr>
<th>Display Content</th>
<th>Typical Approach</th>
<th>Data Visualization</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>N/A</td>
<td>Display the target value for each indicator within a certain amount of time</td>
<td>Provide patients with information about how long it might take them to recover from a certain disease</td>
</tr>
<tr>
<td>Medicine</td>
<td>Text-based</td>
<td>Display the type and amount of medicine patients need to take daily</td>
<td>Supports patients in taking medicines according to instructions</td>
</tr>
</tbody>
</table>

3.2.7 Model Formulation

The overall aim of the model is to use DV techniques to lead to higher quality, improved efficiency and lower cost in the healthcare delivery workflow. For each stage in the workflow, we may design and assess a series of DV techniques. The goal is to determine the optimal arrangement of DV techniques for the entire workflow as exemplified in Figure 3.12.
Assumptions:

1. The quality and efficiency criteria will be measured by scores obtained from the literature review about the user studies for different DV techniques.

2. The cost criteria will be measured by the complexity of the techniques provided by researchers in certain areas based on domain expertise.

3. Only one DV technique can be selected for each stage.

4. Scores for quality, cost and efficiency will be assigned to each DV technique.

Define Variables:

\[ x_{ij} = \begin{cases} 
1 & \text{if at } i\text{th stage the } j\text{th DV technique is chosen} \\
0 & \text{otherwise} 
\end{cases} \]

\[ c_{ij} \]: The cost for \( j \)th DV techniques at \( i \)th stage

\[ e_{ij} \]: The efficiency score for \( j \)th DV techniques at \( i \)th stage

\[ q_{ij} \]: The quality score for \( j \)th DV techniques at \( i \)th stage

\[ i = 1, 2, 3, 4, 5; j = 1, 2, 3 \]
Table 3.6 Coefficient Table

<table>
<thead>
<tr>
<th>j</th>
<th>i</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( c_{ij} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( e_{ij} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( q_{ij} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>( c_{ij} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( e_{ij} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( q_{ij} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>( c_{ij} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( e_{ij} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( q_{ij} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Constraints:** Only one DV technique can be selected for each step:

\[
\sum_{j=1}^{3} x_{1j} \leq 1
\] (3.1)

\[
\sum_{j=1}^{3} x_{2j} \leq 1
\] (3.2)

\[
\sum_{j=1}^{3} x_{3j} \leq 1
\] (3.3)

\[
\sum_{j=1}^{3} x_{4j} \leq 1
\] (3.4)

\[
\sum_{j=1}^{3} x_{5j} \leq 1
\] (3.5)

**Objective:** Find optimal combinations with three objectives: quality, efficiency and cost:

**Quality (P1):** \( Max \sum_{i=1}^{5} \sum_{j=1}^{3} q_{ij} x_{ij} \) (3.6)

**Efficiency (P2):** \( Max \sum_{i=1}^{5} \sum_{j=1}^{3} e_{ij} x_{ij} \) (3.7)

**Cost (P3):** \( Max \sum_{i=1}^{5} \sum_{j=1}^{3} q_{ij} x_{ij} \) (3.8)

**Goal Programming:** Goal programming (Dylan et al., 2010) may be used to determine the weights of the three goals:
\[
\text{Min } P_3 \sum_{i=1}^{5} \sum_{j=1}^{5} c_{ij} x_{ij} - P_1 \sum_{i=1}^{5} \sum_{j=1}^{5} q_{ij} x_{ij} - P_2 \sum_{i=1}^{5} \sum_{j=1}^{5} e_{ij} x_{ij}
\]
Chapter 4

Simulation of the Workflow Problem

4.1 Goal of Simulation

In this chapter, a simulation model is built for the purpose of comparing the total workflow efficiency with and without DV techniques. A further analysis based on the simulation results is also presented in 4.3.

4.2 Model Assumptions and Development

Several assumptions are made in simulating the healthcare workflow. On the basis of the assumptions, a conceptual model is developed, and a model is construction in Simio where tasks are represented as servers and are processed in a temporal view. The simulation results provide us with the process time for each task and for the overall workflow.

Step 1: Assumptions

1) Each server represents a single task in the workflow problem.

2) All the data are from the literature.

3) A certain probability is assigned to the path from question to diagnosis1 and the path from question to test. Another probability is assigned to the path from diagnosis1 to suggestion and the path from diagnosis1 to diagnosis2.

4) When patients enter the workflow, no interruptions are allowed (i.e., no balking).

5) There is no upper bound on the waiting time of each patient (i.e., no patient leaving during the waiting time).
6) All physicians in the system can share information with each other and have ability to treat all the patients.

Step 2: Performance Metrics

The performance metric of interest is the expected total time that each patient spends in the workflow. It is used to assess the impact of the DV intervention.

Step 3: Model Logic

Upon patient arrival, a series of questions are asked and recorded as evidence, followed by the diagnosis by physicians. There is a probability that the patient is in a particular condition or state. He or she may be able to leave the hospital after consultation with the physician. With another probability, the patient needs further test to determine his or her disease. In this case, the patient will have the required testing and then wait for the diagnosis by the physician. After the second diagnosis by the physician, a decision is made about whether the patient may leave the hospital without any treatment. If the diagnosis indicates that the patient needs further treatment, he or she remains in the hospital. Otherwise, the patient can leave the hospital after getting certain suggestions from the physician. The overall process can be summarized in a flowchart as shown in Figure 4.1.
Step 4: Simulation Model

The simulation model corresponds to the model logic in Figure 4.1. Each server represents a task conducted between the patients and the physicians, such as questions, diagnosis1, diagnosis2, etc. The source (enter) and the sink (exit) represent and monitor the number of patients arriving and leaving the hospital respectively. The arrival rate is set at a larger value to ensure that there won't be any idle time for the physician after the patient enters the hospital. The arrival rate can be seen in Table 4.1.

The passing rules for all servers are set as First In First Out (FIFO), meaning that the patients who enter the server first are sent out first. The dispatching rule can be changed based on specific situations in the healthcare practice scenarios. For example, the patients can be divided into different groups according their severity (i.e., I, II, III, IV and V), representing different priority. The dispatching rules will be set as Smallest Value First (SVF) accordingly to distribute the patients according to the severity of their disease, with the most serious patients being treated firstly. In our simulation model, we simplify the case by setting the passing rule as FIFO. The process times are established based on typical values found in the literature.
Table 4.1 Input Table

<table>
<thead>
<tr>
<th></th>
<th>inter-arrival time (hr)</th>
<th>questions (hr)</th>
<th>diagnosis1 (hr)</th>
<th>diagnosis2 (hr)</th>
<th>test (hr)</th>
<th>treatment (hr)</th>
<th>suggestions (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DV</td>
<td>Random. Exponential (0.1)</td>
<td>Random. Exponential (0.1)</td>
<td>Random. Uniform (0.1, 0.05)</td>
<td>Random. Exponential (0.03)</td>
<td>Random. Uniform (0.25, 0.15)</td>
<td>Random. Triangular (0.1, 0.2, 0.3)</td>
<td>Random. Uniform (0.05, 0.01)</td>
</tr>
<tr>
<td>Non DV</td>
<td>Random. Exponential (0.1)</td>
<td>Random. Exponential (0.09)</td>
<td>Random. Uniform (0.07, 0.05)</td>
<td>Random. Exponential (0.03)</td>
<td>Random. Uniform (0.15, 0.15)</td>
<td>Random. Triangular (0.1, 0.2, 0.3)</td>
<td>Random. Uniform (0.05, 0.01)</td>
</tr>
</tbody>
</table>

Servers are connected by different paths. The route problem can be monitored according to the assignment of probabilities to the paths in the Simio model. For example, when a patient is about to leave diagnosis1, there are two choices for him, diagnosis2 or test. At this point, the two paths starting from diagnosis1 are assigned two different link weights, which control the probability for each path. The selection weights for Path 4 and Path 7 are set as 0.4 and 0.6 respectively.

The Simio models remain the same for both the workflow with DV interventions and the one without DV interventions. The arrival rates for the two workflows are also set at the same value to ensure the comparisons are made by the same standard. The only difference lies in the process time for each task where different coefficients are assigned to represent the different efficiencies in the workflow.
We assume that at the beginning of the simulation, there are no patients in the hospital. The maximum arrivals in the source (*enter*) are set as infinity to ensure that the stopping condition is controlled by the run length (i.e., 10 hours). The entities per arrival are set as 1, indicating that only one patient arrives at hospital per arrival. The initial capacities for all the servers are set as 1, which means only one patient can be treated at each time. The input and output buffers’ capacities for all the servers are set as infinity and there are no failures (i.e., no breakdown time for any servers) during the running of the model in Simio.

Step 5: Results

After running the simulation model for 10 hours, the simulation result report was generated in Figure 4.3 and Figure 4.4. As we can see from the result report, the performance measure of the simulation, which is the average time in system, is approximately two hours for...
the workflow with DV interventions, about 10 minutes less than that of the workflow without DV interventions. The difference between the simulation result for workflow with DV and that without DV is 4.85%.

As for the individual tasks within the workflow, the process time and utilization rate are selected as the measurements to compare the two workflows. From the results, we can see that tasks such as questions, tests, and treatment have higher utilization rates, while the tasks such as suggestions, diagnosis1 and diagnosis2 have relatively lower utilization rates. The results are consistent with the real world situation because the first three tasks are required for all patients regardless of what diseases they contract or the level of seriousness. However, the remaining tasks are assigned to patients based on their individual situations.
Figure 4.3 Workflow with Intervention of Data Visualization Techniques
Figure 4.4 Workflow without Intervention of Data Visualization Techniques

4.3 Analysis and Discussion

According to the results shown above, we can conclude that the workflow with DV interventions has a higher efficiency compared with the one without the DV interventions in terms of process time for the patients and physicians. However, the process time from simulation results for each task only captures the efficiency for the workflow problem. The other two criteria, quality and cost, are not taken into consideration in this simulation. This limitation is partly due to the fact that Simio is mainly designed for simulating the time related flow problems with little emphasis on other attributes for each task. Therefore, the simulation results can only provide us an aspect of insights for the performance of DV interventions in a healthcare delivery workflow.
In order to further test the workflow, other research methods are required to compare the results from aspects such as quality, efficiency and cost both for patients and physicians.

For the quality criteria, experiment design need to be conducted to testify the percentage of misunderstandings, overall understanding of the disease, the time span for concentration, and the switch of tasks for both patients and physicians.

For the efficiency criteria, the time spent for each patient in the workflow and the number of patients treated by each physician can be seen as the efficiency criteria. However, certain assumptions have to be made to make the result more accurate. For example, patients with different severity will have different treatment time, so it makes more sense if the patients with the same severity are compared in the same group.

The cost criteria include the implementation cost of DV techniques, the cost of training of using the DV techniques, and the cost for errors, etc. It requires further experiments to test its performance by using the real world data.

Based on our analysis, the lack of real world data is one of the limitations for our simulation. Another limitation lies in the fact that our subject is a large and complex system (i.e., healthcare system), including multiple criteria and different stages. Therefore, other methodologies (e.g., system dynamics) should be applied to deal with such complex systems with multiple relationships. The results we generated by Simio can be used to evaluate the efficiency of the healthcare delivery workflow. In addition, it can also be treated as a reference for performance evaluation and be used to compare with other results generated by other methodologies.
Chapter 5

Case Study

In this chapter, an application of DV techniques is discussed in detail. Based on the complexity of the diagnosis and treatment cycle, tuberculosis (TB) is selected for study. Some background on TB is provided, followed by a detailed description of the workflow for each stage. A series of customized DV interventions are displayed for TB treatment and management to assist the communication between patients and physicians. Finally, the optimization model developed in Chapter 3 is applied to determine the best DV technique for each stage.

5.1 Background on TB

TB is the second most communicable disease that causes death around the world, after HIV/AIDS (Frieden et al., 2003). According to the Centers for Disease Control and Prevention (CDC), TB is an infectious disease caused by germs spreading from person to person through the air. It usually attacks the lungs, but it can also affect other parts of body (CDC, 2011). In order to help patients better understand TB, a selected set of customized questions about TB are categorized into three groups covering TB, diagnosis and treatment, and patient education as shown in Figure 5.1. These questions are addressed by the DV techniques introduced in this chapter.
According to Frieden (2003), some people have a higher risk of getting TB than others, such as people who are elderly, infants and those who have weakened immune systems. In addition, the rate of TB is related to the environment and other factors such as the rate of HIV infections, the number of homeless people, and the appearance of drug-resistant strains of TB (Frieden et al., 2003).

**Figure 5.2 High Risk Groups**

### 5.2 TB Workflow

In Chapter 3, a general workflow in health care system is presented to show the main sequential stages from asking questions and ordering tests to the diagnosis of the disease, to the treatment plans, and finally to the patient education stages. This section explains the four stages in TB workflow in detail and provides the relationship for each stage.
5.2.1 Questions and Tests

In this stage, patients and physicians meet for the first time, so we assume that the physician has no background knowledge and information about this patient. Thus, in order to make informed decisions, all the required information needs to be obtained from asking questions and performing tests based on each patient’s condition.

The communication between the patients and physicians starts from the standard questionnaire, including the basic information about the patient, medical history, family history, and the reasons for healthcare visit. A physical examination may also be conducted to screen out some factors. Then, a set of more detailed and customized questions are asked sequentially by the physician to determine what kind of disease the patient might have. After asking both the standard and customized questions, the physician will have a potential disease list, which includes all the possible diseases at this point and thus needs further tests. In this case study, there are three types of TB that require different combinations of tests to differentiate. Different tests are ordered based on the patient’s condition and the physician’s experience and judgment.

![Diagram of TB testing process]

Figure 5.3 Test for Three Types of TB

57
5.2.2 Diagnosis

In the diagnosis stage, the main purpose is to confirm the presence of the disease (distinguishing from other possibilities). All the information and test results have been collected from the previous stage, such as the symptoms, the signs, and the test results as shown in Figure 5.4. The physician summarizes and synthesizes all the useful information by using their professional knowledge of TB, and then makes the final decision for the patient. In this stage, the communication starts from this point. The physician is responsible for answering all the potential questions that may concern patients to help them better understand the disease and be more adherent in the treatment cycle.

Figure 5.4 Diagnosis

5.2.3 Treatment

In the treatment stage, the main goal is to find out the best treatment plan for the patient to recover in terms of quality, time, and cost. Therefore, it is necessary to include the patient in the
decision making process. One of treatment plans for TB patients is provided in Figure 5.5, including the medical treatment for patients with different severity and the instruction for different medicines. One aspect of the treatment stage for TB is that treatment plans are typically adjusted about every two weeks according to patients’ condition because some of the medicine may cause side effects on the liver. Therefore, we also need to incorporate these factors into the evaluation of treatment plans when making the decisions.
### Treatment

#### Goal

Kill growing and semidormant bacilli

#### Categorization of patients

<table>
<thead>
<tr>
<th>Severity I</th>
<th>Severity II</th>
<th>Severity III</th>
</tr>
</thead>
<tbody>
<tr>
<td>New cases with severe form</td>
<td>Previously treated case</td>
<td>New cases with less severe form</td>
</tr>
<tr>
<td>2 months HRZE(3) or HRZS(3)</td>
<td>2 months HRZE or 1 month HRZE(3)</td>
<td>2 months HRZE(3)</td>
</tr>
<tr>
<td>2 months HRZE or HRZS</td>
<td>2 months HRZE or 1 month HRZE</td>
<td>2 months HRZE</td>
</tr>
<tr>
<td>4 months HR (3)</td>
<td>5 months HRE(3)</td>
<td>4 months HR(3)</td>
</tr>
<tr>
<td>4 months HR</td>
<td>5 months HRE</td>
<td>4 months HR</td>
</tr>
<tr>
<td>6 months HE</td>
<td>6 months HE</td>
<td>6 months HE</td>
</tr>
</tbody>
</table>

#### Drugs to kill bacilli

<table>
<thead>
<tr>
<th>Drugs to kill bacilli</th>
<th>When and how to use</th>
<th>Adverse reactions</th>
<th>Recommended regular monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isoniazid</td>
<td>In the first phase</td>
<td>Increases in hepatic enzymes; hepatitis; peripheral neuropathy etc.</td>
<td>Hepatic function tests (if baseline abnormal)</td>
</tr>
<tr>
<td>Pyrazinamide</td>
<td>Reduce the duration of treatment from 9 to 6 months</td>
<td>Gastrointestinal upset; hepatotoxicity; hyperuricaemia; arthralgias; gout, rash</td>
<td>Hepatic function tests (if baseline abnormal)</td>
</tr>
<tr>
<td>Ethambutol</td>
<td>When initial drug resistance is present and the burden of organisms is high</td>
<td>Diminished red-green colour discrimination; decreased visual acuity; auditory and renal toxicity; hypokalemia; hypomagnesaemia</td>
<td>Hepatic function tests (if baseline abnormal)</td>
</tr>
<tr>
<td>Rifampicin</td>
<td>Directly observed to prevent emergence of resistance to rifampicin</td>
<td>Hepatitis, fever, thrombocytopenia, flu-like syndrome</td>
<td>Hepatic function tests (if baseline abnormal)</td>
</tr>
<tr>
<td>Streptomycin</td>
<td>Directly observed to prevent emergence of resistance to rifampicin</td>
<td>Auditory and renal toxicity; hypokalemia; hypomagnesaemia</td>
<td>Audiometry, renal function, and electrolytes</td>
</tr>
</tbody>
</table>

**Figure 5.5 Treatment**
5.2.4 Patient Education

In the patient education stage, the main task is to impart information to patients to help them have a better understanding of their disease and treatment methods, and thus improve their health status and enhance their adherence. For patients who are diagnosed with TB, the health information may include the time schedule for medicine, the suggested life style and the foods that should be avoided.

5.3 Data Visualization

The DV techniques developed in Chapter 3 are used for TB to help enhance the quality of communication and decision making process between patients and physicians. As can be seen from Figure 5.6, TB usually consists of a treatment cycle due to its unique characteristics (i.e., relatively long time to cure and infectious). The DV technique for each stage is presented in this cycle to help patients and physicians’ communication.
Figure 5.6 Data Visualization Display for TB
5.4 Optimization

The optimization model developed in Chapter 3 is applied in this case study to determine the optimal sequence of the DV interventions in the workflow.

Assumptions:

1. The quality and efficiency criteria will be measured by scores obtained from user studies.
2. The cost criteria will be measured by the complexity of the techniques based on domain expertise.
3. Only one DV technique can be selected for each stage.
4. Scores for quality, cost and efficiency will be assigned to each DV technique.

Define Variables:

\[ x_{ij} = \begin{cases} 1 & \text{if at } i\text{th stage the } j\text{th DV technique is chosen} \\ 0 & \text{otherwise} \end{cases} \]

\( c_{ij} \): The cost for \( j \)th DV techniques at \( i \)th stage

\( e_{ij} \): The efficiency score for \( j \)th DV techniques at \( i \)th stage

\( q_{ij} \): The quality score for \( j \)th DV techniques at \( i \)th stage

\( i = 1,2,3,4,5; j = 1,2,3 \)

Table 5.1 Coefficient Table

<table>
<thead>
<tr>
<th></th>
<th>( i )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( c_{ij} )</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>( e_{ij} )</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>( q_{ij} )</td>
<td>5</td>
<td>3</td>
<td>7</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>( c_{ij} )</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>( e_{ij} )</td>
<td>3</td>
<td>7</td>
<td>8</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>( q_{ij} )</td>
<td>2</td>
<td>8</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>( c_{ij} )</td>
<td>1</td>
<td>5</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>( e_{ij} )</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>( q_{ij} )</td>
<td>5</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td>7</td>
</tr>
</tbody>
</table>
**Constraints:** Only one DV technique can be selected for each step.

\[ \sum_{j=1}^{3} x_{1j} \leq 1 \]  \hspace{1cm} (5.1)\\
\[ \sum_{j=1}^{3} x_{2j} \leq 1 \]  \hspace{1cm} (5.2)\\
\[ \sum_{j=1}^{3} x_{3j} \leq 1 \]  \hspace{1cm} (5.3)\\
\[ \sum_{j=1}^{3} x_{4j} \leq 1 \]  \hspace{1cm} (5.4)\\
\[ \sum_{j=1}^{3} x_{5j} \leq 1 \]  \hspace{1cm} (5.5)\\

\( x_{ij} \geq 0 \) and all \( x_{ij} \) are integers for \( i = 1,2,3; j = 1,2,3 \)

**Objective:** Find optimal combinations with three objectives: quality, efficiency and cost:

Quality (P₁): \( \text{Max} \ \sum_{i=1}^{5} \sum_{j=1}^{3} q_{ij} x_{ij} \)  \hspace{1cm} (5.6)\\

Efficiency (P₂): \( \text{Max} \ \sum_{i=1}^{5} \sum_{j=1}^{3} e_{ij} x_{ij} \)  \hspace{1cm} (5.7)\\

Cost (P₃): \( \text{Min} \ \sum_{i=1}^{5} \sum_{j=1}^{3} c_{ij} x_{ij} \)  \hspace{1cm} (5.8)\\

**Programming:** Goal programming (Dylan et al., 2010) is used to determine the arrangement of these three goals: quality (P₁), efficiency (P₂) and cost (P₃). The weights assigned in this example are (3, 2, 1) and (1, 5, 7) respectively.

\[ \text{Min} \ P₃ \sum_{i=1}^{5} \sum_{j=1}^{3} c_{ij} x_{ij} - P₁ \sum_{i=1}^{5} \sum_{j=1}^{3} q_{ij} x_{ij} - P₂ \sum_{i=1}^{5} \sum_{j=1}^{3} e_{ij} x_{ij} \]  \hspace{1cm} (5.9)

**5.5 Results**
The result obtained by Solver is displayed in Table 5.2 and Table 5.3. The objective value equals to 147 and 124 respectively. The optimal solution is highlighted in Table 5.2 and Table 5.3, representing the chosen DV techniques for each stage.

### Table 5.2 Optimization Result with P=(3, 2, 1)

<table>
<thead>
<tr>
<th></th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
<th>Stage 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>DV1</td>
<td>x11</td>
<td>x12</td>
<td>x13</td>
<td>x14</td>
<td>x15</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>DV2</td>
<td>x21</td>
<td>x22</td>
<td>x23</td>
<td>x24</td>
<td>x25</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DV3</td>
<td>x31</td>
<td>x32</td>
<td>x33</td>
<td>x34</td>
<td>x35</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Sum</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 5.3 Optimization Result with P=(1, 5, 7)

<table>
<thead>
<tr>
<th></th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
<th>Stage 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>DV1</td>
<td>x11</td>
<td>x12</td>
<td>x13</td>
<td>x14</td>
<td>x15</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>DV2</td>
<td>x21</td>
<td>x22</td>
<td>x23</td>
<td>x24</td>
<td>x25</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>DV3</td>
<td>x31</td>
<td>x32</td>
<td>x33</td>
<td>x34</td>
<td>x35</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Sum</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

#### 5.6 Analysis and Discussion

The application of DV in the TB healthcare workflow provides us with an example of how these techniques can be applied in the case of a particular disease. Based on the workflow we developed in Chapter 3, the information content in TB care is studied and categorized for each stage in the workflow, including the definition, the signs, the diagnosis, and the treatment. The information content in TB care is then displayed by using the techniques developed in Chapter 3. All the data and information about TB are from the literature and analysis of available reports. The DV intervention at each stage helps integrate, synthesize, and then display the information...
about TB in a user friendly way. Instead of presenting the information purely in text and without performing any processing, we process the data at first, and then use DV techniques to display them for the patients. Since the visualized information is more self-explanatory and conveys the main point at each stage, it reduces the time to convey the information, the probability of misunderstanding during the communication between the patients and the physicians.

Since we are concerned about the overall performance of the workflow in healthcare system with DV interventions, our purpose is to find the global optimal solution in the workflow in terms of quality, efficiency and cost. The optimization model is applied with these three criteria of interest. As can be seen from the results and the highlighted coefficients in Table 5.4, the DV techniques with higher quality coefficients and lower cost coefficients will have a higher chance to be selected, which is consistent with the weights distributed to these three criteria. As we change the value of P for each criterion, the results will change accordingly. As is shown in Table 5.4 and Table 5.5, the selected DV techniques for the last two stages are different due to the difference in the value of P, which means the value of P for each criterion determines the selection of DV techniques in each stage. Therefore, the value of P should be determined collaboratively by both the patients and physicians in terms of quality, efficiency and cost.

<table>
<thead>
<tr>
<th>j</th>
<th>i</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>c_{ij}</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>e_{ij}</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>q_{ij}</td>
<td>5</td>
<td>3</td>
<td>7</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>c_{ij}</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>e_{ij}</td>
<td>3</td>
<td>7</td>
<td>8</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>q_{ij}</td>
<td>2</td>
<td>8</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>c_{ij}</td>
<td>1</td>
<td>5</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>e_{ij}</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>q_{ij}</td>
<td>5</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td>7</td>
</tr>
</tbody>
</table>
Table 5.5 Highlighted Coefficient Table for P=(1, 5, 7)

<table>
<thead>
<tr>
<th>j</th>
<th>i</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$c_{ij}$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>$e_{ij}$</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>$q_{ij}$</td>
<td>5</td>
<td>3</td>
<td>7</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>$c_{ij}$</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>$e_{ij}$</td>
<td>3</td>
<td>7</td>
<td>8</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$q_{ij}$</td>
<td>2</td>
<td>8</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>$c_{ij}$</td>
<td>1</td>
<td>5</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>$e_{ij}$</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>$q_{ij}$</td>
<td>5</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td>7</td>
</tr>
</tbody>
</table>

In this case study, due to insufficient information for the performance of the DV interventions, the coefficients for each criterion are estimated according to the surveys and experiments conducted by other researchers. Future studies and surveys are required to determine the coefficients for each criterion. They could be determined by the experts and professional researchers in DV area, where rating and ranking methods could be applied as an evaluation tool (Ravindran, 2008). Other evaluation methods could also be applied to test the performance of the DV interventions in TB workflow. System dynamics is an approach that can deal with the behavior of complex systems dynamically (Forrester, 1971). It can help explain the relationship among the three criteria in the workflow over time, so that we can have a better understanding of the structure and change of the complex workflow problem in healthcare system. System dynamics and the potential for its use in research in this area is further discussed in Chapter 6. Despite these limitations, the optimization model presented here provides insights about the impact of DV for the physician-patient encounter workflow.
Chapter 6

Conclusion and Future Research

6.1 Conclusion

The wide range of types, structures, and uses of data in the healthcare system calls for new approaches for system improvement. The concerns and attention from both the government and the public also set high expectations for high quality care and efficient healthcare workflow. At the same time, DV approaches have developed so fast in recent decades that they have been deployed in a variety of applications in and beyond healthcare. With these challenges and opportunities, we see the possibilities of combining DV approaches with the workflow structures in the healthcare system to achieve the goal of enhancing the overall quality and efficiency of the workflow. In particular, in this study we were concerned with the overall performance of the physician-patient encounter workflow that may integrate DV interventions. Accordingly, DV techniques were directed and developed at each stage to integrate, synthesize, and display the information for a certain disease condition in a patient-centric manner. Instead of presenting the information in the more commonly used text or technical format, we propose processing the data and information, and then using the selected DV techniques to display this information for the patients. Since the visualized information is well-designed to convey the main point at each stage, it should greatly reduce the probability of misunderstandings in communication between physicians and patients. Given the low rates of health literacy, and association with poorer disease outcomes, engaging DV techniques and overcoming literacy barriers would be expected to improve health outcomes.

Starting with the expectations from patients and physicians, we first investigated the questions that patients may be interested in when they come to a hospital, followed by a possible solution set for each question that involved DV techniques. The workflow was developed from
the input stage to the treatment cycle stage, considering each step in the decision making process. Based on the solution set obtained from the previous step, DV solutions were mapped to the stages in the newly designed workflow. The DV techniques were then described in detail based on characteristics, functions and advantages, with a focus on the specific display and how it could help patients and physicians better communicate.

An optimization model was formulated based on the framework of the newly designed workflow, focusing on identifying one DV technique for each stage so that the overall objective is optimized. Since there are three criteria – quality, efficiency and cost – for this optimization model, goal programming was used to combine different criteria into one single overall criterion. The three criteria can be assigned different weights based on patients’ conditions and requirements, emphasizing the concept of patient-centric healthcare. A simulation analysis conducted using Simio provided us with insights about the performance of the workflow with DV intervention and that without DV intervention. The results showed that the workflow with DV interventions has a relatively shorter processing time.

A case study on TB disease was presented to show how this methodology can be implemented. The case study explored the design of the workflow, the utilization of DV techniques, and the development of the goal programming model for TB. Not surprisingly, the results showed that the assignment of different weights for the three criteria changes the optimal deployment. However, we did gain insight into what further work is required to evaluate and validate the performance of the new workflow.
6.2 Future Work

This research forms an initial step into the area of DV interventions in healthcare delivery workflow. Future research may be built upon the methodology presented here in order to further evaluate the performance of the workflow with DV interventions. With the development of the presented DV techniques, more advanced DV techniques may be added to the workflow as a candidate to be selected for certain stages. Currently, in our demand investigation stage, most of the questions and issues were obtained from a review of the literature. However, the results would be more refined using first-hand interviews with patients, physicians and healthcare providers.

With respect to DV, different techniques could be applied for different types of diseases. Therefore, in order to better utilize the DV techniques in the healthcare workflow, further research can be focused on customized DV techniques for each type of disease. The methodology could also be extended with value stream mapping using real data collected from hospitals, so that more insightful and meaningful results can be obtained for the performance of the workflow.

The model we built for the optimization problem depends several assumptions and coefficient selections. Therefore, future work could relax some of the assumptions and redesign the method for determining the coefficients. For example, it is possible that future research incorporates the quality, efficiency and cost coefficients in the questionnaires or surveys and lets experts and physicians determine the value for each coefficient by using a rating method. In addition, a different approach could be used to evaluate the performance of the quality, efficiency and cost for the workflow instead of using the current goal programming method and simulation study formulated by Simio. The simulation by Simio performs well when it is used to capture the time related issues in a linear fashion. However, when it comes to multiple criteria other options may be appropriate.
System dynamics, which is briefly introduced in Chapter 5, has been applied in large and complex systems to show the interdependencies among different aspects and criteria in a non-linear fashion, which is more realistic compared with the linear and open-loop mode of intervention (Morecroft, 1997). In our optimization model, there are more than two conflicting criteria. The selection of different DV techniques contributes to the changes in the criteria (i.e., quality, efficiency and cost), which clearly impacts the overall performance of the workflow. The system dynamics approach is able to represent the whole system, showing the connections and relationships for each criterion and how changes in one DV technique might propagate to others and return (Morecroft, 1997). After a system dynamics simulation model is built for the workflow problem, the performance of the simulation can then be investigated over time from interlocking feedback loops. Obviously, the advantages for this approach lie in the fact that it expresses the interconnected relationships in the system in a concise and visual way. Moreover, it displays the changes both interactively and dynamically, capturing the changes for each criterion and providing us important facts about the performance of the workflow.

We also note the important intersection between DV and Data Mining (DM). DV techniques can help transform raw data and summary statistics into tangible information that can be communicated both to patients and physicians. For example, such techniques can be applied to rapidly and meaningfully allow physicians and entire healthcare organizations an overview of population-level care quality and disease indicators, as necessitated by recent healthcare reform. In addition, while raw data and summary statistics provide a solid foundation for communicating information (e.g., the presence and severity of a disease), DM techniques can be employed to discover the hidden, previously unknown knowledge about underlying reasons for healthcare problems (e.g., discovering not only the presence or severity of a disease, but also the latent factors and trends that cause the disease itself).
The coupled use of DV and DM therefore presents an exciting research opportunity to provide a platform for communicating complex models to both patients and doctors for decision making purposes. For example DM Unsupervised Learning models could provide patients with insight into the similarity of their disease with another common or uncommon disease. DM Supervised Learning models could predict the chance of a patient's family members also contracting the disease. DV techniques would enable these complex models to be communicated in a clear and concise manner by mapping mathematical models into visual communication output.

Finally, we believe that DV and DV/DM interventions in the healthcare workflow are promising future research directions in improving the overall quality and efficiency of the healthcare delivery system. With the concerns and efforts from patients, physicians, and researchers in healthcare area, deeper investigation and understanding of workflow in healthcare, and the advanced DV techniques that are developing every day, we can expect many improvements toward higher-quality healthcare delivery workflow in the near future.
APPENDIX

Microsoft Excel 14.0 Answer Report
Worksheet: [OPTIMIZATION.xlsx]Sheet1
Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine
- Engine: Simplex LP
- Solution Time: .016 Seconds.
- Iterations: 5 Subproblems: 0

Solver Options
- Max Time 100 sec, Iterations 100, Precision 0.000001
- Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 5%, Solve Without Integer Constraints, Assume NonNegative

Objective Cell (Max)
<table>
<thead>
<tr>
<th>Cell</th>
<th>Name</th>
<th>Original Value</th>
<th>Final Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$28</td>
<td>Q</td>
<td>113</td>
<td>124</td>
</tr>
</tbody>
</table>

Variable Cells

<table>
<thead>
<tr>
<th>Cell</th>
<th>Name</th>
<th>Original Value</th>
<th>Final Value</th>
<th>Integer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$8</td>
<td>x11</td>
<td>1</td>
<td>1</td>
<td>Contin</td>
</tr>
<tr>
<td>$C$8</td>
<td>x12</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$D$8</td>
<td>x13</td>
<td>1</td>
<td>1</td>
<td>Contin</td>
</tr>
<tr>
<td>$E$8</td>
<td>x14</td>
<td>1</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$F$8</td>
<td>x15</td>
<td>0</td>
<td>1</td>
<td>Contin</td>
</tr>
<tr>
<td>$B$10</td>
<td>x21</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$C$10</td>
<td>x22</td>
<td>1</td>
<td>1</td>
<td>Contin</td>
</tr>
<tr>
<td>$D$10</td>
<td>x23</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$E$10</td>
<td>x24</td>
<td>0</td>
<td>1</td>
<td>Contin</td>
</tr>
<tr>
<td>$F$10</td>
<td>x25</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$B$12</td>
<td>x31</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$C$12</td>
<td>x32</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$D$12</td>
<td>x33</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$E$12</td>
<td>x34</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$F$12</td>
<td>x35</td>
<td>1</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>Cell</td>
<td>Name</td>
<td>Cell Value</td>
<td>Formula</td>
<td>Status</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
<td>------------</td>
<td>--------------</td>
<td>---------</td>
</tr>
<tr>
<td>$G$8</td>
<td>SUM OF 3</td>
<td>1</td>
<td>$G$8&lt;=1</td>
<td>Binding</td>
</tr>
<tr>
<td>$G$10</td>
<td>SUM OF 3</td>
<td>1</td>
<td>$G$10&lt;=1</td>
<td>Binding</td>
</tr>
<tr>
<td>$G$12</td>
<td>SUM OF 3</td>
<td>1</td>
<td>$G$12&lt;=1</td>
<td>Binding</td>
</tr>
<tr>
<td>$G$14</td>
<td>SUM OF 3</td>
<td>1</td>
<td>$G$14&lt;=1</td>
<td>Binding</td>
</tr>
<tr>
<td>$G$16</td>
<td>SUM OF 3</td>
<td>1</td>
<td>$G$16&lt;=1</td>
<td>Binding</td>
</tr>
</tbody>
</table>
Microsoft Excel 14.0 Answer Report
Worksheet: [OPTIMIZATION.xlsx]Sheet1
Result: Solver found a solution. All Constraints and optimality conditions are satisfied.
Solver Engine
Engine: Simplex LP
Solution Time: .031 Seconds.
Iterations: 5 Subproblems: 0
Solver Options
Max Time 100 sec, Iterations 100, Precision 0.000001
Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 5%, Solve Without Integer Constraints, Assume NonNegative

Objective Cell (Max)
<table>
<thead>
<tr>
<th>Cell</th>
<th>Name</th>
<th>Original Value</th>
<th>Final Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$28</td>
<td>Q</td>
<td>65</td>
<td>65</td>
</tr>
</tbody>
</table>

Variable Cells
<table>
<thead>
<tr>
<th>Cell</th>
<th>Name</th>
<th>Original Value</th>
<th>Final Value</th>
<th>Integer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$8</td>
<td>x11</td>
<td>1</td>
<td>1</td>
<td>Contin</td>
</tr>
<tr>
<td>$C$8</td>
<td>x12</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$D$8</td>
<td>x13</td>
<td>1</td>
<td>1</td>
<td>Contin</td>
</tr>
<tr>
<td>$E$8</td>
<td>x14</td>
<td>1</td>
<td>1</td>
<td>Contin</td>
</tr>
<tr>
<td>$F$8</td>
<td>x15</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$B$10</td>
<td>x21</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$C$10</td>
<td>x22</td>
<td>1</td>
<td>1</td>
<td>Contin</td>
</tr>
<tr>
<td>$D$10</td>
<td>x23</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$E$10</td>
<td>x24</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$F$10</td>
<td>x25</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$B$12</td>
<td>x31</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$C$12</td>
<td>x32</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$D$12</td>
<td>x33</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$E$12</td>
<td>x34</td>
<td>0</td>
<td>0</td>
<td>Contin</td>
</tr>
<tr>
<td>$F$12</td>
<td>x35</td>
<td>1</td>
<td>1</td>
<td>Contin</td>
</tr>
</tbody>
</table>

Constraints
<table>
<thead>
<tr>
<th>Cell</th>
<th>Name</th>
<th>Cell Value</th>
<th>Formula</th>
<th>Status</th>
<th>Slack</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$8</td>
<td>SUM OF 3</td>
<td>1</td>
<td>$G$8&lt;=$1</td>
<td>Binding</td>
<td>0</td>
</tr>
<tr>
<td>$G$10</td>
<td>SUM OF 3</td>
<td>1</td>
<td>$G$10&lt;=$1</td>
<td>Binding</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>SUM OF 3</td>
<td></td>
<td></td>
<td>Binding</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>----------</td>
<td>---</td>
<td>-----</td>
<td>---------</td>
<td>---</td>
</tr>
<tr>
<td>$G12$</td>
<td>SUM OF 3</td>
<td></td>
<td>$G12$ &lt;= 1</td>
<td>Binding</td>
<td>0</td>
</tr>
<tr>
<td>$G14$</td>
<td>SUM OF 3</td>
<td></td>
<td>$G14$ &lt;= 1</td>
<td>Binding</td>
<td>0</td>
</tr>
<tr>
<td>$G16$</td>
<td>SUM OF 3</td>
<td></td>
<td>$G16$ &lt;= 1</td>
<td>Binding</td>
<td>0</td>
</tr>
</tbody>
</table>
REFERENCES


Bloodbeat.org, 2013, Available at: http://bloodbeat.org/blood-pressure-chart/.


80


Ware, C., 2000, Information visualization Vol. 2, San Francisco: Morgan Kaufmann.


