AN ABSTRACT OF A DISSERTATION

UNIVERSAL SYSTEMATIC PLATFORM DESIGN FOR REAL-TIME PATIENTS FLOW CONTROL AND RESOURCE UTILIZATION IN HEALTHCARE ORGANIZATIONS

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Doctor of Philosophy Degree in Engineering

The cost of care (COC) and quality of care (QOC) have been a central issue in the US healthcare system for several years. Patient waiting time and resource allocation, which can be controlled in real time, are two of the major factors that affect the cost and quality of care in healthcare organizations (HCOs). The objective of this work is to minimize the patient waiting time, while maximizing the utilization of the resources for HCOs.

First, using the augmented System Engineering Multiple-Domain Matrix (SE-MDM) as well as a concept of traceability, it is shown that a network topology can be developed to provide a universal structure for a model-based approach to automate patient flow and resource utilization in any HCOs. Second, the problem of patients flow control and resource utilization is formulated as an optimization problem. The solution to this problem is an optimal global routing strategy (OGRS) to control the patient flow and resource utilization in real time for a HCO; assuming that the OGRS can be ideally implemented in a HCO. The solution is then extended to include practical situations, in which the ideal OGRS cannot be implemented due to realistic events such as delay in care time and unpredictable events such as arrival of patient with high risk factors, etc. The extension uses the concept of feedback control systems, where healthcare professionals provide the feedback information.

The proposed solution is tested, on the basis of scenarios that took place in an ambulatory HOC of visiting patients, and compared to that of the existing best performing solutions. It was found that the proposed solution outperforms these solutions by at least a fifteen-percent in terms of reducing patient waiting time and maximizing resource utilization. Considering the *ad hoc* approach currently practiced by the majority of hospitals, the total patient waiting times is about thirty-eight percent higher compared to the proposed solution. To show the effectiveness of the proposed feedback solution, simulation experiments were conducted for an ambulatory HCO of few patients to larger HOCs of 50 patients competing on different resource nodes. The results suggest that the proposed system is effective in tackling the uncertainties encountered in care delivery. The contribution of this work includes a universal structural model as well as systematic solution to the control problem of patients flow and resource utilization. Both contributions are applicable to any HOCs. Furthermore, the proposed control solution can be adopted to extend the theory of resource allocation for non-sequential tasks scheduling.

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DEDICATION

To my mother, Makbolah Alruwaili, for your enduring
love and great patience being worlds away.
To the memory of my father, Ali Alkhaldi, I am truly glad to know that he was happy to see this process started offering the support as well as plenty of unforgettable words of wisdom while being the best example possible in practice. I miss him every day.
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To my children Yousef, Hussain, Mohammed, Ali, Ruya and Thabit;
you all have been so wonderful and patient with your dad.
To every patient and his/her family. I am happy to put the time and efforts in this work hoping to improve their experiences while receiving care by healthcare organizations.

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LIST OF ABBREVIATIONS

AHRQ – Agency for Healthcare Research and Quality

CCT – Current Care Time

CMS – Center of Medicare and Medicaid

SDRN – Healthcare Service Delivery Resource Node (RN)

COC – Cost of Care

CT – Care Time

DOC – Demand of Care

DP – Dynamic Programming

ED – Emergency Department

GRS – Global Routing Strategy

HCOs – Healthcare Organizations

HCP – Healthcare Professional

HL – Health Level

HS – Hospital System

HSRs – Healthcare Services

LOS – Length of Stay

MT – Maximum Tolerance

OGRS – Optimal Global Routing Strategy

PA_j – the j^{th} Patient

PF – Priority Factor

POCs – Processes of Care

PP – Patient Care Plan

PRCT – Patient Remained Care Time

PWT – Patient Waiting Time

QOC – Quality of Care

RAS – Resource Allocation Systems

RCT – Remained Care Time

SS – Scheduling System

WHO – World Health Organization

CHAPTER 1

INTRODUCTION

1.1 Background Information

Medicine in the United States (US) has been leading worldwide in most fields of clinical research, training, and practice [1]. However, the cost of healthcare has been rising exponentially, Figure 1 [2], [3], [4], which has made the US healthcare system far more in spending per capita than other counties with similar life expectancy, Figure 2, [5]. This becomes a burden on the economy and the health and overall well-being of many Americans [1], [6]. In fact, a healthcare affordability problem already exists in the U.S. [1], [6], [7]. About 87 million Americans cannot afford healthcare coverage and are forced to skip or delay medical care, [6], [7]. This can lead to a higher COC at a later stage of their lives [8].

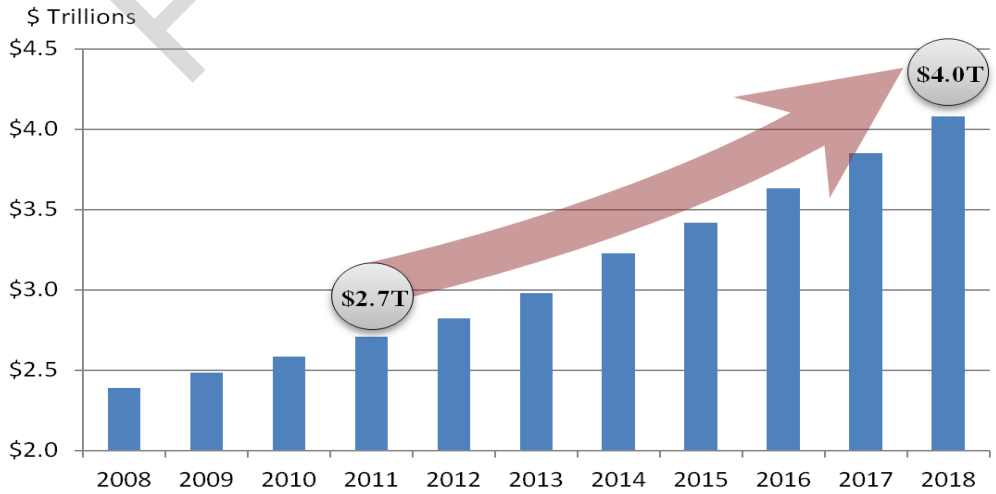

Figure 1: U.S. healthcare cost over the last decade [4], [5]

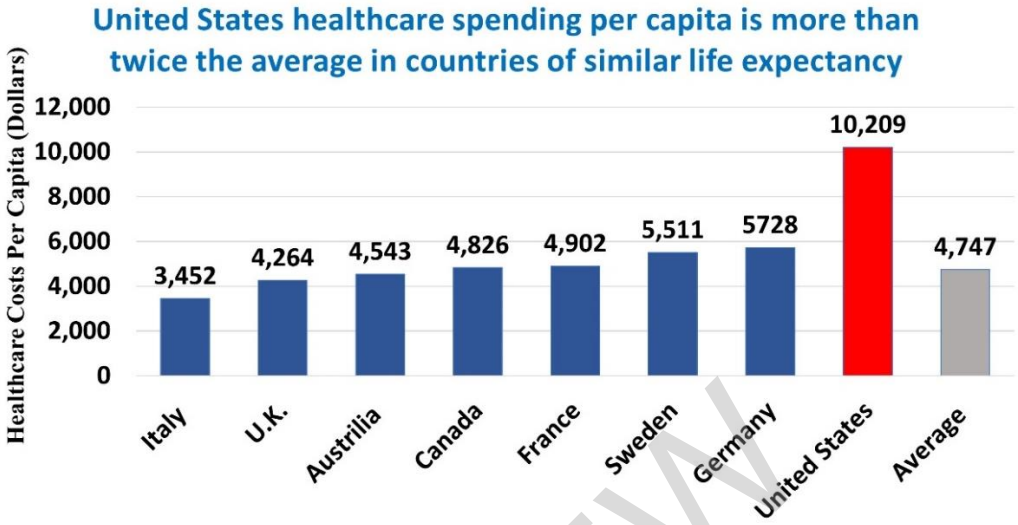

Figure 2: The U.S. Healthcare cost per capita compared with other countries [5]

This healthcare cost problem [8] has made the performance and value of healthcare delivery, rather than the volume of healthcare services, the focus in the current and future of healthcare systems [9], [10], [11].

As a consequence, there has been growing efforts and literature to make better use of healthcare resources and contain the COC [6], [11], [12], [13]. Attempts have been made [6], [8], [14] at several levels. At the government level, attempts have been mainly via creating a competitive environment among healthcare organizations (HCOs), deploying electronic health record for patients, and recommending policies and rules to avoid inducing higher cost [6], [15], [16], [17]. An example of this approach is by creating a healthcare organization compare program, which is a consumer-oriented website, [18], that provides information on how well healthcare organizations, particularly hospitals, provide care to their patients. This information can help consumers make informed decisions about

where to go for healthcare need. The information includes payment and value of care. At the HCO business level [14], cost reduction was mainly achieved by replacing physicians with nurse practitioners and/or physician assistants for certain patients [19]. This could adversely impact the QOC [6]. Other efforts being undertaken by governmental and non-governmental entities to contain costs and improve health outcomes in the US healthcare delivery system include: (1) requiring hospitals to be paid a fixed amount per admission, on the basis of the patient's principal diagnosis, regardless of how long the patient stays in the hospital, by the act: Tax Equity and Fiscal Responsibility Act [6], (2) increase collaboration among HCOs, such as mergers alliances, etc., which increase access to different healthcare services, medical technologies, etc., at a lower cost [10], (3) conduct prospective utilization review to determine the appropriateness of utilization before the care actually delivered to reduce over utilization of healthcare resources [6], [9], [20], [21]. These efforts are mainly focus on the policy and business levels and continuous evaluation of care delivery, but do not address operational inefficiencies during care delivery in HCOs.

Currently in the US, hospitals and other HCOs are responsible for their own healthcare delivery improvements [6], [9], [20], [22]. However, they are expected to report on at least 64 measures of quality to the Hospital Compare program [6], [15], to rate their overall quality and cost. Current practices to reduce cost and improve performance are limited to mainly applying relevant healthcare delivery standards, and/or protocols, such as that of assigning each patient upon arrival a severity index [23] to prioritize patients at higher health risk, which promotes faster interventions so that to avoid more health complications that may induce higher cost to address [2], [6], [24], [25]. These approaches fall short when addressing the costly waste that exists in virtually every HCO due to

operational inefficiencies [1]. As they are not designed [8], [19] to address operational problems found in HCOs [26], [27], including longer patient waiting times, underutilized resources, uncertainties in care delivery, such as significantly longer care times than expected, human factors (of health professionals and patients), and unpredictable events such as arrival of patient with high risk factors, etc., [11].

Currently, these problems are approached in HCOs using methods that study at-rest relevant data of the targeted HCO, such as the data of patients' duration of utilization of a resource, and may include information/assumptions based on age, gender, etc., to develop statistical distributions and provide models for analysis and/or prediction/estimation purposes only [11], [28], [29], [30], [31]. However, for real-time control use, they cannot provide continuous exact solutions. This is because there is a need of adaptive techniques (i.e., adapt: the uniqueness of each individual patient, and processes of care carried by different healthcare professionals) with the capability of handling event-driven actions, which is beyond the ability of the aforementioned approaches. On the other hand, in the engineering discipline, this real-world problem of uncertainties during the care delivery to patients can be effectively handled by capturing the system transitions at the physical world, with the ability to use this information to provide the exact solutions and real time automated decisions to meet desired outcomes [32].

Recently, the United States President's Council of Advisors on Science and Technology (PCAST), [20], National Academy of Engineering (NAE) jointly with Institute of Medicine (IOM), [1], and other engineering institutions in the US, [33], strongly encouraged systems engineering studies that could address interrelated quality and expenditure problems facing the healthcare delivery system today [11]. In a report by

PCAST, [20], entitled: "*Better Health Care and Lower Costs: Accelerating Improvement through Systems Engineering,"* it has been detailed that one of the main reasons that caused the continuous rapid increase in healthcare expenditure is due to daily operational inefficiencies within HCOs, which contribute to a significant portion of the healthcare costs that does not lead to better health or better care provision [1], [11], [20]. This gave rise to the concept of the *health value* of the healthcare services (HSRs) provided to patients by HCOs [11].

Improving the *health value* of the HRSs at the operational level has recently captured the attention of many researchers, [8], [11], [12], [30], [34], [35], [36], [37], [38]. Engineering related work to healthcare delivery has been used [39], [40], [41], [42], [43], [44], [45], [46], [47]. However, existing engineering real-time approaches are limited and scattered [48], [49], [50]. Furthermore, they are usually *ad-hoc* based and do not guarantee optimal solutions, customized solutions, and lack generalization and universality [50], [51], [52].

1.2 Research Motivation

Existing research related to COC reduction considers operational inefficiencies within HCOs to improve the health value of HSRs [11], [20], [43], [49], [53]. However, such efforts still lack universality and systematic approach that can bring improvement to the health value of HSRs in real time at the operational level [50], [51]. This research is a step toward providing a systematic approach to design and prototype a control system, which can be applied to any HCO, that is capable of improving the health value of HSRs

at the operational level. Furthermore, the proposed solution accounts for each patient's uniqueness and the inherent uncertainties in care delivery. It is worth noting that the improvement of the health value automatically helps reducing the COC, while maintaining or improving the QOC.

1.3 The Research Scope

The scope of this research is:

- Review of the state of the art.
- Develop a universal topological model that is applicable to any HCO.
- Use the patient waiting time and rate of resource utilization as the parameters that can be controlled in real time to help minimizing the COC. Then formulate the savings as an optimization problem.
- Solve the optimization problem.
- Development of the open-loop control prototype.
- Extend the solution to account for practical complications in HCOs.
- Preform simulation to show the effectiveness of the proposed solution, including the closed-loop feedback control.

1.4 The Outline of the Dissertation

In this research, we concentrate on designing a universal (i.e., applicable to any HCOs) control system that can effectively (i.e., aligning with the medical procedures) manage patient flow and resource allocation at the operational level. The control system must be capable of realizing each patient uniqueness while handling inherent uncertainties in care delivery and variation in care demands. For this, the dissertation contains and is organized as follows.

In Chapter 2, a literature review is provided. It includes background information about HCOs and care delivery in general. Relevant fundamental characteristics of healthcare systems are discussed. The similarities between the manufacturing system and a HCO is briefly covered. The discussion then addresses factors in HCOs that affect the COC and QOC. Factors that can be affected in real time are pointed out. This leads to the following section of the literature review, which detailed the effect of the patient waiting time and rate of resource utilization on the COC and QOC. The last section of the literature review surveys in detail the engineering work done to improve the timeliness of care and resource utilization.

In Chapter 3, a theoretical background is provided.

In Chapter 4, a universal structural model for HCOs is developed. The model development starts by defining the system major components, populated then by their elements, which directly related to delivering care at the operational level and contribute to the COC and QOC using a concept of traceability. Once the model is developed, it is