The Application of Model-Based Systems Engineering to the Practice of Clinical Medicine

Inas S. Khayal, Amro M. Farid

Abstract—Humanity is currently facing an unprecedented chronic disease burden. Healthcare needs have significantly shifted from treating acute to treating chronic conditions. Chronic diseases tend to involve multiple factors with complex interactions between them evidenced by the continually growing medical knowledge base. The health profession requires the ability to manage this rapidly deepening knowledge base to assimilate the lessons from research and clinical care experience by systematically capturing, assessing and translating it into the highest level of reliable care. A more systems approach to practicing medicine exists and is referred to as functional medicine. It takes into account the many subsystems in the human body and their many interactions. Although the science behind treating the patient as a system exists, the application of systems tools and techniques have not been utilized. It is only natural to begin to formalize the systems thinking using the established tools from the systems engineering field. Specifically, this paper is the first to contribute to the need for systems tools in the practice of clinical medicine and includes an example application of model-based systems engineering to clinical medicine.

Keywords: engineering systems, model-based systems engineering, managing knowledge complexity, improving health outcomes

I. INTRODUCTION

Humanity is currently facing an unprecedented disease burden. Although science and technology have allowed for significant advancements in health treatments, these treatments tend to be either 1.) curing, in many cases, of acute conditions or 2.) managing, at best, in cases of chronic conditions.

Healthcare needs have significantly shifted from treating acute conditions to treating chronic conditions. Given that 78% of total healthcare costs in the United States are due to chronic disease [7], clinical medicine needs to evolve and shift to specifically address the growing chronic disease epidemic.

Healthcare needs have significantly shifted from treating acute conditions to treating chronic conditions. Chronic conditions, unlike acute conditions, are particularly complex in that they tend to involve multiple factors with multiple interactions between them [1]. It is now established that combating chronic disease requires treating the patient more holistically [1]–[11]. This is currently a challenge given that the science of clinical medicine is fundamentally reductionist [1]. Many domains within the health field believe that the limit of reductionist thinking has been achieved and to understand the whole system one must start to apply systems thinking [1], [2], [4]–[6]. The paradigm shift to a more whole patient focus where the patient is treated as a system exists and is called functional medicine [7].

Functional medicine is a systems approach to practicing medicine. It takes into account the many subsystems in the human body and their many interactions. Although the science behind treating the patient as a system exists, the application of systems tools and techniques have not been utilized. It is only natural to begin to formalize the systems thinking using the established tools from the systems engineering field.

This paper first describes in Section II the background concepts of systems engineering, systems thinking in the health field and functional medicine and in Section III shows an example application of model-based systems engineering tools to clinical medicine.

II. BACKGROUND CONCEPTS

This section serves to introduce Section II-A describing the basic concepts of systems engineering related to complexity management in this work, Section II-B discussing the two health areas that have incorporated systems thinking and Section II-C includes a brief description of a systems approach to the practice of medicine: Functional Medicine.

A. Systems Engineering as Complexity Management

Systems engineering has emerged as an approach to synthesize and design large complex systems [12], [13]. That said, the process is also highly analytical in that it encourages the development of multiple complementary models to view, describe and communicate the system at varying levels of detail, abstraction and complexity.

The pertinent background concepts needed to understand systems engineering application to clinical medicine include:

Concept 1: system function, form, and their allocation
Concept 2: scale and scope
Concept 3: system properties (e.g. emergence, robustness, modularity, etc.)

These concepts can be applied to clinical medicine by utilizing the latest tools and techniques such as SysML.

1) Concept 1: System Function, Form, and their Allocation:

One of the most fundamental ideas in systems engineering is that a system has 1.) one or more functions, 2.) a physical form or structure, and 3.) their allocation as the mapping between the former to the latter. In the human body, there

I. S. Khayal is with the Faculty of the Dartmouth Institute of Health Policy & Clinical Practice and The Population Health Collaboratory @ D-H, Geisel School of Medicine at Dartmouth, Dartmouth College, Lebanon, NH 03766, USA.
A. M. Farid is with Faculty of Thayer School of Engineering at Dartmouth, 14 Engineering Dr, Hanover, NH 03755, USA and a Research Affiliate at the MIT Department of Mechanical Engineering, Cambridge, MA
exists high level functions (e.g. Assimilation (digestion & absorption), Defense and Repair, Energy Regulation, Elimination, Transport, Communication). As these functions occur they evolve an individual’s health “state”. These functions may be performed by specific primary high level structures of multiple-organ systems (e.g. Digestive System, Immune System, Cardiovascular System). Their mutual allocation or mapping is typically found in the knowledge base of medicine describing the functions of different organs and specific cells within them. This knowledge base is continually growing in size, detail, and complexity based on the continued research of scientists and experience of clinicians, ultimately providing a new big data application.

The complexity of systems, arises from the elemental size of a system. Systems with more than $7^n$ where $n \geq 3$ are considered fundamentally complex [14]. These elements can be parts of the system form or the system function. The human body is therefore complex not just by virtue of its trillions of cells but also by virtue of its many functions. Secondly, systems may also be classified as complex because these elements of function and form may interact. Finally, complexity arises when there is not a 1-to-1 exclusive mapping between elements of function and form.

2) Concept 2: Scale and Scope: Given the complexity of the human body, it is important to discuss the concepts of system scale and scope in the context of complexity management. The structure of the human body is organized into several (length) scales. In anatomy and physiology this is typically referred to as “Levels of Organizations”. In systems engineering terminology, there is the scale of the human body as a whole, followed by the 2nd highest level consisting of organ systems (e.g. nervous system), followed by individual organs (e.g. the brain), followed by organ structures (e.g. the cerebellum). The function of the human body is organized into several temporal scales ranging from long term effects (e.g. aging) to fleeting transients (e.g. neuron firing). Naturally, the complexity of a system grows with the number of scales under consideration. Therefore, it is often important to restrict the scope of study to a certain length or temporal scale in form or function; potentially leading to reductionist approaches. In contrast, systems tools facilitate the integration of multiple length or temporal scales so as to give both broad holistic views with lower resolution as well as detailed views at higher resolution. Consequently an individual’s health state can also viewed at varying levels of granularity associated with scale and scope.

3) Concept 3: System Properties: Complex interconnected systems exhibit system properties which would not necessarily have appeared from understanding the individual parts alone. For systems engineering, these are often called “life-cycle properties” and often take a grammatical form ending in “ility” (e.g. flexibility, reconfigurability) [13], [14]. The functional medicine literature (to be discussed in the next section) has paid particular attention to three such system properties namely: emergence, robustness, and modularity [7]. Emergence refers to the properties such as larger entities, patterns, and/or regularities that arise through interactions of smaller entities that themselves do not exhibit such properties and cannot be predicted from an understanding of the individual parts. This is primarily why medicine has started to recognize that a reductionist approach is not providing a realistic picture of some of the manifestations that can arise in people’s overall health [1], [15]. Robustness is the ability of a systems to maintain itself in the face of changing environmental conditions. Modularity refers to a system that is comprised of functional units working together to produce an outcome that cannot be produced by any of the units working independently [12], [16]. The more complex a system is, the more these properties manifest themselves in seemingly unpredictable ways.

4) SysML as a Complexity Management Tool: The systems engineering field has developed many tools and techniques to build and manage complex systems in defense, aerospace, and infrastructure. These are specifically intended to manage systems with many form and function elements, their interactions and their mapping. In recent years, the Systems Modeling Language (SysML) [17], [18] has emerged as a de facto standard of systems engineering process [13]. It is a graphical modeling language that facilitates the description of system function, form, and their allocation. It also supports parametric descriptions which may be used to develop quantitative models in coherent and well-organized ways. Therefore, SysML is chosen as an appropriate analytical tool in this work to model the complex, interconnected, and hetero-functional nature of human health with the ability to handle this big data application.

B. Systems Thinking in the Health Field

Similar to most of the sciences, the health field is based on reductionist thinking. Systems thinking tools and techniques have only recently gained strides within the biological and health fields. The domains where systems tools have been applied to the health field include 1.) Healthcare Systems Engineering and 2.) Systems Biology.

Healthcare Systems Engineering can be viewed as a health application of industrial engineering and operations research. Specific applications generally focus on improving hospital outpatient flow [19], [20], improving emergency room operations [21] and improving patient safety [22].

Systems Biology has a goal of understanding complex biological processes in sufficient detail to allow for the development of a computational model. This model would then allow for the simulation of system behavior thus elucidating system function [23]. This can be viewed as applying systems theory at the cellular and sub-cellular level, one of the smaller physical scales.

There have been suggestions of extending Systems Biology theory to a higher physical scale, sometimes referred to as Systems Medicine [6], [24]–[29]. The term has been used in a few articles, but the meaning it represents varies significantly. The idea though is trying to apply systems thinking to a higher physical scale than cells. However, this has generally been in theory rather than with practical methods.
C. Functional Medicine: A Systems Approach to the Practice of Medicine

Functional medicine is a systems approach to medicine that is not a separate discipline or specialty; rather, it is an approach to clinical care that is patient-centered, personalized, and grounded in the science of clinical medicine [7], utilizing diagnostic tools and analytical mechanisms of disease [7], [30]. It addresses chronic conditions by treating the individual as a system of complex interactions of multiple organ systems and multiple physiological and biochemical pathways with internal genetic predispositions and external environmental influences [7]. Functional medicine practitioners have published on chronic diseases discussing them in an interconnected and systemic fashion. The foundation of functional medicine stands on the identification of the primary functions/processes of the body, which through the systemic interconnectedness in the body manifest as dysfunction.

The goal of applying systems tools to clinical medicine is to manage the complexity of medical knowledge to effectively improve patient care and health outcomes at lower costs. The Institute of Medicine’s 2010 report [31] states that “Pervasive inefficiencies, an inability to manage a rapidly deepening clinical knowledge base, and a reward system poorly focused on key patient needs, all hinder improvements in the safety and quality of care... Achieving higher quality care at lower cost will require fundamental commitments to the incentives, culture, and leadership that foster continuous learning, as the lessons from research and each care experience are systematically captured, assessed, and translated into reliable care.”

III. APPLICATION OF SYSML TO FUNCTIONAL MEDICINE: AN EXAMPLE

In this section, the Model-Based Systems Engineering tool SysML is utilized to translate aspects of the functional medicine text to produce graphical models. A small yet interconnected example of the beginning stages of digestion is chosen. This will keep the example manageable yet enlightening as a first example of translating medical knowledge into graphical models. Section III-A describes the semantics of SysML and finally Section III-B describes the SysML model.

The text translated for the SysML example is from Chapter 24 (Digestive, Absorptive and Microbiological Imbalances) of the Textbook of Functional Medicine pages 327-328 [7]. An example of digestion was chosen given that visits for GI distress of one kind or another account for significant healthcare visits [32]–[34].

A. SysML Semantics

Figure 1 describes the semantics needed to describe SysML for the model developed in Section III-B but not detailed enough as to serve as a complete reference for SysML. Other sources generally referred to are referenced here [17], [18].

B. SysML Model

The SysML model developed includes 5 figures: 1 block diagram (structure), 1 primary activity diagram (function) with 2 sub-activities and an allocation diagram. Fig. 2 shows the structure with the block diagrams consisting of the defined system: digestive system (defined in this example as the mouth to the stomach), the subsystems (mouth, esophagus and stomach), the external components that interact with the system (lower GI/intestines, central nervous system, body physical state, mental state, enteric nervous system and the normal system) and the human body block they all belong to. Fig. 3 shows the functions within the primary activity diagram. Fig. 4 shows a deeper level activity diagram of the action Masticate from within the primary activity diagram, while fig. 5 shows the deeper level activity diagram of the action Store & Mix from within the primary activity diagram. Additionally, fig. 6 shows the allocation of function (the activities) to the form (the structures). The allocation clearly shows functions, within the form system, occurring and/or affecting far reaching external structure blocks.

IV. DISCUSSION

This paper presents the need for system tools in the practice of clinical medicine with the goal of managing knowledge complexity to effectively improve patient care and health outcomes. An example of the model-based systems engineering
Fig. 3. The primary activity diagram describes the function or action of digestion. This includes 3 primary actions: Masticate, Transport and Store & Mix with several external parameters, inputs and an output to this activity.

Fig. 4. The secondary activity diagram describes more specifically the function masticate. This involves several inputs, several activity parameters with an output to the function masticate.

Fig. 5. The secondary activity diagram describing in more detail the function Store & Mix. This involves several inputs, several activity parameters and an output to Store & Mix.

Fig. 6. The allocation matrix includes form on the vertical scale and function on the horizontal scale. The form include the system components followed by the external components. The function include 3 primary activity figures with each separated to include the inputs/outputs, the external factors affecting the activities and the internal activities.

tool SysML was utilized to translate functional medicine text to produce visual graphical models. To our knowledge this is the first paper applying systems engineering tools to clinical medicine at the patient level. At the sub-cellular level, another system engineering modeling language, OPM, has been applied [35]. However, OPM is primarily intended for conceptual modeling rather than complex informatic descriptions which are necessary to incorporate the large bodies of information and knowledge. With this example in place, the discussion can return to the systems thinking concepts introduced in Section II.

Systems thinking allows for a practice of medicine that truly addresses chronic conditions, from both structure and function, rather than “re-working” or “re-applying” of acute care models.

While some of these clinically-applied systems thinking concepts are similar to those found in Systems Biology, there are two critical distinctions between the typical techniques used in Systems Biology and the model-based systems engineering approach proposed here. First, the model-based systems engineering method is fundamentally a top-down approach. It fixes the scope of the model and grows its size as one drills down further and adds greater detail. In contrast, the Systems Biology approach is intrinsically a bottom-up approach. It begins with one or more more relatively detailed “building-block” models (e.g. translations, transcriptions of RNA, proteins) and then grows its size outward in scope to include interactions between these smaller models. Some would argue that Systems Biology is better categorized as a middle-out approach [36]. Nevertheless, the approach “is based on conceptualizing insight at whichever level there is a good understanding of data and processes, and on then incorporating greater levels of structural and functional integration [37]. Therefore, the two approaches have very different approaches to model development.

The second distinction has to do with the fundamental difference in data used to build and develop these models. In the clinically-applied model-based systems engineering approach, the data comes from mining patient histories, records, and case studies. The fidelity of this model is driven by the existing medical science as it is already published and hence...
the translation of medical text used as an example in this paper.

Systems biology, in contrast, is biologically focused and uses data from wet lab experiments or first principles of the natural sciences. Although systems thinking at the patient level is not novel, this paper begins to formalize the systems thinking using the established tools from the systems engineering field.

V. CONCLUSION & FUTURE WORK

In conclusion, this paper presents the need for system tools in the practice of clinical medicine with the goal of managing knowledge complexity to effectively improve patient care and health outcomes. To our knowledge, this is the first paper presenting the utilization of system tools and providing an example at the patient level. Specifically, the example model demonstrated how model-based systems engineering tools can be utilized for clinical medicine, ultimately giving a new big data application. This presents opportunities for collaboration between clinical stakeholders, research stakeholders, systems engineers and patients with the goal of developing these tools to be utilized within clinical medicine.

REFERENCES


