AC 2007-122: CONCEPTUAL FRAMEWORK OF HEALTHCARE SYSTEMS ENGINEERING AND PILOT CURRICULUM DEVELOPMENT

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Introduction

This paper presents a conceptual framework of Healthcare Systems Engineering (HSE). By instilling systems thinking into the context of healthcare systems improvement, this framework outlines the context, contents and relationships of this increasingly important, multidisciplinary engineering domain. A very important issue therefore is for the educators, students and practitioners to develop a sound understanding of what “healthcare systems engineering” actually means. This paper attempts to address this issue by, based on lessons learned from system improvement efforts in the industrial sectors, presenting healthcare systems engineering in a number of key terms, which logically relate to the main study areas that need to be considered.

The paper also reports how this framework is providing a logical basis for a number of current initiatives in the University of Missouri-Columbia, involving faculty from the MU College of Engineering (Industrial Engineering), MU School of Medicine - Health Management and Informatics, MU University Hospitals and Clinics, and MU College of Education. In particular, with the support from the National Science Foundation (CCLI Program), MU College of Engineering is developing and pilot implementing a HSE program for engineering undergraduate students at the university. The coursework included in this program will prepare future engineers who are capable of applying structured and systematic approaches in the analysis, design and continuous improvement of healthcare services and systems.

Need for Healthcare Systems Engineering

With rapid technological advances and changes paralleling what occurred during the past two decades in the industrial sectors, the healthcare sector appears to be in the midst of a new “industrial revolution.” There is an urgent need to apply the principles of engineering, science, management, and technology to healthcare improvement. It is now widely accepted that a systems engineering approach should be adopted as an important basis for the future efforts to approach the tremendous challenges and opportunities in patient safety, service quality, and healthcare costs containment, and hence there is a need for multi-skilled professionals with qualifications in healthcare systems engineering.

For example, in the U.S. healthcare costs reached $1.678 trillion in 2003, which represents 15.3% of the nation’s total GDP[1]. In addition, the nation’s projected annual growth rate of healthcare spending is at an estimated 7.2%. Consequently, hospital payments have been, for thirty years, the single largest components of health costs in the U.S., and these high costs are directly affecting the nation’s industrial competitiveness. The need to improve system efficiency in the healthcare sector in terms of service safety, quality and cost (SQC), has become more important over the last twenty years, and from all quarters there have been calls for improvement[2].

What is the right approach for achieving healthcare service improvements? This is the crucial question. Based on lessons learned from system improvement efforts in the industrial sectors during the past two decades, the authors and their colleagues had proposed previously that a systems approach is an important basis for future efforts in healthcare service improvement[3]. Accordingly, there is a need for multi-skilled professionals with qualifications in Healthcare Systems Engineering. This view has now been firmly confirmed by the recommendations of a recent report from a committee jointly supported by the U.S. National Science Foundation, the National Institutes of Health and the Institute of Medicine entitled: *Building a Better Delivery System: a New Engineering/Health Care Partnership*[4], which recommends:

- "Thus, it is reasonable to suggest that the use of information/communications technologies and systems tools could lead to higher productivity, better quality care, and improved patient satisfaction."

- "Federal agencies and private founders should support the development of new curricula, textbooks, instructional software, and other tools to train individual patients and care providers in the use of systems-engineering tools."

- "Health care providers and educators should ensure that current and future health care professionals have a basic understanding of how systems-engineering and information/communication technologies work and their potential benefits. Educators of health professionals should develop curricular materials and programs to train graduate students and practicing professionals in systems approaches to health care delivery and the use of systems tools and information/communication technologies."

The philosophy of Healthcare System Engineering

In essence, similar to the engineering discipline of manufacturing systems engineering[5], within the context of HSE, the requirements of systems thinking in healthcare improvement can be summarized in terms of three key principles: systems perspective of healthcare processes, structured problem-solving, and the closed-loop of continuous system improvement. These can be encapsulated in a conceptual framework of continuous system improvement, which identifies the key functional areas and the relevant analytical tools[3].

Despite their diversity, all systems have some characteristics in common. As a result, systems concepts have been applied in many of the fundamental fields of science and most branches of engineering and management. However, until recently the traditional approach to healthcare improvement has been based on specialized and isolated segments. Very rarely was a healthcare process viewed from a systems perspective as an integrated combination of processes, equipments, people, organizational structures, information flows, control systems and computers, designed and operated in order properly to support a coherent goal. Our approach aims to rectify this situation by adopting:

Table 1. Philosophy of Healthcare Systems Engineering

	(1) RIGHT PEOPLE AND ORGANIZATION, TECHNOLOGICAL ADVANCEMENT, INFORMATION INTEGRITY AND INTEGRATION
+	**(2) EFFECTIVE METHODOLOGY FOR CONTINUOUS SYSTEMS IMPROVEMENT**
=	**A BETTER CHANCE TO SUCCEED**

Furthermore, we summarize the requirements of systems thinking in *Healthcare Systems Engineering* into the three key principles as shown below:

Table 2. Three Principles of Systems Thinking in Healthcare Improvement

- *Systems perspective of healthcare processes.* Any problem domain (process or unit) must be analyzed, designed, and operated within a systems context where the necessary equipment, personnel, and information interact effectively to carry out the process(es) involved with a high level of efficiency and integrity.
- *Structured problem-solving.* The effective adaptation of structured problem-solving methodology for the generation of system options, and for the identification of problem solutions.
- *Closed-loop of continuous system improvement.* A continuous cycle that involves: **{**Set Goal – Analyze/Design – Implement – Operate – Monitor Performance/Benchmarking**} – {**Reset Goal – Analyze/Redesign – Implement – Operate – Monitor Performance/Benchmarking**} –** …

In particular, the general philosophy and principles of Table 1 and 2 are logically encapsulated in our conceptual HSE framework that consists of three inter-interrelated models: (i) a HSE context model, (ii) a healthcare process reference model, and (iii) an analysis and design process model. Together, they provide the logical basis for the development of HSE curriculum and prototype syllabi. The foundation and practical value of this framework has been well developed and validated in an industrial setting. Currently we are utilizing this expertise and combine it with expert knowledge from the healthcare sectors to establish the context and contents of HSE, to evaluate its practical value and relevance, to develop a preliminary curriculum, and to introduce this into our educational system.

Context and contents of Healthcare Systems Engineering

From a system's perspective, many healthcare procedures and operations can be compared to a particular type of manufacturing situation, known as job-shop production, where each operation needs to be individually scheduled, and the crews, equipment and all other necessary materials must be planned and made available at the right time and in the right place for the operation to proceed. Similar to a hospital situation, the modern manufacturing system embraces a wide range of applied methodologies and technologies, processes a variety of materials, and the rates of change in these and in factory and business architectures are considerable. To design and operate the modern manufacturing system requires engineers with multidisciplinary skills. Most state-of-the-art technologies, when applied on their own, offer localized benefits only. The key issues of attaining excellence rely on the adoption of the appropriate methodology, as well as technology. It is the realization of this situation that led to the recognition of the potential role of manufacturing systems engineering in modernization of manufacturing industry[5]. After many costly failures attempting to increase efficiency through advanced technologies alone, it was finally realized that the potential benefits offered by these new technologies with respect to industrial efficiency would not be fully gained unless there was a corresponding systematic investment in research into the design, evaluation, organization and management aspects associated with industrial systems.

Therefore, for anyone involved in healthcare improvement, one important lesson that must be learned is the need to adopt a systems perspective in problem-solving and performance improvement. This is due to the requirement that the functions and the underlying mechanisms of the relevant systems in question must be sufficiently analyzed and understood as a whole, and dealt with in a holistic manner. It is different from the existing approaches concerned with, for example, healthcare technologies and management. Healthcare systems analysts with a systems engineering background must have a thorough understanding of systems approaches to the design and operation of healthcare systems, so that they can correctly incorporate all the necessary elements into the systems that efficiently support the wider objectives of healthcare, particularly in terms of service quality, patient safety, and system cost. Table 3 outlines the potential contents of this discipline, and the interrelationships of the topics involved. As can be seen, the term *Healthcare Systems Engineering* contains within itself a number of other key terms, which relate to the main study areas that need to be considered:

- *Systems*. Systems theory is needed to enable the development of a systems approach for the study of healthcare. The concepts and ideas of systems study for the purpose of healthcare system design and improvement should cover topics such as the generic concepts of systems (in terms of systems perspective, system structure, system processes, system communication, system hierarchy and control, and the prerequisite conditions for effective system operation), and a specific systems understanding of healthcare processes.

- *Healthcare* (structures, technologies and operations). Knowledge of the types of industry, healthcare, the technical characteristics of various elements of advanced technology and the operations of an industrial or healthcare system are obviously prerequisites for the analysis of a healthcare system.

- *Systems Engineering*. This area involves the techniques of systems analysis, which can be used as a general framework to tackle various problems associated with a systems design and improvement project.

- *Healthcare Systems* (design, evaluation, and improvement). All of the above need to be brought into an overall framework for systems design and analysis.

Table 3 Healthcare systems engineering: context and contents [1]

	THE KEY WORDS	THE STUDY AREAS	THE STUDY TOPICS
HEALTHCARE SYSTEMS ENGINEERING	*SYSTEMS*	*SYSTEMS THEORY*	• basic concepts of systems • 'hard' systems approach • 'soft' systems approach • a systems perspective of healthcare
	HEALTHCARE	*STRUCTURES*	• healthcare system strategy • healthcare system organization • healthcare system location • healthcare system capacity • healthcare processes • …
		TECHNOLOGIES	• medical equipment and facilities • patients care equipment and facilities • pharmacy handling facilities • material handling facilities • healthcare information systems • …
		OPERATIONS	• capacity planning and control • operations scheduling and control • facilities planning and control • materials planning and control • quality control • financial control • …
	SYSTEMS ENGINEERING	*SYSTEMS ANALYSIS APPROACH*	• the general approach • structured decision-making
		SYSTEMS ANALYSIS TECHNIQUES	• input–output analysis • system process/function modeling techniques • information system analysis techniques • operations research models • computer simulation • …
	HEALTHCARE SYSTEMS (Framework of System Design, Evaluation, and Improvement)	*SYSTEM REFERENCE MODEL*	• system facility definition • system informatics definition • system human/organizational definition • definition of functions • definition of operational procedures • definition of structures
		PROCESS MODEL	• healthcare strategy analysis • healthcare strategy/system interfacing • healthcare system design/analysis • system implementation/project management • systems operations management • performance monitoring/bench-marking

Pilot curriculum development

The context, reference and process models together will provide a very effective way to present and teach a diversified range of multidisciplinary topics within a logically integrated HSE curriculum. Accordingly we aim to develop five prototype syllabi, including one in each of the areas in Table 3, plus a Capstone Project:

1. Systems class: Systems Perspective of Modern Healthcare
2. Healthcare class: Introduction to Healthcare Structure, Technologies and Operations
3. Systems Engineering class: Methodologies and Tools of Systems Engineering
4. Healthcare Systems class: Healthcare Systems Analysis and Design.
5. Capstone Project - continuous system improvement in healthcare.

This will establish a new minor degree of HSE at University of Missouri-Columbia. Building upon these efforts, we also anticipate that the new undergraduate minor will provide the foundation to establish a joint Master's program between MU's Department of Industrial and Manufacturing Systems Engineering (School of Engineering) and Healthcare Management and Informatics (School of Medicine); and support a PhD program in the recently established MU Center of Healthcare Systems Engineering, and MU Center of Healthcare Informatics.

Class contents

Together, classes (1) and (2) aim to lay the foundation of systems perspective of healthcare and system-oriented approach to performance improvement. In particular, it will help to clarify what the term "healthcare systems" means. One may argue that healthcare has been traditionally very much function-oriented. This is due to the fact that the area is highly professionalized, and doctor-centered. While this is a necessary requirement due to the very nature of this domain, it may have resulted in a traditional approach to healthcare process that is very much based on a functional perspective. When viewed from a systems perspective, however, any healthcare process/system will have three principal components that must be addressed as a whole:

- The *physical* (facility/processes) architecture represents the 'hard' elements of the systems, such as the medical equipment, patient care equipment, transportation and storage equipment, and any other facilities required to support the treatment and services provided.

- The *human and organizational structure* represents the personnel and organizational structures involving the doctors, nurses, administrators, and the others within the system, defining their roles and responsibilities.

- The *information and control structure* represents the data and information in all its formats, whether paper or computer based, throughout the system.

In addition, proper interaction among the above is also crucial if the system in question is to operate properly and efficiently. Without being properly incorporated into the system structure, any particular entities on their own will not guarantee system efficiency, regardless of how sophisticated they may happen to be. This is particularly important for the assurance of healthcare quality and patient safety. For system improvement purposes, a reference model of necessary system structure will provide a logical basis of crosschecking system completeness and integrity. Based on this model, rules and crosschecking mechanisms can be provided to show how different parts of the system are to be interrelated to guarantee system integrity, and how they should function cooperatively when put into practice.

For example, a system-oriented technique of system analysis, such as the IDEF technique[5], provides an ideal tool for the development of a system perspective and visualization of a complicated healthcare operation. Such a technique provides a structured and logical way for one to present and deal with the inherent complexity involved in a healthcare-delivery situation.

The term 'IDEF' stands for 'Integrated DEFinition'. It was developed to describe the information and organization structure of a complex system. Although essentially a methodology for the functional specification of a manufacturing system, it can be modified to produce a structured representation of the functions of a healthcare system, and the flow paths of information, objects and people that interrelate with these functions. It is by nature a 'top-down' approach, exposing one level of detail at a time. It begins the description process by modeling the system as a whole at the highest level (Figure 1) and then decomposing this model level by level to describe each of the sub-systems within the system hierarchy (Figures 2 and 3).

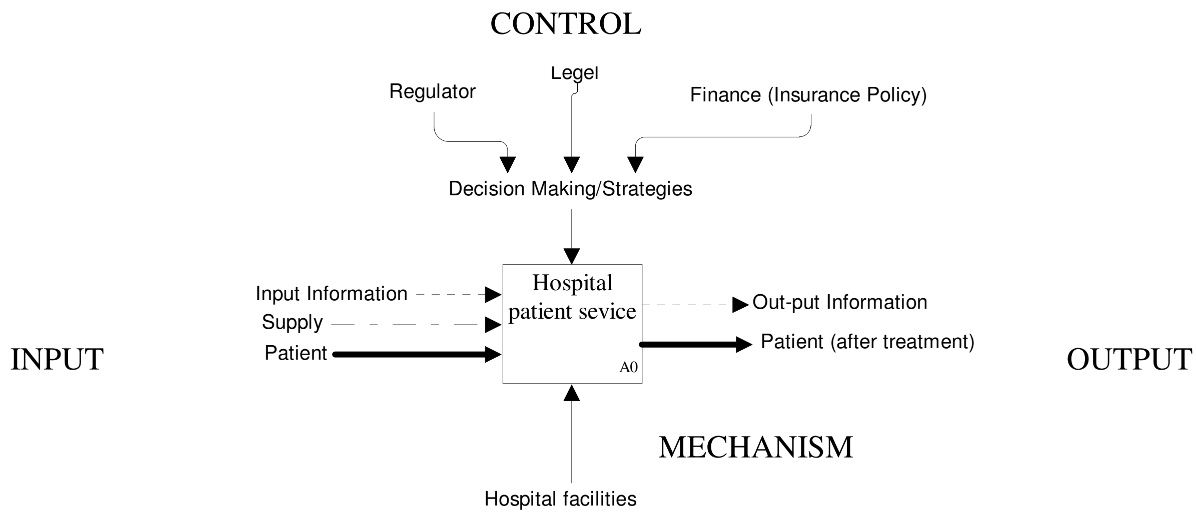

Figure 1 Example top-level view of a healthcare system

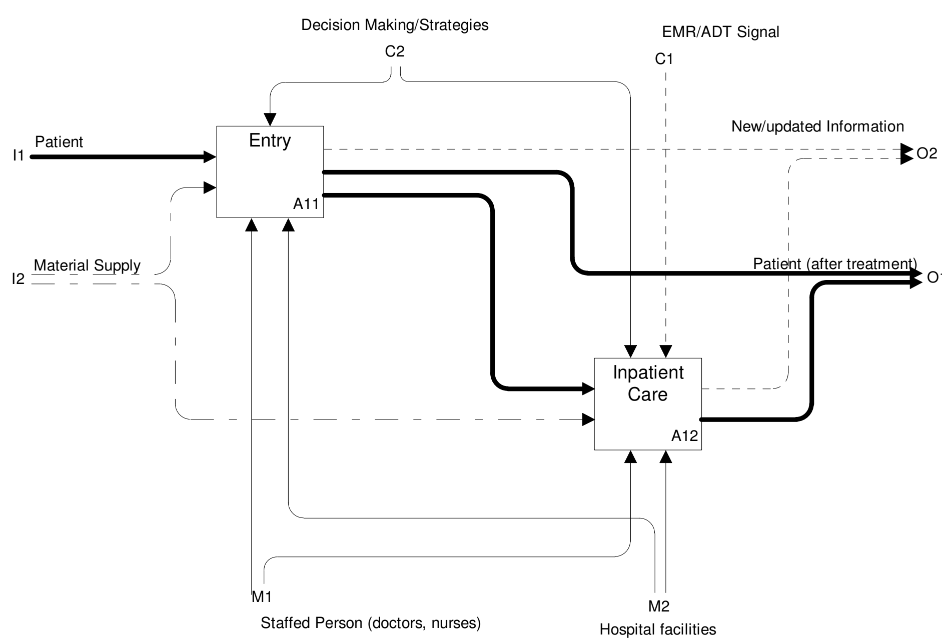

Figure 2 Example lower-level decomposition

The example given in Figures 1-3 shows how such a technique can be used by an analyst to visualize the healthcare system of concern. Such a system model will help to provide an effective means of achieving a systems understanding and systems perspective of a healthcare-delivery situation, and precisely specify the "healthcare system" involved, in terms of its boundary, functions, flows (patient, data, medicine, materials and equipment), interactions and responsibilities.

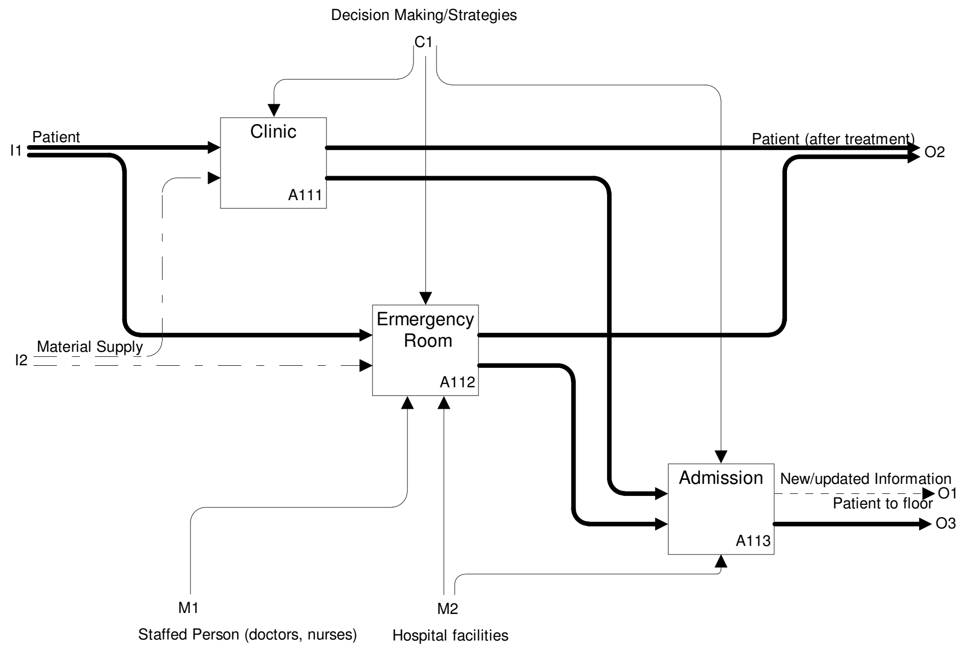

Figure 3 Decomposition of the "Patient Entry" function in Figure 2.

The understanding of a systems perspective of healthcare delivery, together with the ability to apply system analysis tools such as IDEF, provides the basis for a system-oriented approach to healthcare-delivery improvement.

Class (3) will introduce relevant system engineering techniques to tackle various problems associated with a healthcare systems design and evaluation project. Within the domain of healthcare system improvement, the types of problems involved, and the relevant modeling techniques used in evaluating and decision-making can be diversified. The analytical tools can be mathematical, physical, and simulation. Also they can be either quantitative or descriptive, as summarized below. The choice of the modeling approach should consider the characteristics of the system in question and the nature of the problems to be tackled. It is also dependent on the type of problem, nature of performance measure and the objectives. Other factors, such as the amount and type of quantitative information available, the amount of time and money at the analyst's disposal and the facilities available (such as computer hardware and software) should also be taken into consideration. In general, analysis tools in system and design and evaluation can be classified according to the following groups:

- *Static vs. dynamic*. Static analysis refers to a situation where the problems and system parameters involved are fixed in nature. A typical example is the evaluation of the average capacity level required over a relatively long period of time, based on the estimate of the overall demand in that period. When the problem is dynamic, on the other hand, the time dimension must be taken into consideration.

- *Deterministic vs. stochastic*. Models of this type are based on an algebraic relationship. This kind of model is used when the mechanisms governing behavior are understood and thus, the relationships among system variables and parameters become transparent to the model builder. In a stochastic situation, the governing mechanism is not totally understood. Therefore, the relationships among the system parameters—or sometimes the values of system parameters—can only be estimated through techniques provided by statistical analysis.

Also such techniques can also be mathematical or based on computer simulation. The mathematical techniques typically include examples such as linear programming (LP), time series (TS) analysis, queuing theory (QT), statistical analysis, inventory models (IM), economic order quantity (EOQ), analytic hierarchy process (AHP), Petri nets (PN), neuron nets (NN), and numerous heuristics methods (HM). In contrast, computer simulation is fundamentally an experimental approach for studying certain functional properties of an organization by experimenting with an appropriate computer model rather than with the actual system. As far as system analysis is concerned, computer simulation frequently provides a flexible and powerful technique compared with the others. It is one of the most effective tools available, particularly as a method for evaluating the dynamic characteristics of a proposed solution. With a properly constructed computer simulation model, a system analyst may experiment with different manufacturing runs, new operational conditions, new layout of equipment, different cycle times, etc. This allows the designer to predict how the system will perform when put into operation. One of the most widely used types of simulation is known as discrete-event simulation. In contrast to continuous simulation models, which are usually based on certain mathematical equations - as exemplified by the so-called system dynamics (SD) approach which may be used to analyze the progress of an epidemic - discrete-event simulation is concerned with the modeling of a system by a representation in which the state variables change at sudden distinct events (the arrival of a patient, or the operation on a patient). Table 4 provides a sample overview of these approaches, together with some of their typical applications in specific areas of system design and analysis.

Table 4. Examples of relevant analytical techniques and their applications

Area of Design and Analysis		Analytical Techniques and Applications: Mathematical	Analytical Techniques and Applications: Computer Simulation
REQUIREMENTS ANALYSIS	**System Functions**	LP: aggregate capacity planning TS: demand forecast AHP: facility selection	demand forecast, total capacity planning, financial evaluation in this and all of the following areas.
	System Structures	LP: site location QT: order throughput time, overall site capacity NN: parts/sites grouping	SD: overall system structure
	System Procedures	PN: decision network and structure	Simulation of decision processes and functions.
CONCEPTUAL DESIGN	**System Facilities**	LP: detailed capacity planning, facility layout, line balancing, factory/warehouse location QT: as above plus throughput time analysis, capacity utilization NN: cellular formation AHP: process selection	System-wide conceptual design and specification: inventory and capacity planning, scheduling, evaluation of other management decisions, and specification of hospital facilities and layout at the conceptual level.
	Human and Organization	LP: resource planning QT: resource planning	As above, but dealing with human resource requirement planning.
	System Informatics	Input–output analysis Process/function modeling techniques IT system analysis techniques Petra Nets: computer networking	
DETAILED DESIGN	**Processes**	LP: material-handling, facility layout QT: as above plus throughput time evaluation and resource utilization IM: make vs. buy AHP: facility selection	Detailed planning and specification of MS systems in this and all the following areas such as: planning of detailed work loading, study of scheduling and job issuing policies, identifying bottlenecks, facility layout, patients and material handling.
	Facilities	LP: facility layout	
	Supports	QT: support facility capacity TS: maintenance policy	
	Planning	LP: production planning QT: evaluation of planning policies	
	Control	LP: scheduling IM: lot sizes, batch sizes TS: quality assurance AHP: hardware/software selection	
	Human	LP: capacity planning	
	Warehouse and Transport	LP: facility and warehouse location IM: lot sizes, batch sizes, inventory level TS: inventory level QT: throughput & queuing time	

Class 4 will bring the systems concept, the analytical methodologies, and the technological aspects of healthcare elements into an overall framework of healthcare systems design and improvement, through the two interrelated models: (i) A reference architecture model, that provides a system's perspective of healthcare and, during an analysis or design project, can be used as a logical prototype for checking the completeness and integrity of any healthcare process; and (ii) An analysis and design process model, that identifies the key functional areas (such as strategy formulation, system analysis and design, project and change management for implementation, operations management, performance monitoring); specifies the necessary steps, tasks, relevant analytical tools and theirs relationships; and then combines them into a closed-loop to support a structured problem-solving approach, and to provide the basis for an integrated approach of continuous system improvement.

Finally, the Capstone project will allow the students will work in teams, and work with the sponsoring hospitals or healthcare-providers, to solve a real-life problem related to issues of healthcare improvement. Utilizing the general framework and the relevant techniques as outlined above, and collaborating with University Hospitals of University of Missouri, previous and current projects have dealt with a wide number of system improvement projects, with encouraging results. Project scope varied from improvement analysis in the individual system areas of facilities (equipment keeping and management, patient transportation), human resources (clerk job design, hire replacement system), and information (release of medical information, patient registration, administration of pharmacy and medication, medical information integration), to the design of complete operational units (a Post Procedure Care Unit).

Conclusion

Industrial Engineering has a lot to offer to the current effort in healthcare system performance improvement. Our current effort in the development and implementation of a Healthcare Systems Engineering minor degree aims to provide students with multidisciplinary (engineering, healthcare process, management, operational and strategic) skills and a broader viewpoint than the traditional approach, by recognizing and analyzing a situation within an overall perspective - in terms of 'systems'. The purpose of our systems approach is to teach our students to approach a problematic situation in healthcare improvement through a systems perspective. We will encourage our students to consider healthcare activities in their entirety, utilizing systems concepts such as objectives, relationships and transformation. It will help to fill a significant skill gap by providing qualified healthcare systems analysts with a system engineering background and a thorough understanding of systems approaches to the design and operation of healthcare systems, so that they can correctly incorporate all the necessary elements into a system that is effective in terms of service quality, patient safety, and system costs.

The conceptual HSE framework is novel, in the sense that it makes sure a logical and systematic approach is followed in curriculum development, in teaching, and as well as in learning:

- From a teaching perspective, the framework will help establish the key functional areas of HSE through the lifecycle of a healthcare system, and then combine these to provide the basis of an integrated curriculum.

- From a learning perspective, the framework will help the students to develop a coherent view of the subject area, and better understand how the multitude of individual concepts and techniques fits into the overall picture - what functions and analytical techniques are involved, where they belong and how they should be applied in a practical situation.

Therefore, the approach provides a rational foundation of the subject area and, in the long-term, help to establish Healthcare Systems Engineering as a scientific discipline.

Currently in the University of Missouri-Columbia, there are a number of initiatives to further develop the framework and contents of Healthcare Systems Engineering. MU School of Medicine is currently adopting the HSE systems concepts, tools and models as outlined above into their Problem-Based Learning medical curriculum, and we have recently established the MU Center of Healthcare Systems Engineering, as the center of resources and services to facilitate education, research and practice in healthcare systems engineering.

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