Preface

A State-of-the-Art Review of Developments in Health Information System & Technology Models and Methods:
The MEDIA Paradigm

INTRODUCTION

For years, misguided health organizational information technology (IT) leadership, and the lack of available expertise and skills in the application of health IT (HIT) models and methods have somehow predisposed administrators of large-scale health maintenance organizations (HMOs) to become generally reluctant to migrate away from legacy health information systems (HISs). For many health provider organizations, the more recent decline in economic activities over the last few years has also further led to new debates on allocating limited public and private resources so gravely needed to build and sustain large-scale interoperable systems infrastructure in order to achieve such a system migration efficiently and effectively. Not surprisingly, progress towards adopting new health IT initiatives such as innovative e-technologies for the health care industry in the United States (US) has been slower than most other industries. Inadvertently, a major gap in the strategic and opportunistic use of emerging health IT models and methods now exists to significantly transform the apparently fragmented nature of US health services delivery system.

Aside from the fear of costly systems failure, many key stakeholders in the US health care system have, admittedly, been resistant to invest in new and contemporary enterprisewide systems due to the lack of a well-focused national health IT vision and strategy. On the one hand, attempts to successfully diffuse interoperable, integrative HIT applications throughout the US health care system must now depend on the strength of the health IT leadership shouldered by the current Administration. On the other hand, progress in health IT implementation and diffusion will also depend on how quickly many of these health key stakeholder groups who have been technological laggards for one reason or another can be motivated, challenged, and appropriately enticed to design, develop, and deploy large-scale, complex and interoperable computer-based enterprisewide systems. Such enterprisewide systems include, but are not limited to, those that are designed to incorporate integrative health data management models, new biomedical informatic methods, web-based semantic search capabilities, and emerging clinical decision support methodologies. In the context of today’s complex and largely fragmented US health services
systems, specific applications of enterprisewide, interoperable systems can range from patient-centric records and information services systems such as electronic medical records (EMRs), electronic health records (EHRs), personal health records (PHRs), payor-based health records (PBHRs) and computer-based physician order entry (CPOE) systems, to health administrative-aided transaction and health information exchange (HIE) systems such as e-prescribing systems (EPS), supply chain management (SCM), customer relationship management (CRM), enterprise resource planning (ERP), and e-payment systems.

Briefly, key reasons why the diffusion of interoperable, integrative HIT models and methods is needed in the US health care services sector entail:

a. an urgency, as a whole, to contain escalating health care cost - the growing health care cost has become an increasingly unsustainable burden on US taxpayers over the years;

b. the growing complexities and uncertainties in the health information processing and exchange environment of large, medium, and even smaller health organizations populating the US health care system - the expansion of stakeholder groups and increased federal, state, and municipal regulatory oversight mechanisms surrounding health services delivery have and will continue to add to the already intricate health information management (HIM) and services delivery system; and

c. the potential of interoperable, integrative HIT models and methods to aid complex data analysis and semi-structured decision making - such analysis will not only empower care providers, but also enable critical information sharing to occur among referring physicians in consultation with patients, and especially when specialists and a team of caregivers are involved in key administrative and clinical decision making.

With increasing attention paid to the critical role that HIT models and methods can and will play in reforming the US health care system, we are finally seeing a trend in increased projections on health IT spending, which is currently anticipated to exceed 15 billion dollars annually for the US (Lipowicz, 2009). According to the National Coalition on Health Care, in 2008 alone, the US has spent well over 17% of its Gross Domestic Product (GDP) on health care - a percentage that clearly exceeded those spent by many other OCED countries (National Coalition on Health Care, 2009). Sadly, the fact that the US has outspent almost every other country on health care has not translated into better health or even more convenient, accessible, available or affordable health care services delivery for Americans. In fact, findings abstracted from 2007-2008 data in a study championed by the consumer health advocacy group Families USA has revealed that one out of every three Americans under 65 may still have to live, at one point in time or another, without health insurance coverage (Parisi and Bailey, 2009).

Clearly, many of the issues raised here have now taken central stage in the debate raised by the Obama Administration for championing health care reform in the US. As well, various solutions have been considered, chief among them, using and adopting interoperable, integrative HIT applications. Such a strategy is not without merit, as various forms of health technologies have indeed risen over the years to similar challenges; for instance, online claims processing and e-prescribing have been successfully deployed by various HIT vendors to serve as tools to combat rapidly escalating health administrative costs while simultaneously leveraged to reduce wastes, increase efficiencies, eliminate redundancies, and improve the overall quality of clinical care and services.

Raghupathi and Tan (2002, 2008) noted that various strategic applications of HIT models and methods can evidently improve the efficiency and effectiveness of US health care services delivery, adding value to existing, legacy-based HISs, and helping to integrate the islands of health services management
systems. Their arguments not only cited the power of e-technologies to streamline increasingly complex routine HIM processes that may require multi-provider, cross-organizational collaboration, but also the ability of interoperable, integrative HIT capabilities to augment enterprisewide efficiencies and care provider network connectivity.

Accordingly, the key underlying argument for migrating from legacy HISs is that both data and processes linked to diverse functioning information systems must now be shared on an increasingly real-time basis between both on-site and off-site caregivers if we want to improve the quality of patient care. These interoperable, integrative systems can also streamline complex administrative and clinical workload, easing the communication needs among health care administrators, HIT personnel, health engineers, health informatic researchers, and HIT consultants, all of whom need to work closely together in today’s health services delivery systems if major systems bottlenecks are to be effectively managed over time. Figure 1 depicts the Model and Evidence Driven Integrated Analysis (MEDIA) paradigm, an integrated model management framework that is applied in this review to provide an integrative conceptualization of the evolving, state-of-the-art developments in HIT models and methods.

Against this background, existing HIT models and gathered evidence will not simply aggregate but will be seen as complementing each other alongside the MEDIA integration and analysis process. Take the case of the influenza propagation - a disease model - and imagine how it can intermingle with a patient care process model, such as that of a primary clinic. Given the separate evidence about the flu outbreak and patient arrival pattern, running both models in parallel within the MEDIA framework produces either a more realistic health care supply-demand scenario in the context of a real-world community health setting, and/or offers insights into other related and potential issues needed to be addressed when challenged with health hazard preparation such as when an apparent discrepancy is observed to be operative within the overall system. All such information analysis and its integration can be further quantified and addressed consistently. Such multi-attribute analytic capability is crucial to the success of any future applications and developments of HIT models and methodologies.

The rest of this review on health IT models and methods is organized as follows. In Section 2, a high-level systems perspective of HIS information and process flow in the context of applying HIT models and methods is outlined. Fundamentally, the classical information system input-process-output

Figure 1. The model and evidence integrated analysis (MEDIA) paradigm
triad that underlies all systems engineering conceptualization is revisited. In Section 3, the focus will shift to the complexity-uncertainty challenge encountered in the current US health care sector. Following this, in Section 4, the emerging engineering approaches in health services applications at two levels are highlighted. These levels include: (1) the general health engineering level; and (2) the more focused health services modeling level. In Section 5, the MEDIA paradigm, including its three key facets are briefly overviewed: (a) domain ontology modeling and management that lays the foundation for model representation and infrastructural connectivity; (b) hybrid probabilistic modeling that computationally integrates systems and subsystems models; and (c) adaptive knowledge fusion to generate quality assurance that support active information collection and continuing operations management. Essentially, the MEDIA approach is based on a linked series of health engineering concepts, which deviates fundamentally from the traditional health care best practices in which quality is heavily dependent upon the hands-on skills of expert clinical practitioners as well as the deployment of progressively specialized medical instrumentation. The application of the MEDIA paradigm is also illustrated in a case study on risk management. Finally, in Section 6, we conclude this review by speculating on future research directions and practical implications in the field of health IT models and methods.

VIEWING HIT MODELS & METHODS IN THE CLASSICAL HIS FLOW CYCLE MODEL

Owing to the need to deal with increasingly complex health data processing routines and the growing number of participating stakeholders who may need to share information and provide their particular interpretation of such data taken from the very same electronic health databases, an exciting playground for health researchers and practitioners now exists to incorporate efficient medical information processing models and emerging health decision support systems (HDSS) methodologies into interoperable systems linked to existing health databases, model management bases, and knowledge management bases. Despite recent investments in medical information packages such as the Vista medical information system and the GoogleHealth patient record management system, the lack of system interoperability has made it difficult, if not impossible, to integrate isolated health records stored at varying functional levels. Moreover, a key challenge is the integration of HIT models and methods through a knowledge fusion process so as to enhance the capability of viewing and analyzing any chosen set of discrete and continuous events in a health services delivery system such as relating patient-physician encounters and the progression of different disease stages from an enterprisewide and trajectory perspective, for example, the interactions and optimal interventional strategies for a particular patient cohort within a HMO, built up from its connected elements, including the affiliated hospitals, clinics, practicing physicians, nurses, information and personnel resources, labs, and departments linked to its health services delivery system.

Figure 2 depicts a generic health information flow process model in which health administrative, clinical, and service delivery decision and policymaking must necessarily transpire at an enterprisewide level while aided with the use of relevant and applicable HIT models and methods within the traditionally defined input-process-output system triad. In the initial data collection, and information-knowledge gathering stage, a huge amount of raw data, guided protocols, and knowledge elements are often sourced from various input sensors and devices as well as recorded answers to questions asked of the individual patient and/or groups of patients, including underlying reasons for these patients to seek care. All of the
collected information is now ready to be pre-processed into some form of meaningful and intelligent datasets.

These datasets are then stored appropriately either in a centrally located or in multiple electronic locations, typically via databases and data warehouses, waiting for further processing to serve a variety of clinical, research and administrative goals and purposes. Such purposes could range from clinical testing and follow up, to research, administrative billing, and/or mere reporting for managerial decision making. As a case in point, imagine the gathering of demographical data as well as specific vaccination records for a population of young adult patients to guide the clinical management of an ongoing epidemic, such as the “swine flu”. The data gathered should not only be accurately coded but they should also be securely stored in a more or less structured format to be communicated to the attending physicians for further clinical evaluations, testing, and/or diagnosis. In fact, the same information may be aggregated with other data for research analysis or it may be used to establish insurance co-payments to the various care provider groups. Finally, the information may also be critical to plan health vaccination programming by the different workplace or educational institutional settings tied in with the population of young adult patients.

At the data manipulation-information mining-task processing stage, embedded patterns are often sought and hidden knowledge uncovered within the captured datasets to be translated intelligently into meaningful clusters and to provide additional advice and insightful guidance to the end-users, in this illustrative case, the various caregivers. In other words, the same data-information-knowledge collected of the young adult patients may now be further fused with other high-level information, such as expert clinical knowledge about the state of the patient immunization types and dates as well as the state of ongoing epidemics or pandemics, if any. The combined information can then be used to determine the health status of the individual young adults following the immunization, for example, their resistance to prevailing illnesses, their showing signs of some sort of common allergies, and/or their susceptibility to some other atypical reactions. In fact, it is here that the HIT models and methods may be most relevant to aid in the follow-up of crucial clinical and administrative decisions.

Figure 2. A general health information flow process model with Its input-process-output system triad
In operationally organizing, aggregating, mixing, dicing, and mining the stored patient data, various HIT models and methods may be combined in a complex fashion to generate a meaningful and “best” fit for clustering and/or grouping the stored data based on some known statistical patterns. The resulting data pattern classification are in turn routed back, on the one hand, to the clinicians to guide them in making prognostic, diagnostic and other therapeutic decisions, and, on the other hand, to the administrative staff to assist them in determining patient diagnostic codes, and thereby, generate accurate and appropriate third-party billings.

At the end of the data processing-data mining stage, feedback will also typically occur in terms of second opinions, reviews and/or expert evaluations on model validity to further enhance systems fine-tuning and performance outcomes. Such enhancements recognize the possibility for more intelligent decision making in the face of missing or incomplete data and/or the fact that inadequate tools were available to appropriately process such data so that adjustments to these decisions could still be made to further improve accuracy or timeliness of key decisions and outcomes. In our case example, the nursing unit may, at this point, requests for feedback from the attending physicians as to who among these young adults would be due for specific and further vaccination visits, be sent for more clinical testing and evaluations, such as generating referrals to other departments or physician specialists, or they should simply be discharged. This commonly encountered health information flow cycle is characteristic of an open health information processing system that follows the input-process-output triad.

Hence, despite the complexity of HIT models and methods, the potential for these methodologies to contribute significantly to future health services management is evident and apparent. While their applications represent mostly a part of the wider and far reaching field of HIS, it should not and cannot exist in and of itself. It must go hand in hand with the many different types of decisions on health services management that have to be executed routinely alongside the processing of initially gathered data, stored information, and captured knowledge. With a basic understanding on the flow of information and processes through a generic HIS flow cycle model, it is clear that multiple disciplines – including computer and library sciences, medical and/or health informatics, sub-fields in nursing informatics, teleradiology, teledmedicine, telehome care, telematics, biomedical informatics, as well as domains of health IT, health engineering, and health operations research (OR) and management science, HDSS, and even the integration of cognitive sciences, information sciences, and health sciences – must all come together to enrich our ability in using HIT models and methods to meet a diversity and variety of clinical and health administrative decision needs.

Ultimately, in order to achieve high quality health services management and related decision making, not only will we need medical informatics tools such as computers, clinical protocols, formal and informal medical terminologies, but also the integration of various informatic resources, tools, models, devices, techniques, methods, decision aids, and methodologies to optimize the collection, storage, retrieval, analysis, design, and use of health information in health services delivery (Tan and Payton, 2010).

RATIONAL FOR INTEGRATING HIT MODELS & METHODS: THE US HEALTH CARE COMPLEXITY-UNCERTAINTY LANDSCAPE

While the interplay of multiple disciplines and sub-disciplines in managing a growing body of health services information and processes makes the health care system one of the most complex systems to study, the growing intricacies of the US health services sector may also be seen in many real-world events.
The 2007 drug-resistant tuberculosis case, for example, shows the high degree of interdependency that exists in the US health care infrastructure, and uncovers the many hidden flaws, previously ignored, in the management of patients, hospitals, the center for disease control and prevention (CDC), as well as the complex sociopolitical forces that link the US government with other national governments (U.S. House of Representatives, 2007)

**Key Challenges & Risk Management in the US Health Services Sector**

For the US health care sector to achieve greater accessibility, affordability, and accountability, two key determinants for its continuing growth and future developmental success include: (1) ensuring a 24/7 service availability; and, (2) having a focus on service quality.

In the coming years, as the US health care sector experiences sweeping reform, daunting risk and unpredictable challenges will likely arise. Hence, dealing with risk and uncertainty is a critical skill in running any modern-day health services enterprise, and this is precisely where HIT models and methods can and will play a central role. The major threats and challenges facing the US health care sector are depicted in Figure 3. As shown, these challenges include systems complexity, event uncertainty, and the need to share information. Owing to the fact that such threats and challenges will often emerge unpredictably and their diverse manifestations will also typically blur the line of most standard classifications, both health administrators and clinicians will want specialized tools to aid them in their routine policymaking and decision execution, as we moved forward with the US health care reform.

First, with regard to systems complexity, there is the overwhelming intricacy of diverse evolving structures alongside the rapidly expanding health services supply networks. With hospital expansions and alliances formed among various stakeholders, increasing complexities have also followed. Again, with stakeholders trying to leverage on increasingly competitive global health supply chains, the resulting system relations are even more complex. Moreover, stakeholder collaboration across diverse industrial sectors may often follow different policy paths and practices. These factors, and the fact that most such collaboration is developed independently, compound the intricacy. Hence, there is the need for integrated HIT models and methods to guide future decisions.

Second, in regard to event uncertainty, there is the need for systems configuration flexibility. A health service is subject to risk whenever and wherever the stakeholder cannot predict changes to the typical

**Figure 3. Major threats & challenges facing the US health care sector industry**

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<td>• Global supply chains;</td>
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<td>• Regional, national, and international coordination;</td>
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environmental situation. As event uncertainty can arise, without prior warning, from diverse occurrences, such as (a) variations in staff and patient flow, (b) the onset of new, rare or epidemic diseases, and (c) emergencies, whether natural and/or man-made, all such uncertain events will require appropriate and timely adaptation in health services management. These challenges are further convoluted by evolving structures, novel technologies, the constant threats of natural disasters and/or man-made events, including the unpredictable growing number of participating stakeholder groups.

Traditionally, stakeholders including patients, care providers, insurance companies, and the government do not see eye-to-eye. As many health administrators and clinicians tend to focus largely on the details, and likely also to stubbornly stick to their personal heuristic business decision-making biases, challenges of prevailing complexity and uncertainty will become even more evident over time. In light of this, it is not uncommon to have conflicting views shared among the multiple stakeholders. Moreover, health care debates often hinge on highly sensitive issues, and it is unlikely that any lopsided discussions or outcomes will contribute to the overall satisfaction of certain key stakeholder groups. Therefore, given that current management practices rely largely on personal heuristics, qualitative comparisons, and subjective guidelines, without precise accounting and science-based quantitative analysis, the significance of HIT models and methods cannot be overly emphasized.

As today’s health services delivery systems often encompass huge numbers of interacting elements, significant interdependency, and enormous uncertainty and risk, it is very difficult to expect quality and outcomes of the decisions to be appropriately calibrated and/or justified quantitatively. Hence, the attempts to incorporate the latest science and methodological advances in HIT models are some of the ways to ensure better health decision outcomes and policymaking.

Third, in regard to information sharing, it is in the interest of health provider organizations, at the minimum, to ensure that their patients receive prompt and accurate medical care services by increasing the accessibility and availability of health information services on the one side, and ensuring the secured, confidential, and private storage of personal medical records for sharing among affiliated caregivers on the other side. Technologically speaking, effective information sharing has to do chiefly with systems interoperability and the availability of an interoperable enterprisewide infrastructure. This is why a move towards integrative, interoperable HIT models and methods is key to achieving US health care reform.

In summary, the challenges of complexities, uncertainties, and sharing of health data have deterred key stakeholders within the US health care industry sector to work collaboratively, effectively, and productively. But it has also highlighted the importance of having a national health IT strategy and vision as well as building a cumulative effort to apply and diffuse integrative, interoperable HIT models and methods.

**Inadequacy of Health Services Modeling Practice & Research**

Despite the wide range of quantitative models that has emerged to address various performance optimization risks with regards to different parts and/or aspects of health services systems over the years, there is still the need for a system-wide perspective on how these different HIT models and methods may be combined and integrated to aid health care decisions and policymaking.

Roberts (2007), for instance, emphasized models to represent the progression of certain disease categories as well as to predict best treatment timing and cost. Denton, Fowler, Schaefer, Batun, Erdogan, and Gul (2009) detailed scheduling systems that model patient arrival and how they may be queued efficiently and effectively to be served by doctors in operating rooms. Finally, Shehad, Bertino, and
Ghafoor (2005) discussed the application of computational models to quantify information leakage and availability based on the analysis of user communication via a computer infrastructure.

Notwithstanding, each of these isolated attempts represented a series of uncoordinated efforts to address only a small, specific set of health services elements, without adjusting to benefit the greater whole – that is, the limited impact of the individual studies on the total system do not account for the intricate interdependencies among the systems elements. In other words, confined within a limited scope of a system component or sub-system, the performance measures adopted by these studies are typically defined in terms of cost, quality, time, or other specific but narrowly defined criterion, which, without exception, would still impact, one way or another, on other systems elements and components on an unknown basis and scale. Thus, isolated models and methodologies, working in and by themselves, simply cannot address the larger challenges presented in the US health services management system.

With health engineering as an emergent field, researchers interested in HIT models and methods are beginning to redefine the boundary of traditional health care management philosophy. The modeling capability to guide flexible reconfiguration of health care structures, such as new investment and/or rearrangement of provider organizations and facilities, is critical if we are to handle the complexity of systems modeling and analysis appropriately. Arguably, the different levels of local, regional, and national coordination that are actually interconnected (Schnase & Cunnius, 1995) will dictate how the national health infrastructure is to be reconfigured to manage existing resources efficiently, effectively and productively.

All in all, for enterprisewide systems modeling, not only should external disturbance be taken into account, but also losses incurred due, simultaneously, to rising health care cost and the need to minimize poor quality medical (patient) care (Hick, Hanfling, Burstein, DeAtley, Barbisch, Bogdan, & Cantril, 2004) In this sense, many industry leaders and practicing engineers have now recognized the significance of integrating the operation, audit and control management of health supply systems (Barbera & Macintyre, 2002). Unfortunately, most, if not all, of these initiatives are still in their infancy. For instance, many health services institutions still lack the required level of modeling capability and organizational preparedness for dealing with external interfering events.

Indeed, as we attempt to introduce the latest enterprise paradigms such as the system-of-systems and the reconfigurable enterprises across institutions where a large number of participants interact and evolve on a continuous basis, the lag in health services reengineering practices and health performance management research becomes clearly evident. As early as 2003, Woolhandler, Campbell, and Himmelstein (2003) have noted that, by 1999, 31% of the US health expenditures and 16.7% of the same expenditures in Canada were largely health administrative overhead expenses; clearly, this points to the high potential for HIT models and methods to achieve a significant system performance improvement largely through a reduction in health administrative cost. Moreover, just as we set to data mine and understand the interactive behavior of a complex adaptive system (CAS) (Kiel, and Elliott, 1996; Woolhandler et al, 2003) emerging states can also be generated under various systems configuration to be studied so as to achieve across-the-system improvements.

### Comparison to Service Enterprise Risk Management

From a service supply chain management perspective, the dynamics of the US health care system may be conceived as comprising, with special structures and performance requirements, service supply networks of suppliers on the one hand in terms of caregivers and medical resources, and patient demands on the
other hand in terms of patient needs and services. As we know, health systems are, without exception, multi-layered and closely interconnected; these systems must necessarily provide high value to their customers in terms of patient benefits and services; as well as the availability of services, security, and privacy of captured and stored patient information. Many of these factors entail the highest priority in risk management.

Whereas traditional OR techniques such as game theory (Shubik, 2005) derived from artificial intelligence (AI) and economics, and optimization models taken from quantitative analysis have been extensively used for enterprise modeling, current research focuses largely on core strategic and operational issues such as location configuration, demand response analysis, dynamic pricing and contract management, as well as e-commerce challenges (Graves, Kletter, & Hetzel, 1998; Lambert, Cooper, & Pagh, 1998). Risk assessment and risk management cover essentially many forms of risks, including, but not limited to, business risk, financial risk, technological risk, and physical risk (Anupindi & Akella, 1993; Argrawal & Nahmias, 1997; Kouvelis & Milner, 2002; Simchi-Levi, Kaminsky, & Simchi-Levi, 2003).

Lately, research into the applications of HIT models and methods has also taken on a broader perspective. Thomas (2002), for example, analyzed the reliability of a supply chain under contingency when it is being impacted by unexpected disasters. Using Bayesian networks, Pai, Kallepalli, Caudill, and Zhou (2003) provided a conceptual business risk assessment framework. Based on industry practitioners’ input, Blackhurst, Craighead, Elkins, and Handfield (2005) summarized the common themes and issues surrounding supply chain disruption. Hale and Moberg (2005) presented a set cover location model that is used in disaster preparation for identifying the minimum number and possible locations of off-site storage facilities for supplies. Lee and Whang (2005) compared the inspection of hazardous goods, such as for transporting explosives, with total quality management (TQM) in manufacturing. A RAND Corporation (2004) report focused on the impact of terrorist attacks on global container supply chain performance and advocated the importance of fault-tolerance or resilience.

Despite the stream of well-funded research in the area of service supply chain and enterprise management, the emerging body of knowledge has not adequately addressed the growing complexity and uncertainty-risk management dimensions of the US health care sector. Little, if any, of the past scattered research has provided a comprehensive analysis or given enough attention to systems and systems modeling integration, which has resulted in the following significant challenges:

a. Current research is sparse and isolated, lacking a cumulative agenda. Even so, common terminologies or protocols are not often shared to ease communications among future researchers. Ultimately, there is the lack of a bridging theme to aid the systemic interfacing among heterogeneous models and documented evidence;
b. Past researchers generally hold a narrow view, focusing solely on a small subset of traditional risks. In this sense, most studies deal primarily with individual system components or aspects thereof, without an overall context to account for all interlaced challenges and subsystem interactions; and
c. Enterprisewide modeling and analysis is still in its infancy. Moreover, past studies tend to be mostly conceptual and qualitative, with limited applicability to modern enterprises in addressing current challenges.

Put together, the need for a systemic health services management framework, a representation that would exhibit three fundamental characteristics. First, it would encapsulate a family of heterogeneous
models at different levels of detail and for different subsystems, scalable also to the growth of the enterprise and its captured knowledge cannot be overly emphasized. Second, such a representation would bridge high-level qualitative knowledge with quantitative computation by automatic conversion and instantiation, a capability that is crucial to practical deployments of HIT models and methods. Finally, we would also expect such a representation to incorporate quality assurance with confidence and clarity, measured to handle uncertainty in analysis and to guide decision making in all facets of health services management.

The MEDIA paradigm, which we will discuss in Section 5, is such an integrative paradigm exhibiting all of the three fundamental characteristics noted above.

**STATE-OF-THE-ART HIT MODELS & METHODS**

Before overviewing the MEDIA paradigm, however, we will first review the state-of-the-art HIT models and methods by categorizing and highlighting the various bodies of literature with respect to the emerging engineering approaches in health services applications.

Improving a health services delivery system can be achieved through one of two means: (1) relying on medical equipment, technological and/or procedural advances; and, (2) focusing on improved medical, business, clinical and administrative processes. Modern health engineering technologies such as nano-scale materials, genetic informatics, robotics and applications of virtual health have gone a long way to provide effective and reliable prognoses and treatments to a variety of diseases. Such scientific progression foresees an accelerating pattern in light of technological advances. Yet, management theories and practices have taught us that the quality of health services delivery is also dependent on achieving better health information flow and system processes that best fit the type of organizational structure and culture inherent to particular health institutions.

In other words, a solid foundation for health care reform may be achieved only through the appropriate balancing of the health resource configuration and process control. In light of this, a large body of models to address medical and health services delivery issues in health system management has evolved through best practices over the years. This approach, which concentrates on the applications of health IT models and methods, is precisely the focus of this review. It has, in the last decade, gained increasing attention among researchers interested in contributing to enhancing the performance of the US health care sector.

**Health Engineering**

Today, a new body of health engineering models has emerged. These models are applicable at different system levels, including, for example, at the low level of disease progression of individual patients, that of a clinical session process, or at a higher level involving a health facility of interconnected subsystems and components, or even at the level of a complete life cycle of health services delivery of a particular region or country. In the following section, we survey the extant literature on the new “health engineering” paradigm, following which we shift focus then to the more specific health care modeling and simulation domains.

Evidently, health engineering methods and IT models will not only help hospital personnel to reduce medical errors and risk, but aid also in reducing health care costs, improving health services timeliness, and increasing patient satisfaction. In some cases, it is of course possible that the traditional culture and
strict legislation imposed on the health care sector, which uniquely distinguishing it from many other industries, may limit the transferability and diffusion of new concepts and methods.

Today, opportunities and challenges in the health care sector exist for testing and adopting concepts, best practices, and tools from diverse engineering domains to improve the efficiency of systems processes and the effectiveness of health services delivery in terms of quality, safety, and productivity. In this sense, both the goals and challenges of the health care sector match those of other industries where knowledge engineering has provided a long-term basis for resolving bottleneck issues. Hence, the combination of knowledge engineering and health IT applications promises to provide many more reengineering opportunities for health services delivery, for example, the installation of bedside terminals, the adoption of new informatic methods for infectious disease control, and therapies, and the use of innovative data and DSS technologies in medical and clinical settings, including hospital laboratories and pharmacies.

This section reviews emerging operational systems engineering (OSE) research categorized into several different dimensions. Specifically, the focus is on OSE methods abstracted from a mix of engineering disciplines, including human factors, factory and product design, and security engineering. As the managerial processes and services in the health industry are often similar to those of other manufacturing and servicing industries, we argue that the field of health services management can be enhanced through the intelligent applications of traditional health IT OR models, emerging engineering philosophy and methodology, and mature OSE methods.

**Traditional HIT OR Models**

Pierskalla and Brailer (1994) discussed the application of OR models and methods in a broad range of health services management tasks. Major applications of health IT OR models include:

1. **Demand Forecasting** – A fundamental input to many other analyses in health engineering, demand forecasting, such as predicting daily census for the different types of resource needed, is important to improve the efficiency of health resources allocation.

2. **Capacity Planning** - The allocation of bed capacity within the hospital is a critical factor in operational efficiency. Thus, health services capacity planning typically focuses on total bed capacity, bed capacity allocation to different services, surgical system capacity, capital equipment capacity, and ancillary service capacity. Discrete event simulations and semi-Markov process models have been used to examine bed allocation and related capacity questions.

3. **Patient Screening** - Screening of patients for particular disease can improve medical diagnosis on the one hand and disease detection on the other. It may also be applied individually (individual screening) and/or population-wise (mass screening). Specifically, for individuals, the objective is often to prolong a patient’s life, whereas, in mass screening, the objective may be to minimize the cost at the societal level, thereby lowering the prevalence of a specific contagious disease. Clearly, when attempting to achieve any such objective function in OR modeling, there still may be resource constraints and compliance levels to be factored into the solution.

4. **Patient Scheduling** - Scheduling is critical for matching demand with the supply of available but limited resources. Most scheduling systems attempt to optimize the combined objectives of patient and worker satisfaction, as well as the utilization of facilities.

5. **Clinical Decision Making** - Clinical decisions can be aided through OR models that incorporate mathematics and structural analysis. Not only can such analytic models assist in the formulation
of health care policies, but they can also be applied to the structuring of critical medical decisions, and the fine-tuning of health systems performance.

6. Workforce Planning and Scheduling - Human resources management is one of the most costly and intensely unpredictable activities that is to be managed intelligently across health organizations. For example, Hershey, Pierskalla, and Wandel (1981) conceptualized the nurse staffing process as that of a hierarchy of three decision levels over different time horizons and with different precision – that of corrective allocations, shift scheduling, and workforce planning.

7. Cost Cutting – Kumar, Ozdamar, and Zhang (2008) have developed several reengineering conceptual and simulation models, which were used for cost containment within the Singapore’s health industry in the domain of supply chain management process reengineering.

Emerging Engineering Philosophy and Methodology

Over the years, various streams of engineering philosophy and methodology have been applied to improve health systems performance. Process orientation and patient focus are the essential concepts embedded in these methodological philosophies.

Key approaches that have been discussed in the extant literature include: (1) Lean Thinking; (2) Six Sigma; and (3) Theory of Constraints. Young (2005) argues how a clinical session for a patient’s treatment would serve as a good analogy for explaining how these different streams of engineering philosophy and methodology can be combined to address various system bottlenecks encountered in the health services delivery industry.

1. Lean thinking – Kollberg, Dahlgaard, and Brehmer (2007) believed that the idea of lean thinking is applicable specifically to health care systems in a number of ways. For example, just-in-time (JIT), level scheduling, and multi-skilled teams are generic techniques that can create a smooth operation process flow through the matching of the supply-demand level of health care resources. When applying lean thinking to health care, a measurement framework for lean initiatives that reflects both efficiency and effectiveness of health systems performance, such as patient satisfaction, referral management, process mapping, and fulfillment of targets and policies, is needed in order to fully capture lean changes.

2. Six Sigma - This methodology involves standardized data collection and informed reporting protocols based upon a well-controlled quality feedback cycle to minimize variations and quantitatively align production or service quality to a predetermined standard. “Bridges to Excellence” is an example of a national case initiative based on Six Sigma quality feedback methodology launched to improve clinical care quality. This initiative targeted on physicians and their practices to enhance patient care quality (Brantes, Galvin, & Lee, 2003) and had further been incorporated as part of a collaborative product commerce (CPC) approach to health supply chain purchasing (Ford & Hughes, 2007), as highlighted in the next section.

3. Theory of Constraints (ToC) – Similar to Six Sigma, ToC applies the root cause thinking processes for analyzing system bottlenecks. Unlike Six Sigma, however, ToC attempts to deal with managing constraints in CAS not from a technical limitation perspective, but from a “qualitative” and philosophical perspective. The methodology is first applied to identify the most vulnerable constraint, then exploiting and increasing flow through that constraint, working from the weakest link upward to other links between that constraint and the overall system.
Mature OSE Discipline

A maturing OSE discipline focuses on examining, analyzing, and further understanding the operating elements and systems dynamic processes in complex systems to achieve efficient and effective systems performance. This greatly supports the view of health care as a CAS. In this sense, OSE tools and techniques may be applied to achieve a balance for meeting multiple goals, for example, quality patient safety, accessibility, availability, comprehensiveness, and affordability of care.

1. Supply chain management (SCM) – In recent years, SCM topics have gained significance as health services organizations vie to lower the cost and improve the ease of accessibility and delivery of health services and their associated resource supplies (Brantes et al, 2003; Ford & Hughes, 2007). Ford & Hughes (2007) identified potential barriers that health services organizations must overcome in order to apply SCM principles successfully within the health care sector. In their study, they inferred that physician services are the primary channels in a health care supply chain to provide the relevant expertise and services to group practices, hospitals and pharmacies. These practices, in turn, behave as secondary channels, acting as refineries and production facilities to serve health insurance distributors and purchasing programs in the supply chain. Therefore, the starting point for cost containment of health services in SCM will be determined by how physician services are being managed. A specific form of SCM used by US employers is the collaborative product commerce (CPC), which is discussed next.

2. Collaborative product commerce (CPC) – CPC attempts to extend the limited boundaries of enterprise collaboration for product design by leveraging innovative e-technologies to engage members from internal as well as external constituencies. CPC approach differs from other SCM tools in two significant aspects (Swinehart & Smith, 2005): (1) it permits inter-organizational collaboration feeding on a common supply chain or meeting similar consumer product or services needs; and (2) its processes are transparent to all stakeholders. CPC models, therefore, allow health provider organizations and/or third-party payers, who are located in different health care markets, to share in innovative product life cycle designs.

3. Business process reengineering (BPR) – BPR is a process-driven technique to improve the efficiency and effectiveness of a business through meaningful process redesign, change management, and system reorganization. As an example, Kumar, Swanson, and Tran (2009) conducted BPR using simulation modeling on the complex operating theatre (OT) system in a Singapore Hospital. His case simulation produces two recommendations: (1) a need to redesign the OT process in order to maximize its productivity without altering the current workload of surgeons and anaesthetists; and (2) reviewing the OT utilization data periodically so as to derive a meaningful productivity index and accurately gauge its utilization.

4. Health management information systems (HMIS) – HMIS, which has to do with all aspects of business information systems functions in health care, plays an integral part in any modern health services system. As noted earlier, a national health IT strategy to support and ensure systems interoperability to link health services networks throughout America is believed to be a necessary step towards realizing US health care reform (IEEE-USA, 2005). Today, many traditional HMIS functions can be easily and logically augmented to encompass database, model-based and knowledge-based HDSS technologies when trying to build OR models to aid in the management
of health services systems, or more specifically, to improve administrative productivity, increase clinical decision-making responsiveness, and enhance patient care quality.

**Health Services Modeling**

Serving as the foundation for our proposed MEDIA framework to be discussed later, the extant literature in health services models may be further subdivided along the following three dimensions:

1. the scale (level) of health system problems being studied;
2. the goal being sought or performance measure being evaluated; and
3. the modeling method being applied.

The intelligent applications of health IT models and methods depend largely on understanding how each of these dimensions will impact on a specific health services modeling study.

Many variations and types of models exist such as policy models, procedural models, intervention models, graphical models, deterministic as well as stochastic models. As a case in point, Eldabi and Young (2007) indicated that quantitative models, methods or tools can be studied across different organizational levels, from the physical and mechanical design level through the services and policy design level.

**The Scale (Level) of Health System Problems**

This dimension focuses mainly on the extent and/or scale of health services problems to be modeled. Four sub-levels include: (a) Individual patient disease models; (b) Operational process models; (c) Organizational system-level models; and (d) National sociopolitical-level models

Individual patient disease models focus mainly on the biological disease processes occurring in individual patients, that is, the infection processes among either healthy or infected person/population. These models can range from microbiological or cellular, to organ, as well as person-to-person transmission level.

O’Leary (2004), for instance, simulated person-to-person infection by building mathematical models to predict the epidemic path of disease transmission, to assess possible infectious outcomes of events over time, and to test the effectiveness of different intervention measures such as vaccination strategies and quarantine policy. In general, such disease progression models are applicable to evaluating clinical effectiveness or cost effectiveness of different interventions to particular disease (Brailsford, 2007).

The operational process models are devoted to observing and simulating individual patients residing in a ward, a clinic, or a hospital department such as the Emergency Department (ED) or Intensive Care Unit (ICU). Often, such models are used to facilitate business process reengineering, resource allocation, capacity planning, staffing, and scheduling challenges. Tan, Gubaras, and Phojanamongkolkij (2002) for instance, employed a discrete event simulation model for studying capacity planning, staffing, and scheduling of Dreyer Urgent Care Center.

Organizational system-level models combine different departments within a large institution or enterprise, and attempt to study the interactions among the different departments. Typically, such models address longer-term and broader issues, similar to the conceptualization of enterprisewide models. System dynamic (SD) is a common example of organizational system-level model that is often applied at a
strategic level where the stakeholder is interested to look at the forest more than just the trees (Brailsford, Lattimer, Tarnaras, & Turnbull, 2004).

Finally, national sociopolitical-level models encompass and address a wide range of very high-level issues. Having a view at a national sociopolitical level on the state of emergency, for instance, will aid government policymakers and decision makers design a reliable health services delivery policy that will coordinate hospitals, police, and emergency units for a rapid and more readied response. For example, the BioSense Real-Time Clinical Connection Program of the United States (Laudon & Laudon, 2007) builds a national surveillance system model to continuously summarize and analyze the disease and health information by source, day, and syndrome for each ZIP code, state, and metropolitan area. This model is designed to improve the national capabilities for disease detection and monitoring, as well as awareness of real-time health situations.

**Goal Sought & Performance Measures**

In health systems, goals sought are often different from many other for-profit industries, for example, appropriateness of care, safety, and patient satisfaction are critical relative to cost and resource utilization, not just profits. These goals are usually measured by a set of key performance indicators such as patient throughput as measured in system wait time and wait line; length of stay (LOS); system capacity; utilization of staff, equipment, and space; cost; and various other related measures such as service quality in terms of error and patient satisfaction.

Major groupings of studies on various health systems performance measures include the following:

1. **Length of Stay (LOS) and Patient Throughput** – Ramis, Palma, Estrada, and Coscolla, (2002) created a generic simulator within a network of clinics to reduce patient LOS in the system. The simulator also facilitated the appropriation of resources and reallocated these resources based on the number of patients and how quickly they go through the system. Bosire, Wang, Gandi, and Srihari, (2007) modeled a computer tomography (CT) scan facility in a hospital to study how patient wait time can be minimized and how staffs can be used efficiently to increase patient satisfaction.

2. **Resource Allocation and Capacity Planning** – Rico, Salari and Centeno (2007) built a model using ARENA simulation software and OptQuest heuristic optimization to increase system capacity, improving nursing staffing allocation, and augmenting the utilization of equipment and space. They suggested multiple ways in which the number of nurses needed for health services delivery during a pandemic influenza outbreak may be combined. Cahill and Render (1999) created a model to assess ICU bed availability. Their model was applicable for excess capacity rebalancing that would otherwise lead increasingly and unjustifiably to wasting limited health resources such as bed space and personnel in the Cincinnati VA Medical Center.

3. **Cost Containment** - In the Cahill-Render (1999) study cited previously, an additional application of their model was to contain costs by drawing from outside resources in meeting patient needs. Stahl, Roberts, and Gazelle (2003) also investigated the strategy for setting appropriate preceptor-to-trainee ratio in the context of a teaching ambulatory care clinic. The key purpose of their study was to achieve an optimal financial feasibility and to cut system operational cost.

4. **Policymaking** - Policymaking is fueling a resurgence of interest in modeling and simulation to improve health services delivery performance. This is especially applicable in countries such as Canada and the UK, where the system is based largely on a single payer (the government). More
specifically, these systems employ a governmental body of agencies to manage the entire system through a set of national performance measures. A specific example would be the star rating used for measuring wait time targets for emergencies such as how long it takes a patient to be served upon admission into the emergency department (ED) of a hospital. Gunal and Pidd (2005) provided an example in their policy-oriented simulation study that aimed to improve the accuracy of the rating system in the UK National Health Service (NHS) through uncovering performance irregularities.

Modeling Method

As well, a number of modeling methods and techniques have been identified for health care services implementation. Among these, the most influential, useful and widely applied methods are simulation techniques, which include the mainstream methods as well as simulation algorithms based on artificial intelligence as discussed in Cooper, Brailsford, and Davies (2007) and Kuljis, Paul, and Stergioulas (2007)’s study. Table 1 summarizes the current prevalent modeling technologies and simulation methodologies, as well as their potential application domains in health services analysis.

1. Discrete-Event Simulation (DES) - Among the most widely used simulation techniques in health care as evidenced by many previously cited studies, DES appears to be tailor-made for hospital systems to study queuing behaviors of patients waiting for appointments, investigations and treatments. In particular, DES allows the modeler to construct more complex, dynamic and interactive systems. Nonetheless, as Cooper et al. (2007) pointed out in their choice of modeling technique for evaluating health care interventions, it may take more time and money to develop DES models.

2. System Dynamics (SD) – To resolve systems bottlenecks and understand emerging systems states, SD modeled patient flow behaviors in complex health services systems by capturing the feedback loops and inventory control rules for patient arrival, discharge and follow-up visits. This is similar to studying how water flows through a heating system. SD has gained popularity in recent years and some researchers who first applied the DES had switched to SD to deal with the dynamic changes in patient flow. For example, after using DES to redesign the phlebotomy and specimen collection centers in Calgary Laboratory Services (Alberta, Canada), Rohleder, Bischak, and Baskin (2007) have later on decided also to implement a SD model to handle the unexpected performance discrepancies found due to the dynamic interactions within these service centers.

3. Markov process models - Markov models can describe changes in the state of patient health over time such as the case of benign vs. malignant tumors. In this sense, Cooper et al. (2007) argued that Markov models are suitable for chronic disease interventions. Accordingly, they employed a Markov model to evaluate the effectiveness of statins, one of the cholesterol lowering drugs, over time for at risk patients of coronary heart disease (CHD), based on a so-called Southampton CHD model (Cooper, 2005).

4. Monte Carlo Simulation – Essentially, Monte Carlo uses repetitive sampling process to make estimates about key performance variables of interests under uncertainty conditions just like throwing a dice repeatedly to predict the chance of picking a winning stock in the Dow Jones Industrial market. For example, Jacobson, Lindberg, Lindberg, Segerstad, Wallgren, Fellstrom, Hulten, and Jensen-Waern (2001) used the Monte Carlo methodology to sample various potential vaccine price distributions determined by the mix of care providers vis-à-vis parent-guardian acceptance so as to assess the economic values of variously combined vaccines for pediatric immunization.
Continuous Simulation - Continuous simulation is primarily employed to accommodate continuous systems variables and therefore has limitation in its applicability for healthcare studies. Specifically, it is limited predominantly to physical or biological laboratory processes control simulation such as modeling the trajectory of a missile launch. In healthcare, it can, for example, be used to assess the design of equipment to further enhance the production volumes and manufacturing process efficiencies of pharmaceutical products (Kuljis et al., 2007).

Decision tree – Based on a hierarchical tree-like structure, decision trees aid decision making through an assessment of various probabilities in terms of possible consequences corresponding to different options and alternatives. Cooper et al (2007) showed that a decision tree can facilitate comparative decisions on mean life expectancy of CHD patients. Here, the current response states for CHD patients are compared to more efficient ambulance delivery services and thrombolysis (“clot busting” drug) intake that may result in the death and/or the survival of the patients.

In summary, whenever a healthcare problem is encountered, a critical issue then is how to make choose intelligently among various available modeling and simulation techniques. Schriber and Brunner (2007) proposed to explore the nature and logical foundations in every method and software and thus gain a detailed understanding of “how simulation works”. Cooper et al. (2007) stated in their study that the choice of modeling technique depends on several aspects including modeling technique acceptance, model appropriateness, dimensionality, and ease and speed of model development. Generally a decision can be made based on the complexity and dynamics of the system to be modeled in terms of interaction

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### Table 1. Current modeling and simulation techniques and their applications in health

<table>
<thead>
<tr>
<th>Technique</th>
<th>Potential Applications</th>
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</thead>
<tbody>
<tr>
<td>Discrete-Event Simulation (DES)</td>
<td>Process reengineering, ward layout design, patient pathway design, scheduling, queuing management</td>
</tr>
<tr>
<td>System Dynamics (SD)</td>
<td>Strategic and operations management, alteration management, resource and asset management, patient pathway management</td>
</tr>
<tr>
<td>Continuous Simulation</td>
<td>Physical/ biological laboratory processes control</td>
</tr>
<tr>
<td>Monte Carlo Simulation</td>
<td>Decision making under uncertainty conditions, risk analysis in the long run</td>
</tr>
<tr>
<td>Agent-Based Simulation</td>
<td>Demand and supply management, health economics, risk management</td>
</tr>
<tr>
<td>Decision tree</td>
<td>Acute interventions but not for disease recurrence modeling</td>
</tr>
<tr>
<td>Markov process</td>
<td>Cohorts of patients between health states over time, chronic disease intervention</td>
</tr>
<tr>
<td>Operations research</td>
<td>Patient arrival patterns, LOS management, waiting time management, cost management</td>
</tr>
<tr>
<td>Human factors and ergonomic models</td>
<td>Workload analysis, safety monitoring, productivity increasing, error reducing</td>
</tr>
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of systems elements, model size or resource constraints. The introduction of OSE philosophies also helps making a better combination of choices. For instance, Young (2005) studied the philosophies driving changes in health care services delivery such as Lean Thinking and the Theory of Constraints. He proposed that a strategic agenda could be created out of a three-way fusion of health care delivery, industrial process and simulation capacity, on which basis, an appropriate modeling and simulation techniques can then be selected.

**THE MODEL AND EVIDENCE DRIVEN INTEGRATED ANALYSIS (MEDIA) PARADIGM & ITS APPLICATION**

The MEDIA paradigm, which has previously been introduced at the beginning of this review in Figure 1, offers a handle to unraveling today’s highly complex and environmentally uncertain health services enterprises by focusing on the effective integration of operational models and evidence. Three key phases underline the MEDIA paradigm: (a) Referential ontology modeling; (b) Hybrid probabilistic model integration; and (c) Adaptive knowledge fusion for quality assurance.

Referential ontology modeling relates to the qualitative representation of model structure that is generally constrained by the health services systems complexity and uncertainty. Nodes, representative of crucial system artifacts, and the interdependencies among nodes, that represent their relations, typically encapsulate the model structure. Figure 4, for example, shows the nodes and the interdependency links among these nodes for a partial risk assessment model of operational and information risk representation in the context of a generic model structure.

As the purpose of referential ontology modeling is essentially to support the generation of hybrid probabilistic models, probabilistic modeling requirements should first be examined in terms of the domain of enterprise services and elements, environment risks, and their relations (dependency). The emergent systems complexity is then represented by referential knowledge in formal ontology based on description logic domain and the uncertainty among systems relations is often addressed through probabilistic representation for ontology modeling such as applying the Bayes approach. Accordingly, a critical step is the conversion of ontology to probabilistic models.

The next phase, hybrid probabilistic model integration, entails bridging the qualitative ontology representations with computational analysis to quantify the relations among referential nodes and to achieve an integration of heterogeneous models. This quantification process comprises fundamentally an attempt to assign probabilistic distribution to nodes and/or conditional probability to relations among the nodes. It is important to note that boundary nodes are those nodes shared by multiple models and the same quantification process is applied to these nodes to connect among the models. Special procedures such as those algorithms dealing with virtual and soft evidence may have to be instantiated to adjust the associated probabilities to satisfy all of the probabilistic constraints across each of the model to be integrated (Kim, Valtorta, & Vomlel, 2004; Xiang, 2002). In this second phase, the core migration procedures can utilize semantic web techniques such as ByesOWL framework (Ding, Peng, & Pan, 2006) to convert the ontology to probabilistic networks.

The final phase, knowledge fusion, aims at improving the accuracy and confidence of hypothetical estimations about key systems variables based on discrete evidence gathered from multiple locations throughout the systems being studied. Furthermore, adaptive knowledge fusion attempts to achieve a high quality assurance of information collection and operations management decisions in the knowledge
fusion process. Appropriate quality assurance strategies are used iteratively to guide the knowledge fusion process and are typically aided by dynamic quality scores or indices calculated from information entropy of evidence and effectiveness of different operations. Essentially, these strategies will attempt to provide insights to key questions regarding the knowledge fusion process, including: (1) how good the resulting diagnosis or prediction may be; (2) when to engage and/or stop the knowledge integration procedures; (3) where and what information is to be collected; and (4) finally, what resource allocation decisions could be best implemented (Li & Chandra, 2006; Li & Ji, 2005).

MEDIA Procedural Framework

Figure 5 overviews a MEDIA procedural framework that can be used to guide the implementation of the different phases involved in the construction of relevant health IT models and methods for a generic risk management system problem. In the context of the MEDIA paradigm, any kind of a management task such as a risk assessment scenario for a specific system like a hospital in a chosen ontology domain, specifically, health care, will therefore pass through a set of generic procedures.

- **Phase 1a:** Physical constructs and security components are modeled in ontology bases for the chosen domain. These class templates have common attributes and relations sufficient to support the modeling of most management tasks;
Phase 1b: Aided by the domain templates above, two different types of inputs are needed for referential dependency models to be instantiated for the specific system and the risk management task: (i) for an existing model, boundary nodes and their dependency, and (ii) for a new model, complete knowledge about the model structures of nodes and dependencies.

Phase 2: Probabilistic computational models are then generated through ontology translation and parameter fitting to capture the interdependency and their associated uncertainty. This is helped by additional descriptions specific to the system and task, for example, hypothesis nodes of interests and available evidence collection positions designated for risk management.

Phase 3: When evidence can be found, probability distributions for nodes connected within a network as well as quality scores are updated accordingly through probabilistic inferences. The probabilistic inferences that are carried out here should be specific to the different types of models, for example, Markovian process, Bayesian, or DES models.

If a model needs to be modified in terms of both its structure and parameters due to changes in the underlying systems dynamics, or a new model needs to be introduced, the process goes back to Phase 1b to repeat or iterate on the instantiation process (Cooper & Herskovits, 1992; Heckerman, Geiger, & Chickering, 1995).

The rest of this section will turn to discussing the application of MEDIA paradigm in a multi-tier capacity planning system.
MEDIA Application for a Multi-Tier Capacity Planning System

In the past, mathematical models for the optimal timing prediction of individual disease treatments such as cancers and for the best health services scheduling such as emergency and operation rooms scheduling have been developed respectively. Yet it is important for these models to work together as may be necessary for setting up new global optimization strategies.

In the real world, for example, the service appointment and operation room scheduling do not always guarantee that the patient gets the screening test or the surgery at the best chosen timing as dictated by the individual disease progression model. Suboptimal timing for treatment may therefore have to be chosen and analyzed again for potentially undesired consequences to patients. As this might further delay the treatments for patients and jeopardize their life quality while increasing medical cost, these two types of models may have to be reconnected and integrated through their interdependency to optimize the two processes of the overall system.

In addition, the challenging issue of uncertainty arises when we consider the dynamic changes such as an epidemic or more disturbing natural and man-made emergencies. In a normal operating environment, the discussed risk in the abovementioned case may not be very serious. However, if epidemic cases such as SARS or events such as the 9/11 terrorist attack occurring simultaneously, for example, excessive demand on medical aids in responding to these events may easily deprive regular patients of “optimized” treatments. The strategy here then is to factor in the uncertainty by integrating and incorporating additional appropriate models.

Indeed, this integration can even be expanded either horizontally or vertically into as many channels of the health care system as needed such as the sub-units within the same health care enterprise, or the various business processes and institutional structures of a regional health alliance. Naturally, instead of building a new, but highly sophisticated model from scratch by applying the same algorithmic approach or method, applicable existing models and/or the most suitable type of model for each of these processes can now be reused or variously combined to satisfy the overall systems model optimization requirements. Such an application shows the dominant complexity in terms of a large number of participating systems, subsystems, and basic units, and more significantly, their interdependency.

Figure 4, which was also discussed earlier, illustrates a partial risk assessment model of operational and information risk representation in the patient care process. This hybrid probabilistic modeling solution employs a variety of models. A hidden Markov process model (1) predicts the state of power supply for potential power surge. A heterogeneous Markov process model (2) captures the progression of a given type of cancer and estimates the best treatment timings. The predictions from these models enter a Bayesian parameter model (3) that estimates the states of corresponding variables of staff, patient, operation room, and computer network, with the help of other available evidence. Then a simulation model (4) can run to collect statistics on current operating room capacity, using these parameters. Another model in the form of a probabilistic network graph (5) accounts for computer network topology and user configuration. It calculates the risk of information leaking and availability for the different collaboration scenarios based on staffing and computer network situations. Actually this availability prediction can be feedback to the operating room simulation model, if applicable. Moreover, a computational decision model (6) will enable the computation on the utility based on performance information for different allocation actions for given resource constraints. This decision model can also be distributed to more nodes across the system, if and as needed.
Imagine how a comprehensive model of a medical center can be generated through the application of the MEDIA framework. Various sources of evidence can be introduced into this model on a continuing basis, in terms of errors, delays, and clinic starvation alarms from physical, software or human sensory channels, signaling emerging or potential problems. The administrators or doctors, facing an uncertain and complex operational environment, have to ask first, given the evidence, what the big picture really is and where the weakest links may be situated. Then the best decision (where and how) to invest resources (capital and manpower) to avoid further deterioration of the system state and to mitigate the problems can be made intelligently. Moreover, this process will be carried out, not haphazardly and without knowledge, but in an active and timely manner to handle existing incomplete and uncertain information.

Imagine also that this model can further be updated with real-time system status by monitoring facilities/sensors in an “online” fashion. The key decision makers and policymakers are not asked to just (always) rely on the “average” profile about user/disease from collected historical data. For example, patient arrival may fluctuate from day to day; different treatment results of a special disease may require different actions to be taken; and different caregivers as well as health administrators may also be motivated to stick stubbornly to their personal information processing styles and biases in making certain decisions. Therefore the latest evidence, collected on a continuing basis to update information relating to individual “special” patient, at a prescheduled pace and/or for significant events, will all be made available as feedback to the existing model structure. Over time, the model structure or parameters may, of course, be no longer appropriate, relevant or accurate enough for current or future predictions (so called “concept drift”). Then, model learning and knowledge fusion will again be executed at these times as well.

Put together, the MEDIA paradigm is clearly a useful and practical framework that can be applied intelligently across any type of a real-world scenario to enable the mixture and integration of various health IT models and methods to facilitate the making of short-term key health services delivery and management decisions as well as to aid longer-term health systems planning and policymaking.

CONCLUSION

Essentially, our review on existing bodies of knowledge about the state-of-the-art health IT models and methods has led us to become increasingly aware of the need for and significance of having an integrative platform for leveraging existing models and methodologies intelligently such as the MEDIA paradigm. This paradigm aims to offer an appropriate framework for conjugating heterogeneous probabilistic models including the Bayesian network (Pearl, 1998), Markov process models (Doob, 1953), and Monte-Carlo simulation (Fishman, 2001), through virtual or soft evidence update of distributions over boundary nodes. The rationale for achieving such an integration is that: (1) inherent probabilistic representation and inference is able to deal with uncertainty; (2) many such probabilistic models have built-in mechanisms, such as in dynamic Bayesian networks and Markov process models to deal with the temporal dependency; and (3) many of these models support localization of information processing and can be easily implemented into agent-based architectures, aided by the interdependency present in enterprise constructs and model components.

More specifically, just as languages spoken by people, we have seen that ontology representation is necessary for computer models to communicate and interact with each other. Ontology defines the concepts and the relations of generic elements in a domain and provides a common “language” shared
by components and subsystems of MEDIA. It is more than just a classification or a dictionary because
dynamic behaviors of the systems elements are also captured using description logic and language such
as RDF and OWL (Baader, Calvanese, McGuinness, Nardi, & Patel-Schneider, 2003; Barwise, 1997). We
have also seen how the integration of health IT models and methods can benefit through the application
of such a shared “language” for accurate and practical representation of various constructs in information
theoretic terms to represent risk and uncertainty in complex systems environments, thereby permitting
the accurate and rapid assessments of emergency situations and allowing efficient and effective health
services to be delivered productively.

Currently, there is a dire shortage of major studies in the applications of interoperable, integrative
health IT models and methods. As well, inadequate knowledge has yet to be derived from other industrial
and system engineering sectors such as manufacturing enterprises into aiding comparative processes in
health services delivery and management. For instance, the surgery department is always at the core of
many hospitals. Managing operation rooms requires a variety of expensive resources including surgical
space and facility, equipment and material supply, nurse, technician and doctor, to provide timely ap-
pointments to patients. It is a challenging task in and by itself.

Yet, the people manning the surgery department has still to interact with all the inpatient-outpatient
departments and clinics, as well as to be linked to a huge number of medically interconnected compo-
nents that will affect their own behaviors and dynamics at any moment. Reports and requests are largely
the only primary information artifacts interfacing between the operation rooms and other care providers
in the same hospital, and mostly for discrete interactions updated at a fixed time interval. The surgeons
and surgical administrator will often not be familiar or have knowledge of the status of other systems
and organizational components, and without the aids provided to them from an integrated platform of
health IT models and methods, they cannot possibly make the best decisions, including the operation
room assignments.

Ironically, most hospital departments and clinics nowadays have management models, policies, and
supporting software packages in place, but all running individually, to “efficiently” schedule patient
appointments and make medical decisions in an isolated manner. With the MEDIA framework applica-
tion, decisions on such localized “best” operations can now be optimized for the entire system. Feasible
assignments satisfying all of the required health policies for the various connected health provider
institutions can then be assured.

Our case example may now be further generalized to many other equally complex scenarios that
commonly occur in health services delivery. For example, even for a specialty clinic such as the urology
or cardiology unit located within a hospital, it has to deal with many other elements including primary
care, inpatient, outpatient, emergency, surgery, lab testing, logistics, and many other areas in terms of the
different nodes and types of information flow, including patient, provider and material flows. Similarly, an
insurance company has to navigate through patients, medical providers, pharmaceutical companies, and
other vendors or suppliers in order to keep routine financial claim transactions in order. For all of these
health provider organizations, if we do not attempt to empower the different health services managers
with the necessary, interoperable health IT capabilities, there will be no assurance that a well-coordinated
effort in patient care delivery will be sustained.

The need for such a well-coordinated effort and enterprisewide collaboration across the spectrum
of health services delivery is even greater when we consider health alliances, which may be formed
at varying scales, levels and sizes. Frequently emerging out of the cooperation among multiple health
provider institutions of primary clinics, hospitals, research institutes, insurance management organiza-
tions, and even government health agencies, health alliances are dependent on the separate units to work together in order to achieve high quality patient care. Piece-by-piece examination of related management models and systems does not and will not offer much help when local operation decisions have to be made based upon disparate evidence. In such networked systems and sub-systems, a medical provider or manager needs to know far more than his or her own world in order to make better, if not the “best,” decisions for the patients and the health alliance organization as a whole. Often, the critical need is not more models, or even more sophisticated yet isolated models – where abundant, if still not adequate, models have already been developed, implemented, and studied – instead, the primary need here may just be how to integrate existing models productively and intelligently so as to allow interoperable health IT applications to be shared. Then, and if necessary, new models and methods can be added to enhance those aspects of decisions that may still be lacking or have yet to be addressed.

A wonderful developing story for applying the MEDIA paradigm is the 2009 case of the “swine flu” (H1N1) pandemic that is ongoing at this point in time (Esterl, 2009). It is just impossible to have one model or system to capture everything relating or reported about this pandemic, from the private clinics to the US governmental health services sector plan for controlling H1N1 to the different magnitude of H1N1 developments spreading throughout the globe. In other words, it is just not enough to harbor the narrow perspective of a tiny component within the entire global health service system, but having an interconnected worldview of even just how the H1N1 is affecting the different nations will significantly improve the patient survival chance and H1N1 prevention for a particular or entire country. Even so, the demand to integrate models and evidence for seamless analysis and management of a pandemic like H1N1 may be attributed largely to the following facts:

1. The complexity and uncertainty are greatly increasing in the system of systems context of health services supply chains and global health information exchange networks to which any analysis and management systems have to appropriately respond.
2. The rapidly changing medical and health technology landscape and innovative practices in medicine, health management, industry and government policy, as well as the evolving field of health IT models and methods require the constant incorporation of new systems perspective and integrative model approaches.
3. Unfortunately, as noted previously, vast legacy HISs have typically been built piece by piece, resulting in the preservation only of disparate health IT models without the capability to leverage intelligently from evidence aggregated over time from diverse sources embedded in the overall global health care system.

Development of novel technology and unconventional business model has inspired complex enterprise structures to evolve as in the case of the US health services delivery system. These enterprises usually form close partnerships in order to survive and grow under increasing competition, for which decision making and policymaking relying on existing and past discrete models for isolated system segments is no longer sufficient. Another obstacle many of these health enterprises encountered in across-the-organization management is the complicated systems dynamics. This needs to be dealt with by systematically increasing the connectivity of existing models, resulting in the constant understanding and monitoring of the evolving systems states comprising rapid changes in participants and configurations along both temporal and spatial dimensions. As characterizing these different systems states efficiently can simply become overwhelming, health services quality assurance is undoubtedly a very demanding task. Interoperable,
integrative health IT models and methods via the MEDIA paradigm aim at reducing such complexity to meet the demands of high quality health services. The MEDIA paradigm also addresses these systems challenges through referential ontology modeling, hybrid probabilistic model integration, and adaptive knowledge fusion that adopt a real system-wide and process oriented perspective. Thus, the introduction of the MEDIA framework to emerging health IT models and methods research represents a key step to unifying our knowledge for modern health services enterprise management.

The future of health IT models and methods is dependent on the development of even more powerful integrative frameworks beyond the MEDIA paradigm. Such a paradigm will seek to provide a consistent approach to reusing and integrating available knowledge, dealing with complexity and uncertainty dimensions in multiple ways, and encouraging the sharing and exchanging of health information privately and securely across organizational boundaries that do not currently exist. This systematic methodological conjugation represents a departure in traditional integrated modeling and analysis from fitting all systems into just “one type of model” to an emphasis on knowledge interpretation, interaction and fusion among models. This makes it much easier to achieve balance between the local and global representation of different models. In other words, the hybrid probabilistic model integration can actually make use of any available models and/or choose the most suitable ones for each subsystem/task, rather than having to start the modeling process from scratch each and every time one or more new systems problem(s) is encountered.

In closure, the MEDIA methodology or an expansion of such a methodology can further be applied to create novel solutions to new health systems challenges faced in a wide range of practical contexts that vie to achieve the convergence of enterprise systems and processes. The trend toward preventive health, alternative and integrative medicine, e-health and healthy lifestyle promotion, for example, are all virgin grounds for the applications of integrative, interoperable health IT models and methods. Imagine how a self-monitoring community health care system that can be equipped with a regional center that uses interoperable and integrated health IT models and methods to aid in guiding individual residents throughout the community to cope with undue stresses arising from risky driving behaviors on a daily basis, become quickly alerted and fully prepared for emergencies by deploying the community health resources efficiently and effectively on an as needed basis, and channeling any and all unused health resources to evolve the community in multiple ways to adopt a healthy, low risk and more active lifestyle environment within the community.

Joseph Tan
McMaster University, Canada

Xiangyang Li
University of Michigan - Dearborn, USA

Yung-wen Liu
University of Michigan - Dearborn, USA
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