A New Socio-technical Model for Studying Health Information Technology in Complex Adaptive Healthcare Systems

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Abstract

Conceptual models have been developed to address challenges inherent in studying health information technology (HIT). This manuscript introduces an 8-dimensional model specifically designed to address the socio-technical challenges involved in design, development, implementation, use, and evaluation of HIT within complex adaptive healthcare systems. The 8 dimensions are not independent, sequential, or hierarchical, but rather are interdependent and interrelated concepts similar to compositions of other complex adaptive systems. *Hardware and software* computing infrastructure refers to equipment and software used to power, support, and operate clinical applications and devices. *Clinical content* refers to textual or numeric data and images that constitute the "language" of clinical applications. The *human computer interface* includes all aspects of the computer that users can see, touch, or hear as they interact with it. *People* refers to everyone who interacts in some way with the system, from developer to end-user, including potential patient-users. *Workflow and communication* are the processes or steps involved in assuring that patient care tasks are carried out effectively. Two additional dimensions of the model are *internal organizational features (e.g., policies, procedures, and culture)* and *external rules and regulations*, both of which may facilitate or constrain many aspects of the preceding dimensions. The final dimension is *measurement and monitoring*, which refers to the process of measuring and evaluating both intended and unintended consequences of HIT implementation and use. We illustrate how our model has been successfully applied in real-world complex adaptive settings to understand and improve HIT applications at various stages of development and implementation.

Introduction

An ongoing challenge to the design, development, implementation, and evaluation of health information technology (HIT) interventions is to operationalize their use within the complex adaptive health care system that consists of high-pressured, fast-paced, and distributed settings of care delivery. Many conceptual models of user interaction, acceptance, and evaluation exist [1, 2], but most are relatively limited in scope. Given the dearth of models that are specifically designed to address safe and effective HIT development and use, we have developed a comprehensive, socio-technical model that provides a multi-dimensional framework within which any HIT innovation, intervention, application, or device implemented within a complex adaptive healthcare system can be studied. This model builds upon and bridges previous frameworks and is further informed by our own work to study the safe and effective implementation and use of HIT interventions. In this paper we describe the conceptual foundations of our model and provide several examples of its utility for studying HIT interventions within real-world clinical contexts.

Background

Previous analyses of HIT interventions have been limited by a lack of conceptual models that have been specifically developed for this purpose. Examples of models previously applied by HIT investigators include Rogers' diffusion of innovations theory [3,4 5], Venkatesh's unified theory of acceptance and use of technology [6,7,8,9], Hutchins' theory of distributed cognition [10,11,12,13,14], Reason's Swiss Cheese Model [15,16,17], and Norman's 7-step human-computer interaction model [18,19,20]. Although all of these models account for one or more important facets of technology implementation, we believe that the scope of each model limits its utility to address the full range of factors that should be considered in the design, development, implementation, use, and evaluation of HIT interventions. For example, these models were not specifically designed to address the complex relationships between the HIT hardware, software, information content, and the human-computer interface. Furthermore, while most of these models provide general guidance to study the high-level aspects of HIT implementation within a given clinical environment, none of them includes a measurement and monitoring infrastructure (e.g., methods to routinely collect data, create or review reports or conduct surveillance of outcomes). Based on these limitations, our aim was to develop a more comprehensive model to integrate specific technological and measurement dimensions of HIT with other socio-technical dimensions (e.g., people, workflow, communication, organizational policies, external rules and regulations).

Previous Health Information Technology-focused Socio-technical Systems Models

Four related socio-technical models have been particularly influential in providing the foundation of our proposed model. First, Henriksen's model addresses (1) individual provider characteristics; (2) the nature or complexity of the work or task performed; (3) the physical environment where care takes place; (4) the human-system interfaces involved; and (5) various characteristics of the organization (social, environment, and management) [21]. Second, Vincent's framework for analyzing risk and safety proposes a hierarchy of factors that can potentially influence clinical practice [22]. Third, Carayon's Systems Engineering Initiative for Patient Safety (SEIPS) model [23] identifies three domains: (1) characteristics of providers, their tools and resources, and the physical/organizational setting; (2) interpersonal and technical aspects of health care activities; and (3) change in the patient's health status or behavior. Finally, Harrison et al.'s Interactive Socio-technical Analysis (ISTA) framework provides an excellent broad overview of the complex, emergent, inter-relationships between the HIT, clinicians, and workflows within any healthcare system [24].

While these socio-technical models include a "technology" component, none break down the "technology" into its individual components to enable researchers to dissect out the causes of particular HIT implementation or use problems, or to help identify specific solutions. We have found that many HIT problems we are studying revolve around the interplay of hardware, software, content (e.g., clinical data and computer-generated decision support), and user interfaces. Failing to acknowledge these specific technology-specific elements or attempting to treat them separately can hinder overall understanding of HIT-related challenges. For example, the "content" dimension of our model accounts for much of what informaticians do, that is, studying the intricacies of controlled clinical vocabularies that provide the cognitive interface between the inexact, subjective, highly variable world of biomedicine and the highly structured, tightly controlled, digital world of computers [25]. A well-constructed, robust user interface vocabulary can make all the difference in the world to a busy clinician struggling to quickly and accurately enter a complex clinical order for a critically ill patient [26], and it is important to distinguish this aspect of technology from others that may contribute to additional challenges (e.g., a user interface that is difficult to navigate, an order entry application that is slow to respond, or computers that are only available at the main nursing station). Failure to do so, for example, leads to general statements such as "clinicians struggled with the new technology" or "it takes clinicians longer to complete their tasks using the new technology" without providing any insight into specific causes of the problems or their solutions. In this example, without a multidimensional understanding of the technological dimensions of the failed IT application, the researcher may incorrectly conclude that the hardware, application software, or user was responsible, when in fact a poorly designed or implemented clinical vocabulary might have been the root of the problem.

Finally the preceding models do not account for the special monitoring processes and governance structures that must be put in place while designing and developing, implementing, or using HIT. For example, identifying who will make the decision on what, when, and how clinical decision support (CDS) interventions will be added [27]; developing a process for monitoring the effect of new CDS on the systems' response time [28]; building tools to track the CDS that is in place [29]; developing an approach for testing CDS; defining approaches for identifying rules that interact; developing robust processes for collecting feedback from users and communicating new system fixes, features, and functions; and building tools for monitoring the CDS system itself [30].

Moving towards a New Socio-technical Model for HIT

To overcome the limitations of previous models, we propose a new socio-technical model to study the design, development, use, implementation, and evaluation of HIT (Figure 1). Our comprehensive 8-dimensional model accounts for key factors that influence the success of HIT interventions. A major assumption of our model is that the 8 dimensions cannot be viewed as a series of independent, sequential steps. As with other components of complex adaptive systems, these 8 interacting dimensions must be studied in relationship to each other. Clearly, several of our model's components are more tightly coupled than others, for example, the hardware, software, content, and user interface are all completely dependent on one another. However, all the other social components also exert strong influences on these technical components.

In our model, one cannot expect to gain an in-depth understanding of the intricacies of complex HIT interventions simply by integrating the results of studies performed within any single dimension of the model [31]. Rather, HIT interventions must be understood in the context of their simultaneous effects across multiple dimensions of the model. For instance, a recent evaluation of a national program to develop and implement centrally stored

electronic summaries of patients' medical records in the UK revealed their benefits to be lower than anticipated and cautioned that complex interdependencies between many socio-technical factors at the clinical encounter-, organizational- and the national-level are to be expected in such evaluations [32]. These study findings are illustrative of how and why our proposed model could be useful.

The 8 dimensions include:

1. **Hardware and Software Computing Infrastructure.** This dimension of the model focuses solely on the hardware and software required to run the applications. The most visible part of this dimension is the computer, including the monitor, printer, and other data display devices along with the keyboard, mouse, and other data entry devices used to access clinical applications and medical or imaging devices. This dimension also includes the centralized (network-attached) data storage devices and all of the networking equipment required to allow applications or devices to retrieve and store patient data. Also included in this dimension is software at both the operating system and application levels. Finally, this dimension of the model subsumes all the machines, devices, and software required to keep the computing infrastructure functioning such as the high-capacity air conditioning system, the batteries that form the uninterruptable power supply (UPS) that provides short-term electrical power in the event of an electrical failure, and the diesel-powered backup generators that supply power during longer outages.

    In short, this dimension is purely technical; it is only composed of the physical devices and the software required keeping these devices running. One of the key aspects of this dimension is that, for the most part, the user is not aware that most of this infrastructure exists until it fails [33]. For example, in 2002 the Beth Israel Deaconess Medical Center in Boston experienced a four-day computer outage due to old, out-of-date computer equipment coupled with an outdated software program designed to direct traffic on a much less complex network. Furthermore, their network diagnostic tools were ineffective because they could only be used when the network was functioning [34].

2. **Clinical Content**. This dimension includes everything on the data-information-knowledge continuum that is stored in the system (i.e., structured and unstructured textual or numeric data and images that are either captured directly from imaging devices or scanned from paper-based sources) [35]. Clinical content elements can be used to configure certain software requirements. Examples include controlled vocabulary items that are selected from a list while ordering a medication or a diagnostic test, and the logic required to generate an alert for certain types of medication interactions). These elements may also describe certain clinical aspects of the patients' condition (e.g., laboratory test results, discharge summaries, or radiographic images). Other clinical content, such as demographic data and patient location, can be used to manage administrative aspects of a patient's care. These data can be entered (or created), read, modified, or deleted by authorized users and stored either on the local computer or on a network. Certain elements of the clinical content, such as that which informs clinical decision support (CDS) interventions, must be managed on a regular basis [36].

3. **Human Computer Interface**. An interface enables unrelated entities to interact with the system and includes aspects of the system that users can see, touch, or hear. The hardware and software "operationalize" the user interface; provided these are functioning as designed, any problems with using the system are likely due to human-computer interaction (HCI) issues. The HCI is guided by a user interaction model created by the software designer and developer [37]. During early pilot

testing of the application in the target clinical environment, both the user's workflow and the interface are likely to need revisions. This process of iterative refinement, wherein both the user and user interface may need to change, must culminate in a human computer interaction model that matches the user's modified clinical workflow. For example, if a clinician wants to change the dose of a medication, the software requires the clinician to discontinue the old order and enter a new one, but the user interface should hide this complexity. This dimension also includes the ergonomic aspects of the interface [38]. If users are forced to use a computer mouse while standing, they may have difficulty controlling the pointer on the screen because they are moving the mouse using the large muscles of their shoulder rather than the smaller muscles in the forearm. Finally, the lack of a feature or function within the interface represents a problem with both the interface and with the software or hardware that implements the interface.

4. **People**. This dimension represents the humans (e.g., software developers, system configuration and training personnel, clinicians, and patients) involved in all aspects of the design, development, implementation, and use of HIT. It also includes the ways that systems help users think and make them feel [39]. Although user training is clearly an important component of the user portion of the model, it may not by itself overcome all user-related problems. Many "user" problems actually result from poor system design or errors in system development or configuration. In addition to the users of these systems, this dimension includes the people who design, develop, implement, and evaluate these systems. For instance, these people must have the proper knowledge, skills, and training required to develop applications that are safe, effective, and easy to use. This is the first aspect of the model that is purely on the social end of the socio-technical spectrum.

In most cases, users will be clinicians or employees of the health system. However, with recent advances in patient-centered care and development of personal health record systems and "home monitoring" devices, patients are increasingly becoming important users of HIT. Patients and/or their caregivers may not possess the knowledge or skills to manage new health information technologies, and this is of specific concern as more care shifts to the patient's home [40].

5. **Workflow and Communication.** This is the first portion of the model that acknowledges that people often need to work cohesively with others in the health care system to accomplish patient care. This collaboration requires significant two-way communication. The workflow dimension accounts for the steps needed to ensure that each patient receives the care they need at the time they need it. Often, the clinical information system does not initially match the actual "clinical" workflow. In this case, either the workflow must be modified to adapt to the HIT, or the HIT system must change to match the various workflows identified.

6. **Internal Organizational Policies, Procedures, and Culture.** The organization's internal structures, policies, and procedures affect every other dimension in our model. For example, the organization's leadership allocates the capital budgets that enable the purchase of hardware and software, and internal policies influence whether and how offsite data backups are accomplished. The organizational leaders and committees who write and implement IT policies and procedures are responsible for overseeing all aspects of HIT system procurement, implementation, use, monitoring, and evaluation. A key aspect of any HIT project is to ensure that the software accurately represents and enforces, if applicable, organizational policies and procedures. Likewise, it is also necessary to ensure that the actual clinical workflow involved with operating these systems is consistent with policies and procedures. Finally, internal rules and regulations are often created in response

to the external rules and regulations that form the basis of the next dimension of the model.

7. **External Rules, Regulations, and Pressures.** This dimension accounts for the external forces that facilitate or place constraints on the design, development, implementation, use, and evaluation of HIT in the clinical setting. For example, the recent passage of the American Recovery and Reinvestment Act (ARRA) of 2009, which includes the Health Information Technology for Economic and Clinical Health (HITECH) Act, makes available over $20 billion dollars for health care practitioners who become "meaningful users" of health IT. Thus, ARRA introduces the single largest financial incentive ever to facilitate electronic health record (EHR) implementation. Meanwhile, a host of federal, state, and local regulations regulate the use of HIT. Examples include the 1996 Health Insurance Portability and Accountability Act (HIPAA), recent changes to the Stark Laws, and restrictions on secondary use of clinical data. Finally, there are three recent national developments that have the potential to affect the entire health care delivery system in the context of HIT. These include: 1) the initiative to develop the data and information exchange capacity to create a national health information network [41]; 2) the initiative to enable patients to access copies of the clinical data via personal health records [42]; and 3) clinical and IT workforce shortages [43].

8. **System Measurement and Monitoring**. This dimension has largely been unaccounted for in previous models. We posit that the effects of HIT must be measured and monitored on a regular basis. An effective system measurement and monitoring program must address four key issues related to HIT features and functions [44]. First is the issue of availability – the extent to which features and functions are available and ready for use. Measures of system availability include response times and percent uptime of the system. A second measurement objective is to determine how the various features and functions are being used by clinicians. For instance, one such measure is the rate at which clinicians override CDS warnings and alerts. Third, the effectiveness of the system on health care delivery and patient health should be monitored to ensure that anticipated outcomes are achieved. For example, the mean HbA1c value for all diabetic patients in a practice may be measured before and after implementation of a system with advanced CDS features. Finally, in addition to measuring the expected outcomes of HIT implementation, it is also vital to identify and document unintended consequences that manifest themselves following use of these systems [45]. For instance, it may be worthwhile to track practitioner efficiency before and after implementation of a new clinical charting application [46]. In addition to measuring the use and effectiveness of HIT at the local level, we must develop the methods to measure and monitor these systems and assess the quality of care resulting from their use on a state, regional, or even national level [47, 48].

Relationships and Interactions between our Model's Components

Our research and experience has led us, and others, to conclude that HIT-enabled healthcare systems are best treated as complex adaptive systems [49]. The most important result of this conclusion is that hierarchical decomposition (i.e., breaking a complex system, process, or device down into its components, studying them, and then integrating the results in an attempt to understand how the complete system functions) cannot be used to study HIT [50]. As illustrated by the evaluation of centrally stored electronic summaries in the UK, complex interdependencies between various socio-technical dimensions are to be expected and our HIT model (had it existed at the time) might have potentially predicted some of them and allowed them to address them prior to go-live rather than in the evaluation stages of the

project. Therefore, one should not view or use our model as a set of independent components which can be studied in isolation and then synthesized to develop a realistic picture of how HIT is used within the complex adaptive healthcare system. Rather, the key to our model is how the eight dimensions interact and depend on one another. They must be studied as multiple, interacting components with non-linear, emergent, dynamic behavior (i.e., small changes in one aspect of the system lead to small changes in other parts of the system under some conditions, but large changes at other times) that often appears random or chaotic. This is typical of complex adaptive systems, and our model reflects these interactions.

For example, a computer-based provider order entry (CPOE) system that works successfully on an adult, surgical nursing unit within a hospital may not work at all in the nearby pediatric unit for any number of potential reasons, including: 1) hardware/software (e.g., fewer computers, older computers, poor wireless reception, poor placement); 2) content (e.g., no weight- or age-based dosing, no customized order sets or documentation templates); 3) user-interface (e.g., older workforce that has trouble seeing the small font on the screen); or 4) personnel (e.g., no clinical champion within the medical staff). However, each of these dimensions has a potential relationship with one or more of the other dimensions. For instance, computers may have been few or old because of some organizational limitations, there may be no customized order sets because clinician-users did not agree on how best to do it, and there was no clinical champion because the organization did not provide any incentive for the additional time this role would entail. Other reasons could include problems with the user interface and the communication and workflow related to how nurses process new medication orders using the EHR and record administration of medications. These issues, in turn, may have been due to organizational policies and procedures. For example, the unit governance committee may have decided not to approve a request for mobile computers, with the result that nurses spent more time away from patients and therefore had a slower workflow related to processing new orders. The preceding example illustrates the interaction of **six** dimensions of our model: hardware/software, clinical content, user interface, people, workflow, and organizational policies. Additionally, some form of monitoring could have detected these issues. In summary, our model provides HIT researchers with several new avenues of thinking about key technology components and how these dimensions can be accounted for in future research.

The New HIT Model in Action in Real-World Settings

The following sections illustrate how we have used the socio-technical model of safe and effective HIT use within our research. In an attempt to describe how the model can be applied across the breadth of HIT research and development, and to provide examples of different systems and interventions that can be analyzed within this new paradigm, we highlight key elements of our model in the context of several recent projects.

HIT Design and Development

The design and development of CDS interventions within clinicians' workflow presents several challenges. We conducted several qualitative studies to gain insight into the 8 dimensions of our model during the development of a CDS tool within a CPOE application. This CDS intervention was designed to alert clinicians whenever they attempted to order a medication that was contraindicated in elderly patients or one that had known serious interactions with warfarin. We used several methods, including focus groups, usability testing, and educational sessions with clinician users [51], to identify issues related to hardware/software, content, interface, people, measurement, workflow/communication, and internal policies and procedures. These efforts helped us, for example, to understand the need to meet with the organization's Pharmacy and Therapeutics (P & T) committee (i.e.,

internal policy) to convince them to modify the medication formulary as well as the information technology professional (i.e., *people*) who was responsible for maintaining the textual *content* of the alerts (i.e., font size, contents and order of the messages) to fit within the constraints of the alert notification window (i.e., *user interface*) which eliminated the need to train *clinicians* to use the horizontal scrolling capability. This is just one simple example of how use of the 8 dimensional model paid huge dividends during the development and implementation stages of this highly successful project [52,53].

HIT Implementation

In a recent article we described lessons that could be learned from CPOE implementation at another site [54]. One of the most important conclusions from this implementation was that problems could, and often do, occur in all 8 dimensions of the model (see Table 1) [55].

HIT Use

Safe and effective use of an EHR-based notification system involves many factors that are addressed by almost all dimensions of our model [56,57]. This CDS system generates automated asynchronous "alerts" to notify clinicians of important clinical findings. We examined communication outcomes of over 2500 such alerts that were specifically related to abnormal test results. We found that 18.1% of abnormal lab alerts and 10.2% of abnormal imaging alerts were never acknowledged (i.e., were unread by the receiving provider). Additionally, 7–8% of these alerts lacked timely follow-up, which was unrelated to acknowledgment of the alert.

Despite a notification system that ensured transmission of results, it was concerning that abnormal test results did not always receive timely follow-up, even when acknowledged. This study revealed complex interactions between users, the user interface, software, content, workflow/communication, and organizational policies related to who was responsible for abnormal test follow-up. Our findings thus highlighted the multiple dimensions of our model that need to be addressed to improve the safety of EHR-based notification systems and perhaps other forms of CDS (see Table 1) [59, 60, 61, 62]. We are now applying the socio-technical model to study barriers, facilitators, and interventions for safe and effective test result notification through EHRs.

HIT Evaluation

Our model recently provided us guidance in HIT evaluation, reminding us that however technologically savvy we make our patient care processes, we must also carefully monitor their impact, effectiveness, and unintended consequences. We recently evaluated why, despite implementation of an automated notification system to enhance communication of fecal occult blood test (FOBT) results, providers did not take follow-up actions in almost 40% of cases [63]. Again, our findings highlighted multiple dimensions corresponding to our socio-technical model. For instance, we found that clinician non-response to automated notifications was related to a software configuration error that prevented transmission of a subset of test results but we also found that if the institution was using certain types of workflows related to test performance and that if organizational procedures for computerized order-entry of FOBTs were different, the problem may not have occurred. Thus, we found our multi-dimensional approach, which accounted for interactions, to be useful for comprehensive evaluation of HIT after implementation.

Conclusions

The 8 dimensions of the safe and effective HIT use model introduced in this manuscript establish a new paradigm for the study of HIT. We have successfully applied this model to

study several HIT interventions at different levels of design, development, implementation, use and evaluation. We anticipate that additional study of the 8 dimensions and their complex interactions will yield further refinements to this model and, ultimately, improvements in the quality and safety of the HIT applications that translate to better health and welfare for our patients.

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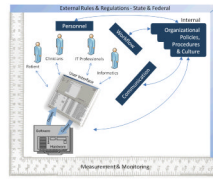
Figure 1.
Illustration of the complex inter-relationships between the 8 dimensions of the new Socio-technical model.

Table 1

Illustration of how the 8-dimensions of our socio-technical model have been used to analyze different HIT-related interventions and how other dimensions might need to be addressed for every dimension

Socio-technical model dimension	Lessons Learned from Implementation of Computer-based Provider Order Entry	Follow-up of Alerts related to Abnormal Diagnostic Imaging Results
Hardware and Software	The majority of computer terminals were linked to the hospital computer system via wireless signal, communication bandwidth was often exceeded during peak operational periods, which created additional delays between each click on the computer mouse.	Alerts should be retracted when the patient dies or if the radiologist calls, or the patient is admitted before the alert is acknowledged. However, this can be done only through a centralized organizational policy.
Clinical Content	No ICU-specific order sets were available at the time of CPOE implementation. The hurried implementation timeline established by the leaders in the organization prohibited their development.	Interventions to reduce alert overload and improve the signal to noise ratio should be explored. Unnecessary alerts should be minimized. However, people (physicians) may not agree which alerts are essential and which ones are not [58].
Human Computer Interface	The process of entering orders often required an average of 10 clicks on the computer mouse per order, which translated to 1 to 2 minutes to enter a single order. Organizational leaders eventually hired additional clinicians to "work the CPOE system" while others cared for the patients.	Unacknowledged alerts must stay active on the EMR screen for longer periods, perhaps even indefinitely, and should require the provider's signature and statement of action before they are allowed to drop off the screen. However, providers might not want to spend additional time stating their actions; who will make this decision?
People	Leaders at all levels of the institution made implementation decisions (re: hardware placement, software configuration, content development, user interface design, etc.) that placed patient care in jeopardy.	Many clinicians did not know how to use many of the EMR's advanced features that greatly facilitated the processing of alerts so training should be revamped. However, providers are only given 4 hours of training time by the institution
Workflow and Communication	Rapid implementation timeline did not allow time for clinicians to adapt to their new routines and responsibilities. In addition, poor hardware and software design and configuration decisions complicated the workflow issues.	Communicating alerts to 2 recipients, which occurred when tests were ordered by a healthcare practitioner other than the patient's regular PCP, significantly increased the odds that the alert would not be read and would not receive timely follow-up action. No policy was available that states who is responsible for follow-up. Additionally, back-up notification required by the institution to improve critical test result follow-up, a Joint Commission goal.
Organizational Policies and Procedures	Order entry was not allowed until after the patient had physically arrived at the hospital and been fully registered into the clinical information system.	Every institution must develop and publicize a policy regarding who is responsible (PCP vs the ordering provider, who may be a consultant) for taking action on abnormal results. Also meets External Joint commission requirements.
External Rules, Regulations, and Pressures	Following the IOM's report "*To Err is Human: Building a Safer Health System*" and subsequent congressional hearings the issue of patient safety has risen to a position of highest priority among health care organizations.	Poor reimbursement and heavy workload of patients puts productivity pressure on providers The nature of high-risk transitions between health care practitioners, settings, and systems of care makes timely and effective electronic communication particularly challenging.
System Measurement and Monitoring	Monitoring identified a significant increase in patient mortality following CPOE implementation.	An audit and performance feedback system should be established to give providers information on timely follow-up of patients' test results on a regular basis. However, providers may not want feedback or the institution does not have the persons required to do so.