3

Designing and Integrating Clinical and Computer-based Simulations in Health Informatics: From Real-World to Virtual Reality

Elizabeth Borycki, Andre Kushniruk, James Anderson, Marilyn Anderson

1. Introduction and Motivation

Simulations were first used in health care over 40 years ago when Denson and Abrahamson (1969) developed and used a simulator (i.e., Sim One) to train medical residents to perform two medical procedures (endotracheal intubation and anesthesia induction) and demonstrated the usefulness of the simulator in teaching medical students how to perform these medical procedures. Although innovative at the time, simulation was not readily adopted as a methodology for training health care professionals and students until the 1980's. In the mid 1980's there was a resurgence of interest in using simulation to train health professionals with improvements in the availability of computers. Computer-based simulations were identified as a method for teaching health professional students clinical knowledge that could be used in decision-making involving patient care. Computer-based simulations were found by researchers to be helpful as an aid in educating physicians and other health professionals about the anatomy and physiology of the human body and its pharmacologic treatment. Unfortunately, these computer-based simulations did not provide health professional students with sufficient opportunities to develop both the practical knowledge and the technical skills that were needed in real-world clinical situations involving patients. Computer-based simulations could not adequately mimic real-world, patient health care events characteristic of those found in physician office, clinical and hospital environments (Byrick & Wylands, 2009).

In the mid to late 1980's Gaba (1988) developed a simulator that allowed medical students to learn how to manage real-world, life threatening patient health events. Gaba's simulator involved the use of patient mannequins that could be programmed to mimic a wide variety of human responses (from periods of health to end-stage disease). Gaba's computer controlled mannequins were able to mimic real-life patient illness and disease and thereby improved the quality of medical students' training - providing opportunities to use knowledge gained in the classroom setting in situations representative of the real-world. Gaba's simulator was used to train medical students on a range of real world procedures from the simple to the complex in a range of situations representative of real-world patient health situations. The simulator afforded medical students the opportunity to experience real-world critical events in a safe environment that would allow them to improve their knowledge while at the same time having the opportunity to practice their skills. As a

consequence, students when confronted with similar situations in a real-world setting (e.g., a patient in an operating room) were better able to respond to the situation, having practiced it with a computer controlled mannequin or simulator.

Today, computer-based simulation continues to be used by health professionals to improve clinical knowledge. In addition, physical simulators (i.e., computer controlled mannequins) are also being used to teach differing health professionals (e.g., physicians, nurses, pharmacists, respiratory therapists) additional knowledge and skills that can be used in the care of patients. Both these technologies continue to be used to teach health professional students. As well, both these technologies are being used to teach health care practitioners about new and emergent medical procedures, therapies, treatments and the role of differing types of medical interventions in the spread and progression of disease (as in the case of computer-based simulation use in public health surveillance) (Byrick & Wynands, 2009).

The use of computer-based simulations and simulators is not limited to teaching health professionals. Computer-based simulations and simulators have been used in the field of biomedical engineering to prototype, test and determine the impact of new medical devices before their being used in health care settings such as hospitals. More recently, clinical simulations (i.e. simulations involving observation of health professionals interacting with systems in carrying out simulated clinical activities) are being extended for use to the field of health informatics (i.e., the study of health information systems and their use in health care settings) (Borycki et al., 2009a; Borycki et al., 2009b; Kushniruk et. al., 2005). In health informatics simulations are being used to prototype, test and evaluate health information systems (i.e., to determine the safety of these systems and their ability to support physician, nurse and other health professional information seeking and decision-making) (e.g., Kushniruk et. al., 2005; Borycki et. al., 2009). As well, simulations are being used to evaluate the organizational impacts of implementing differing health information systems and their associated devices in physician office, clinic and hospital settings (Kushniruk et al., 2005; Kushniruk et al., 2006). Such use of simulations is necessary to support health administrator decision-making involving the procurement, customization and implementation of health care software and devices in the clinical settings (Borycki et al., 2009c; Kushniruk et al., 2009). This is a new area of research in health informatics that has shown considerable promise in improving the safety of health information systems and their associated devices as well as their fit with the clinical environment before an implementation has occurred (Borycki & Kushniruk, 2005). In this book chapter we will present an overview of a new and emerging area of research that examines the role of clinical and computer-based simulation in assessing the safety and task-technology fit of health information systems software and devices that are to be implemented in health care settings. More specifically, the authors of this book chapter will begin by presenting their work in this area of health informatics. We will describe how clinical simulation and computer-based simulation have been used in health informatics and how these two types of simulation can be integrated to support the decision-making of health professionals and health administrators when procuring, selecting and implementing such systems for use in real-world clinical settings. Lastly, the authors will discuss future directions for the use of clinical, computer-based and hybrid simulations in health informatics and the potential role of computer programmed mannequins in future research.

2. Clinical Simulations

2.1 Introduction

Clinical simulations are increasingly being used by health care organizations (e.g., hospitals and home care agencies) to evaluate health information systems (i.e., software applications) and their associated devices (e.g., computer workstations, hand held devices and wireless carts). Such simulations typically involve the observation and recording (i.e., audio and video) of human subjects (e.g., healthcare professionals) as they interact with real or simulated patients using information technology and healthcare devices, under realistic conditions (Borycki & Kushniruk, 2005; Kushniruk & Borycki, 2005). Clinical simulations can help organizations to evaluate software applications or devices prior to their real-world implementation in a hospital, physician office or home care setting (Borycki et al., 2009).

In using clinical simulations health care organizations and vendors can identify potential issues arising from software applications, devices and software/device integrations prior to their use in real-world settings. More specifically, clinical simulations offer vendors and health care organizations the opportunity to evaluate the real-world impacts of a technology(ies) upon health professional work processes (e.g., workflow) and patient outcomes (e.g., medical errors, adverse events, and vaccination rates) prior to their real-world use (Borycki et. al., 2009c; Kushniruk et al., 2009).

Clinical simulations have emerged as a new form of evaluation in the field of health informatics. They are unlike traditional evaluations (e.g., randomized clinical control trials or pre-test post-test quasi-experimental studies that have been used to evaluate systems) which typically take place after a technology(ies) has been implemented (Anderson et al., 2005; Friedman & Wyatt, 2008). Clinical simulations can lead to significant cost savings as they allow for modification of the software application and/or device prior to an organization wide implementation (Patton, 2001). If the software application and/or device is modified prior to a system wide implementation, the costs associated with re-implementing the application and re-training users could be avoided or significantly reduced if the application/devices workflows and impact upon patient outcomes can be improved or optimized (Borycki et al., 2009b).

Therefore, clinical simulations allow the vendor or healthcare organization to identify those intended and unintended consequences arising from a software application and/or device that influence health professional's work processes and outcomes to be addressed before it affects the organization and its health professionals and patients. For example, there have been several studies published in the medical and health informatics literature that have reported that electronic health record applications such as physician order entry can facilitate medical errors (i.e., inadvertently cause technology-induced errors) (e.g., Ash et al., 2007; Borycki & Kushniruk, 2005; Koppel et al., 2005; Kushniruk et al., 2005). In most cases these studies have reported upon the role of the technology in increasing some types of errors only after the software application and/or device has been implemented (e.g., Ash et al., 2007; Campbell et al., 2006). In some cases these errors were "new" types of errors as they did not exist in the paper patient record environment that has characterized most hospitals in North America (Borycki & Kushniruk, 2008; Shulman et al., 2005). These publications led some researchers to call for the development of evaluative approaches that

could be used to identify such error facilitating aspects (i.e., features and functions of software applications and/devices before their implementation in real-world health care settings). Clinical simulations were developed by a group of researchers in an effort to identify these types of unintended consequences prior to real-world implementation so that these error facilitating aspects of the software application and/or device could be addressed before being used in a hospital (Kushniruk et al., 2005).

Such knowledge early in the software development lifecycle (SDLC) prior to organizational implementation can prevent the occurrence of unintended consequences that may affect health professionals and patients (i.e., elimination of the unintended error facilitating aspects of applications/devices or technology-induced errors that may lead to harm). Such apriori knowledge allows organizational decision makers to consider the impact of changes to health professional work arising from such changes resulting from the introduction of an application or a device and take into account process and outcome changes arising from those changes involving technology. Organizations can in response make proactive decisions about whether to redesign or modify an application and/or device. Alternatively, organizations can better customize the application/device to the local organizational context (i.e., improve task-technology fit) or provide interventions that would prevent the occurrence of such events (e.g., additional training and support during the period when the application/device is being implemented) (Borycki & Kushniruk, 2008; Borycki et al., 2009b).

2.2 Development of Clinical Simulations

The construction of clinical simulations involves several phases: the design of a representative environment (e.g., a clinic or a hospital room), the development of a representative situation (the healthcare scenario or task) and the selection of representative users (e.g., physicians or nurses). The development of a representative environment involves identifying a location in an organization that is representative of the real-world. The organizational location should include the equipment that is typically used by individuals in that organization. For example, a hospital that is implementing a new software application and devices that could be used by a physician in managing a patient's care could use an empty room in a hospital that has a hospital bed, bedside table and computer workstation that a physician or nurse would use when reviewing patient data or documenting patient information. The development of a representative situation involves identifying the conditions and positions that health professionals would find themselves in when using the software application/device. Here, representatives of the organization would identify those scenarios where the physician or nurse would interact with the application/device. For example, a nurse may interact with a medication administration system and a wireless cart while giving patient medications. Organizational representatives may then identify those tasks that would be part of that scenario. Using our example of a nurse using a medication administration system and wireless cart to give a patient medication, the tasks involved in administering a medication may include such tasks as verifying the patient's identity, verifying that the correct medication is being given, giving the medication and documenting that the medication has been given using the software application (Borycki et al., 2009b; Kushniruk et al., 1997).

2.2.1 Data Collection

Data collection during the clinical simulation takes three forms: (1) video data of the user interacting with the software application and/or device and the surrounding organizational environment, (2) audio data of the user(s) while interacting with the applications and devices in an organizational environment, and (3) screen recordings of the users' interaction with the software application under study. Video and audio data can be collected using a video camcorder. Screen recordings of the software application can be collected using a software screen recording program such as Hypercam® (See Kushniruk and Borycki, 2005 for more detail). In many studies subjects may be audio recorded as they interact with systems and may be asked to "think aloud" or verbalize their thoughts. Other audio recordings may be of the subject (e.g., physician) interacting with a patient or someone playing the role of a patient – i.e., a "simulated patient") while using a health information system. For example in Figure 1 we have a picture of a health professional interacting with a workstation while "thinking aloud". As can be seen in the figure a video camcorder is recording both video and audio data. On the workstation a screen recording program is recording all interactions the health professional is having with the software application (resulting in a digital movie of the computer screens and audio track). Once the video, audio and screen recording data is captured, the audio data needs to be transcribed. Transcriptions are then annotated with data collected from the screen recordings and descriptions of interactions between the health professional, software application, device and the organizational environment (see Borycki & Kushniurk, 2005). Interesting or problematic user interactions with the system under study can be annotated. Data can also be coded using a predefined coding scheme. For example, pre-defined codes may include categories for identifying errors and human-computer interaction issues such as problems with system navigation, display visibility or consistency of interface design. New codes are added if the existing codes do not adequately describe the audio, video or screen recording data. Audio, video and screen recording data can be triangulated. The transcript and annotations provide both qualitative and quantitative data. Qualitative codes provide insights into how the software application and device perform in a given organizational environment during specific scenarios and during specific work tasks. Qualitative codes can also be quantified. Quantification of qualitative data provides frequencies of occurrence for specific types of events such as errors or the occurrence of specific types of cumbersome workflows. Here, the evaluator can determine the cumbersome workflows and errors that occur most frequently and then attempt to modify the software application or they can select a device that prevents the cumbersome workflow or error from occurring. In addition to this the evaluator can recommend that the implementers of the software application and device provide specific types of education or training for users that would reduce the effects of the application/devices changes on workflow and error rates (Borycki et al., 2009a).

Fig. 1. A Health Professional Being Video Recorded as He Interacts With a Health Information System in a Clinical Simulation

2.2.2 Application

The authors have used clinical simulations to identify the features and functions of software applications that may facilitate medical errors. They have conducted a study where they examined the relationship between usability and medical error and found that specific types of usability problems were related to specific device and interface features. For example, in one study it was found that device size affected display visibility and there was a relationship between medical errors rates and display visibility. They also found that interface design features such as default menu options provided by a system (for medications, dosages etc.) were related to medical error, when health professionals would choose such defaults when they were inappropriate (Kushniruk et al., 2005). In another study the researchers used clinical simulation to identify cumbersome workflows resulting from the introduction of a medication administration system that included a wireless cart and a medication administration system application. In the study the researchers asked health professionals (i.e., physicians and nurses) to administer medications. Participants in the study were asked to administer several differing types of medications to a simulated patient (i.e., a mannequin was brought in to serve as the patient). From the simulation the researchers found that the software application and device (i.e. wireless medication administration cart) could seriously affect the sequence of workflow activities, could increase the complexity of work activity, could lock out the user from some activities and could impose a specific order of tasks upon clinical work. Such information was then used to inform software application design or re-design and organizational implementation of the software application and device (i.e., customization of software applications to the local

organizational environment, selection of devices for the organization, training of users, and implementation approaches for the system in a healthcare organization) (Kushniruk et al., 2009).

2.3. Advantages of Clinical Simulation

Clinical simulations have a number of advantages associated with their use. For example, clinical simulations allow one to determine the impact of a software application in conjunction with a software device or constellation of devices upon patient care processes (i.e., health professional workflows involving patients) and patient outcomes (i.e. quality of the patient's health care) (Borycki et al., 2009a; Kushniruk et al., 2006). Clinical simulations allow one to test software applications and equipment in a safe environment (outside of the hospital or physician office) so that the "unintended consequences" that may arise from introducing a new software application and/or device into a hospital or clinic do not affect health professional work or patient health care significantly. For example, a clinical simulation could be used to predict potential changes in workflow, information seeking behaviors and medical error rates prior to system implementation (Borycki et. al., 2009a; Kushniruk et al., 2005). This would reduce the already high rate of adoption failures in health care - it is estimated that 65% of all health information systems fail to be adopted by health professionals (Rabinowitz et. al., 1999). In addition to this clinical simulations reduce organizational risks - reducing the need for re-implementation. When an application or device fails to be adopted by health professionals or it is adopted in such a way that the full functionality of the application/device is not used to improve patient care, the organization will need to re-implement the application/device (Ash et. al., 2007; Granlien et al., 2008). There are significant costs associated with re-implementation such as further customization of the application, switching costs associated with identifying a new device to implement and re-training of staff who will be using the device. Clinical simulations allow one to make software application and device changes based on observed evidence that the application/device work with the given health care environment, the situations health professionals encounter and the tasks they perform. Such use of clinical simulations would reduce the need for re-implementation (Borycki & Kushniruk, 2005).

Clinical simulations allow organizations to determine if applications and/or devices introduce "new errors". In the health informatics literature there has been significant research that has shown that technology can introduce new types of errors - technology-induced errors. Clinical simulations allow an organization to assess the potential for these new types of errors occurring and by identifying their cause prevent them. This is important as a clinical simulation may be used to assess the safety of a application and/or device. Clinical simulations allow for such evaluation activities to take place and avoid the use of "live" patients and patient data (Kushniruk et al., 2005). In addition to this health professionals avoid exposure to situations that may cause "real life" errors to occur.

Such knowledge would be extremely useful if taken into account during the procurement of a software application or device. Information from the clinical simulations could be used to determine the level of task-technology fit between an application, device and the organizational context where it will be deployed. Lastly, clinical simulations have the potential to inform organizational decisions during procurement and implementation.

Organizations typically implement differing constellations of software applications and devices. Clinical simulations may help organization to select applications and devices that best meet organizational needs (Borycki et al., 2009c).

Clinical simulations can also be used to inform organizational decisions involving the type of implementation that will be undertaken (i.e., should the application and software be implemented organization wide or in a single department). They also have the ability to inform the type of approach taken during training. For example, an organization may choose to train users using a "hands on approach" involving the device and the software application versus a pure lecture format if the clinical simulation demonstrates there is a need to directly work with the application and device (Borycki et. al., 2009). In summary, clinical simulation involving software applications and/or devices offer organizations the opportunity to assess task-technology fit with the organizational environment. As a result, the impact of the application and device upon health professional work processes and outcomes is learned. This allows the organization to make modifications to the software application and device prior to its implementation in a real-world setting. Such knowledge is a key to preventing technology adoption failures and future modification and training costs associated with reimplementation after the software application and device has failed.

3. Computer-Based Simulations

3.1. Introduction

Many health informatics applications cannot be evaluated with traditional experimental methods involving human subjects. In these instances computer simulation provides a flexible approach to evaluation. The construction of a computer simulation model involves the development of a model that represents important aspects of the system under evaluation. Once validated, the model can be used to study the effects of variation in system inputs, differences in initial conditions and changes in the structure of the system (Anderson, 2002a,b). In addition, as will be described in a subsequent section, the outputs of clinical simulations (described in the previous section) can be used as inputs into computer-based simulations.

3.2. The Modeling Process

3.2.1 Systems Analysis

Construction of a computer simulation model begins with the identification of the elements of the system and the functional relationships among the elements. A systems diagram is used to depict subsystems and components and relationships among them (Anderson, 2003). The diagram should also show critical inputs and outputs, parameters of the system, any accumulations and exchanges or flows of resources, personnel, information, and system performance measures. Relationships may be specified analytically, numerically, graphically, or logically and may vary over time.

Many information technology applications that are to be evaluated are multifaceted. Subsystems and components are interrelated in complex ways and may be difficult to completely understand. Model development requires the investigator to abstract the

important features of the system that generate the underlying processes. This requires familiarity with the system that is being evaluated and its expected performance.

3.2.2 Data Collection

Qualitative and quantitative information are required in order to adequately represent the system. Qualitative research methods are useful in defining the system under investigation. Quantitative data are necessary in order to estimate system parameters such as arrival and service distributions, conversion and processing rates, error rates, and resource levels. Data may be obtained from system logs and files, interviews, expert judgment, questionnaires, work sampling, etc. Data may be cross-sectional and/or time series.

3.2.3 Model Formulation

In general, there are two types of simulation models, discrete-event and continuous. Swain (1997) reviews 46 simulation software packages and provides a directory of vendors. The example below uses a continuous simulation model to describe a medication error reporting system.

Discrete-event models are made up of components or elements each of which perform a specific function (Banks & Carson, 1984). The characteristic behavior of each element in the model is designed to be similar to the real behavior of the unit or operation that it represents in the real world. Systems are conceptualized as a network of connected components. Items flow through the network from one component to the next. Each component performs a function before the item can move on to the next component. Arrival rates, processing times and other characteristics of the process being modeled usually are random and follow a probability distribution. Each component has a finite capacity and may require resources to process an item. As a result, items may be held in a queue before being processed. Each input event to the system is processed as a discrete transaction. For discrete-event models, the primary objective is to study the behavior of the system and to determine its capacity, to assess the average time it takes to process items, to identify rate-limiting components, and to estimate costs. Simulation involves keeping track of where each item is in the process at any given time, moving items from component to component or from a queue to a component, and timing the process that occurs at each component. The results of a simulation are a set of statistics that describe the behavior of the simulated system over a given time period. A simulation run where a number of discrete inputs to the system are processed over time represents a sampling experiment. Applications of discrete event simulation are provided in Anderson (2002a).

Continuous simulation models are used when the system under investigation consists of a continuous flow of information, material, resources, or individuals. The system under investigation is characterized in terms of state variables and control variables (Hannon & Ruth, 1994). State variables indicate the status of important characteristics of the system at each point in time. These variables include people, other resources, information, etc. An example of a state variable is the cumulative number of medication orders that have been written on a hospital unit at any time during the simulation. Control variables are rates of change and update the value of state variables in each time period. An example of a control

variable is the number of new medication orders written per time period. Components of the system interact with each other and may involve positive and negative feedback processes. Since many of these relationships are nonlinear, the system may exhibit complex, dynamic behavior over time.

The mathematical model that underlies the simulation usually consists of a set of differential or finite difference equations. Numerical solutions of the equations that make up the model allow investigators to construct and test models that cannot be solved analytically (Hargrove, 1998).

3.2.4 Model Validation

Once an initial model is constructed it should be validated to ensure that it adequately represents the system and underlying processes under investigation. One useful test of the model is to choose a model state variable with a known pattern of variation over some time period. The model is then run to see if it accurately generates the reference behavior. If the simulated behavior and the observed behavior of the system correspond well, it can be concluded that the computer model reasonably represents the system. If not, revisions are made until a valid model is developed (Law & Kelton, 1991; Oreskes, Schrader-Froechette & Belitz, 1994). The behavior of the model when it is manipulated frequently provides a much better understanding of the system. This process has been termed postulational modeling (Katzper, 1995).

Sensitivity analyses also should be performed on the model. Frequently, the behavior of important outcome variables is relatively insensitive to large changes in many of the model's parameters. However, a few model parameters may be sensitive. A change in the value of these parameters may result in major changes in the behavior pattern exhibited by the system. It is not only important to accurately estimate these parameters but they may represent important means to change the performance of the overall system.

3.3. Application

In this section we describe an example of a computer simulation model that can be used to explore organizational changes that are required to improve patient safety based on a medication error reporting system. (Anderson, Ramanujam, Hensel & Anderson, 2005). The model is used to illustrate the fact that patient safety initiatives require more than clinical initiatives. In order to be successful, these initiatives must be designed and implemented through organizational support structures and institutionalized through enhanced education, training, and implementation of information technology that improves work force capabilities (Anderson, 2004).

In an effort to determine whether hospitals working collectively to report medical errors can improve patient safety, a coalition was formed consisting of 40 hospitals. These hospitals implemented a voluntary retrospective reporting system. The MEDMARX system was implemented to report medication errors. Data from these hospitals were used to validate the model.

A computer simulation model was constructed in order to model medication error reporting systems and organizational changes needed to improve patient safety. STELLA was used to create the model represented in Figure 2. The model consists of three stages. In stage 1, medication errors are generated and a certain proportion of these errors are reported. Medication errors are of two types: errors that do not harm patients (Categories A-D) and errors that harm the patient (Categories E-I). Next, the model includes communication about the errors that are reported. Information about the errors may be shared with the staff who made the error, with the caregivers more generally and with the patient. Medication errors may also result in qualitative changes to the communication process

The third stage of the model involves organizational actions taken in response to medication errors. These organizational changes may involve changes in policies, technology, personnel and organizational culture. Changes in goals involve policy and procedure modification in response to medication errors. Technological changes may involve changes in the hospital's formulary and/or modifications to the computer software used in the medication process.

The model was used to simulate medication error reporting in a typical hospital over twelve quarters. The model predicts the number of medication errors reported by type and organizational actions taken as a result of reported errors. Figure 3 shows the results over the 12 quarters. As can be seen from the graph, the number of errors reported increases over time. This suggests that, as a hospital gains experience with the error reporting system, health care providers report a greater proportion of errors that occur.

In order to validate the model, the model predictions for the first five quarters were compared to actual data from a regional coalition of 40 ewhospitals. Predicted values are quite close to the actual number of reported errors, especially for first three quarters. Model predictions are a little high for quarters 4 and 5.

3.4. Advantages of Simulation

Simulation provides a powerful methodology that can be used to evaluate medical informatics applications. Modifications to the system or process improvements can be tested. Once a model is created, investigators can experiment with it by making changes and observing the effects of these changes on the system's behavior. Also, once the model is validated, it can be used to predict the system's future behavior. In this way, the investigator can realize many of the benefits of system experimentation without disrupting the practice setting in which the system is implemented. Moreover, the modeling process frequently raises important additional questions about the system and its behavior. In summary, computer-based simulations provide organizations with opportunities to develop models that represent actual systems or systems that are under evaluation. As a result, they allow organizations to study the effects of variation upon system inputs and changes in system conditions and structures upon system behaviors.

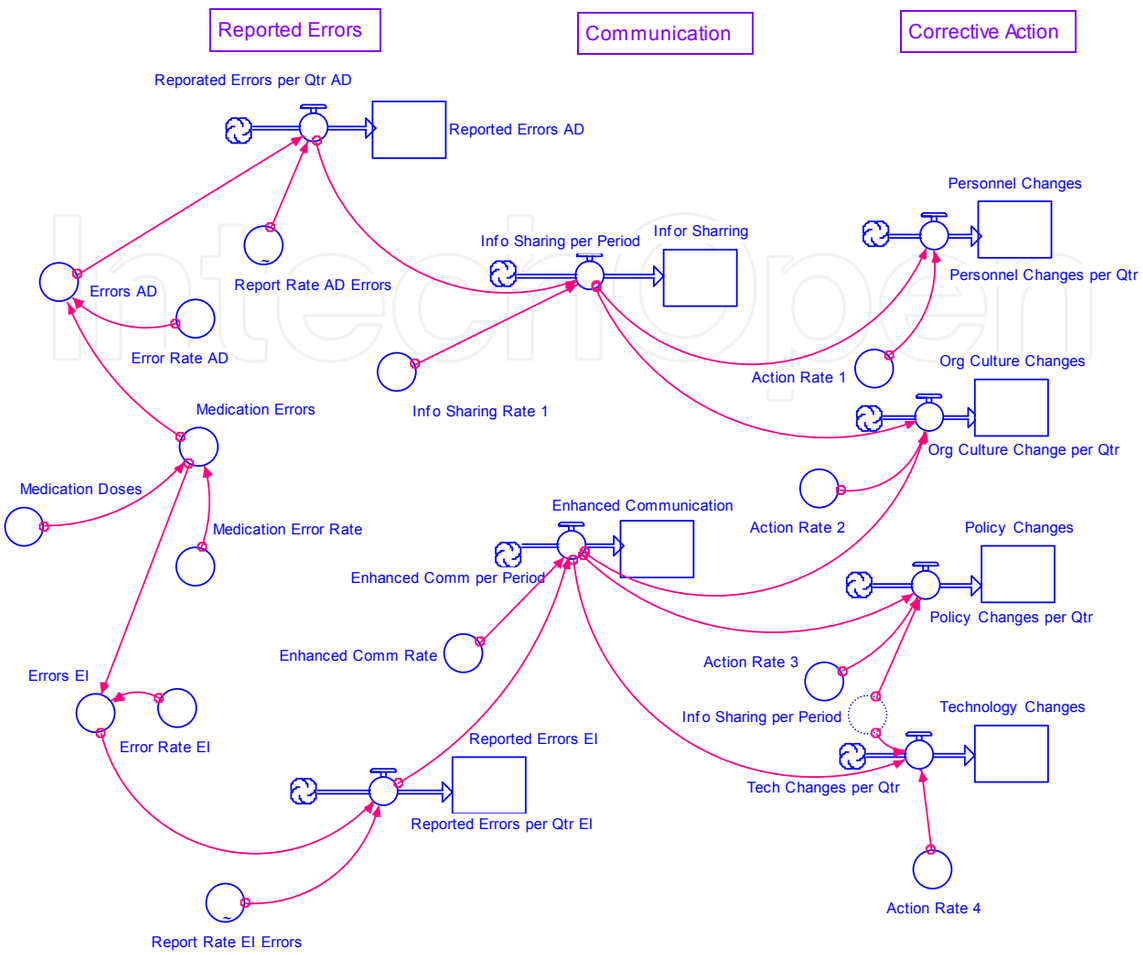


Fig. 2. Hospital Medication Error Reporting System

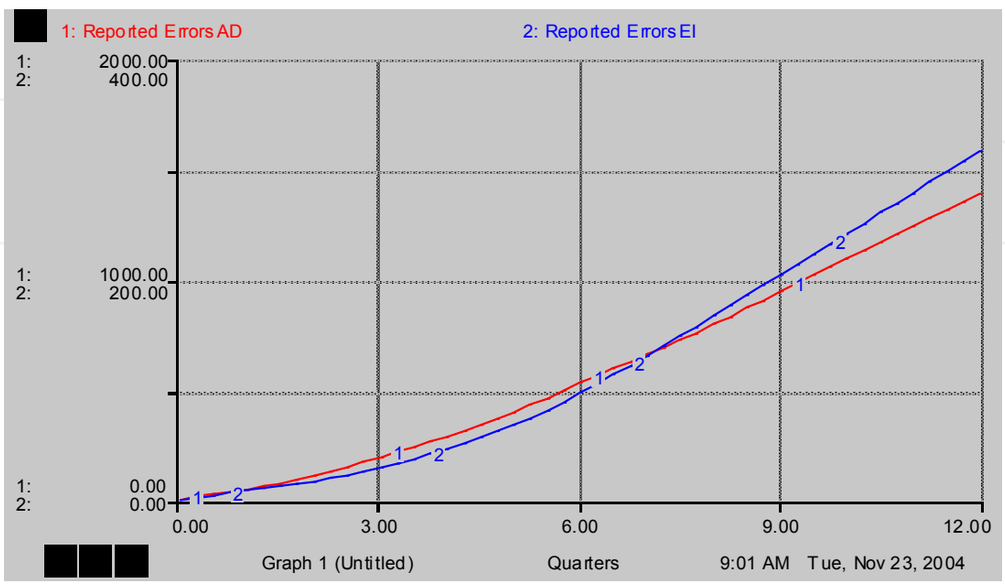


Fig. 3. Medication Errors Over Twelve Quarters

4. Hybrid Simulations: Combining Clinical Simulation with Computer-Based Simulation

4.1. Introduction

As noted above, in order to develop computer-based simulations (e.g., of healthcare processes or errors) the researcher needs to input starting parameters (e.g., number of patients, number of errors etc.) into the simulation and underlying mathematical model. Such information may be obtained from analysis of system logs and files, interviews, expert judgment, questionnaires, work sampling, etc. Also such starting data may be obtained from values published in the scientific literature and previous empirical studies where applicable. In addition, data used for computer simulations (as described above) may be obtained directly from the running of clinical simulations (targeted at obtaining baseline data on things like medication error rates and usability problems). Such studies, which combine results from clinical simulations (involving study of human subjects interacting with systems, as described above) with computer-based simulations (providing baseline data to be used by the computer-based simulation) can be termed "hybrid simulations". We will illustrate this hybrid approach with an example from our work in the analysis, detection and forecasting of technology facilitated error in health informatics.

4.2 Application

In this section we describe an example of use of hybrid simulations that connect work from clinical simulations with computer-based simulations to predict impact of a new handheld prescription writing application (that allows physicians to record medications in a PDA, a personal digital assistant). The initial part of this work (Phase 1) involved conducting a clinical simulation where physicians were asked to "think aloud" while entering prescriptions (given to them on a piece of paper) as accurately as possible into a handheld PDA application (Kushniruk et al., 2005). The physician subjects were also asked to interact with the system while interviewing a research collaborator who played the part of a patient (i.e., a "simulated patient"). Subjects consisted of ten physicians who were familiar with PDA applications but had never used the one under study before. The procedure consisted of recording all subject interactions with the application, specifically all of the screens of the application were video recorded (by projecting the PDA display on to a projection screen using a data projector and video recording the projections using a video camera) while subject's verbalizations were audio recorded as they carried out medication order entry tasks. Medication order entry tasks included entering medication orders into the PDA application from a list of medications on a piece of paper that was provided to subjects. The resultant data consisted of video and audio recordings of the subjects' entering medications into the application.

The analysis of the data resulting from the clinical simulation in Phase 1 consisted of coding the video and audio data for the occurrence of the following: (a) usability problems involving aspects of interface design and (b) medication errors. The following specific categories of user interface and usability problems were identified when the transcripts were annotated by a researcher with a background in human-computer interaction: (1) data entry problems; (2) display visibility problems; (3) navigation problems; (4) locating problems; (5) procedure problems; (6) printing problems; (7) speed problems; and (8)

attention problems. In addition, problems regarding content of the information displayed were also noted, including the following: (1) database content problems; (2) inappropriate default problems, and (3) training manual deficient problems. Thus, the main categories of usability problems could be considered to be a result of specific issues with the application's user interface and the content of information displayed by the system. The same video data (of user interactions) was also independently coded for inaccurate or errors in the entry of medications, which were divided into: (a) Slips – which were mistakes caught by the subject before finalizing their data entry (e.g., a typo that was corrected) and (b) Mistakes – errors that were made in the medication entry (e.g., wrong dose) which were not caught by the subject and were recorded in the health information system. In the final phase of the analysis the investigators explored the relationship between usability problems and errors in medication entry. For each medical error identified, the record of coded usability problems was examined to determine if the usability problem had been associated with an actual data entry error. For example, the presence of a "display visibility" problem was highly associated with occurrence of a medication error (84% of coded display visibility problems were associated with an error). Overall 37% of coded usability problems were associated with one or more medication errors made by the physician subjects. The intent of this analysis was to determine the relationship between specific usability problems and the occurrence of slips and mistakes (to determine base rates for number of errors and their statistical relationship to specific usability problems).

In the second part of this work (Phase 2), in order to extend the findings from phase 1 to provide input into development of computer-based mathematical models (to predict the occurrence of technology-induced error in populations of users in large real-world organizations), the output of Phase 1 (i.e. the base rates of error associated with each category of usability problem) was used as data to serve as the base rate parameters for a computer-based mathematical simulation of medication error rates. Initially, a computer simulation model was constructed in order to represent how health information technologies may increase the incidence of certain types of medical errors using base rates from Phase 1. The simulation software package STELLA was used to create the model. Based on the results of the Phase 1 clinical simulation, usability problems may arise because of the nature of the interface with the technology or because the content of the medication database is incomplete. Each of these problems can result in error (the simulation models error rates that occur when new prescriptions are entered that have usability problems associated with them as described in Phase 1 above). In the initial STELLA model (based on Phase 1 findings) overall 41% of usability problems related to the PDA application's interface resulted in errors; while 16.7% of the content problems resulted in errors. Several simulation runs were created, to assess over time the impact of removing specific user interface features, as well as to simulate the impact of the learning curve of users over time on total number of medication errors. For example, see Figure 4 showing four successive runs of the STELLA simulation (the lines labeled 1 to 4 in the graph) showing a decrease in mistakes over time as specific user interface problems are fixed in each of the simulation runs. This information can be used for assessing potential impact of systems (as well as specific user interface features and their impact on error rates).

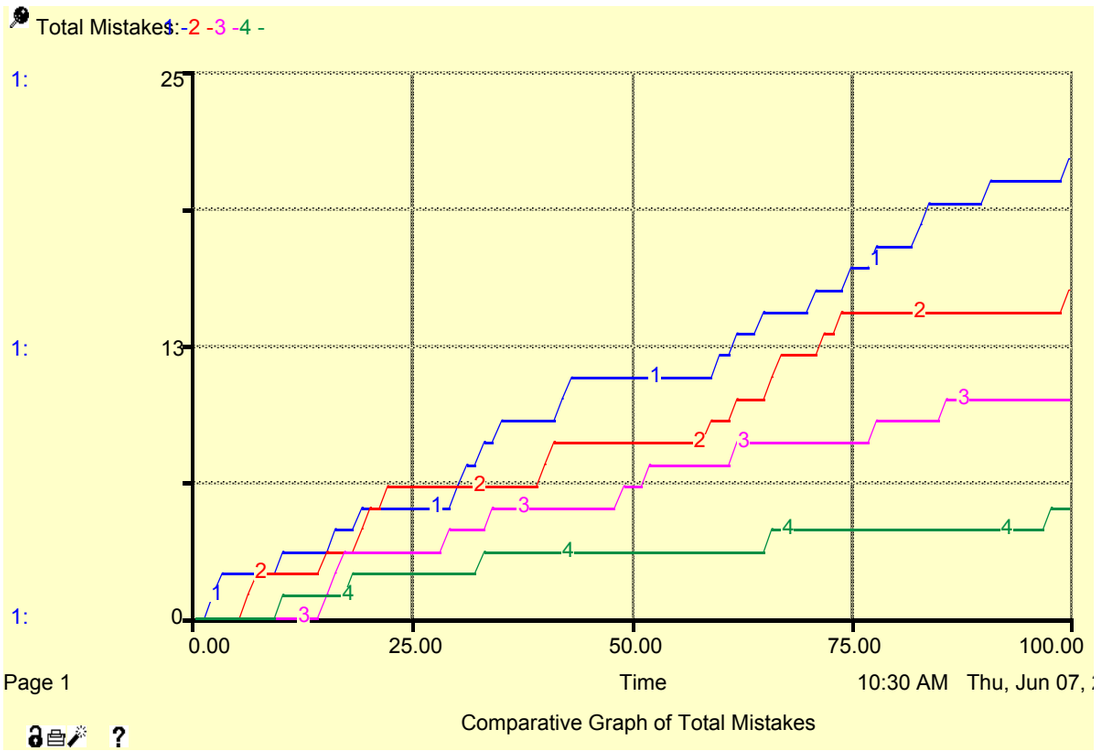


Fig. 4. Graph of Total Mistakes Over Four Simulation Runs

5. Future Research

5.1 Health Informatics and Simulation

The authors of this book chapter have highlighted three areas of work at the intersection of the fields of health informatics and simulation research, namely: (a) the use of clinical simulations to evaluate health care software applications and their associated devices, (b) the use of computer-based simulations to evaluate the effects of health care system level changes (such as introducing a new health information system upon system inputs, throughputs and outputs), and (c) the integration of both (i.e., hybrid approaches) by using data collected from clinical simulations as the basis for computer-based models of introducing new software applications/devices upon a systems outputs (i.e., number of technology-induced errors). The use of this full range of simulations in health informatics for testing systems is a relatively new phenomenon. Early work in this area by Anderson (2005) proved that health care systems (e.g., physician offices, emergency rooms) could be modeled and the effects of implementing a health information system could be observed before a software application was introduced to a hospital or clinic environment. Work by Borycki, Kushniruk and Kuwata (2009b) demonstrated that clinical simulations could be used to evaluate the effects of software application/device constellations upon health professional work. Both these approaches have been integrated in a hybrid model of simulation (one where clinical simulations provide inputs for computer-based models) drawing on the advantages of using both approaches.

5.2 Computer Controlled Mannequins, Health Information Systems and Devices

Research at the intersection of health informatics and simulation continues to advance. Our most recent research involves using computer controlled simulation mannequins to prototype, test and evaluate new health information system applications (e.g., personal health records, electronic patient records, electronic medical records). The use of computer controlled simulation mannequins allows health information systems and their associated devices to be tested using a range of health professionals (e.g., nurses, physicians, respiratory therapists etc.) involving the a full continuum of health care situations and events (where the patient is healthy or experiencing a critical life event as well as routine and atypical or rare patient situations involving rare illnesses/diseases) and over the full course of the software development lifecycle (i.e., from design, development, customization to the organization, implementation, evaluation, operation to maintenance of the system and its associated devices). Our research will be further extended to include computer-based simulations to forecast the effects of the software and hardware upon health professional work. Our initial experience suggests that such an approach would serve as a significant decision support and risk management tool for health care administrators. Health care administrators could use the information from simulations to reduce organizational risks associated with software application and hardware procurement, selection, customization and implementation processes (Borycki et. al., 2009c).

5.3 Electronic Health Record Portal and Electronic Health Record Simulators

Other research that we are conducting includes the development of an Electronic Health Record portal that provides health professional students with access to several differing types of electronic health records. The portal is essentially an electronic health record simulator. At present there are few opportunities for medical, nursing and other health professional students to learn how to use an electronic health record in the safe environment (where there is no live patient data) in the context of a university or college setting under the supervision of an educator. Such use of electronic health record simulators allows students to develop skills around documentation, use of differing communication and decision support tools. Presently, most health professional students learn how to use electronic health records using real patient data in the context of real health care organizations. There is a need to provide students with opportunities to learn how to manage patient illness and disease processes as well as learn how to use differing types of electronic health records and their decision support tools (as they often must learn to work with more than one electronic health record application at the same time or across the course of their professional career).

These electronic health records are pre-populated with representative, artificial patient information representing a wide range of patient states of health and illness. The electronic health record simulator allows health professional students to learn about how to review patient information, document and utilize decision support tools (such as alerts, reminders, checklists and electronic dashboards) in the management of patients in a "safe" environment (i.e. students can access the "simulated" patient data contained in the electronic health records remotely over the WWW). The students have used our electronic health record simulator to evaluate the strengths and weaknesses of differing electronic health record features, functions, designs and workflows in the classroom and from their homes as part of classroom assignments.

One of the portal's simulated electronic health records has been used by medical school faculty to present patient cases to medical students learning about the management of patient health and disease using the electronic health record. Nursing school faculty have used the electronic health record simulator to teach nursing students about the features and functions of the electronic health record that support their practice. Health informatics faculty have used the electronic health record simulator to teach health informatics students about the design, development, testing and evaluation of health information systems. The portal's simulated electronic health records are providing differing types of health professional students with significant learning opportunities while at the same time supporting the instruction of key aspects of health professional curricula by faculty from the health disciplines.

The portal simulation environment we have created will ultimately be used both for health professional education (by providing health professional students with access to representative systems remotely) and also as a test-bed for conducting analyses of impact of a range of electronic health record systems, as the systems available on-line through the portal can be tested within any clinical environment (e.g., accessed within a clinician's office in the simulation study of impact of electronic health records on workflow) (Armstrong et al., 2009; Borycki et. al., 2009d).

We are also extending our work to the professional community (i.e., those physicians, nurses, other health professionals, policy makers and health services administrators) who are considering purchasing an electronic health record. The electronic health record portal provides access to varying electronic health records with differing design metaphors and embedded workflows. Policy makers and health services administrators have used the portal to learn about the types of systems that are available and how they might be viewed on differing devices across the continuum of care (from hospital to community). Such knowledge provides policy makers with the requisite knowledge to craft organizational policies that would promote adoption and appropriation of technology by health professionals. Health services administrators have accessed the portal also. Health service administrators have used the portal to better understand how such a technology and its devices could be deployed in a health care setting (i.e., hospital, physician office, or patient's home) to improve the quality and safety of patient care as well as improve patient health outcomes. Lastly, for those health professionals who are purchasing systems the portal and the electronic health record simulators allow professionals to view an electronic record in their own organizational context and to make decisions about how to select and deploy a system to improve their work. As in the example, of a physician who would like to purchase an electronic health record, the portal and the electronic health record simulator allows the physician to access differing electronic health records over the WWW in their office and their exam room on a wireless laptop and to identify those parts of the office and the examination room where the record and device can be placed to provide support and to be enhance rather than be disruptive to office work flow.

We are also currently exploring the integration of simulated electronic health records with computer controlled mannequin simulations. Historically, computer controlled mannequins have been used to prototype and test differing types of medical devices for their utility and

safety. In our work we are integrating two types of simulators: (1) computer controlled mannequins simulators and (2) electronic health record simulators and exploring their effects upon health professional information seeking and decision making across a range of patient health situations from critical life events to routine medical or nursing care of patients. This work is important as computer controlled mannequin simulators are increasingly being used to educate health professionals. The computer controlled mannequins are taking the place of patients. Much of the work involving computer controlled mannequin simulations to date and to our knowledge has not integrated differing electronic health records (with differing design metaphors) into the health care situations that are being used to train students. Such work is necessary so that students and student health professional teams learn how to integrate information from the patient (i.e. computer controlled mannequin), the devices that are being used to provide life support (e.g., intravenous pumps, ventilators etc.) and the electronic health record via a workstation or wireless device such as a Palm device.

5.4 Virtual Reality and the Simulation of Virtual Worlds

Recent advances in the field of virtual reality and simulation of virtual worlds will also extend this research. Increasingly, we are moving towards developing virtual representations of patients and we are simulating virtual worlds (including physician offices, clinics and hospitals). National Library of Medicine initiatives including The Visible Human Project® (National Library of Medicine, 2009) now provide image data that has been used to develop computer-based prototypes of the anatomy and physiology of the human body. In our future work with these software applications we plan to provide such information during student learning involving computer controlled mannequins in an environment that also provides access to the electronic health record. As well we believe that this work will be a prelude to complementing computer controlled mannequins that currently simulate real-life patient health events for health professional students (used to prototype, test and evaluate health information system software applications and devices) with the use of virtual reality computer controlled patient simulators located in virtual environments where there is an electronic health record simulator available.

An extension to this is to use of virtual world simulations such as Second Life® to test applications within the context of a simulated health care environment that is representative of the real-world and to be able to visualize the implications of software and device changes upon virtual physicians, nurses, other health professionals and patients. In addition, this approach allows for extending these changes to computer-based models that can help health care decision makers to understand the long term effects of these types of changes upon health care organizational inputs, throughputs and outputs and visualize their impact in a virtual hospital or clinic environment. Organizations such as the Center for Disease Control and the National Library of Medicine are already providing health care consumers with access to virtual worlds where virtual conferences, meeting and interactions with other health professionals are already taking place to educate individuals about health care (i.e. Second Life) (Maged, Boulos, Hetherington & Wheeler, 2007). In our work we plan to extend our experiences to the development of these virtual worlds with electronic health record simulators being available in these virtual organizations. These advancements in simulation are significant and will continue to influence software application prototyping, testing and

evaluation. Such work is necessary as simulations can lead to cost savings. Cost savings associated with preventing health information system implementation, failure and the need for re-implementation as well as cost savings associated with health information system modification and reimplementation.

6. Conclusions

Use of simulations in health informatics is a rapidly expanding field of study. With the exponential rise in the development and implementation of health information systems globally by health care consumers and other health care organizations (e.g., clinics and hospitals), there has developed a growing need to evaluate these applications for their health care system effects. Current estimates suggest up to 65% of health information system applications fail to be adopted by health professionals (Rabinowitz et al., 1999). As well, many health information systems and devices fail to be used to their fullest extent by the individuals for whom they have been designed (such as patients, physicians, nurses and other health professionals). In addition to this, research has emerged suggesting that health information systems may negatively affect health professionals work processes through the introduction of cumbersome workflows (Kushniruk et al., 2006) and may inadvertently facilitate medical errors (i.e. technology-induced errors) (Koppel et al., 2005; Kushniruk et al., 2005).

Health informatics researchers have shown that clinical simulations, computer-based simulations and hybrid simulations can be used to test software applications for task-technology fit, their error facilitating features and functions, their effects on health care organizations and health care systems. Simulations can be used to evaluate software applications/devices. Clinical simulations can be used to evaluate the effects of differing constellations of software applications and devices upon aspects of health professional work (i.e., work processes and outcomes) with considerable ability to predict possible issues associated with software application and/or device usage (Borycki et al., 2009b). Such knowledge can provide organizations with information that can influence their decision-making during the organizational processes of procurement, selection and implementation of systems that can prevent downstream costs associated with application modification and switching to devices that better support health professional work. Future research will involve extending simulation from clinical and computer-based simulations to those involving computer controlled mannequins involving simulated electronic health records in virtual reality environments and virtual worlds.

7. References

Anderson, J.G. (2004). Information technology for detecting mediation errors and adverse drug events, *Expert Opinion on. Drug Safety*. 3(5), 449-455.

Anderson, J.G. (2003). A system's approach to preventing adverse drug events. In S. Krishna, Balas E.A., Boren S.A. (Eds.) *Information Technology Business Models for Quality Health Care: An EU/US Dialogue*. IOS Press, The Netherlands, pp. 95-102.

Anderson, J.G. (2002a). Evaluation in Health Informatics: Computer Simulation, *Computers in Biology and Medicine*, 32, pp. 151-164

Anderson, J.G. (2002b). A Focus on Simulation in Medical Informatics, *Journal of the American Medical Informatics Association*, 9(5), 554-556.

Anderson, J.G., Aydin, C.E. (2005). *Evaluating the organizational impact of healthcare information systems* (2nd ed.). New York: Springer Verlag.

Anderson, J.G, Ramanujam, R., Hensel, D., & Anderson, M. (2005). *Proceedings of Health Sciences Simulation 2005*, J.G. Anderson and M. Katzper (eds.), San Diego, CA, The Society for Modeling and Simulation International, pp. 9-14.

Armstrong, B., Kushniruk, A., Joe., R. Borycki, E. (2009). Technical and architectural issues in deploying electronic health records (EHRs) over the WWW. *Studies in Health Technology and Informatics, 143*, 93-8.

Ash, J.S., Sittig, D.F., Poon, E.G., Guappone, K., Campbell, E., Dykstra, RH. (2007). The extent and important of unintended consequences related to computerized provider order entry. *JAMIA, 14*(4), 415-423.

Banks, J. & Carson, J.S. (1984). *Discrete-Event System Simulation*, Prentice Hall, Englewood Cliffs, NJ.

Borycki, E.M., Kushniruk, A. W. (2005). Identifying and preventing technology-induced error using simulations: Application of usability engineering techniques. *Healthcare Quarterly, 8*, 99-105.

Borycki, E.M., Kushniruk, A.W. (2008). Where do technology induced errors come from? Towards a model for conceptualizing and diagnosing errors caused by technology (pp. 148-166). In A. W. Kushniruk and E. M. Borycki (Eds.) *Human, Social and Organizational Aspects of Health Information Systems*. Hershey, Pennsylvania: IGI Global.

Borycki, E.M. & Kushniruk, A.W. (in press). Use of Clinical Simulations to Evaluate the Impact of Health Information Systems and Ubiquitous Computing Devices Upon Health Professional Work. In S. Mohammed and Jinan Fiaidhi *Ubiquitous Health and Medical Informatics: The Ubiquity 2.0 Trend and Beyond*. Hershey: Pennsylvania: IGI Global.

Borycki, E.M., Lemieux-Charles, L, Nagle, L., Eysenbach, G. (2009a). Evaluating the impact of hybrid electronic-paper environments upon nurse information seeking. *Methods of Information in Medicine, 48*(2), 137-43.

Borycki, E.M., Kushniruk, A.W., Kuwata, S., Watanabe, H. (2009b). *Simulations to assess medication administration systems* (pp. 144-159). In B. Staudinger, V. Hob and H. Ostermann (Eds.). Nursing and Clinical Informatics: Socio-technical Approaches. Hershey, Pennsylvania: IGI Global.

Borycki, E.M., Kushniruk, A.W., Keay, E., Nicoll, J., Anderson, J., Anderson, M. (2009c). Toward an integrated simulation approach for predicting and preventing technology-induced errors in healthcare: Implications for healthcare decision makers. *Healthcare Quarterly*, in press

Byrick, R. J. & Wynands, J. E. (2009). Simulation-based education in Canada: Will anesthesia lead in the future? *Canadian Journal of Anesthesia, 56*: 273-278.

Campbell, E. M., Sittig, D.F., Ash, J.S. et al. (2006). Types of unintended consequences related to computerized provider order entry. *JAMIA., 13*: 547-56.

Denson, J. S. & Abrahamson, S. (1969). A computer-controlled patient simulator. *JAMA*, 208: 504-8.

Friedman C.P. & Wyatt J.C. (2005). *Evaluation methods in biomedical informatics.* New York: Springer Verlag.

Gaba, D. M. & DeAnda, A. (1988). A comprehensive anesthesia simulation environment: Recreating the operating room for research and training. *Anesthesiology, 69*: 387-94.

Granlien, M.F., Hertzum, M., Gudmundsen, J. (2008). The gap between actual and mandated use of an electronic medication record three years after deployment. *Studies in Health Technology and Informatics, 136*: 419-424.

Gordon, G. (1969). *System Simulation*, Prentice Hall, Englewood Cliffs, NJ.

Hannon, B.& M. Ruth, M. (1994). *Dynamic Modeling*, Springer-Verlag, NY.

Hargrove, J.L. (1998*). Dynamic Modeling in the Health Sciences*, Springer-Verlag, NY.

Katzper, M. (1995). Epistemological Bases of Postulational Modeling, In J.G. Anderson and M. Katzper (eds.), *Health Sciences, Physiological and Pharmacological Simulation Studies*, pp. 83-88. Society for Computer Simulation, San Diego, CA.

Koppel, R, Metlay P, Cohen A et al. Role of computerized physician order entry systems in facilitating medication errors. JAMA. 2005;293(10): 1197-1203.

Kushniruk, A., Triola, M., Stein, B., Borycki E., Kannry J. (2005). Technology induced error and usability: The relationship between usability problems and prescription errors when using a handheld application. *International Journal of Medical Informatics, 74*(7-8): 519-26.

Kushniruk, A.W., Borycki, E., Kuwata, S., Kannry, J. (2006). Predicting changes in workflow resulting from healthcare information systems: Ensuring the safety of healthcare. *Healthcare Quarterly, 9*: 114-8.

Kushniruk, A.W., Borycki, E.M., Myers, K., Kannry, J. (2009). Selecting electronic health record systems: Development of a framework for testing candidate systems. *Studies in Health Technology and Informatics, 143:* pp. 376-9.

Kushniruk, A.W., Borycki, E.M. (2005). Low-cost rapid usability engineering: Designing and customizing usable healthcare information systems. *Healthcare Quarterly, 9*(4): 98-100.

Law, A.M. & Kelton, W.D. (1991). *Simulation Modeling and Analysis*, 2nd ed. McGraw Hill, NY.

Maged, N., Boulos, K., Hetherington, L. & Wheeler, S. (2007). Second life: An overview of the potential of 3-D virtual worlds in medical and health education. *Health Information and Libraries Journal, 24*, 233-245.

National Library of Medicine. (February, 2009) The Visible Human Project. http://www.nlm.nih.gov/research/visible/visible_human.html

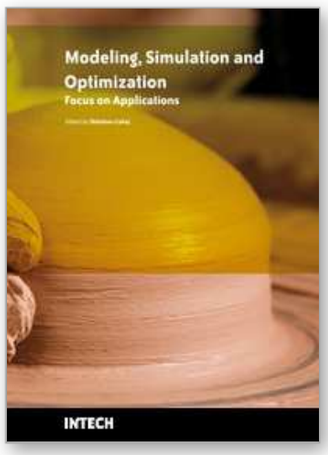
Oreskes, N., Schrader-Frechette, K. & Belitz, K. (1994). Verification, Validation and Confirmation of Numerical Models in the Earth Sciences, Science, *2163*: 641-646.

Patton, R. (2001). *Software testing.* Indianapolis, Indiana: SAMS.

Rabinowitz et al. (1999). Is there a doctor in the house? *Managing Care*, 8(9), 42-44.

Shulman, R., Singer, M., Goldstone, J., Bellingan, G. (2005). Medication errors: A prospective cohort study of hand-written and computerised physician order entry in the intensive care unit. *Critical Care, 9*(5): R516-21.

Swain, J.J. (1997). Simulation Goes Mainstream, 1997 Simulation Software Survey, *ORMS Today* 24(5): 35-46.



Modeling Simulation and Optimization - Focus on Applications
Edited by Shkelzen Cakaj

ISBN 978-953-307-055-1
Hard cover, 312 pages
Publisher InTech
Published online 01, March, 2010
Published in print edition March, 2010

The book presents a collection of chapters dealing with a wide selection of topics concerning different applications of modeling. It includes modeling, simulation and optimization applications in the areas of medical care systems, genetics, business, ethics and linguistics, applying very sophisticated methods. Algorithms, 3-D modeling, virtual reality, multi objective optimization, finite element methods, multi agent model simulation, system dynamics simulation, hierarchical Petri Net model and two level formalism modeling are tools and methods employed in these papers.

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

IntechOpen