Simulation-Based Electronic Health Record Usability Evaluation: A Proof of Concept

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Short Paper

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Abstract

Poor usability of Electronic Health Records (EHR) solutions is directly associated with physician burnout. While the survey and observational methods have been utilized widely in the usability evaluation of EHRs, it does not seem to be helping with the continuous improvement of EHR design and user satisfaction. We address this gap by presenting a discrete event simulation-based model that can add objectivity to the extant EHR usability methods. Evaluating EHR usability from the perspective of operations and workflow can help vendors design and develop better systems. This short paper presents a proof-of-concept simulation model with assumed task-time distributions. Our main research question is how we can use simulation techniques to objectively evaluate EHR usability? The simulation model results in terms of resource (clinician) utilization metrics can serve as a proxy to evaluate the efficiency component of the EHR usability at the departmental level.

Keywords: Electronic Health Records, Clinician Burnout, Usability, Simulation, Clinician Utilization

Introduction

Poor usability of Electronic Health Records (EHR) is linked with clinician burnout (Melnick et al. 2020), as clinicians spend significant time working on EHR outside of their regular working hours (Adler-Milstein et al. 2020; Sinsky et al. 2016). More recently, the surgeon general of the United States has declared clinician burnout and well-being a national priority citing documentation burden as one of the contributing factors (Murthy 2022). In addition, poor EHR usability can potentially impact patient safety outcomes (Howe et al. 2018). To this end, the ONC 2015 edition EHR certification requires evidence of user-centered design (UCD) and user test results. However, the EHR system development and implementation process falls short in usability testing (McDonnell et al. 2010) as it is one of the most difficult criteria for EHR vendors (Ratwani et al. 2015). It is also discussed that EHR usability evaluation can be standardized using objective metrics such as the number of clicks, time to complete tasks, and error rates because it can help EHR vendors identify usability issues resulting in an enhanced version of the system (McDonnell et al. 2010).

Improved EHR usability significantly reduces cognitive workload among clinicians (Mazur et al. 2019). However, despite EHR vendors' increased effort in incorporating UCD, there is a significant gap in the validity of their usability evaluation results as the test cases may not represent the real clinical scenarios (Hettinger et al. 2021; Ratwani RM 2020). Therefore, there is a need to devise improved usability evaluation methods beyond traditional instruments such as System Usability Scale (SUS) (Hettinger et al. 2021).

It is noted that objective evaluation of digital solutions is one of the pressing problems in digital healthcare, and a recent article (Guo et al. 2020) has called for innovative methods in this domain. Oztekin et al. (2013) used machine learning algorithms to evaluate the usability of eLearning systems. They devise a severity index to rank the system characteristics that are the most pertinent predictors of system usability that can eventually be used to identify features that need improvement. However, this work also utilizes perception-based survey data for model development. Further, Guo et al. (2020) suggest utilizing simulation techniques to incorporate objectivity in usability evaluation methods. We build upon this gap and attempt to present a proof of concept that can objectively augment the extant EHR usability methods using simulation techniques.

Thus, our main research question is *how can we use simulation techniques to evaluate EHR usability?* In this work, we build a proof-of-concept (POC) model that simulates Emergency Department (ED) operations using the discrete-event simulation (DES) technique. The model results produce metrics such as clinician utilization and idle time that can serve as proxy objective measures of EHR usability evaluation at a clinical department level. Our proposed POC solution can be a quick and cost-effective solution for EHR vendors to objectively evaluate system usability and determine if the EHR system delivers operational value for clinicians at the clinical department level.

Literature Review

Usability is defined as the effectiveness, efficiency, and satisfaction with which users can accomplish goals in particular environments; the capability to be used by humans easily and effectively; quality in use; how easy it is to find and use the information displayed on a web-based system; ultimate quality factor for software architecture (Oztekin et al. 2013). Usability evaluation can be *formative*, i.e., conducted during iterative systems development, or *summative*, i.e., post-hoc testing of completed systems (Kushniruk and Patel 2004).

While subjective methods such as SUS (Brooke 1996) have been utilized widely in the usability evaluation of EHRs, it does little to help with the continuous improvement of EHR design and user satisfaction (Ellsworth et al. 2016; McDonnell et al. 2010). Other methods like pre-post implementation evaluation are also common (Ellsworth et al. 2016); however, they are time and cost-intensive (Guo et al. 2020) and inflexible with respect to understanding why the system fails the assessment (Kushniruk and Patel 2004).

Recent literature in healthcare has extensively focused on the usability evaluation of EHR systems. For example, Sinsky et al. (2020) proposed core EHR use measures that reflect a practice efficiency – total EHR time, work outside of work, time on encounter note medication, time on prescriptions, time on inbox, teamwork for orders, and undivided attention. In addition, Ellsworth et al. (2016) utilized a systematic review to highlight the most common methods for evaluating EHR usability, these are – survey, think-aloud, interview, heuristics, cognitive walkthrough, focus group, task analysis, and clinical workflow analysis. Among these methods, the type of evaluations used are – pre-post implementation, prototype, requirements/development, and mixed. They also highlight that only 23% of the studies report objective data such as time to task completion, task completion accuracy, usage rates, mouse clicks, and cognitive workload.

Thus, there is a dearth of research that presents scientifically valid and reproducible usability evaluation for various stages of EHR system development (Ellsworth et al. 2016). In addition, there is a need to move toward EHR design and usability evaluation that focus on the "socio-technical" and "human factors" aspects of it (Carayon and Salwei 2021). We argue that this can be achieved by simulating real-world clinical settings and developing models capable of evaluating EHR usability.

A simulation is the imitation of the operation of a real-world process or a system over time. It can be used to investigate a wide variety of 'what-if' questions about a real-world system using mathematical models based on probability theory (Cochran and Bharti 2006). Simulation techniques are ideal for complex system behavior involving humans, where experimentation costs are high, and time and resources are limited. Thus, it can be used to predict the performance of a system at the early design stage, thereby saving costs that may arise from post-implementation evaluation and improvement efforts (Banks et al. 2013). DES is best suited for analyzing healthcare processes as it considers system complexities and stochastic nature in the form of downtimes, failures, and time spent repairing failures (Vahdat et al. 2018). In the past, several studies have used DES to examine operational outcomes in an ED (Connelly and Bair 2004; Doudareva and Carter 2022; Hoot et al. 2008; Ordu et al. 2020; Vahdat et al. 2018). However, there is limited to no work that use DES to evaluate the efficiency component of the EHR usability based on clinician utilization and efficiency metrics. Thus, we extend the idea of DES to add objectivity to the extant EHR usability evaluation methods.

Research Design

Our main research question is *how we can use simulation techniques to evaluate EHR usability?* We intend to utilize the task-time data published in clinician workflow/ time-motion studies to approximate the task distributions and, based on them, build a simulation model that can assess the usability of an EHR system. Several studies have reported clinician's EHR task-time data for different specialties during and after regular working hours (Adler-Milstein et al. 2020; Arndt et al. 2017; Asan et al. 2015; Ballermann et al. 2011; Carayon et al. 2015; Hefter et al. 2016; Kim et al. 2012; Overhage and Johnson 2020; Sinsky et al. 2016; Tipping et al. 2010; Young et al. 2018). Based on the task-time data in these published studies, we plan to identify task-time distributions for clinical workflows in emergency departments, pediatrics, family medicine, oncology, and intensive care units using distribution fitting software such as ExpertFit®. These distributions will then serve as an input to a discrete event simulation model built using software such as Simio®. We choose ExpertFit® and Simio® for our model development as we have ready access to these widely used software through our affiliated institution.

We will follow the standard simulation model development methodology (Joines and Roberts 2015) that includes 11 sequential steps - problem formulation (determining the scope); setting of objectives, and overall project plan (justifying if the simulation is the suitable method for the problem at hand); model conceptualization; data collection; model translation using a tool like Simio, Excel or C++; model verification (to check if the model is coded correctly); model validation (to check if the model represents the real system); experimental design (to check the alternatives); production runs and analysis; conducting more runs (to have tighter confidence intervals); and finally documentation and reporting.

Model Development: A Proof of Concept

We aggregate the above simulation model development methodology into four key steps, as discussed below. By doing so, we present a proof-of-concept simulation model that shows how we can use discrete event simulation techniques to evaluate the usability of an EHR system at a clinical department level. Below we model an example workflow of an emergency department.

Step 1: Problem Formulation, Objective and Plan

We illustrate a proof-of-concept simulation model that can be used to objectively evaluate the usability of an EHR system at the specialty or department level. Using Simio®, we model an emergency department with four ED clinicians or resources that serve patients using an EHR system. Since a clinician works in tandem with other clinicians in utilizing EHR, we believe an individual department level is the most appropriate to assess whether an EHR system is useful or not.

To validate our problem formulation, we interviewed two ED physicians to explore if and what aspects of EHR systems cause stress. The excerpt from the interviews is presented below verbatim. We found that ED physicians feel that their EHR interfaces can be designed efficiently as delivering care with speed is of utmost importance to them.

> *"You have to click CBC and then you have to click a dropdown arrow or drop-down menu that says where it where it's collected. Like even though we're in the E.R. you have to select the ER man. You have to select what time you want to collect it. I mean it's like instead of something so simple of just one click it's like they had you know four or five steps just to get one order done. So, I think that's probably the thing that stresses me out the most … It's a big mess. Definitely a frustration that we deal with in our specialty… It's like I don't know who comes up with these with these programs. I mean it just. And I'm sure they have medical personnel obviously come in helping contribute to these programs these EHR we use. But it's I don't know. I feel like. On our side it's like oh my gosh this could be so much you know this would be so much simpler or if we could just do it this way"– ED Physician 1*

> *"In the emergency room you know we kind of pride ourselves on giving the best care the fastest way possible. You know sometimes. Time is of the essence in emergencies….No. 1 less clicks, I think. And then I think number two just that if you could get it down to maybe just scrolling down through one page instead of having to go through many different window openings and closings, I think that would. Like I said I don't know how that would be possible. I don't know how to design that. But I think you know I think it would be beneficial" – ED Physician 2*

To this end, we argue that simulating the real-world setting to test the usability of a system seems more than reasonable. Therefore, our level of analysis is a clinical department, while our unit of analysis is clinicians. By doing so, we can objectively assess the usability of an EHR system for clinicians within a clinical department.

We limit the scope of our model to the activities of four clinicians that each work 40 hours per week. Simulation models can make several assumptions to incorporate the complexity of the care delivery process, such as the requirements of one clinician and one nurse simultaneously for service delivery (In this work, the term clinician refers to a physician). However, in this work, we limit the scope and only assume that a clinician is needed before the patient is serviced, as is the case during a typical patient encounter. This means that a clinician starts working on the encounter before seeing the patient.

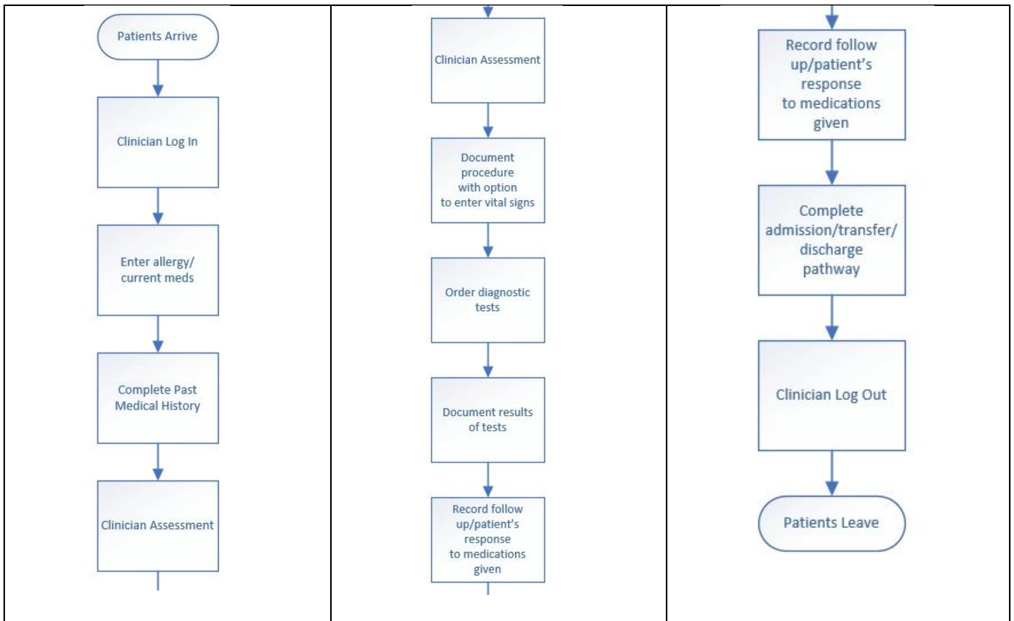

Figure 1: An Example Clinician-EHR Interaction Flowchart of an Emergency Department - Based on Kim et al. (2012)

Step 2: Model Conceptualization and Data Collection Plan

We conceptualize our model using an example clinician-EHR interaction flowchart (Figure 1) of an emergency department (Kim et al. 2012). The example workflow illustrates a typical set of tasks an ED clinician will carry out using an EHR system. Each of these tasks will have an estimated time duration which can be captured either by using observational methods (Asan et al. 2015) or EHR log data (Sinsky et al. 2020). We have created a data collection template (available on request) that utilizes the clinician-EHR interaction workflow sequence and corresponding approximate task-times from published literature. Based on this data, we plan to identify our task time distributions and eventually build our final simulation model.

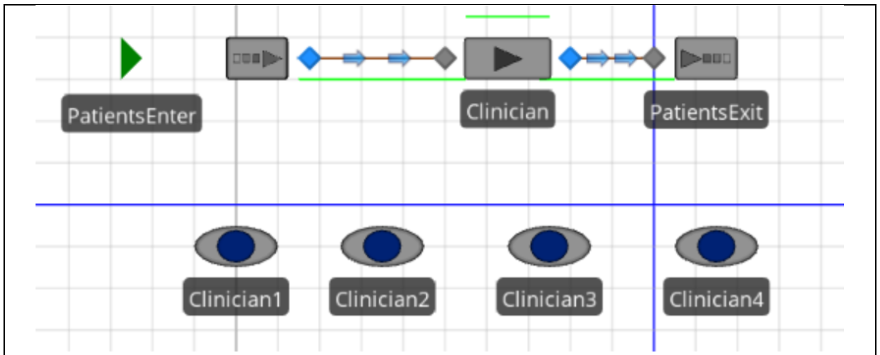

Figure 2: An example Simio® Simulation Model of an Emergency Department with Four Clinicians

Step 3: Model Translation Using Simio®

We use following model inputs to develop and translate our conceptual model in Simio®, as shown in Figure 2:

- Patients arrive exponentially with an interarrival time of 6.5 minutes
- Service time follows a Pert distribution with a minimum of 60 mins, maximum of 120 minutes, and a mode of 90 minutes
- Clinician resources have a reliability logic setup that allows clinicians to respond to emergency calls. 'Uptime Between Failures' follow an exponential distribution with a mean of 6 hours, and 'Time to Repair' follows a Random.Pert(40,55,60) distribution. The former metric represents the time the clinician works before experiencing any failure/hurdle while the latter represents the time it takes for a clinician to fix that failure/hurdle.
- The capacity of the clinician server is not constrained, i.e., set to infinity
- A list of resources is created from which the model can pick
- Patients can request a specific clinician, and then after service, the clinician will be released

	HoldingTime InStation (Average)	HoldingTime InStation (Max)	HoldingTime InStation (Min)	TotNum Entered-Throughput	TotNum Exited-Throughput
Clinician Server	1.50 hours	1.95 hours	1.1 hours	101	97

Table 1: Clinician Processing Statistics

Finally, the model is run for 40 hours, and example results are reported in Tables 1 and 2, where 'HoldingTimeInStation' is the waiting time in the queue. 'TotNumEntered-Throughput' is the number of patients that entered the system (a clinical department in this context). 'TotNumExited-Throughput' refers to the total number of patients served by the system (a clinical department in this context). Further, in Table 2, 'Capacity Utilization' represents the % of patients a clinician can serve out of the total patients allocated. Please note that the sum of "Patient Allocated" in Table 2 is equal to 'TotNum Entered-Throughput' in Table 1. Next, 'Time Busy(%)' refers to the percentage of time the clinician is busy serving the patients. It is calculated by dividing the time spent serving patients by the total time available. Similarly, 'Time Idle(%)' represents the percentage of time the clinician is idle. 'Time Failed(%)" is the time the clinician has failed due to some hurdle. Finally, "Time Failed Busy" is the time clinician is busy repairing the failure/hurdle.

Example Results

Our proof-of-concept EHR usability evaluation model for an ED was run for 40 hours, and clinician server statistics are reported in Table 1, with 97 patients being served in a week with an average processing time of 1.5 hours for each patient. Clinician capacity utilization metrics for all four clinicians are reported in Table 2, with a grand mean clinician capacity utilization of 93.23%.

The results can also be used for model validation. For example, 20 patients per day in an emergency department seem to be a reasonable approximation of reality. However, the inter-arrival time of 6.5 minutes may need further validation.

Clinician utilization and time-based results from Table 2 can be used to comment on whether an EHR system delivers operational efficiency for clinicians – a key component of usability. For example, suppose a clinician is busy 100% of the time and mostly spends time fixing failures/hurdles. In that case, it indicates 1) that the clinician user is overworked and 2) the EHR is not usable in terms of providing operational efficiency for clinicians. Although, this argument is against the traditional wisdom to keep clinician idle time as low as possible (Fetter and Thompson 1966; Wijewickrama and Takakuwa 2005), we argue that >=100% clinician 'time busy' may lead to stress and burnout (Thorwarth et al. 2009).

	Capacity Metrics		Resource State Metrics							
	Capacity Utilization (%)	Patients Allocated	Time Busy (%)	Time Busy (hours)	Time Idle (%)	Time Idle (hours)	Time Failed (%)	Time Failed (hours)	Time Failed Busy (%)	Time Failed Busy (hours)
Clinician1	96.8%	25	87%	34.8	0.01%	0.006	3.19%	1.28	9.69%	3.88
Clinician2	90.60%	25	84.10%	33.64	0.22%	0.09	9.17%	3.67	6.50%	2.60
Clinician3	94.22%	27	89.46%	35.78	1.33%	0.53	4.45%	1.78	4.76%	1.90
Clinician4	91.30%	24	84.17%	33.66	2.57%	1.03	6.12%	2.45	7.13%	2.85
GrandMean	93.23%	25.25	86%	34.47	1.03%	0.41	5.73%	2.30	7.02%	2.80

Table 2: Simulation Results

Step 4: Model Verification and Validation

Model verification answers the key question- Does the simulation model behave the way we expect? This question can be answered by tweaking the various model assumptions and observing changes in the output metrics. For example, a longer processing time should lead to longer times in the system. Therefore, we verified our model using shorter clinician processing time - Pert (10,15,20) and found that utilization metrics go down and clinician idle time goes up, as shown in Tables 3 and 4. Thus, our POC model is verified.

	HoldingTime InStation (Average)	HoldingTime InStation (Max)	HoldingTime InStation (Min)	TotNum Entered-Throughput	TotNum Exited-Throughput
Clinician Server	16 mins	27 mins	10 mins	230	230

Table 3: Clinician Processing Statistics with Shorter Processing Times

	Capacity Metrics		Resource State Metrics							
	Capacity Utilization (%)	Patients Allocated	Time Busy (%)	Time Busy (hours)	Time Idle (%)	Time Idle (hours)	Time Failed (%)	Time Failed (hours)	Time Failed Busy (%)	Time Failed Busy (hours)
Clinician1	58%	82	56%	22.34	33%	13.18	9.37%	3.75	1.85%	0.74
Clinician2	47.70%	68	47.40%	18.96	45.48%	18.19	6.82%	2.73	0.29%	0.12
Clinician3	33.26%	50	31.92%	12.76	61.06%	24.43	5.67%	2.27	1.35%	0.54
Clinician4	21.72%	30	21.20%	8.48	69.62%	27.85	8.65%	3.46	0.52%	0.21

Table 4: Simulation Results with Shorter Processing Times

Model validation answers the key questions- Does the simulation produce performance measures consistent with the real system? This question can be answered by developing a model that closely approximates the factors that impact our output metric of interest. In our case, our output metric of interest is capacity utilization and time-based metrics. We want optimal utilization of clinicians. Suppose a clinician's utilization and 'time busy' is more than 100%. In that case, they may work outside their regular hours, implying that the current EHR system is not delivering operational value for its key users and therefore does not fare well on the efficiency component of EHR usability. Therefore, it will be imperative for our model to 1) closely map each ED workflow task sequence and 2) obtain valid task-time measures.

Projected Activities

Moving forward, we will conduct a detailed literature review to collect and validate the published data on the clinician workflow sequence of tasks and the corresponding task times. This step would be similar to a meta-analysis of published EHR time-motion studies. Alternatively, we could also collect time-motion data using observation. However, due to the time and access constraints in getting observational data, we plan to use the data that is already been published (Adler-Milstein et al. 2020; Arndt et al. 2017; Asan et al. 2015; Ballermann et al. 2011; Carayon et al. 2015; Hefter et al. 2016; Kim et al. 2012; Overhage and Johnson 2020; Sinsky et al. 2016; Tipping et al. 2010; Young et al. 2018).

Next, we will obtain valid task time distributions using distribution fitting software such as ExpertFit®. For example, to determine task-time distributions, we will pick the mean, min, and max from the published time-motion studies. The challenge, however, will be to find consistency in the published task times. Nevertheless, we will try to mitigate this problem by limiting the scope of the ED workflow or only considering studies that have used a standardized time-motion tool developed by Pizziferri et al. (2005). The Agency of Healthcare Research and Quality (AHRQ) recommends the latter tool. There are about 30 studies that fulfill this criterion, and a detailed evaluation is still in progress. Finally, a simulation model will be developed and validated, as discussed, and shown in the previous sections. The model's outcome in terms of efficiency and utilization metrics of clinicians can serve as a proxy to evaluate the efficiency component of the usability of electronic health records.

In addition, we argue to develop simulation-based usability evaluation models separately for each clinical specialty, such as - emergency departments, pediatrics, family medicine, oncology, and intensive care units. However, we limit the scope of this work to an emergency department. By doing so, we attempt to achieve better model verification and validation. Finally, we also plan to increase the complexity of the model by using task sequences within the server processing station that will further enhance the model's validity.

Expected Contributions

The three components of usability are – effectiveness, efficiency, and satisfaction, and it is important to note that the extant EHR usability evaluation methods are limited in evaluating the efficiency component of usability. This work is intended to be a proof of concept that paves the road towards a more comprehensive and objective evaluation of EHR system usability. First, we expect our results to help open a new avenue for using simulation-based techniques to evaluate EHR usability objectively. Doing so can determine whether an EHR system can deliver operational value for clinicians within a clinical specialty. Second, this usability evaluation method can bridge the gap between the conflicting results of qualitative and survey based quantitative EHR evaluation. The former reports a negative user perception of EHR, while the latter reports that the negative impact is insignificant (Zheng et al. 2010). Third, simulation-based usability evaluation can substitute time-motion-based pre-post evaluation methods that are costly, time-consuming, and often of little use as they are conducted post-implementation (Guo et al. 2020). Finally, with the increasing popularity of digital health solutions and IoT (Internet of Things) in healthcare, this method can also be used to evaluate the usability of other digital health solutions.

In summary, healthcare IT is touted as the most promising fix to the high cost of healthcare in the United States. However, on the flip side, poor usability of EHR systems has contributed to clinician dissatisfaction and burnout (Melnick et al. 2020). Thus, it is incumbent upon researchers to find better methods to evaluate EHR usability in a way that mitigates its unintended consequences. Furthermore, achieving optimal EHR design and user satisfaction is difficult without proper and standardized EHR usability evaluation tools and techniques. Thus, this work fills this gap and proposes a usability evaluation solution that helps EHR vendors design better EHR systems and continually improve them.

References

Adler-Milstein, J., Zhao, W., Willard-Grace, R., Knox, M., and Grumbach, K. 2020. "Electronic Health Records and Burnout: Time Spent on the Electronic Health Record after Hours and Message Volume

Associated with Exhaustion but Not with Cynicism among Primary Care Clinicians," *Journal of the American Medical Informatics Association* (27:4), pp. 531-538.

Arndt, B. G., Beasley, J. W., Watkinson, M. D., Temte, J. L., Tuan, W. J., Sinsky, C. A., and Gilchrist, V. J. 2017. "Tethered to the Ehr: Primary Care Physician Workload Assessment Using Ehr Event Log Data and Time-Motion Observations," *Annals of Family Medicine* (15:5), pp. 419-426.

Asan, O., Chiou, E., and Montague, E. 2015. "Quantitative Ethnographic Study of Physician Workflow and Interactions with Electronic Health Record Systems," *International journal of industrial ergonomics* (49), pp. 124-130.

Ballermann, M. A., Shaw, N. T., Mayes, D. C., Gibney, R. T. N., and Westbrook, J. I. 2011. "Validation of the Work Observation Method by Activity Timing (Wombat) Method of Conducting Time-Motion Observations in Critical Care Settings: An Observational Study," *BMC Medical Informatics and Decision Making* (11:1).

Banks, J., Carson, J. S., Nelson, B. L., and Nicol, D. M. 2013. *Discrete-Event System Simulation: Pearson New International Edition*. Pearson Higher Ed.

Brooke, J. 1996. "Sus: A "Quick and Dirty'usability," *Usability evaluation in industry* (189:3).

Carayon, P., and Salwei, M. E. 2021. "Moving toward a Sociotechnical Systems Approach to Continuous Health Information Technology Design: The Path Forward for Improving Electronic Health Record Usability and Reducing Clinician Burnout," *Journal of the American Medical Informatics Association* (28:5), pp. 1026-1028.

Carayon, P., Wetterneck, T. B., Alyousef, B., Brown, R. L., Cartmill, R. S., McGuire, K., Hoonakker, P. L. T., Slagle, J., Van Roy, K. S., Walker, J. M., Weinger, M. B., Xie, A., and Wood, K. E. 2015. "Impact of Electronic Health Record Technology on the Work and Workflow of Physicians in the Intensive Care Unit," *International Journal of Medical Informatics* (84:8), pp. 578-594.

Cochran, J. K., and Bharti, A. 2006. "A Multi-Stage Stochastic Methodology for Whole Hospital Bed Planning under Peak Loading," *International Journal of Industrial and Systems Engineering* (1:1-2), pp. 8-36.

Connelly, L. G., and Bair, A. E. 2004. "Discrete Event Simulation of Emergency Department Activity: A Platform for System-Level Operations Research," *Academic Emergency Medicine* (11:11), pp. 1177-1185.

Doudareva, E., and Carter, M. 2022. "Discrete Event Simulation for Emergency Department Modelling: A Systematic Review of Validation Methods," *Operations Research for Health Care*), p. 100340.

Ellsworth, M. A., Dziadzko, M., O'Horo, J. C., Farrell, A. M., Zhang, J., and Herasevich, V. 2016. "An Appraisal of Published Usability Evaluations of Electronic Health Records Via Systematic Review," *Journal of the American Medical Informatics Association* (24:1), pp. 218-226.

Fetter, R. B., and Thompson, J. D. 1966. "Patients' Waiting Time and Doctors' Idle Time in the Outpatient Setting," *Health services research* (1:1), p. 66.

Guo, C., Ashrafian, H., Ghafur, S., Fontana, G., Gardner, C., and Prime, M. 2020. "Challenges for the Evaluation of Digital Health Solutions—a Call for Innovative Evidence Generation Approaches," *npj Digital Medicine* (3:1), pp. 1-14.

Hefter, Y., Madahar, P., Eisen, L. A., and Gong, M. N. 2016. "A Time-Motion Study of Icu Workflow and the Impact of Strain," *Critical Care Medicine* (44:8), pp. 1482-1489.

Hettinger, A. Z., Melnick, E. R., and Ratwani, R. M. 2021. "Advancing Electronic Health Record Vendor Usability Maturity: Progress and Next Steps," *Journal of the American Medical Informatics Association* (28:5), pp. 1029-1031.

Hoot, N. R., LeBlanc, L. J., Jones, I., Levin, S. R., Zhou, C., Gadd, C. S., and Aronsky, D. 2008. "Forecasting Emergency Department Crowding: A Discrete Event Simulation," *Annals of emergency medicine* (52:2), pp. 116-125.

Howe, J. L., Adams, K. T., Hettinger, A. Z., and Ratwani, R. M. 2018. "Electronic Health Record Usability Issues and Potential Contribution to Patient Harm," *Jama* (319:12), pp. 1276-1278.

Joines, J. A., and Roberts, S. D. 2015. *Simulation Modeling with Simio: A Workbook*. Simio LLC Pittsburgh.

Kim, M. S., Shapiro, J. S., Genes, N., Aguilar, M. V., Mohrer, D., Baumlin, K., and Belden, J. L. 2012. "A Pilot Study on Usability Analysis of Emergency Department Information System by Nurses," *Applied clinical informatics* (3:1), pp. 135-153.

Kushniruk, A. W., and Patel, V. L. 2004. "Cognitive and Usability Engineering Methods for the Evaluation of Clinical Information Systems," *Journal of biomedical informatics* (37:1), pp. 56-76.

Mazur, L. M., Mosaly, P. R., Moore, C., and Marks, L. 2019. "Association of the Usability of Electronic Health Records with Cognitive Workload and Performance Levels among Physicians," *JAMA Network Open* (2:4), pp. e191709-e191709.

McDonnell, C., Werner, K., and Wendel, L. 2010. "Electronic Health Record Usability," *Vendor Practices and Perspectives: AHRQ, James Bell Associates, The Altarum Institute, Rockville*).

Melnick, E. R., Dyrbye, L. N., Sinsky, C. A., Trockel, M., West, C. P., Nedelec, L., Tutty, M. A., and Shanafelt, T. 2020. "The Association between Perceived Electronic Health Record Usability and Professional Burnout among Us Physicians," *Mayo Clinic Proceedings*: Elsevier, pp. 476-487.

Murthy, V. H. 2022. "Confronting Health Worker Burnout and Well-Being," *New England Journal of Medicine*).

Ordu, M., Demir, E., and Tofallis, C. 2020. "A Decision Support System for Demand and Capacity Modelling of an Accident and Emergency Department," *Health Systems* (9:1), pp. 31-56.

Overhage, J. M., and Johnson, K. B. 2020. "Pediatrician Electronic Health Record Time Use for Outpatient Encounters," *Pediatrics* (146:6).

Oztekin, A., Delen, D., Turkyilmaz, A., and Zaim, S. 2013. "A Machine Learning-Based Usability Evaluation Method for Elearning Systems," *Decision Support Systems*).

Pizziferri, L., Kittler, A. F., Volk, L. A., Honour, M. M., Gupta, S., Wang, S., Wang, T., Lippincott, M., Li, Q., and Bates, D. W. 2005. "Primary Care Physician Time Utilization before and after Implementation of an Electronic Health Record: A Time-Motion Study," *Journal of biomedical informatics* (38:3), pp. 176-188.

Ratwani, R. M., Fairbanks, R. J., Hettinger, A. Z., and Benda, N. C. 2015. "Electronic Health Record Usability: Analysis of the User-Centered Design Processes of Eleven Electronic Health Record Vendors," *Journal of the American Medical Informatics Association* (22:6), pp. 1179-1182.

Ratwani RM, S. C., Melnick ER. 2020. "Closing the Electronic Health Record Usability Gap," in: *The Petrie-Flom Center staff*.

Sinsky, C., Colligan, L., Li, L., Prgomet, M., Reynolds, S., Goeders, L., Westbrook, J., Tutty, M., and Blike, G. 2016. "Allocation of Physician Time in Ambulatory Practice: A Time and Motion Study in 4 Specialties," *Annals of internal medicine* (165:11), pp. 753-760.

Sinsky, C. A., Rule, A., Cohen, G., Arndt, B. G., Shanafelt, T. D., Sharp, C. D., Baxter, S. L., Tai-Seale, M., Yan, S., and Chen, Y. 2020. "Metrics for Assessing Physician Activity Using Electronic Health Record Log Data," *Journal of the American Medical Informatics Association* (27:4), pp. 639-643.

Thorwarth, M., Arisha, A., and Harper, P. 2009. "Simulation Model to Investigate Flexible Workload Management for Healthcare and Servicescape Environment," *Proceedings of the 2009 Winter Simulation Conference (WSC)*: IEEE, pp. 1946-1956.

Tipping, M. D., Forth, V. E., O'Leary, K. J., Malkenson, D. M., Magill, D. B., Englert, K., and Williams, M. V. 2010. "Where Did the Day Go? - a Time-Motion Study of Hospitalists," *Journal of Hospital Medicine* (5:6), pp. 323-328.

Vahdat, V., Griffin, J. A., Stahl, J. E., and Yang, F. C. 2018. "Analysis of the Effects of Ehr Implementation on Timeliness of Care in a Dermatology Clinic: A Simulation Study," *Journal of the American Medical Informatics Association* (25:7), pp. 827-832.

Wijewickrama, A., and Takakuwa, S. 2005. "Simulation Analysis of Appointment Scheduling in an Outpatient Department of Internal Medicine," *Proceedings of the Winter Simulation Conference, 2005.*: IEEE, p. 10 pp.

Young, R. A., Burge, S. K., Kumar, K. A., Wilson, J. M., and Ortiz, D. F. 2018. "A Time-Motion Study of Primary Care Physicians' Work in the Electronic Health Record Era," *Family Medicine* (50:2), pp. 91-99.

Zheng, K., Haftel, H. M., Hirschl, R. B., O'Reilly, M., and Hanauer, D. A. 2010. "Quantifying the Impact of Health It Implementations on Clinical Workflow: A New Methodological Perspective," *Journal of the American Medical Informatics Association* (17:4), pp. 454-461.