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UTILIZATION OF DISCRETE EVENT SIMULATION IN THE PROSPECTIVE DETERMINATION OF OPTIMAL CARDIOVASCULAR LAB PROCESSES

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ABSTRACT

The clinical character of cardiovascular disease creates challenges in optimizing cardiovascular catheterization lab (CVL) throughput. These challenges are due to case load fluctuations caused by unscheduled Emergency Department patients and simultaneous conflicting demands on cardiologist time. The simulation model provides insight into the complex relationship between patient acuity, treatment, occurrence of queues and bottlenecks in the transfer of patients. The study performed a comparative analysis between CVL operational schemes and assessed how those schemes impacted a variety of metrics related to throughput improvement. A current state model was developed, pertinent data was collected for the patient group and validation of the model was performed. Analysis of simulation results determined the most efficient CVL schedule and resource allocation to improve throughput and resource utilization. The study provides objective guidance to the optimal process modification and allows comparison of the relative differences in cost between the several redesign options.

1 INTRODUCTION

Healthcare costs have dramatically increased and at the same time, healthcare organizations have been under pressure to provide increased quality of care for their patients. The challenge to improve healthcare quality, reduce medical errors, increase efficiency and deliver appropriate evidence-based health services is stronger than ever. These challenges generate significant interest in how resources can be utilized to maximize patient throughput and minimize patient wait time without incurring additional costs. Current strategies for process improvement measure process behavior against the current operational state and are not designed to explore process performance against hypothetical future operational states. Clinical or organizational judgment might not be optimal because the decision maker may not consider other favorable alternatives. Discrete Event Simulation models provides insight into the complex relationship between patient acuity, treatment, occurrence of queues and bottlenecks in the transfer of patients between the ED and the hospital ward (Ceglowski, Churilov and Wasserthiel 2007).

Healthcare processes typically are fairly complex constructs, involving a variety of human participants interacting with each other and with numerous forms of technology. The clinical areas that are often the focus of process redesign efforts are frequently high-volume, high revenue-generating venues and make traditional methods utilizing iterative process changes

problematic. Traditional redesign efforts often lead to process degradation rather than improvement and result in significant operational impact. Additionally, because the cycle time from redesign to implementation to outcome analysis is typically measured in months, the move towards an optimal construct is significantly delayed and maximal benefits are diluted. Accordingly, we sought to test the applicability of discrete event simulation as a virtual method of testing competing CVL process designs and its ability to provide prospective comparison of the resulting operational, clinical and financial outcomes.

The operational schemes of cardiovascular catheterization laboratories (CVL) are complex and can be very challenging due to significant uncertainty in the number of patients transferred from the emergency department (ED) to the CVL and the variability of CVL procedure durations. The complexity is enhanced by the highly unpredictable nature of ED patient arrivals which significantly impacts scheduling, leading to artificially long wait times for all but the highest acuity cases. The highly variable CVL patient volume not only affects patient care and satisfaction, but greatly complicates maintaining appropriate staffing levels (Siegrist et al. 2009).

We developed a discrete event simulation model of the throughput processes to address this complexity. The iterative impact associated with traditional redesign methods was eliminated by using simulation techniques. The model followed patients with Acute Coronary Syndrome (ACS) beginning at the point of hospital admission through arrival in the CVL and predicted the ACS patient throughput consequences of increased patient volume demand on the current CVL process construct. In addition, simulations of potential CVL process redesigns were carried out and the absolute and relative performance of the different redesign schemes, in terms of ACS patient throughput impact, were determined.

2 METHOD

2.1 Study Selection

The parameters involved in patient scheduling and admissions are: 1) day of the week; 2) time of day; and 3) procedure length. Scheduling involves rules that determine when appointments can be made (morning vs afternoon) and spacing of time between appointments (Klassen and Rohleder 2004). Klassen and Rohleder also considered dynamic scheduling, where clients call for appointments throughout the day and are scheduled without knowledge of the type and number of clients that will call later (Klassen and Rohleder 1996).

The volume of patient arrivals in the ED is highly unpredictable, significantly impacting scheduling and resource allocation. Isken, Ward, and McKee modeled outpatient obstetrical clinics to analyze the demand, appointment scheduling, examination room allocation, patient flow patterns and staffing (Isken, Ward, and McKee 1999). Guo, Wagner, and West presented a simulation model to minimize the delays in appointments while simultaneously maximizing provider utilization and overall clinic efficiency (Guo, Wagner, and West 2004). These issues can have a significant impact on how resources can be optimally utilized to maximize patient throughput and minimizing patient wait time without incurring additional costs. Denton, Viapiano, and Vogl showed that a sequencing rule based on surgery duration variance can be used to generate substantial reductions in total surgeon and operating room (OR) team waiting, OR idling, and overtime costs (Denton, Viapiano, and Vogl 2007).

The reviewed literature has limited content on the simulation of patient flow from ED to CVL though there are published papers on patient scheduling. The challenge is how to make the transfer a seamless process across venues in different physical locations. The analysis demonstrates the importance of CVL scheduling and addressing the variability associated with the process. The improvement of CVL scheduling is possible by the integration of patient flow with patient data. It is critical to understand the impact of any volume change on CVL operations and to test potential process design.

In this study, the focus was on process variability. The integration of the electronic medical record with the simulation process provides credence to data-driven decision making. "Clinical Expert Consensus Document on Cardiac Catheterization Laboratory Standards" suggests the time for balloon inflation should be within 60 to 120 min of admission (Bashore et al. 2001). Meeting that benchmark for door-to-balloon inflation is important for the hospital. The inability to schedule a CVL procedure leads to longer lengths of stay either in the ED or Chest Pain Unit (CPU). The increased wait time in the ED or CPU negatively impacts patient satisfaction and is a hindrance to the achievement of the benchmark.

Arena simulation software, version 12.0 developed by Rockwell Automation was used to run simulations of CVL scheduling.

2.2 Study Objectives

The goals for the study were to reduce patient wait times for cath procedures and increase utilization of resources, given an anticipated increase in patient volume:

- Measure the average amount of time a patient spends in the system based on the patient acuity type. The time in the system was categorized by the following patient types: 1) Scheduled patient; 2) ST Elevation Myocardial Infarction (STEMI) patient; 3) Same day ED patient; 4) Weekday overnight ED patient; 5) Weekend ED patient.
- Measure the average queue size for: 1) Same day ED patients; 2) Weekday overnight ED patient; 3) Weekend ED patients.
- Determine the optimal allocation of scheduling slots that should be left open for ED and transfer patients so they can be served sooner and determine whether the outcome differs from the current CVL schedule.

2.3 Current State Process

The process that ACS patients experience in the clinical environment is aggregated into three principal phases: 1) pre-CVL; 2) intra CVL; and 3) post CVL. In this study, only the pre-CVL and intra-CVL processes were considered. The pre-CVL phase involves patient entry into the clinical process by one of three arrival venues: 1) Chest Pain Center (CPC) within the ED; 2) Chest Pain Unit (CPU) – the inpatient telemetry unit; or 3) Outpatient Holding (OP) – the outpatient area near the CVL. Upon entry into the process stream, ACS patients undergo diagnosis-specific clinical protocols aimed at diagnostic confirmation and preparation for subsequent therapy. Specific clinical protocols exist for three different patient acuity levels (in order of decreasing acuity): 1) STEMI; 2) Non-ST Elevation Myocardial Infarction (NSTEMI); and 3) Unstable Angina (UA). Typically, asymptomatic chest-pain patients who arrive via the outpatient venue prior to the CVL do not undergo specific clinical protocols other than routine pre-procedural preparation.

2.3.1 Pre CVL

Upon arrival and completion of the appropriate diagnosis-specific clinical protocol, if cardiac catheterization is indicated, the patient enters the pre-CVL process stream. Specific patient movement within this stream is governed by patient acuity, arrival venue, timing of the decision to perform catheterization and the existing CVL queue length. Clinical emphasis is placed upon accelerating movement of patients to the CVL when appropriate and is generally driven by defined process behaviors. For patients in the CPC, efforts are made to proceed directly to the CVL without prior transfer to the CPU. In some cases this is not possible and transfer to the CPU prior to CVL occurs. Outpatients arriving by the OP venue are all scheduled and as such undergo pre-procedural preparation and subsequently move to the CVL based on CVL scheduling protocols.

2.3.2 Intra CVL

ACS patient movement to the CVL and within the CVL is governed by scheduling methodologies, CVL physical resources (CVL rooms), CVL human resources (Cardiologist and CVL nurses and technicians) and procedural protocols. CVL physical resources vary by day of the week and time of the day. Inpatient scheduling priority is driven by patient length of stay at the time of the clinical decision to proceed to the CVL. Once the daily CVL schedule is set, patients proceed through the queue as preceding cases are completed. Patients arriving during the day may be added to the queue (same day add-ons) as CVL capacity permits. STEMI patients are taken directly to the CVL regardless of time of day or existing CVL queue. Although the majority of ACS patients proceed to the CVL once scheduled, by virtue of unscheduled emergencies or prolonged case durations, patients may be removed (bumped) from the CVL queue prior to catheterization. These patients (overnight holdovers) are held in the CPC until the next day and re-enter the CVL queue at that time.

2.4 Data Collection and Analysis

Matching model detail with quality of data is important because the results of the simulation study are only as reliable as the model and its inputs. Data related to registration and location history, encounter history in the ED and CVL history was mined from repositories of hospital data. The data was systematically analyzed and mapped to the process activities to provide new insights.

Data for a period of six months (study period November 2007 to April 2008) was evaluated for CVL patients arriving in the ED. The arrival time and patient type was recorded for each patient arrival. The data repository included detailed clinical data from the electronic health record system, shown in Table 1. The timestamp in the system provided the ability to calculate the time taken for each step in the patient flow.

Table 1: Data related to the registration, location, and encounter that was captured in the electronic health record system and reported in Cerner PowerInsight Data Warehouse.

Data Element	Data Format
ED Walk-In Patient	Yes/No
ED to ED Transferred In Patient	Yes/No
Registration to ED	Date/Time
Registration to Hospital	Date/Time
Cath Lab Procedure	Date/Time
Pre Procedure Holding In	Date/Time
Pre Procedure Holding Out	Date/Time
ED Disposition Documented	Date/Time
PCI Performed	Date/Time
Cath Lab Notification of STEMI Arrival	Date/Time

CVL cardiovascular physiological monitoring and information systems provided CVL in-room times. Table 2 depicts data captured during procedure documentation.

Table 2: CVL procedure data that was captured in the Witt Biomedical Corp. information system.

Data Element	Data Format
Patient In-Room	Date/Time
Patient Out-Room	Date/Time
Recovery Unit In-Room	Date/Time
Recovery Unit Patient Out Room	Date/Time
Procedure Begin	Date/Time
Procedure End	Date/Time
PCI Performed	Number (1 or 0)

This study considered the variation in patient arrival rates throughout the day by basing the statistical model on a relatively large data sample. The arrival time data was converted into number of arrivals per day of the week and per hour of the day.

2.4.1 Arrivals: ED Arrival Rate for ACS Patients

The ED patient arrival rate was computed by adding the total number of "ED Walk-In Patient" and "ED to ED Transferred In Patient." The "Registration to ED" date/time stamp was separated into individual date and time variables. Figure 1 displays the frequency distributions of the arrival of ED patients for day of week (Sunday = 1; Saturday = 7)

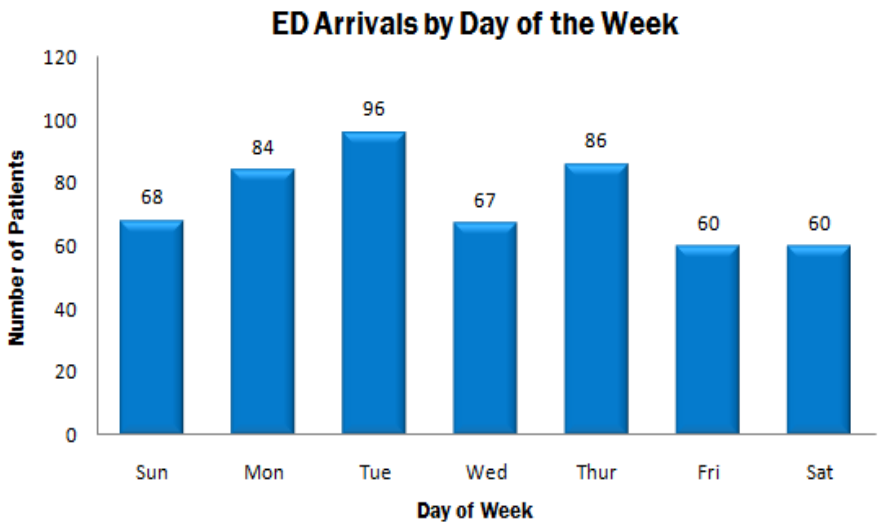

Figure 1: Histogram showing the number of ED arrivals on a given day of the week.

This simulation study focused on the hour-to-hour variation in the patient arrival as seen in Figure 2 to ensure accuracy of generating random numbers.

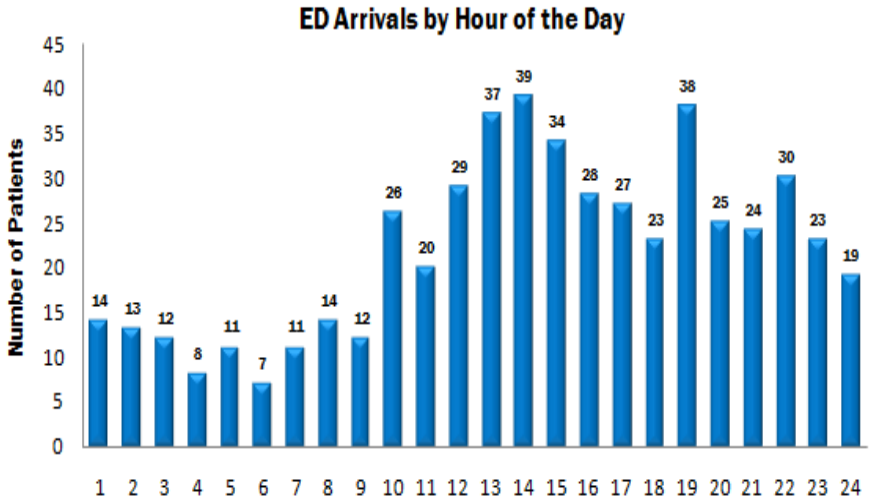

Figure 2: Histogram of the number of ED arrivals on a given hour of the day.

Considering the hour-to-hour variation in patient arrivals and the distribution of the patient arrival pattern, the data accurately represents the unscheduled patient arrival pattern and offers a reasonable degree of predictability of the future arrival pattern (Swartzman 1970). This data was then analyzed for any trend in the number of arrivals per hour to identify whether the number of arrivals in any hour was significantly different from the number of arrivals in other hourly segments. The arrival rate for each hour of each day of the week was calculated. The patient arrivals are then represented as a non-stationary Poisson process with piecewise constant.

2.4.2 Key Data Elements

Table 3: Summary of the mean time values generated from the PowerInsight and Witt data

Data Element	Mean (minutes)
Time Spent in ED (STEMI)	33
Time Spent in ED (NSTEMI)	135
Time Spent in ED (Unstable Angina)	201
Procedure Duration (PCI)	120
Procedure Duration (Diagnostic)	70

3 RESULTS

3.1 Validation

Validation of the CVL model was performed by clinical subject matter experts to ensure that the model accurately represented the care coordination process for the purpose of experimentation. The validation process involved examination of the simulation method to ensure that the simulation model accurately reflected the operational aspects of the CVL system. The following checks were performed in the simulations to assess the model:

- Ensured that the inputs to the model were correct
- Verified that relationships among data values were valid
- Verified that the control flow was executing correctly

A three-step process for the validation of the model (Ledin 2001) was followed: 1) compilation of the source code; 2) setup and execution of the simulation run; 3) analysis of the data collected during the run. The analysis sought to determine if there were errors in the model or problems with insufficient model fidelity.

A face validation of the operational model was performed by comparing historical data obtained from the system against data generated from the simulation model. The subject matter experts used input and output data collected from the CVL system to test the simulation results. The same input data that was attained in the CVL system was used to drive the simulation and the simulation model outputs compared to the system outputs. This provided evidence that the simulation model was an accurate representation of the actual system.

3.2 Scenarios

Analysis of historical volume trends suggested that there would be a year-over-year 12% volume increase for the coming years. Accordingly, we chose to use 7%, 12% and 17% as the simulation volume increases for the model and developed the following scenarios:

1. Current CVL resources and current CVL procedure volume
2. Current resources with 7%, 12% and 17% increases in CVL procedure volume
3. Extended resource hours with current, 7%, 12% and 17% increases in CVL procedure volume (increased functional capacity)
4. Additional CVL resources with current, 7%, 12% and 17% increases in CVL procedure volume (increased physical capacity)

The simulation model predicted results of ACS performance and patient satisfaction metrics as the procedure volume increased. As is shown in Figure 3, at baseline, with a value of 23.1 hours, the current process is meeting the 24-hour door-to-cath quality benchmark for NSTEMI patients. Performance degraded as procedure volumes increased. By increasing the functional capacity, average door-to-cath times were 21.8 hours at baseline and 24.4 hours at the 7% increase. At volume increases of 12% and 17%, the quality benchmark was exceeded. Increasing physical capacity accommodated up to a 12% procedure volume increase while remaining below the door-to-cath benchmark.

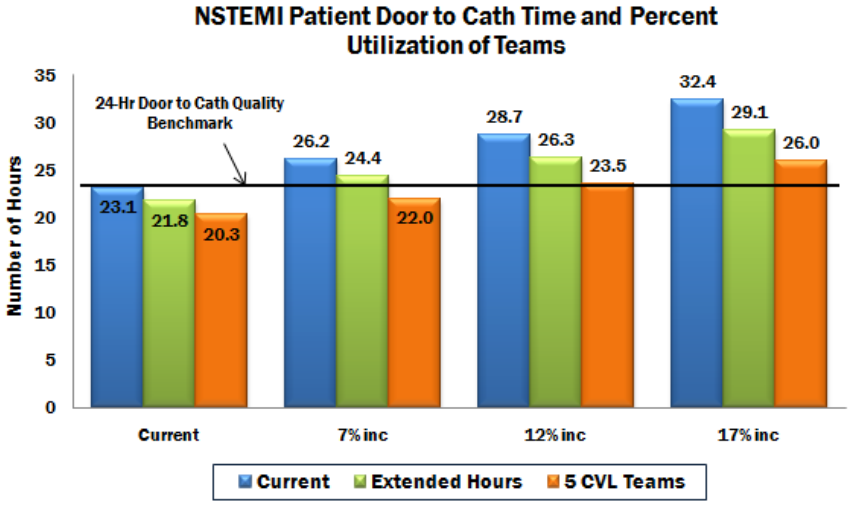

Figure 3: Histogram of NSTEMI patient door to cath times based on the current, extended hours, and 5 CVL team operational scenarios at the current CVL procedure demand as well as a 7, 12, 17% increase in the CVL procedure demand.

The simulation model predicted the impact on the patient satisfaction measure of the number of patients held more than one night as is depicted in Figure 4.

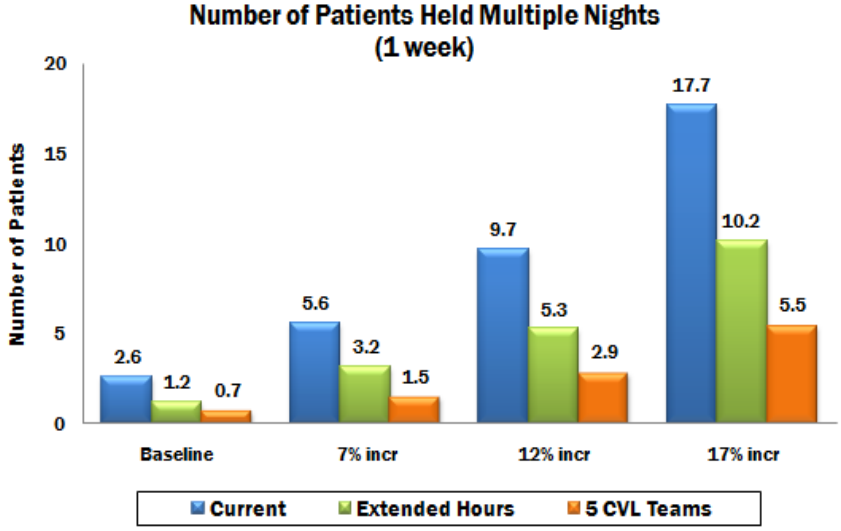

Figure 4: Histogram of number of patients being held more than 1 night a week based on the current, extended hours, and 5 CVL team operational scenarios at the current CVL procedure demand as well as a 7, 12, 17% increase in the CVL procedure demand.

At baseline, on average 2.6 patients were held more than one night each week. This measure increased exponentially to 17.7 patients as the procedure volume increased to 17%. Increasing either functional or physical capacity had a positive effect. Increasing functional capacity decreased the number by nearly one half, while increasing physical capacity decreased the number by two thirds.

The ability to go directly from the ED to the CVL without the need for an intermediate transfer to the CPU decreases, based on the current, extended hour and 5 CVL team operational scenarios at the current CVL procedure demand as well as at the 7%, 12% and 17% increased CVL procedure demand levels.

From the above analysis, it is safe to conclude that extending resource hours is only a viable option up to a 7% increase in patient volume; an additional CVL team is required to meet resource utilization and quality benchmarks for patient volume increases greater than 7%.

3.3 Financial Analysis and Considerations

Increasing physical capacity necessitates hiring a new CVL team and comes at a significantly higher cost. The simulation returned the number of annualized pre-cath inpatient days saved as seen in Figure 5 by decreasing the door-to-cath times in each scenario.

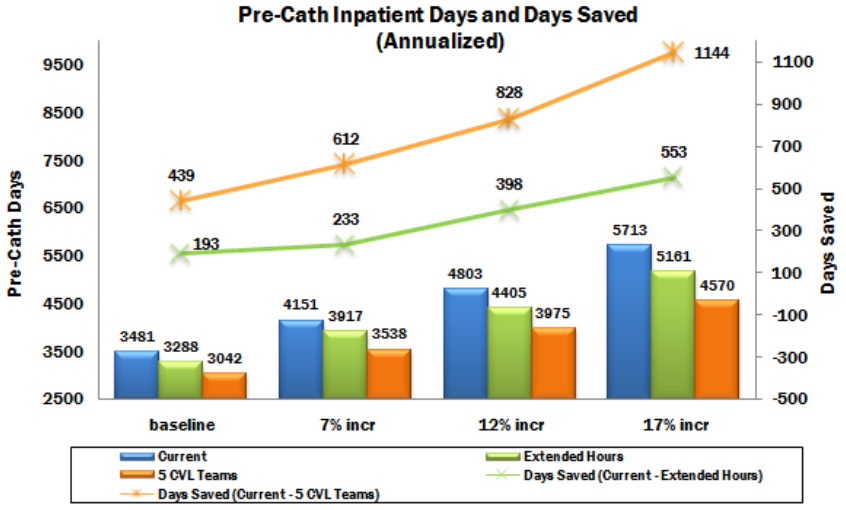

Figure 5: Histogram of the number of Pre-Cath days based on the current, extended hours, and 5 CVL team operational scenarios at the current CVL procedure demand as well as a 7, 12, 17% increase in the CVL procedure demand. Additionally, trend lines display the number of Pre-Cath days saved against the current by using extended hours and 5 CVL teams at the baseline and increased procedure demands.

To further assist in the decision making process, a return on investment analysis was completed and displayed in Table 4. Days saved resulted in cost reduction and are balanced against the cost of implementing each scenario.

Table 4: Breakdown of the return on investment for the extended hours and 5 CVL team scenario at baseline, 7, 12, and 17% increase in procedure demand

	Extended Hours			5 CVL Teams		
	Reduced Inpatient Cost	Additional Resource Cost	Cost Savings	Reduced Inpatient Cost	Additional Resource Cost	Cost Savings
Baseline	$162,120	$76,440	$85,680	$368,760	$254,800	$113,960
7% Increase	$196,560	$76,440	$120,120	$514,920	$254,800	$260,120
12% Increase	$334,320	$76,440	$257,880	$695,520	$254,800	$440,720
17% Increase	$463,680	$76,440	$387,240	$960,120	$254,800	$705,320

Taking into account the cost savings, hiring the 5th CVL team is the best option at patient volume increases over 7%.

4 CONCLUSION

Effective and efficient patient flow is indicated by high patient throughput, low patient wait times and a shortened length of stay while maintaining adequate clinician utilization rates (Jun, Jacobson, and Swisher 1999). Increasingly, healthcare delivery systems focus on methodologies to improve patient flow and, as a result, predictive modeling is becoming a requisite component of management strategies. Although useful, traditional process improvement methodologies create an environ-

ment where empiric "best guesses" at needed process changes are made and implemented, driving iterative cycles of process evaluation and redesign in order to arrive at an optimal design. The application of discrete event simulation to CVL processes enables: 1) evaluation of the performance delivered by current operational constructs in response to changes in future conditions, e.g., case volume; and 2) prospective evaluation of the performance delivered by proposed operational constructs against current or future conditions.

From the analyses of CVL processes, it was evident that the current CVL process was not sustainable with significant procedure volume increases with regard to performance benchmarks and patient satisfaction measures. This model allows the prospective evaluation of process redesign strategies both from the perspective of performance and return on investment. The modeling analyses provided objective guidance as to the throughput, clinical and financial implications of various process modification and allowed comparison of the relative differences in cost between the several redesign options.

The primary limitations in this approach relate to the accuracy and complexity with which clinical processes can be captured as model inputs and rules. If significant process steps or clinical behaviors are not adequately described, the model output predictive capability can be significantly limited. In utilizing these techniques, care must be taken to adequately observe clinical processes, interview stakeholders and validate model assumptions.

Future areas of development include the modeling of more comprehensive clinical processes which not only capture single venues of care, but integrate and describe the interaction between the multiple venues of care which occur during the typical patient encounter. The highly variable CVL patient daily volume and procedure durations significantly impacts the utilization of downstream nursing units.

Another primary area for further investigation relates to the modeling of human resource availability within given health care workflows. As the pool of skilled healthcare providers diminishes against a backdrop of increasing consumer demand, the identification of techniques which allow the accurate forecasting of human resource requirement, in particular the redesign of existing workflows to optimally deploy available human resources, will become critical.

In a healthcare environment of steadily shrinking resources and accelerating demand, process improvement strategies that not only assess current state process performance, but also allow the prospective evaluation of redesigned processes and facilitate estimation of operational return on investment are needed. This model offers these capabilities and has the potential to become a valuable component of clinical process improvement programs.

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