

A SYSTEM DYNAMICS MODEL OF FLOW OF PATIENTS FROM THE ICU THROUGH THE STEP-DOWN UNITS

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ABSTRACT

A System Dynamics (SD) model is presented to study the flow of patients from the ICU to the step-down units in a local hospital. The model maps the current state of the system and quantifies the impact of future increase in demand on system performance. Two measures of performance are used in the model that relate to customer dissatisfaction and the need for future capacity expansion respectively. The model captures a number of elements and their interactions that include current operating procedure, current efficiency and resource capacity. The model offers the capability to study different “what if” conditions based on a SD model that will help make good decisions to improve system performance. A follow-up research, currently in progress, combines a SD model with a Discrete-Event Simulation (DES) model to develop a framework to study the proposed system both at strategic as well as at operational level.

Key words: System Dynamics model, ICU capacity expansion and Healthcare system design.

1 INTRODUCTION

Demand of healthcare services has accelerated its pace over the years due to aging population, varying demographic trends, increased expectations, government regulations, etc. This substantial increase has led to growing need for more resources such as beds, medicine and medical staff delivering various services. There is an urgent need now to balance the cost of resources with the service quality and availability. The unbalance between supply and demand of resources requires effective tools to capture

the causes and analyze the effects by observing the relations of various components in the system with each other and exogenous factors as well.

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Moreover, increasing patient volumes will entail advance planning to maintain the same level of care (Marmor et al. 2011).

Eldabi et al (2007) describe that there is dramatic increase in healthcare studies since 2000. Healthcare organizations show complexity in both detailed and dynamic, and consist of many interrelated drivers and subsystems. This complexity has encouraged policy makers to use simulation-based models due to importance of resource and budget allocation through more informed and effective decisions.

Integrated care units such as Intensive Care Unit (ICU), Progressive Care Unit (PCU) or Regular Care Unit (RCU) provide different levels of care as the patients advance through their treatment. Yet ICU is the most critical unit in a hospital, the availability of ICU beds has direct impact on system performance. Bed blocking occurs when the patient cannot be transferred from high level of care to reduced care due to non-availability of beds in step-down units. Incoming patients in turn cannot be placed because of shortage of bed and must wait leading to delayed discharge. Increase in patient volume requires detailed planning to maintain the same level of service.

This paper presents the current state of the system under study and evaluates the adequacy of existing capacity of Intensive Care Unit (ICU) and two step-down units (Progressive Care Unit and Regular Care Unit). The objective of this study is to understand how the system responds to increase in demand and to ascertain if there is a need for possible capacity expansion to improve system performance. A System Dynamics model is used as a decision support tool to capture the complexity of the overall system and model how the patients flow among different resources.

2 LITERATURE REVIEW

System dynamics is an analytical modeling approach based on the philosophy that the components or different elements of the system influence each other and the resulting interaction determines the behavior of the system as a whole over time. SD was first introduced in the 1950s by Jay Forrester under the name of “Industrial Dynamics” at the Massachusetts Institute of Technology (Forrester 1960). It has been applied in wide range of areas, yet it is not a well-known approach in the Operation Research community. SD models clarify the cause and effect of the problem, demonstrating the components along with internal feedback loops and time delays leading to observed dynamic behavior. SD models used to help managers improve their understanding of the industrial processes and now being used in both public and private sector for policy analysis and design.

Qualitative and quantitative are two distinct aspects of SD (Brailsford, 2008). This qualitative side is represented as a casual loop diagram. A casual loop diagram (CLD) simply reveals the structure by capturing the interaction between components. CLD enhances understanding the behavior over time and shed light on the system being analyzed. The elements are connected with arrows and they have signs to indicate increasing or decreasing relationship between the elements. There are two types of

feedback loops: balancing and reinforcing. Balancing loops keep the system in balance, whereas reinforcing loops cause system to get out of control.

Brailsford and Hilton (2001) explain CLD with an example to demonstrate notation. While eating increases food in stomach, shown by a “+”; as digestion increases, food in stomach decreases and it is shown by a “-”. Balanced loops have an odd number of “-” signs, whereas reinforcing loops contain an even number of “-” signs. The figure represents a balanced loop, keeps the system in control. Authors argue that the hungrier we are, the more we want to eat. Food increases in our stomach by eating. This eventually causes feeling less hungry and then stops eating.

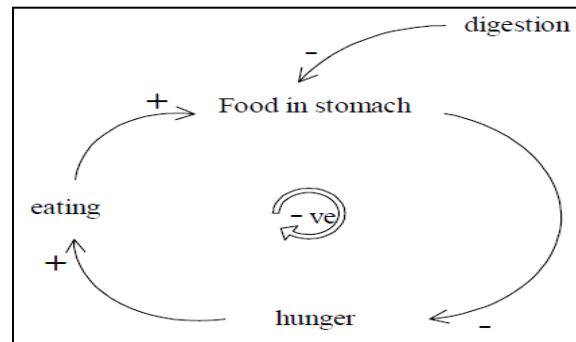


Figure 1: Influence diagram to demonstrate notation (Brailsford and Hilton, 2001)

Stock-flow diagrams are quantitative form of SD transformed from CLD, assist to gain more insight of the system. Stock-flow diagrams are built and simulated by computer software. A stock is the expressions for continuous entities that accumulates or lessen over time. A flow is the rate of change in a stock.

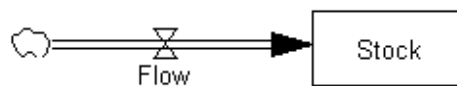


Figure 2: Simple stock and flow diagram

(Brailsford, 2008) illustrates the stock-flow model for hospital admissions. There are two clouds named source and sink. Entities are the patients going through the system. The rectangle represents a stock or level of patients, occupying in hospital. The arrows denote admissions and discharge, and the valves are the rate of flow. System can have “auxiliary” or “soft” variables that they may not have a direct influence on system but still affect the behavior. The model needs to be parameterized subsequently, can be developed easily with one of SD software.

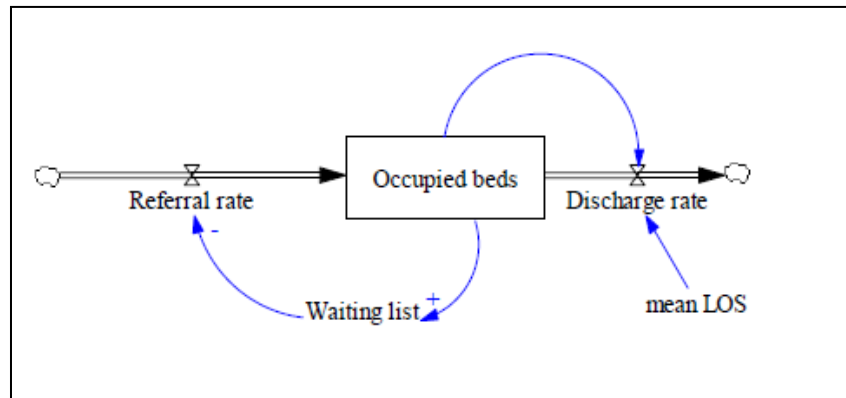


Figure 3: Stock-flow model for hospital admissions (Brailsford, 2008)

The use of SD has exhibited a considerable increase over last ten years, essentially in healthcare domain. The system dynamic approach has been applied to population health issues since 1970s (Homer and Hirsch 2006). System dynamics model assists policy makers to gain more insight of the complexity inherited in the system. System dynamic modeling aims to understand the relative impacts of alternative assumptions and interventions rather than predict future values of the system (Homer et al. 2006).

Lane et al (2000) described the formulation and calibration of a SD model of the interaction of demand pattern, A&E resource deployment, other hospital processes and bed numbers; and the outputs of policy analysis runs of the model under different operating conditions. The important result was that reductions in bed numbers do not increase waiting times for emergency admissions; instead they increase sharply the number of cancellations of admissions for elective surgery. They suggested that A&E policy solely on any single criterion will transfer the effects of a resource deficit to a different patient group.

Lane et al (2003) evaluated the collaborative process of building a SD model in order to understand patient waiting times in an A&E department. They explored the issues that arise when health care professionals are involved in model development.

Lattimer et al (2004) described the components of an emergency and urgent care system within one health authority and to investigate ways in which patient flows and system capacity could be improved. They used a qualitative system dynamics (SD) approach to build a conceptual map of the system illustrating patient pathways from entry to discharge. Then map is used to construct stock-flow diagram to experiment different scenarios.

Brailsford et al (2004) described how system dynamics is used as a central part of a whole-system review of emergency and on-demand health care. They developed a 'conceptual map' of the system based on interviews with 30 key individuals across health and social care, showing potential patient pathways through the system. The result was used to construct a stock-flow model to simulate patient flows and to identify system bottlenecks. Modeling indicated a range of undesirable outcomes associated with continued growth in demand for emergency care, but also considerable potential to intervene to alleviate these problems, in particular by increasing the care options available in the community.

Evenden et al (2005) analyzed genital Chlamydia trachomatis infection with the help of System Dynamics model to capture dynamics within a population, including different risk groups, and provide a cost-benefit study for screening. They also demonstrated key risk groups to determine the overall infection dynamics of the system, and quantify screening rates in order to manage infection prevalence within the wider population.

Cooke et al. (2007) discussed the use of system thinking and system dynamics modeling as tool for evaluating alternative health policy decision working in emergency care services and colorectal cancer screening, in Alberta, Canada.

Lane and Husemann (2008) aimed to assess the usefulness of SD to elicit proposals concerning ways of improving patient experience. Initial interviews and hospital site visits generated a series of stock/flow maps. NHS staff was able to propose ideas for improving patient flows and the elicited data was subsequently employed to create a finalized suite of maps of a general acute hospital through the workshops held. The maps and ideas were communicated back to the DH and subsequently assisted the work of the Modernization Agency.

Faezipour and Ferreira (2013) explored important factors and their relationships in healthcare social sustainability regarding patient satisfaction using system dynamics approach. They applied system thinking approach to analyze the social aspect in healthcare systems.

User-friendly SD software has led modelers to make simultaneous and quick decisions without any programming knowledge. Stella and Vensim are the two of them having drag and drop interfaces as some of DES software provide to their users. The objects can simply be connected through setting up desired properties. Both paradigms have their own proponents. Some vendors, for example Technomatix, have been trying to integrate continuous process modeling to their DES software to capture dynamics of the system. In addition to that, some of them, for example Anylogic, have standard libraries for each area providing multi-method simulation modeling.

3 PROBLEM STATEMENT

The objective of this study is to develop a system dynamics model that captures the flow of patients from the Intensive Care Unit to the step-down units in a hospital. This is necessary to take care of new arrivals to the ICU. The capital intensive resource such as ICU bed cannot be put into service in the short run to take care of spike in demand. The usual practice is to move some patients who are in less critical condition from the ICU to next step-down unit, termed Progressive Bed. Overflow from the Progressive Bed unit is routed to the next step-down unit termed Regular Bed. The level of care offered to a patient drops down as the patient moves through the step-down units. Capacity constraints also become less severe as we move through the step-down units. For example, it is relatively easy to add extra beds in the Regular Bed unit.

The SD model presented in this paper captures the flow of patients through the step-down units including both regular flow and over flow among the units. The objectives of this study are as follows: (1) Is current capacity adequate to meet the current demand? (2) Is the facility capable of handling efficiently expected increase in future demand?

The SD model presents a deterministic model that also includes daily demand for ICU, Progressive and Regular beds as random elements. Each random element is represented by a suitable statistical distribution. The model closely resembles the operation of a local hospital. The model parameters are also set at values based on discussion with domain expert of a local hospital.

3.1 The Causal Loop Diagram

The causal loop diagram (CLD) is shown next. The diagram shows the cause and effect relationships among different elements of the system. Each node represents an element of the system that may be quantitative or qualitative in nature. The CLD shows that increase in demand increases ICU backup, PB occupancy as well as Regular Bed occupancy. “Customer Dissatisfaction” and “Need for more capacity” are examples of qualitative or soft variables. The CLD also shows that increase in “Available Capacity” will lower ICU backup, PB Occupancy as well as Regular Bed Occupancy. The CLD diagram shows the different interactions that are converted into mathematical equations shown next in Figure 6 through 9.

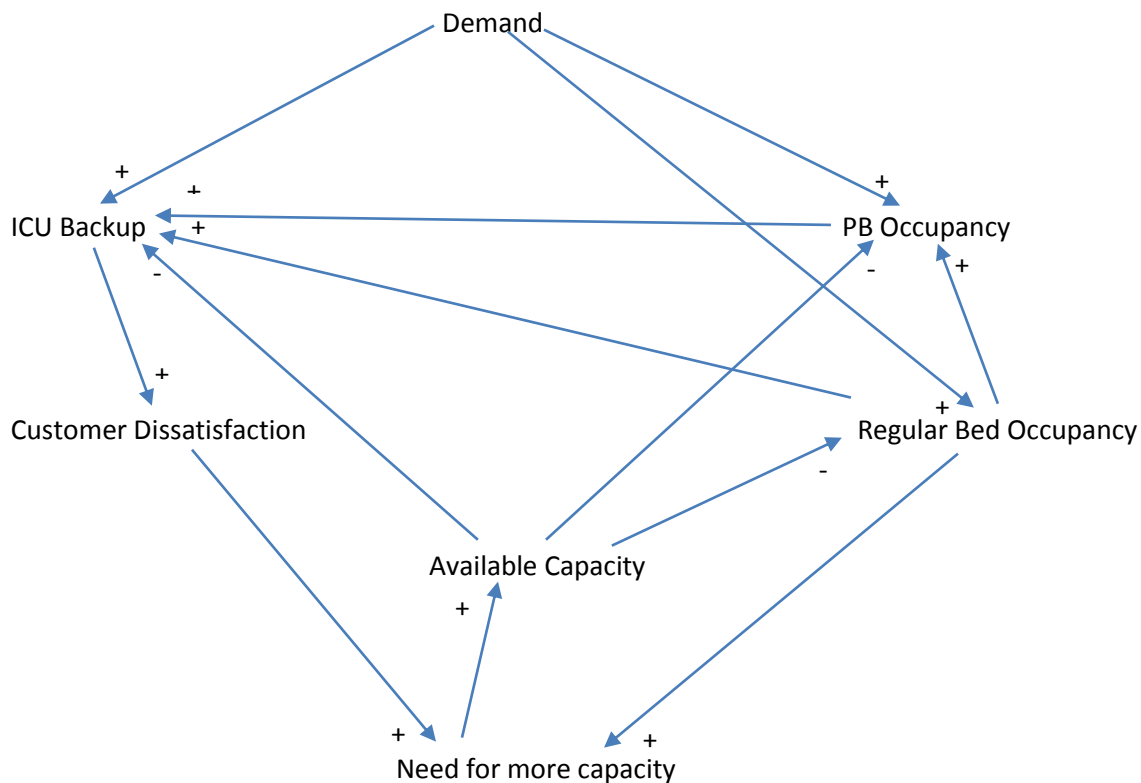


Figure 4: Casual loop diagram (CLD) for system elements and their effects on capacity

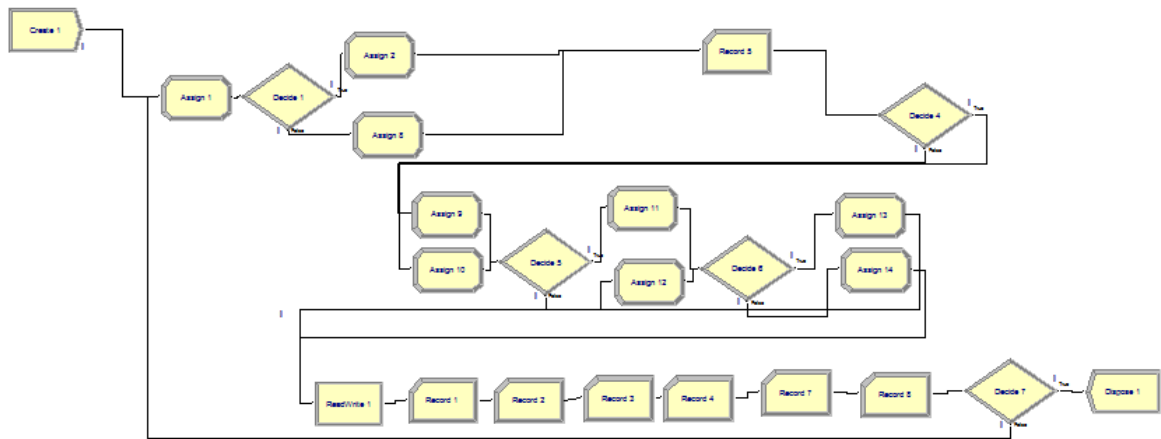


Figure 5: Screenshot of Arena model used to simulate the system behavior

The Arena model shown above captures the mathematical equations shown earlier. The system has three random elements and they are daily demand for ICU beds, Progressive beds and Regular beds. The Arena model is run to generate the results shown later in the paper. Arena software is typically used to model discrete-event simulation. However, the software offers capability to model the mathematical relationships captured in the CLD. The Appendix explains each element included in the Arena model. We have used the random number generator as well as statistical distributions offered by the Arena software.

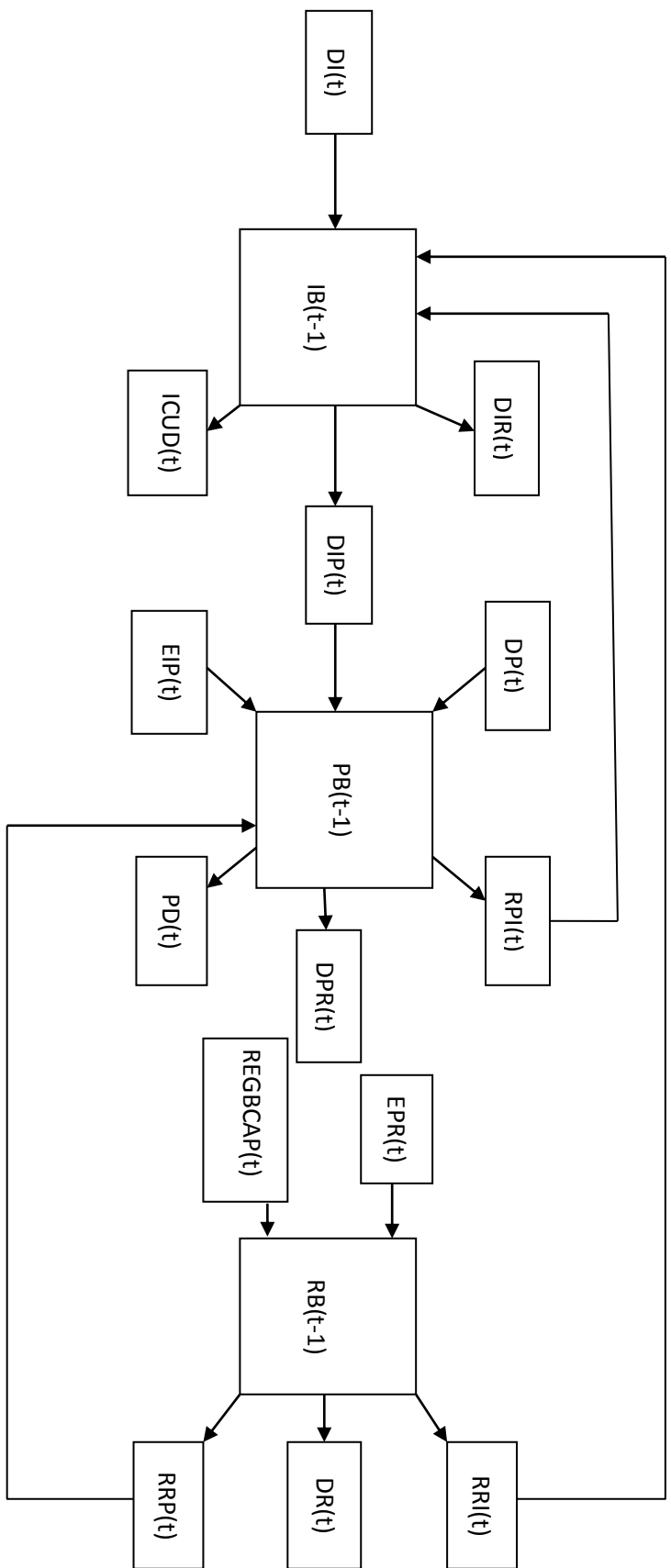


Figure 6: Flow of patients between Intensive Care Unit and two step-down units.

3.2 Equations Relating Different System Variables

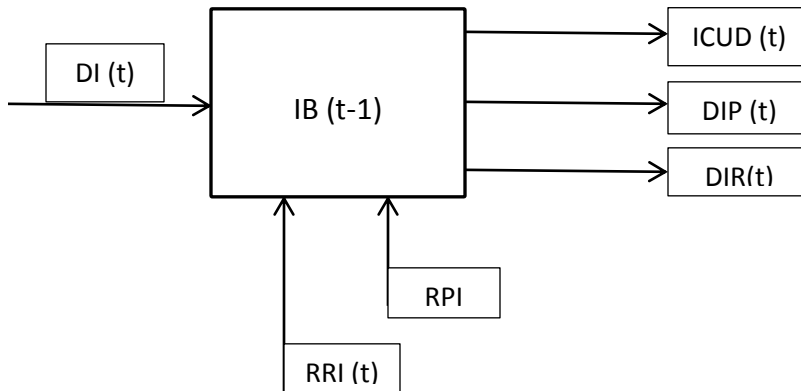


Figure 7: Intensive Care Unit Flow Diagram

$$IB(t) = IB(t-1) + DI(t) + RPI(t) + RRI(t) - ICUD(t) - DIP(t) - DIR(t)$$

$$MLOSI=4$$

$$DIP(t) = 0.7 \cdot IB(t-1) / MLOSI$$

$$DIR(t) = 0.24 \cdot IB(t-1) / MLOSI$$

$$ICUD(t) = 0.01 \cdot IB(t-1) / MLOSI$$

$$RPI(t) = 0.01 \cdot PB(t-1)$$

$$RRI(t) = 0.05 \cdot RB(t-1)$$

$$IB(t) > ICUCAP$$

$$EIP(t) = IB(t) - ICUCAP$$

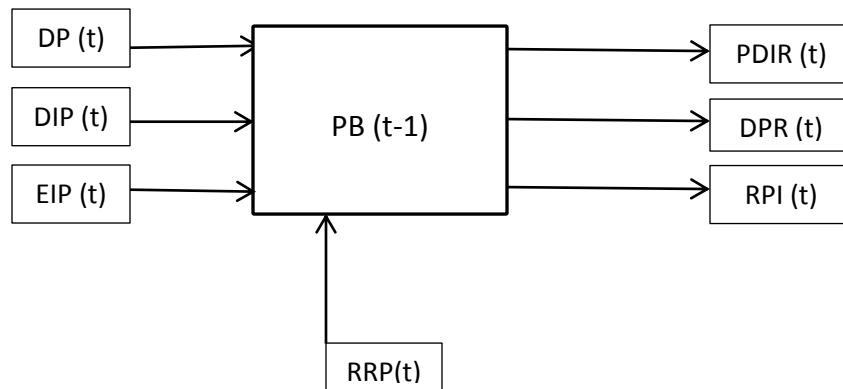


Figure 8: Progressive Care Unit Flow Diagram

$$PB(t) = PB(t-1) + DP(t) + DIP(t) + EIP(t) + RRP(t) - PDIR(t) - DPR(t) - RPI(t)$$

$$MLOSP=3.1$$

$$PDIR(t) = 0.05 * PB(t-1) / MLOSP$$

$$DPR(t) = 0.95 * PB(t-1) / MLOSP$$

$$RPI(t) = 0.1 * PB(t-1)$$

$$PB(t) > PBCAP$$

$$EPR(t) = PB(t) - PBCAP$$

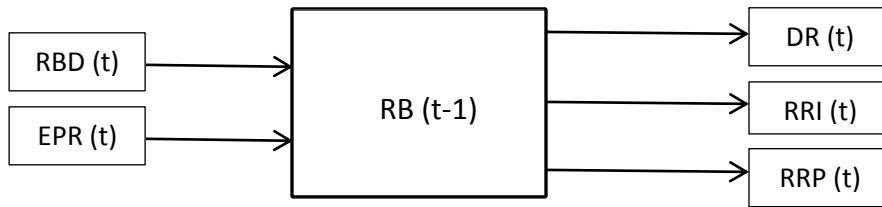


Figure 9: Regular Care Unit Flow Diagram

$$RB(t) = RB(t-1) + EPR(t) - DR(t) - RRI(t) - RRP(t)$$

$$MLOSR=3.4$$

$$DR(t) = RB(t-1) / MLOSR$$

$$RRI(t) = 0.05 * RB(t-1)$$

$$RRP(t) = 0.1 * RB(t-1)$$

4. MODEL RESULTS, GRAPHS AND TABLES

The Arena model is run for different number of days and demand rates to compare system behavior under different operating conditions. Table 1 presents the results from SD mode, with run lengths of 100, 150, 200, and 250 and 300 days respectively. Data from Table1 show small increase in both average backup ICU queue length as well as required average regular bed capacity. However, data from table 2 show significant increase in both backup queue length at the ICU and capacity of regular bed unit. The results indicate that there will be considerable blocking in the ICU area leading to longer wait time as well as potential for ambulance diversion. Every hospital aims at avoiding this condition that because it leads to patient dissatisfaction as well negative publicity for the hospital.

Table 1: SD model results for average and maximum ICU queue length and number of Regular bed needed.

Number of days	Avg Backup (Queue of ICU)	Max Backup (Queue of ICU)	Avg Regular Bed	Max Regular Bed
100	1.6271	7.0012	211.69	228.02
150	1.3584	7.0012	210.65	228.02
200	1.7958	10.778	210.92	230.03
250	2.1381	13.741	210.84	230.03
300	2.0482	13.741	210.59	230.03

Table 2: SD model results for different rate of increase in demand.

Demand Rate	Avg Backup (Queue of ICU)	Max Backup (Queue of ICU)	Avg Regular Bed	Max Regular Bed
0.50%	0	0	201.62	230.26
1%	6.036	85.847	208.66	247.12
1.50%	52.947	482.88	214.15	260.53
2%	137.5	1036.9	219.32	275.57

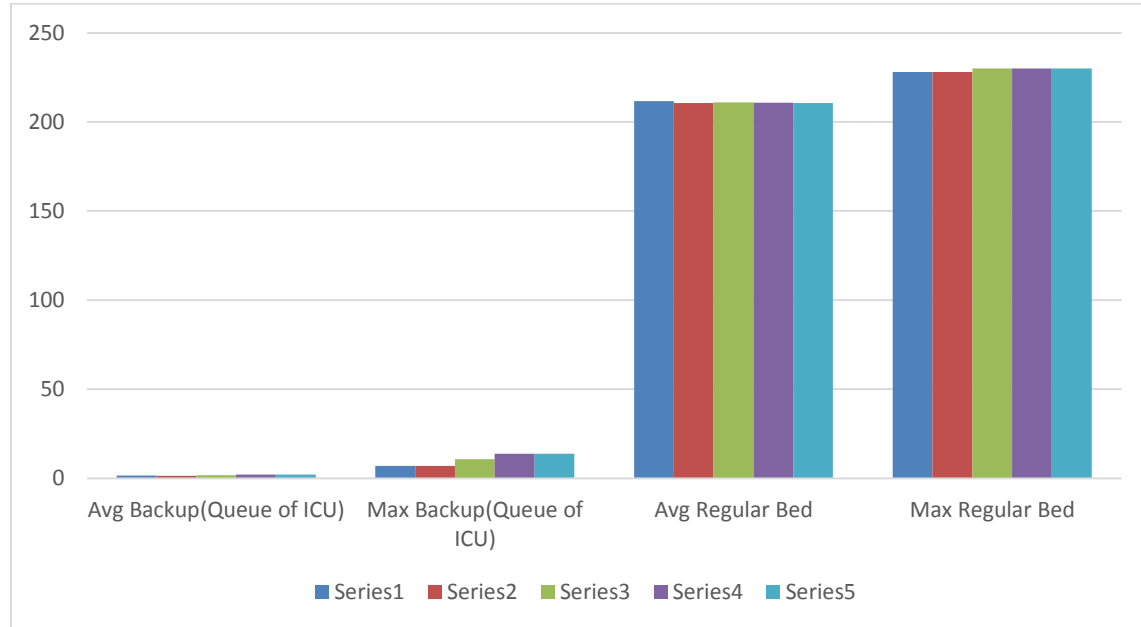


Figure 10: Graphical representation of results vs. run length

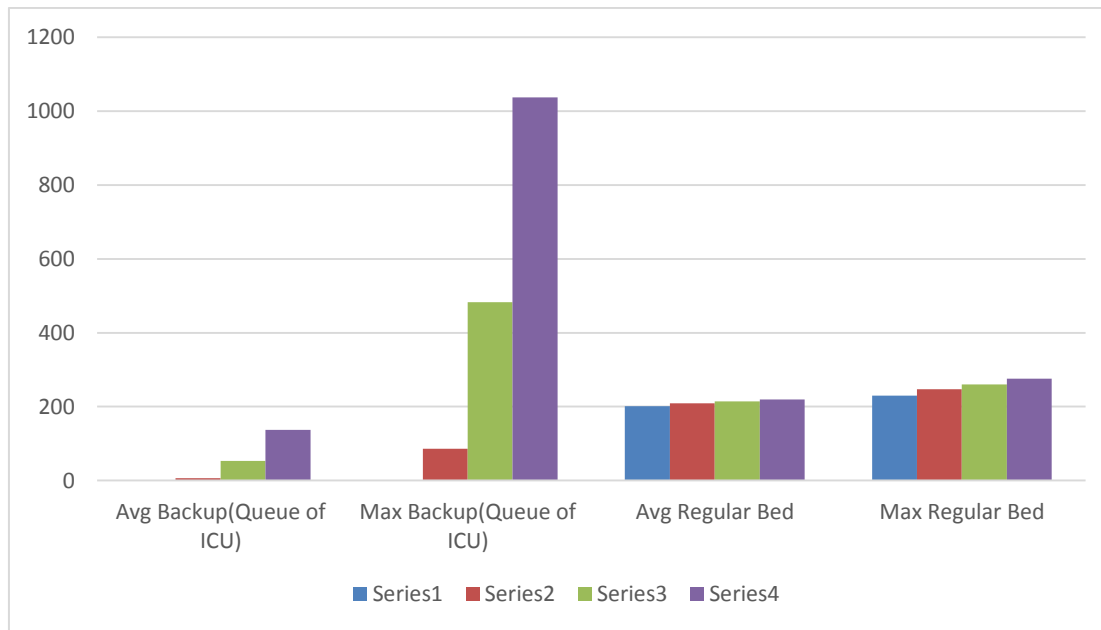


Figure 11: Changes on performance measures resulted from increase in demand

5 CONCLUSION AND FUTURE RESEARCH

This paper presents a System Dynamics model that captures the inter-relationships of a number of elements that affect the flow of patients through step-down units in a hospital. ICU, Progressive-bed unit and Regular-bed unit are considered in this study. Daily demand for beds in different units is the only random variable included in the model. All other elements represent average system behavior. Two measures of performance used in the model are: (1) the number of patients waiting in ICU for beds because of insufficient capacity, (2) the maximum capacity used in the Regular-bed unit. The first measure of performance can be equated with the level of patient dissatisfaction and second measure indicates the potential need for future expansion in the Regular-bed unit. A realistic limit on maximum capacity of the Regular-bed unit may be used to judge the scope of potential future expansion.

The study shows how a SD model can be utilized to map the current state of a system. This study also shows how the same SD model can be used to find out how the system performance changes with increase in demand. **As expected, both measures of performance indicate lower level system performance with steady increase in demand.** Future research will study the sensitivity of the different elements included in the model. This is an ongoing research and we plan to show additional results during the presentation in the conference.

We plan to combine a SD model with a DES model in a follow-up research. The SD model determines the number of ICU beds available each day. This serves as input to a DES model that will perform more detailed analysis at the operational level. We expect that this hybrid approach to the patient flow problem will provide valuable insights by combining the benefits from both models.

APPENDIX

Nomenclature of the SD Model

DI (t) – Demand for ICU bed on t^{th} day

IB (t-1) – ICU Beds Occupied at the end of day (t-1)

ICUD () - Direct discharge from ICU

DICU () – Daily demand for ICU Bed

DIP () – Daily discharge from ICU to Progressive Bed

DIR () – Daily discharge from ICU to Regular Bed

RPI () – Daily return from Progressive Bed to ICU

RRI () – Daily return from Regular Bed to ICU

EIP () – Emergency overflow from ICU to Progressive Bed

PD () – Daily Demand for Progressive Bed

RBD () – Daily demand for Regular Bed

INITIB – Initial Number of ICU bed

INITPB- Initial Number of Progressive Bed

INITRB – Initial Number of Regular Bed

PDIR () – Daily Direct discharge for Progressive Bed

DPR () – Daily Discharge from Progressive Bed to Regular Bed

RRP () – Daily Return from Regular to Progressive Bed

DR () – Daily Direct discharge from Regular Bed

EPR () – Daily Emergency overflow from Progressive Bed to Regular Bed,

ICUCAP – ICU Bed capacity

PBCAP – Progressive Bed capacity

REGBCAP – Regular Bed capacity

MLOSI – Mean length of stay in Intensive Care Unit

MLOSP – Mean length of stay in Progressive Care Unit

MLOSR – Mean length of stay in Regular Care Unit

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Biography

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