2018 Annual INCOSE
Great Lakes Regional Conference
SYSTEMS AT THE CROSSROADS
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Systems Engineering (SE) Driven Modeling and Simulation of a Mid-Size Emergency Department Operation

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Presenters’ Bio

Hazim El-Mounayri, Ph.D.

Dr. El-Mounayri is an associate professor of Mechanical Engineering and the director of the Initiative for Product Lifecycle Innovation (IPLI) at IUPUI, which aims at advancing process and product lifecycle practice in the manufacturing, healthcare, and life sciences industries. He received his PhD in Advanced Manufacturing in 1997. His research focus and interest are in digital manufacturing and advanced product/process development. Currently, he is leading an initiative to develop a Systems driven product development (SDPD) ecosystem for promoting SDPD practice, supporting industry 4.0, and training the workforce of tomorrow. Dr. El-Mounayri has 20 years working in this field, including on applied research that aims at developing innovative digital manufacturing solutions that are rapidly transferred to industry to improve existing practice. Dr. El-Mounayri has more than 125 publications in his areas of expertise, and is a member of INCOSE, ASME, ASEE, and SME.

Rapeepan Promyoo, Ph.D., ASEP

Dr. Promyoo is a research associate at the department of Mechanical and Energy Engineering and Initiative for Product Lifecycle Innovation (IPLI) at IUPUI. She received her Ph.D. in Mechanical Engineering from Purdue University in 2016. Her research focus and interest are in advanced manufacturing, modeling and simulation, and nanotechnology. Dr. Promyoo has more than 25 publications in her areas of expertise, and is a member of INCOSE, ASME, ASQ and SME.

Business Challenges

To address industry 4.0 need to competitively develop modern products, which are increasingly becoming smart connected systems or “systems of systems”.

Complexity resulting from managing:	Complexity resulting from dealing with:
• Multiple sub-systems • Multiple design groups and multiple sites • Multiple engineering domains • Multiple disparate tools in each domain • Growth of software / electronic systems • Multiple variants and system architectures • Exploding requirements and test cases	• Subsystem interactions • System integration

To establish a MBE (Model-based Engineering) framework & simulator for the digital enterprise that can be used to demonstrate best practice in developing modern products.

To educate the next generation of engineers for industry 4.0

Current challenges/Limitations (faced by Academia)

Lack of education (curriculum/certification) for industry 4.0, including MBSE, MBE (SDPD), Digital twin, and digital thread.

MBE (SDPD) skills not clearly articulated/defined by industry

Cost of infrastructure (both hardware and software)

Limited ability to deliver graduates with the required skills to support/drive the digital transformation

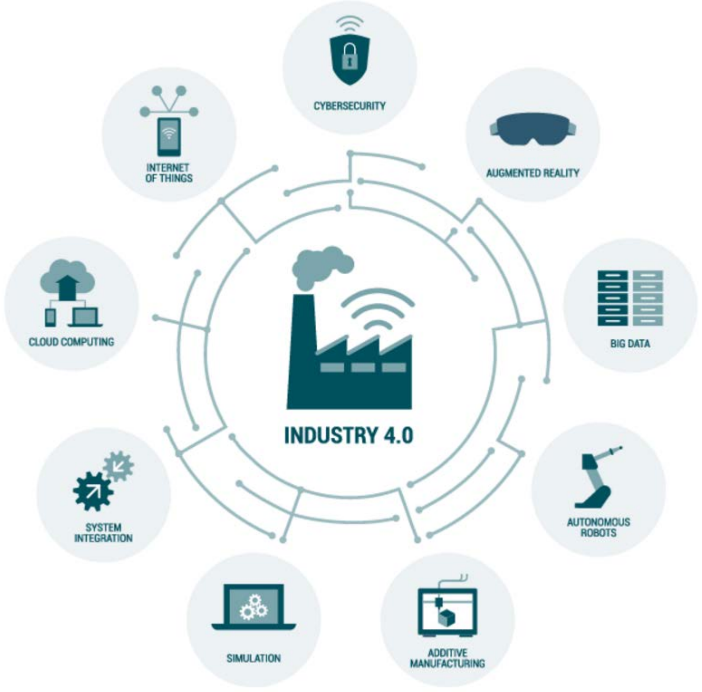
Limited ability to support the needs of industry for the digital transformation

IPLI

IUPUI

INITIATIVE FOR PRODUCT LIFE CYCLE INNOVATION

INDIANA UNIVERSITY–PURDUE UNIVERSITY Indianapolis



IPLI aim is to advance the field of product and process lifecycle and to drive innovation through an interdisciplinary team from IUPUI as well as consortium of industry, key stakeholders, national initiatives, and professional organizations.

IUPUI campus wide inter-disciplinary initiative that focuses on advancing the state of disruptive technologies of industry 4.0

Consortium to support the digital transformation and enable/facilitate the implementation of the digital enterprise

cientivegroup
No Magic
UI LABS
SIEMENS PLM SOFTWARE
SIEMENS
V4 Institute
INCOSE
R·I·T
Rockwell Automation
ICTT System Sciences
CAE-net
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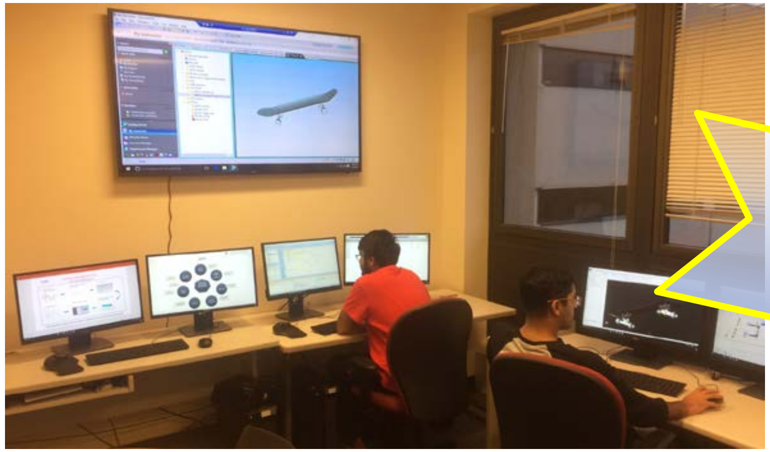
KELLEY SCHOOL OF BUSINESS

IPLI – Simulator & Infrastructure

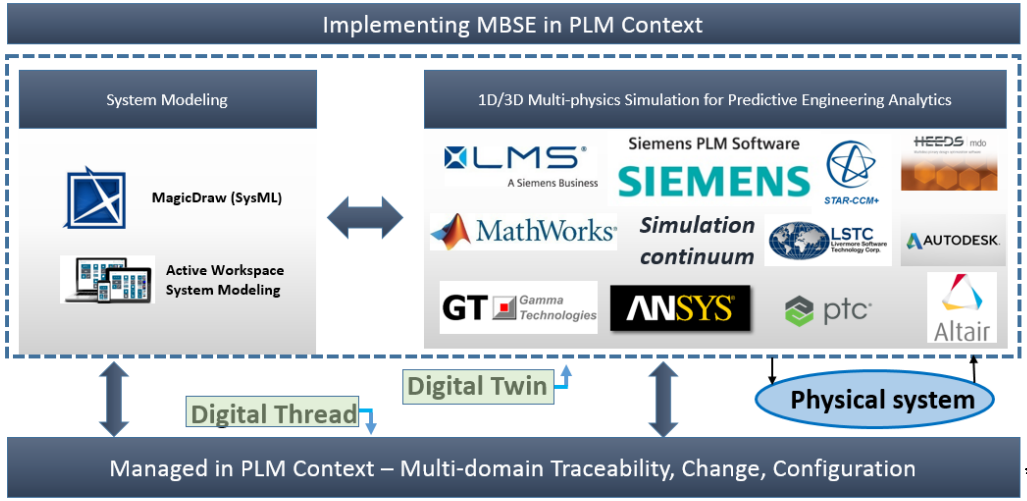


Dedicated Simulator

IPLI SDPD Simulator facility (ET 314C)

SDPD Educational facility (45 workstations)

More than 30 Software tools & 1,000's of license seats



***NoMagic/Siemens*

SDPD ecosystem (Digital twin + Digital thread)

- **Access to Simulator: Testbed, Digital twin, modeling & simulation continuum, Assessment platform.**
- **Access to State-of-the-art tools**
- **Training/Workforce development**
- **Certificate/Certification**
- **Consulting**
- **Implementation (Industry case studies)**
- **Special projects**

Outline

- Stakeholder
- Stakeholder needs
- Stakeholder Requirements
- System Decomposition
- System Architecture
- System Modeling and Simulation
- Verification and Validation
- Conclusion

Outline

- **Stakeholder**
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Stakeholder

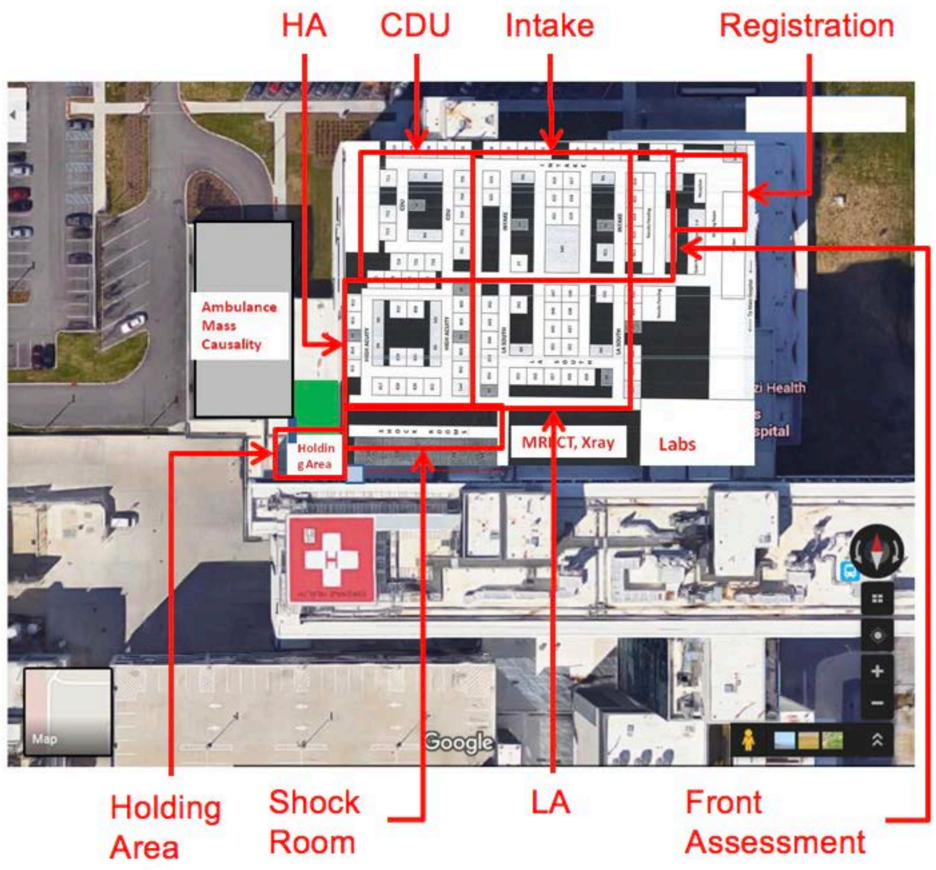
- **Michael & Susan Smith Emergency Department at Eskenazi Health, Indianapolis.**

Eskenazi ED has:

- 90 bed capacity
- 16 bed clinical decision unit (CDU)
- 30+ physicians
- 120+ nurses

ED Unit:

- Registration
- Front Assessment
- Intake
- Low Acuity (LA)
- High Acuity (HA)
- Clinical Decision Unit (CDU)
- Shock Room
- Holding Area



Outline

- Stakeholder
- **Stakeholder Needs**
- Stakeholder Requirements
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Stakeholder Needs

- Quality health care delivery
- Eliminate/minimize LWBS (Left without being seen)
- Medical staff workload that limits/eliminates potential hazards/errors
- Real time visibility into resource utilization
- *Optimum allocation of resources*
- *Below average LOS (Length of stay)*

Outline

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Stakeholder Requirements

- LWBS percent shall be less than 2%
- *Average LOS shall be decreased by 20%*
- *Average time to room shall be less than 15 minutes*
- *Average time to doctor shall be less than 30 minutes*
- *Resource utilization shall be greater than 80%*
- Hazards/errors shall be less than 0.1%
- Real time visibility of resource utilization shall be 100%

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- Stakeholder
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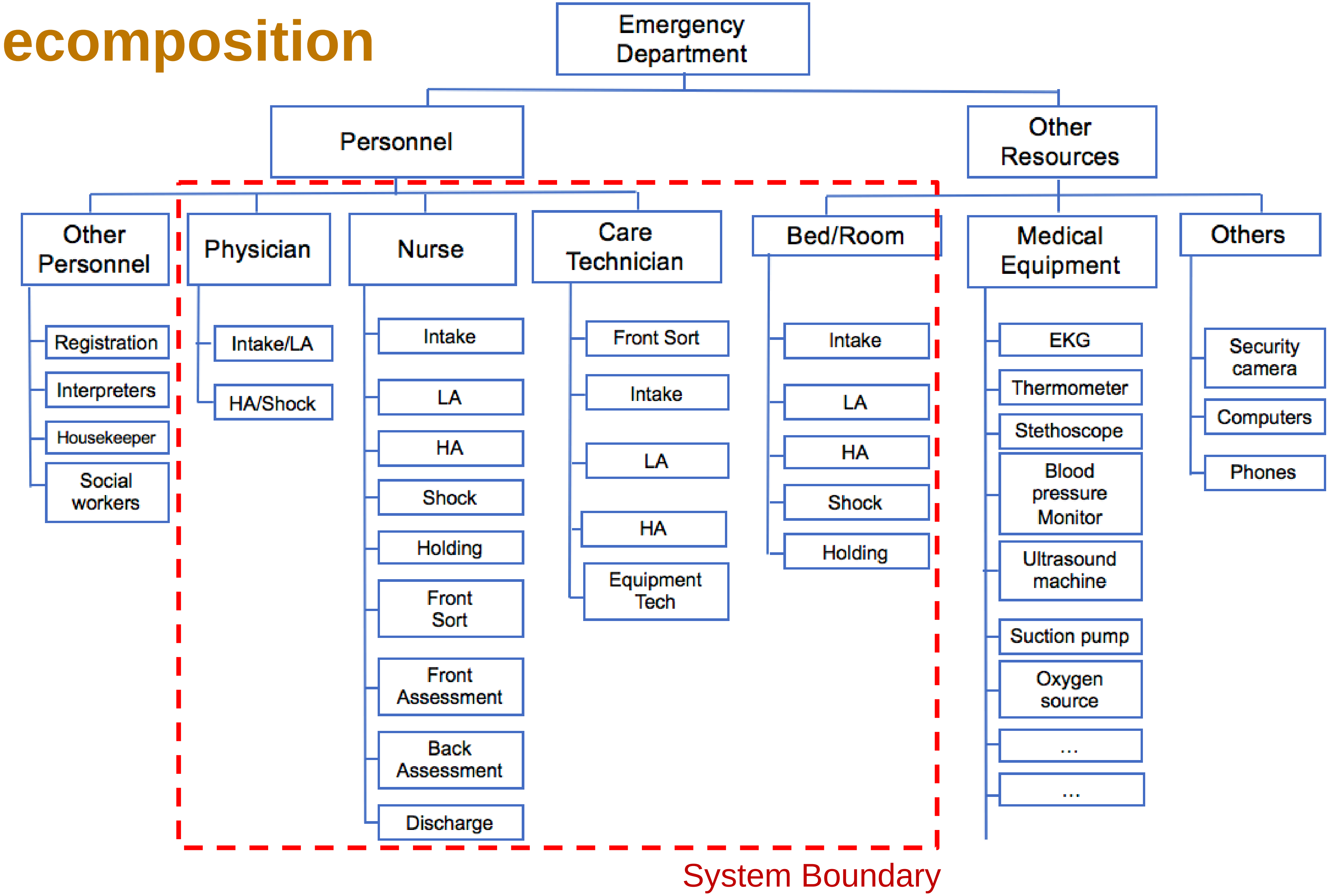
System Decomposition

ED System Decomposition



System Decomposition

ED Process Decomposition

Level 1

Level 2

- ED Task List
  - 1.Checking in
    - 1.1 Quick registration
    - 1.2 Identify life threatening conditions
    - 1.3 Full registration
  - 2. Transferring
    - 2.1 Transfer to room
    - 2.2 Transfer to Lab
    - 2.3 Transfer to Radiology
  - 3. Assessing
    - 3.1 Initial assessment
    - 3.2 Measure heart rate
    - 3.3 Measure blood pressure
    - 3.4 Measure temperature
    - 3.5 Create chief complaint
    - 3.6 Physician assessment
  - 4. Treating
    - 4.1 Order medication
    - 4.2 Provide medication
    - 4.3 Provide medical procedure
    - 4.4 Monitor patient
    - 4.5 Stabilize patient
  - 5. Discharging
    - 5.1 Approve from physician
    - 5.2 Prepare for disposition
    - 5.3 Printing report
    - 5.4 Advise patient
    - 5.5 Disposition
    - 5.6 Clean bed/room

Outline

- Stakeholder
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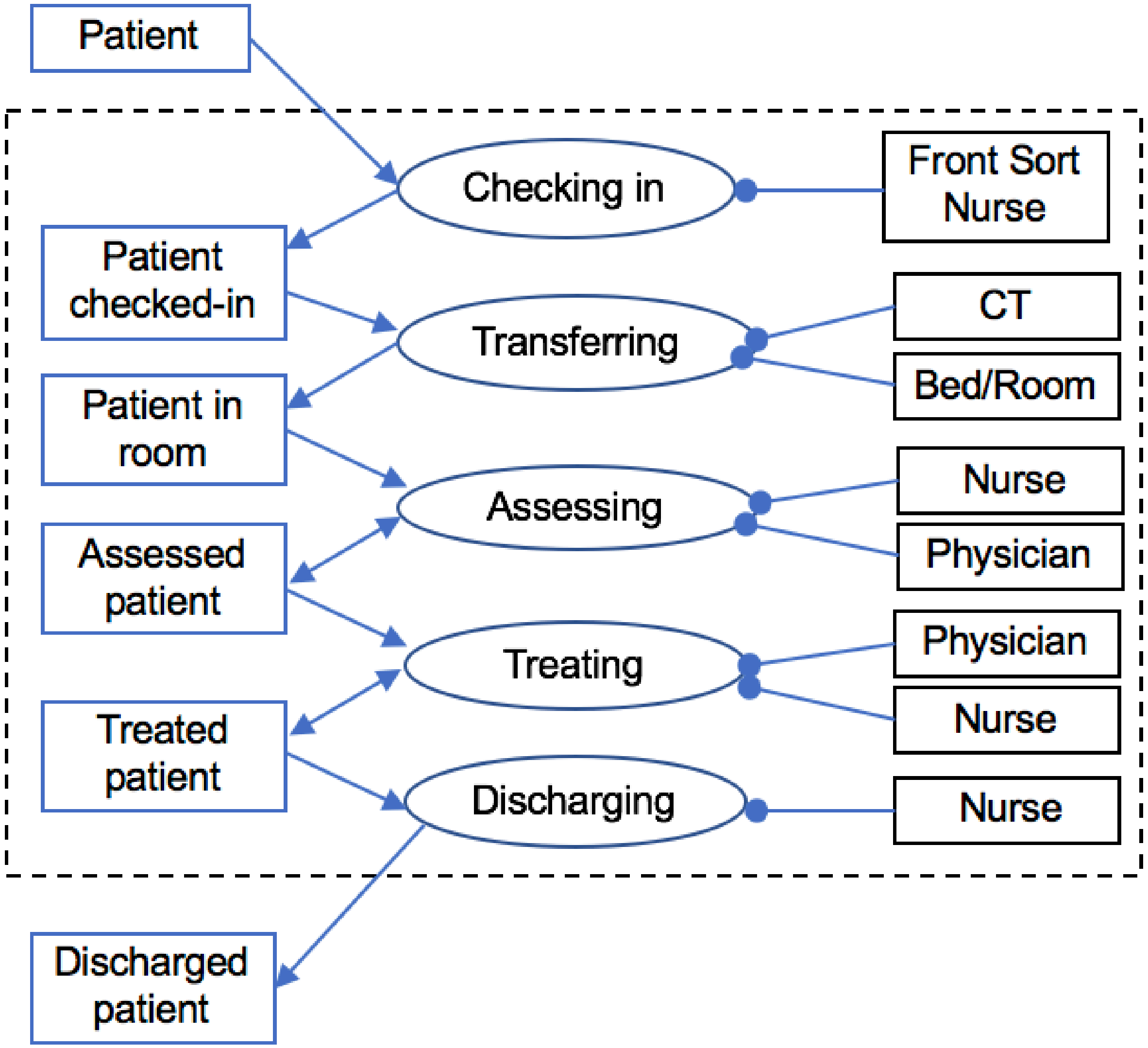
- System Decomposition
- **System Architecture**
- System Modeling and Simulation
- Verification and Validation
- Conclusion and Future Work

System Architecture

Object-Process Methodology (OPM) Diagram

Level 1 Decomposition



System Architecture

Task-Based Design Structure Matrix (DSM)

		1	2	3	4	5	6	7	8	9	10	11	12	13	1	15	16	17	18	19	20	21	22	23
1.1 Quick registration	1																							
1.2 Identify acuity	2	x																						
1.3 Full registration	3		x																					
2.1 Transfer to room	4		x														o							
2.2 Transfer to lab	5												x				o							
2.3 Transfer to radiology	6												x				o							
3.1 Initial assessment	7				x																			
3.2 Check vital signs	8				x												o							
3.3 Measure blood pressure	9				x												o							
3.4 Measure temperature	10				x												o							
3.5 Create chief complaint	11							x	x	x	x						o							
3.6 Physician assessment	12											x			o	o	o							
4.1 Order medication	13												x			o	o							
4.2 Provide medication	14													x			o							
4.3 Provide medical procedure	15													x			o							
4.4 Monitor patient	16														x	x								
4.5 Stabilize patient	17																x							
5.1 Approve from physician	18																	x						
5.2 Prepare for disposition	19																		x					
5.3 Print report	20																			x				
5.4 Advise patient	21																				x			
5.5 Disposition	22																					x		
5.6 Clean bed/room	23																						x	

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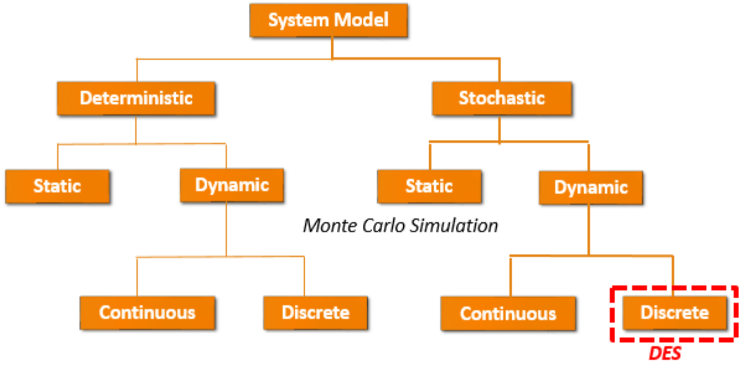
System Modeling and Simulation

Discrete Event Simulation (DES)



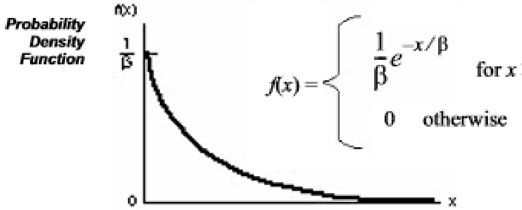
In a stochastic DES, the value associated with event is a random variable, that is its value has an associated probability. DES uses the probability theory including conditional probability as follows:

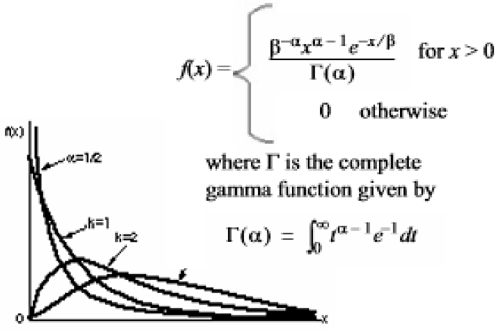
<u>DES Model Inputs:</u>

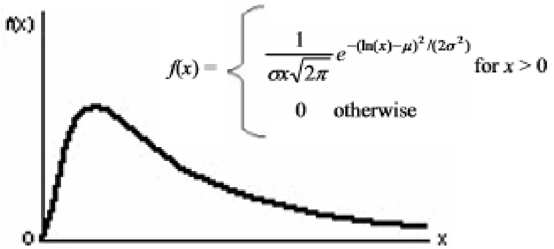
- Patients' arrival data (Probability Distribution function or Time stamp)
- Processing time and routing data data (Probability Distribution functions)
- Resources data
- Work flow

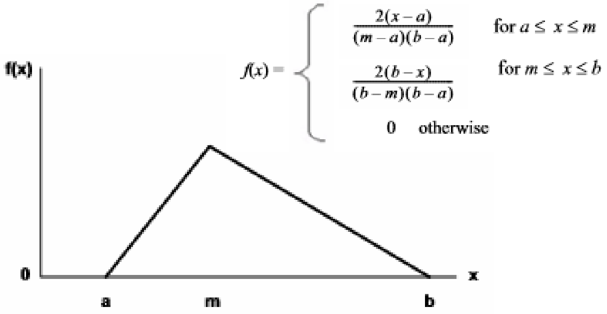
<u>Probability Distribution Types:</u>

- Exponential – Patient arrival
- Gamma – Processing time
- Lognormal – Processing time
- Triangular – Processing time



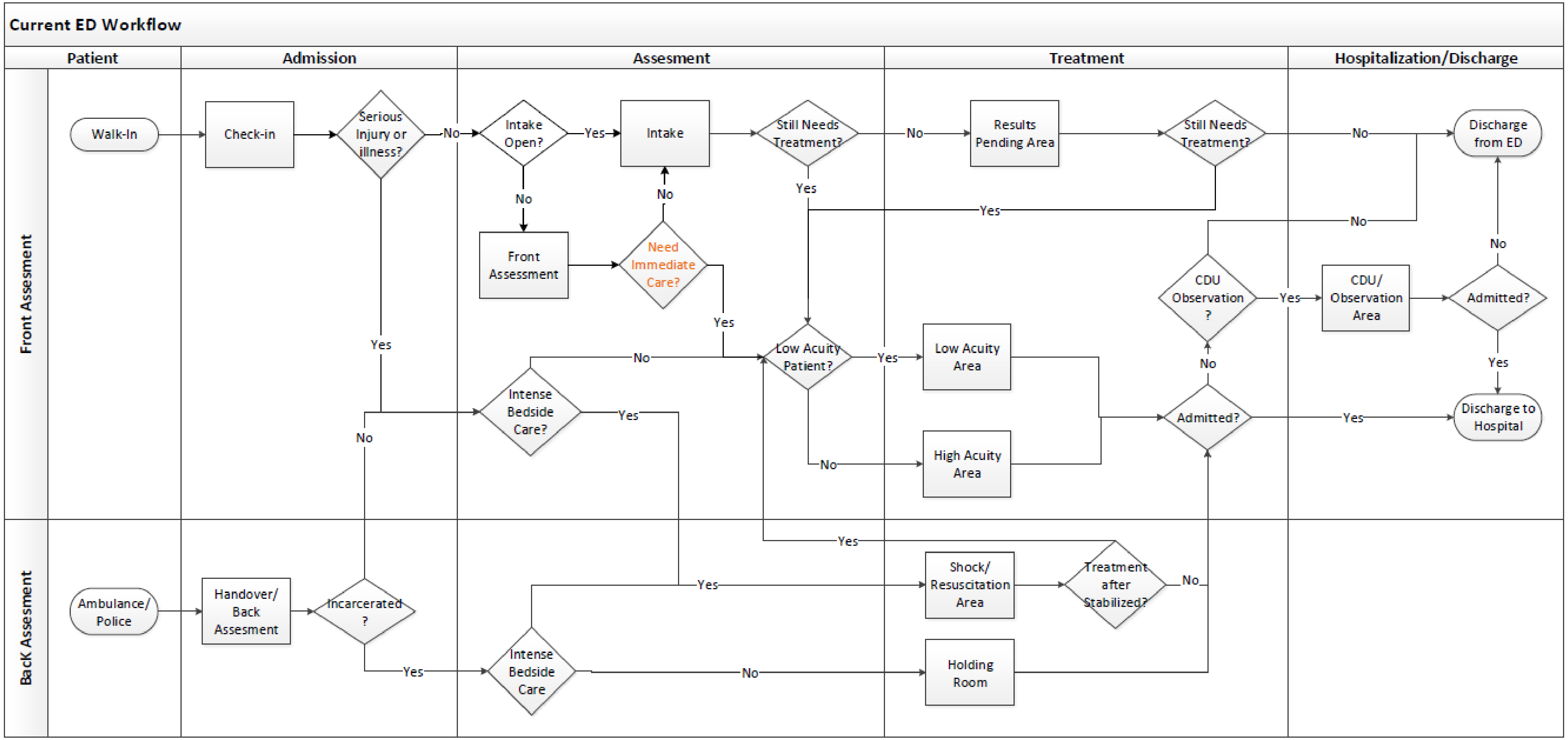






System Modeling and Simulation

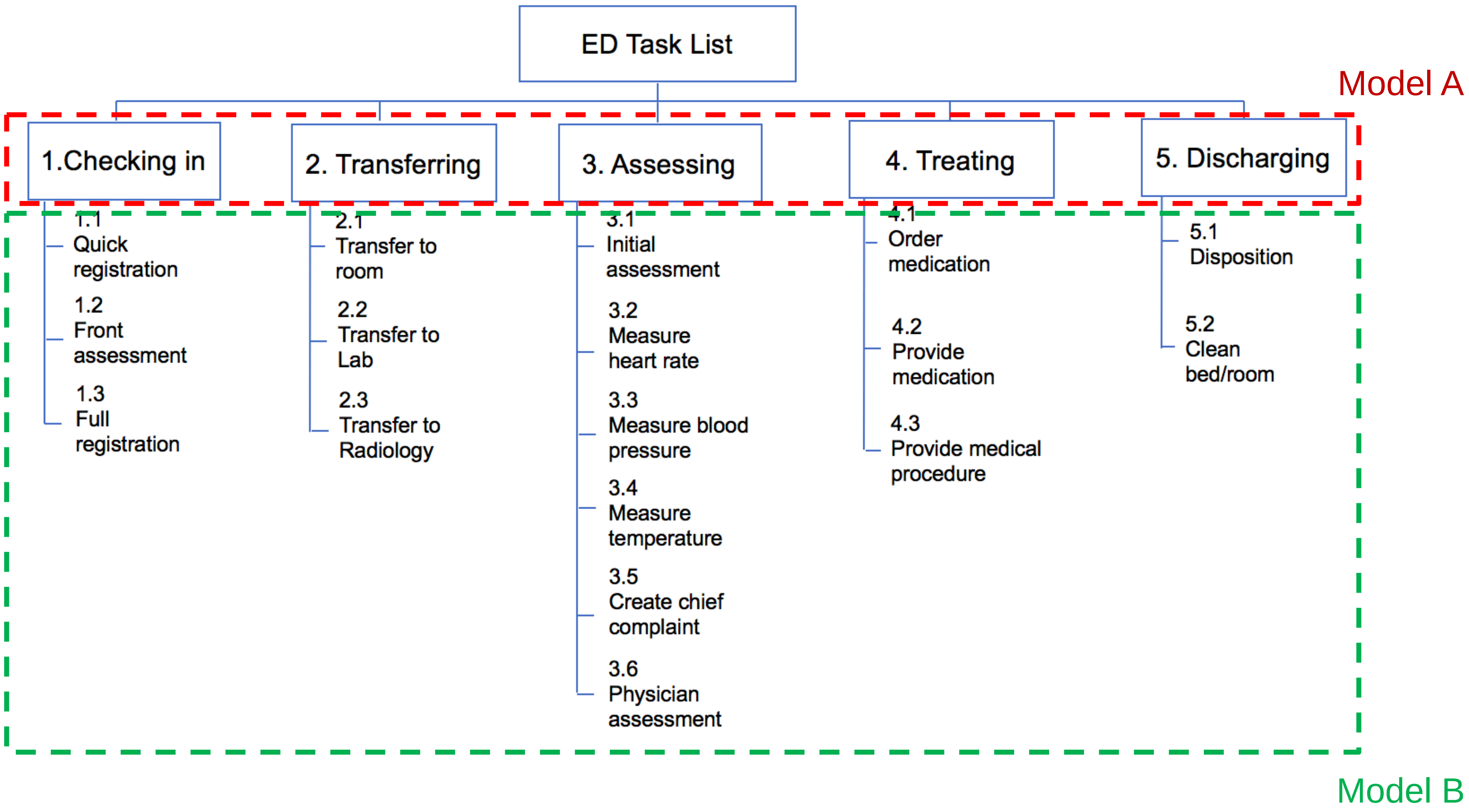
DES Model Implementation – ED Process Review



System Modeling and Simulation

DES is used to simulate the **ED process** and predict the key performance outcomes. Two simulation models were implemented:

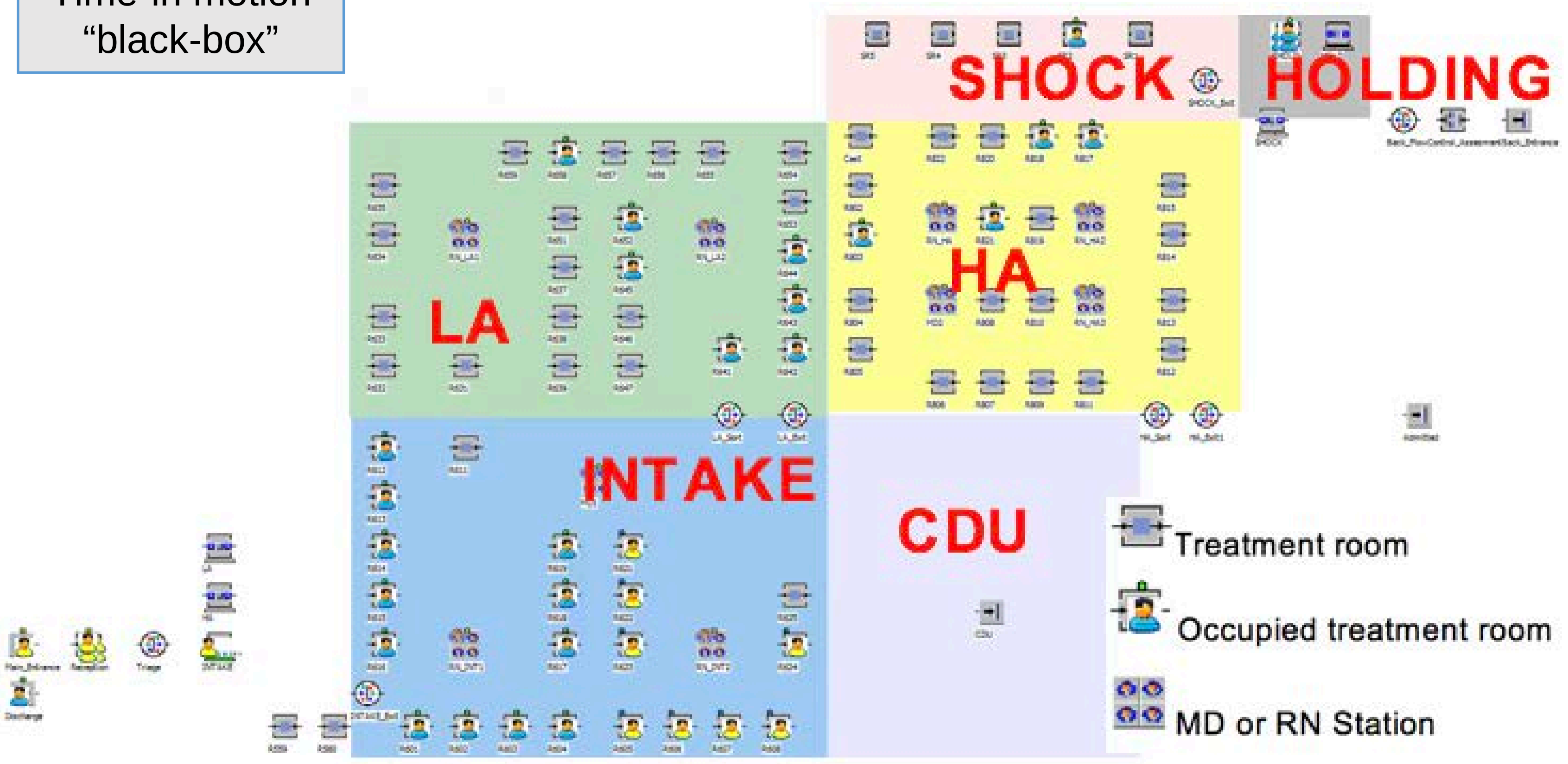
- Model A: Models the ED process at the “black box” level. Used to estimate the high-level patient and room utilization data
- Model B: Models the interactions between patients and clinicians at the treatment units. Used to estimate human resource utilization rates and perform trade analysis



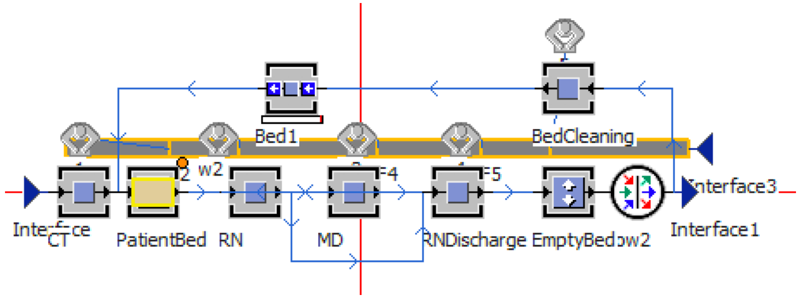
System Modeling and Simulation

DES Model Implementation – ED Process Review

Model A
Time-in motion
"black-box"



Model B
Capturing
more details
inside each
treatment
room



System Modeling and Simulation

Model Input

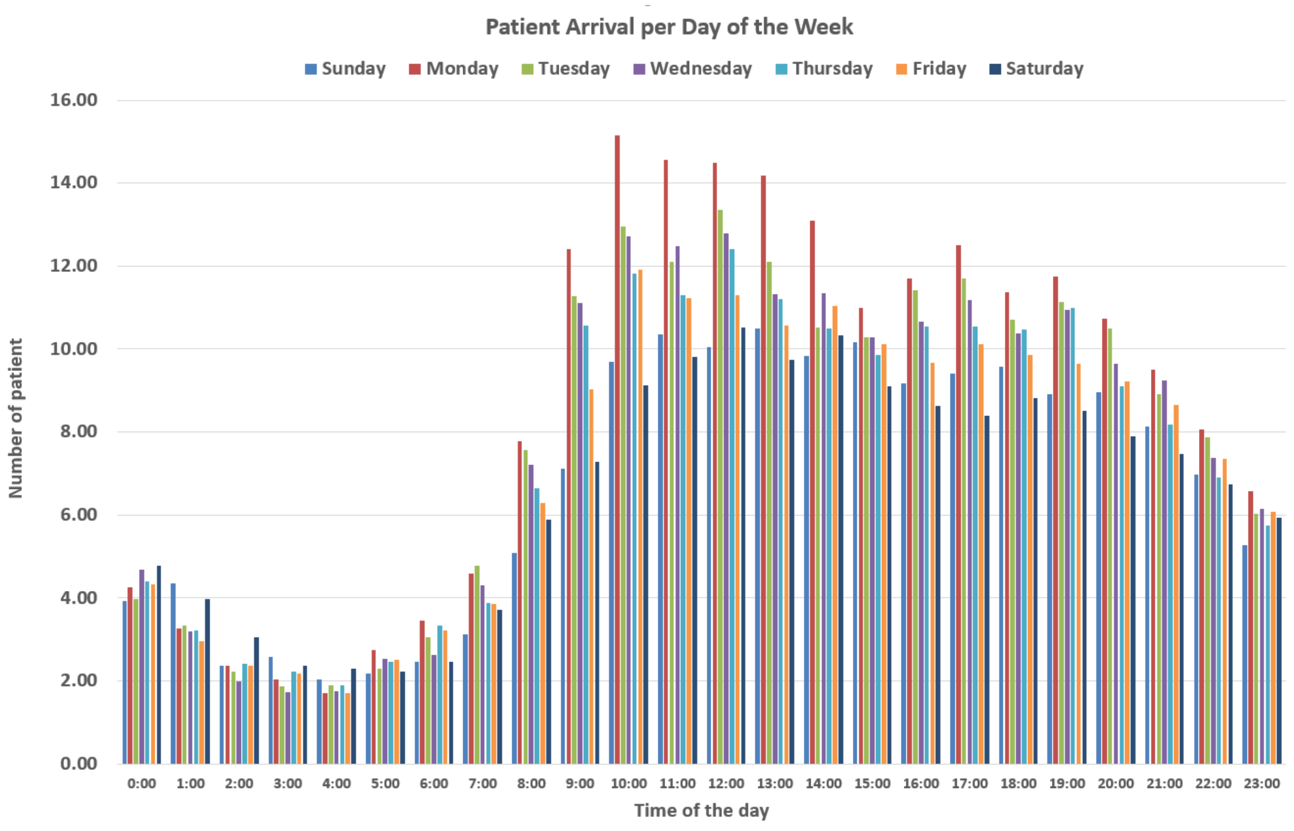
Input	Source
Arrival data	EMR System
Processing time (registration)	Observation
Processing time (Intake, LA, HA, Shock)	Observation
Processing time (Holding unit)	EMR System
Room assignment	EMR System
Number of patients rooms	Nursing Charts and ED Input
CT shifts and schedules	Nursing and CT grid
RN shifts and schedules	Nursing and CT grid
MD shifts and schedules	Physicians' grid

Observation Data Collection

- Duration: over 45 days
- ED Units observed: Registration, Intake, LA, HA and Shock room.
- Data collected for a total of 126 patients

System Modeling and Simulation

Input Data



	string 0	real 1	real 2	boolean 3	real 4	real 5	boolean 6	real 7	real 8	boolean 9	real 10	real 11	real 12	string 13	string 14	string 15
string	Distribution	Chi statistic	Chi value	Result Chi	KS statistic	KS value	Result KS	AD statistic	AD value	Result AD	Parameter1	Parameter2	Parameter3	Parameter 1	Parameter 2	Parameter 3
1	Normal	7.1470	16.9175	true	0.9111	1.3580	true	1.0437	2.4920	true	23.055178...	11.049021...		Mu = 23	Sigma = 11	
2	Logistic	9.8571	16.9175	true	0.6296	1.3580	true	0.7899	2.4920	true	23.055178...	11.082052...		Mu = 23	Sigma = 11	
3	Erlang	13.1778	15.5051	true	0.9410	1.3580	true	1.3015	2.4920	true	23.835844...	11.917922...		Mu = 24	Sigma = 12	
4	Paralogistic	13.7143	16.9175	true	0.9593	1.3580	true	1.0174	2.4920	true	2.7768069...	33.910731...		Alpha = 2.8	Theta = 34	
5	Laplace	15.4286	16.9175	true	0.7825	1.3580	true	0.9583	2.4920	true	22.585	12.049857...		Mu = 23	Sigma = 12	
6	Gamma	16.3346	15.5051	false	1.1345	1.3580	true	1.3295	2.4920	true	3.8689930...	5.9589610...		Alpha = 3.9	Beta = 6	
7	Weibull	17.8571	16.9175	false	0.7841	1.3580	true	0.6945	2.4920	true	2.2026518...	26.043004...		Alpha = 2.2	Beta = 26	
8	Lognorm	30.9183	15.5051	false	1.5356	1.3580	false	3.1074	2.4920	false	23.559077...	14.276204...		Mu = 24	Sigma = 14	
9	Triangle	34.0000	15.5051	false	2.2635	1.3580	false	12.8037	2.4920	false	18.77	3.79	58.03	c = 19	a = 3.8	b = 58
10	Loglogistic	37.5714	16.9175	false	1.3560	1.3580	true	5.5111	2.4920	false	21.026894...	4.2658110...		Alpha = 21	Beta = 4.3	
11	Cauchy	72.2759	15.5051	false	2.5290	1.3580	false	11.0575	2.4920	false	18.77	6.97		Mu = 19	Theta = 7	
12	Frechet	85.8571	16.9175	false	13.0900	1.3580	false	674.3242	2.4920	false	3.6786244...	18.361898...		Alpha = 3.7	Theta = 18	
13	Uniform	90.7143	16.9175	false	4.3971	1.3580	false	27.5282	2.4920	false	3.79	58.03		Start = 3.8	Stop = 58	
14	Negexp	121.0000	18.3061	false	3.2718	1.3580	false	20.8361	2.4920	false	23.055178...			Beta = 23		
15	Pareto	133.4286	16.9175	false	3.3570	1.3580	false	43.4194	2.4920	false	1.4159910...	9.9578733...		Alpha = 1.4	Theta = 10	
16	Gumbel	1000.0000			1.1177	1.3580	true	1.5636	2.4920	true	23.055178...	11.082052...		Mu = 23	Sigma = 11	

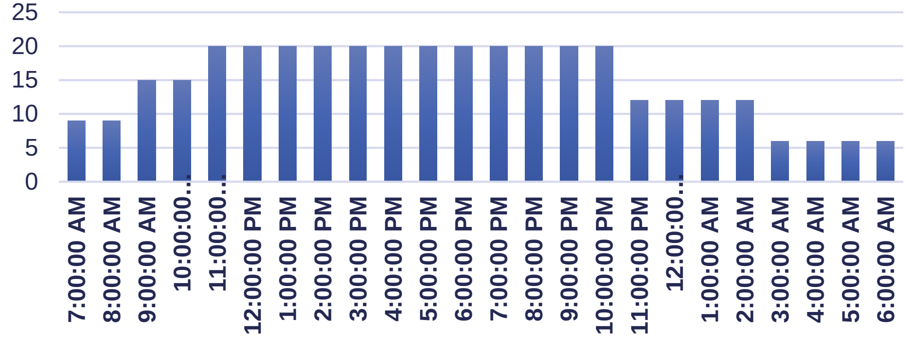
Input	Value
Patient Processing Times Inside Each Unit	
Intake	Gamma (alpha = 4.86, beta = 19:17.31)
LA	Gamma (alpha = 3.47, beta = 37:37.7)
HA	Gamma (alpha = 7.17, beta = 22:35.77)
Shock	Gamma (alpha = 2.19, beta = 43:30.6)
Check-in	Constant (10:00, 5:00, 1:00, 1:00, 1:00)
Holding	Log-norm (alpha = 22138.06, beta = 961.98)

System Modeling and Simulation

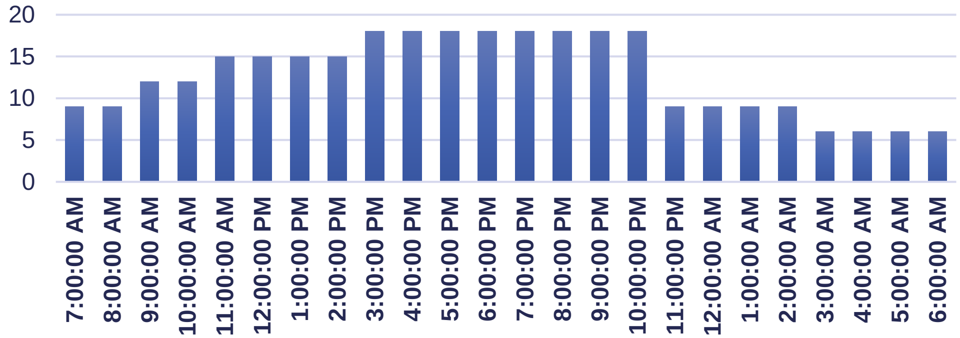
Input Data Analysis - Resource Availability

Rooms Availability

Number of available rooms
(Monday - Friday)

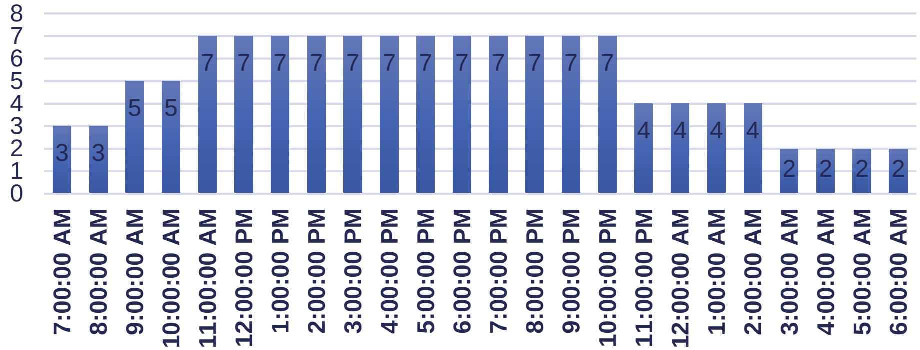


Number of available rooms
(Saturday & Sunday)

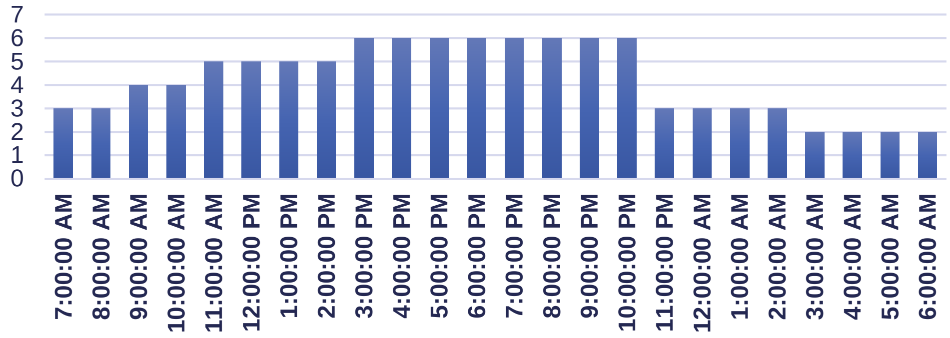


Nurses Availability

Number of available nurses
(Monday - Friday)



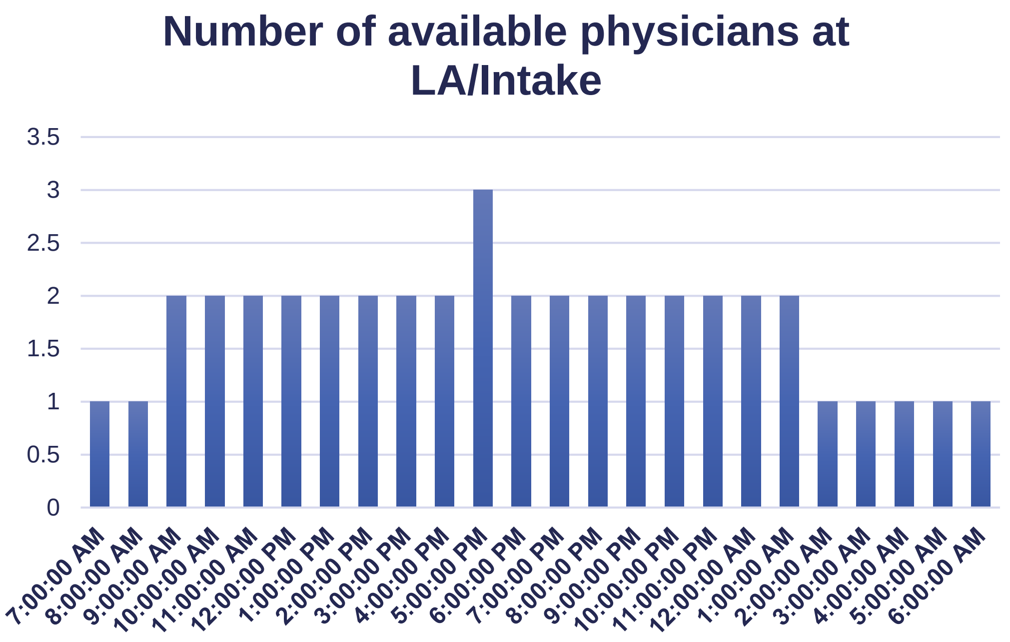
Number of available nurses
(Saturday & Sunday)

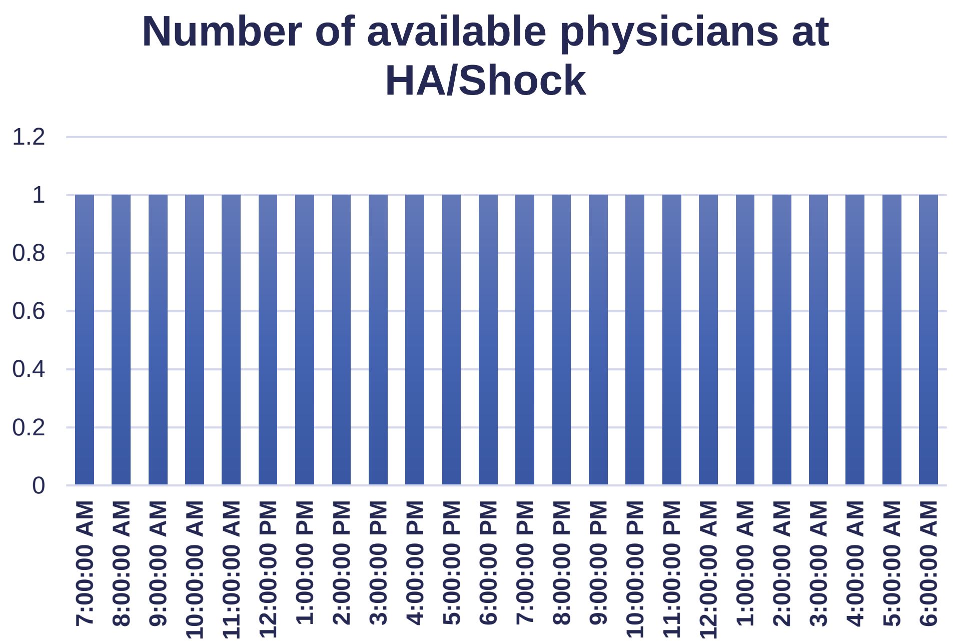


System Modeling and Simulation

Input Data Analysis - Resource Availability

Physicians Availability





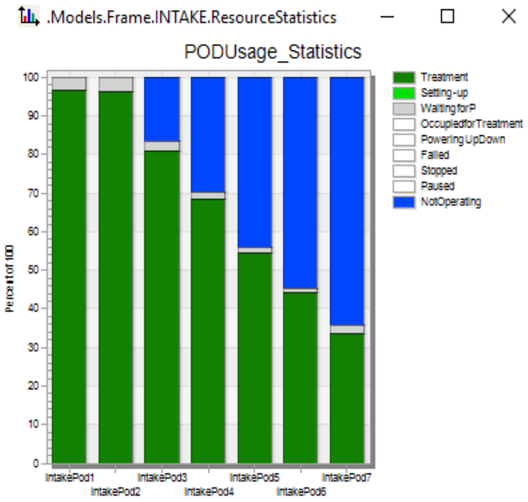
Data is based on February 2017 Physicians Assignment

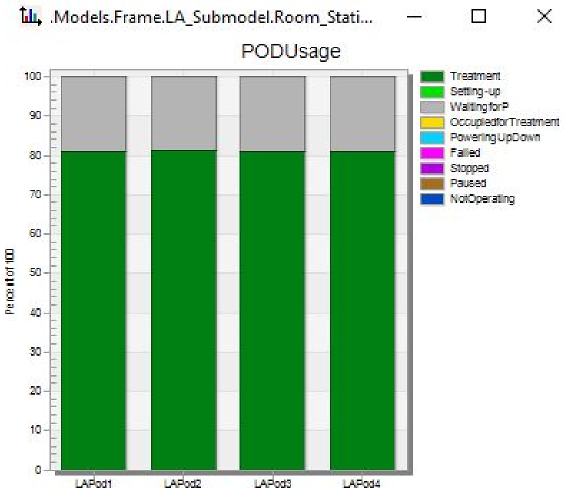
System Modeling and Simulation

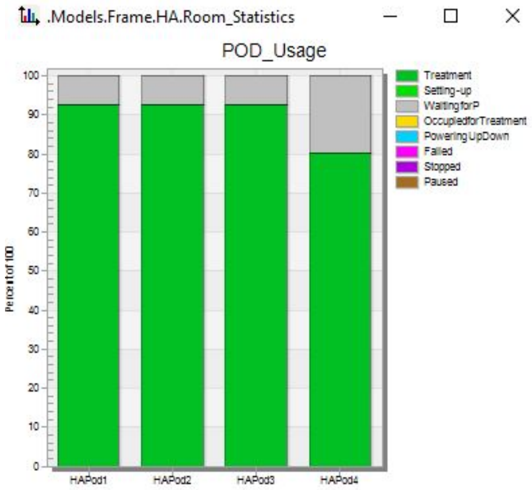
Model Output

- Patient Throughput.
- Average LOS.
- LOS for different days of the week and different times of the day.
- LOS for each discharged patient.
- Time to room.
- Time to doctor.
- Room utilization.
- Room idle time.
- Human resource utilization.

Model A Results – Room Utilization







Intake

Patient occupancy = 67.71%
Non-operating time = 29.92%
Idle time = 2.36%
Pod to room ratio = 1/3

LA

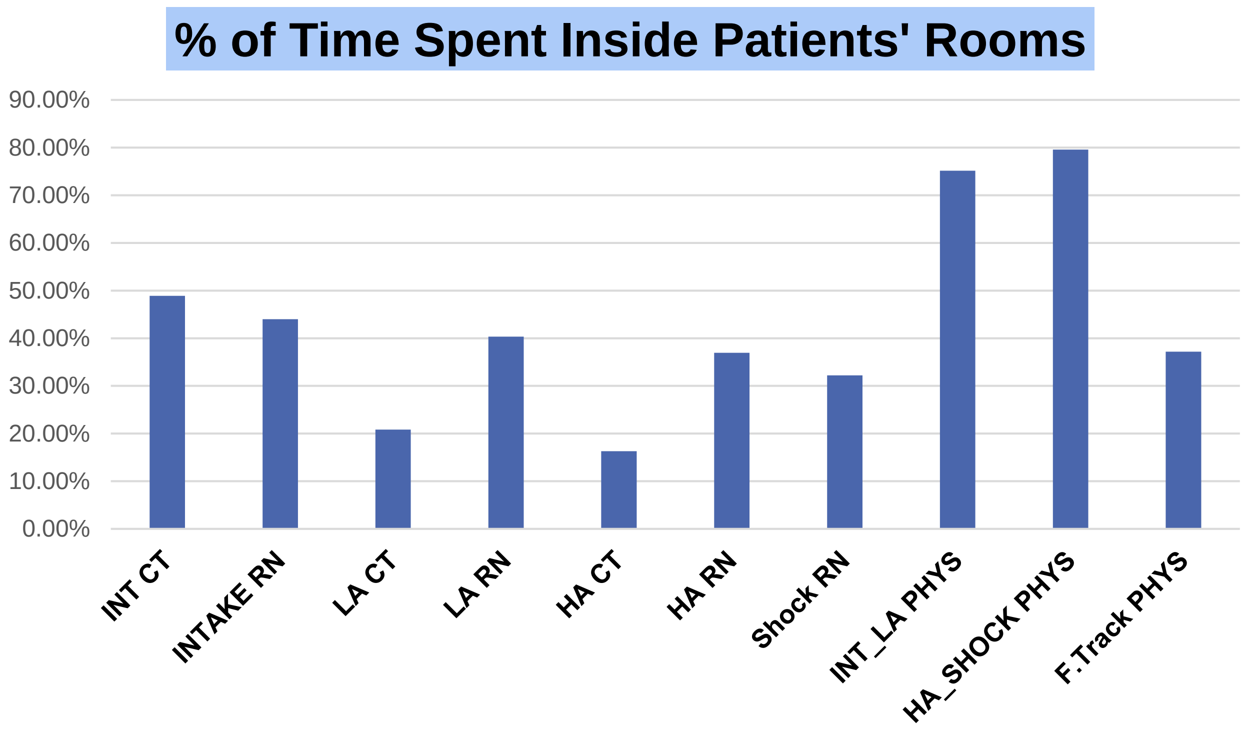
Patient occupancy = 79.64%
Non-operating time = 0%
Idle time = 20.36%
Pod to room ratio = 1/6

HA

Patient occupancy = 84.44%
Non-operating time = 4.17%
Idle time = 11.39%
Pod to room ratio = 1/4

Model B Results – Human Resources Utilization

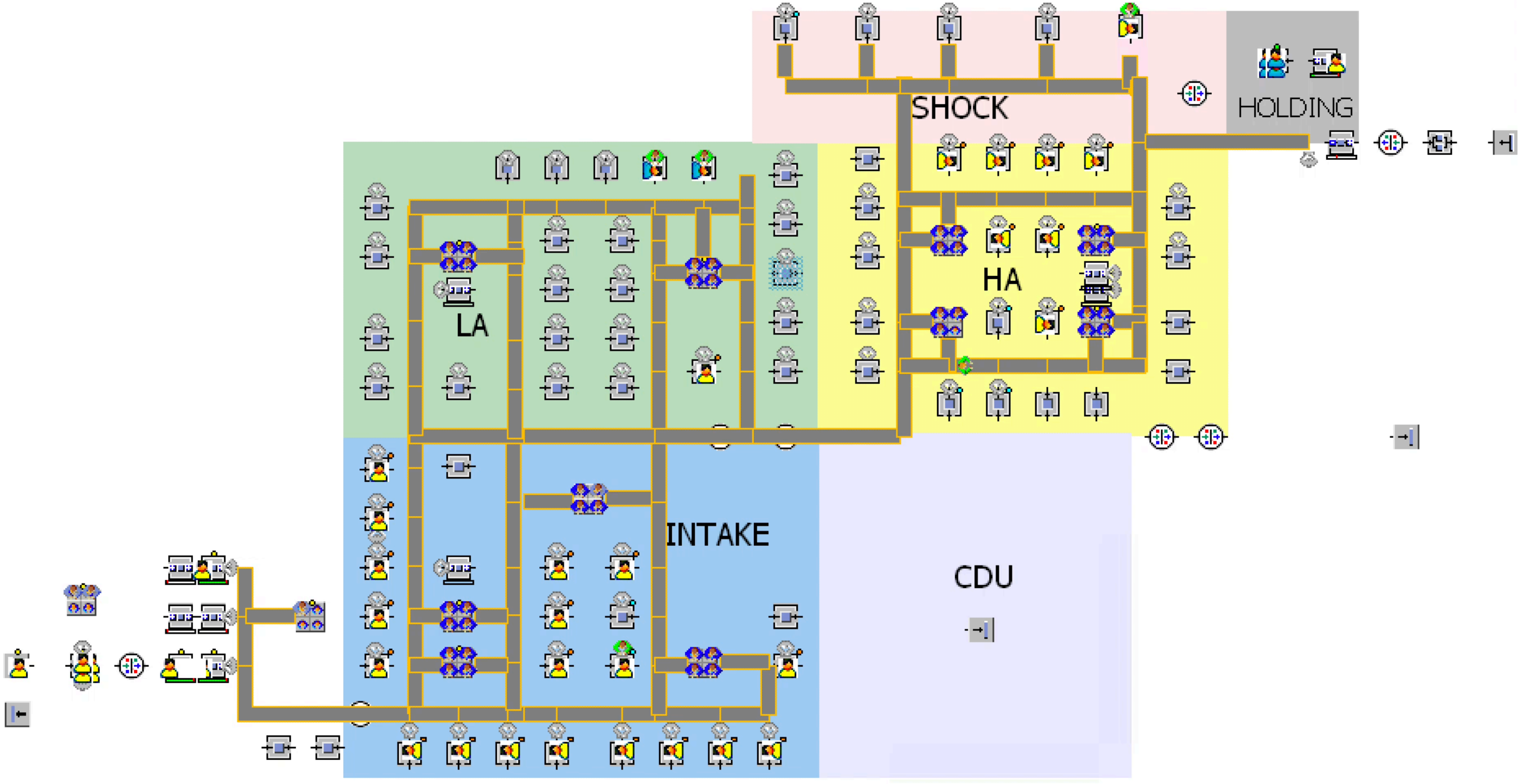
HR	Utilization Rate (Inside Patients' Rooms)
INT CT	48.9%
INTAKE RN	44.01%
LA CT	20.82%
LA RN	40.35%
HA CT	16.31%
HA RN	36.94%
Shock RN	32.23%
INT_LA PHYS	75.16%
HA_SHOCK PHYS	79.59%
F. Track PHYS	37.18%



System Modeling and Simulation

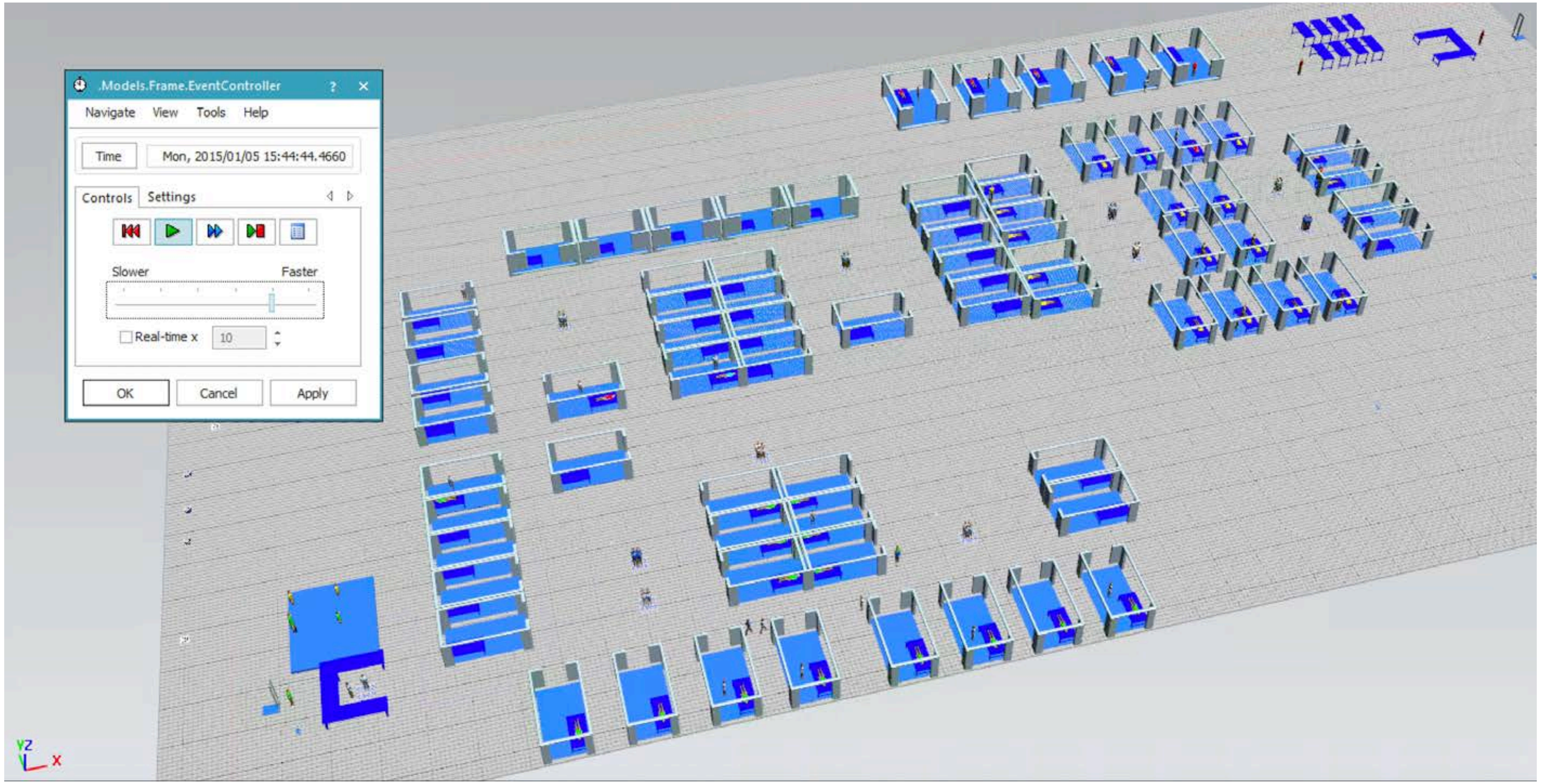
Model Animation

Tecnomatix 2D Simulation



System Modeling and Simulation
Model Animation

Tecnomatix 3D Simulation



3D simulation shows the flow process at treatment units. The care technician guides the patient to his room, then the nurse and the physician serve the patient inside his room

Design of Experiments Approach for Resource Allocation Optimization

Objective: To minimize the average LOS, Time to room, Time to doctor by optimizing resource allocation using two different methods:

1. Optimization of existing ED resource (added cost = 0).

2. Allocating more staff to the ED.

Design Variables:

1. Human Resources Availability and Shifts
2. Allocation of ED rooms.

Constraints:

- Addional Staffing Budget shall be <= $1,000,000 (based on ED Estimation)
- Improvement in performance measures shall be => 10% of the current
- Patients’ LOS shall not be less than two hours to retain its clinical value

What If Scenarios – Senstivity on HA/Shock Physicians

Exp. No.	Added HRs	Added Cost
1 (Current State)	0	0
2	+1 physician	$240,000
3	+2 physicians	$480,000
4	+3 physicians	$720,000
5	+4 physicians	$960,000
6	+5 physicians	$1,200,000

- **Statistics of output values**

The ExperimentManager does not execute the variance analysis if you entered more than 50 experiments.
You can view the p-values for all pairs of experiments by selecting *Tools > Analysis of Variance* in the dialog of the ExperimentManager.

Output value *Patients Average LOS*

	Mean value	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	3:42:51.2744	55.4423	3:41:28.9672	3:43:49.9383	3:41:42.1712	3:44:00.3776
Exp 2	3:17:41.4816	28.4625	3:17:13.3516	3:18:14.7905	3:17:06.0060	3:18:16.9572
Exp 3	3:12:34.5362	11.9432	3:12:15.9410	3:12:47.6492	3:12:19.6502	3:12:49.4222
Exp 4	3:10:45.7982	16.5133	3:10:28.7441	3:11:07.5165	3:10:25.2161	3:11:06.3803
Exp 5	3:10:23.6310	17.0655	3:10:00.6991	3:10:43.1016	3:10:02.3607	3:10:44.9014
Exp 6	3:10:06.0997	15.5990	3:09:46.4497	3:10:24.0829	3:09:46.6571	3:10:25.5422

What If Scenarios – Senstivity on Intake/LA Physicians

Exp. No.	Added HRs	Added Cost
1 (Current State)	0	0
2	+1 physician	$240,000
3	+2 physicians	$480,000
4	+3 physicians	$720,000
5	+4 physicians	$960,000
6	+5 physicians	$1,200,000

- **Statistics of output values**

The ExperimentManager does not execute the variance analysis if you entered more than 50 experiments.
You can view the p-values for all pairs of experiments by selecting *Tools > Analysis of Variance* in the dialog of the ExperimentManager.

Output value *Average Patient LOS*

	Mean value	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	3:43:34.4524	1:05.0363	3:41:52.3807	3:44:47.0331	3:42:13.3913	3:44:55.5135
Exp 2	3:23:22.7185	58.4716	3:22:31.0219	3:24:59.5442	3:22:09.8396	3:24:35.5974
Exp 3	3:17:17.3577	1:20.3680	3:15:15.3782	3:18:39.1329	3:15:37.1872	3:18:57.5281
Exp 4	3:06:38.8923	25.2148	3:06:19.4052	3:07:21.4689	3:06:07.4646	3:07:10.3200
Exp 5	2:52:39.6154	36.8939	2:52:04.8010	2:53:38.1918	2:51:53.6310	2:53:25.5999
Exp 6	2:51:58.2653	33.2121	2:51:21.7695	2:52:43.6553	2:51:16.8698	2:52:39.6607

What If Scenarios – Combination

Optimum Scenario
Cost: $960,000
% Improvement in LOS: 25.5%

- **Statistics of output values**

The ExperimentManager does not execute the variance analysis if you entered more than 50 experiments.
You can view the p-values for all pairs of experiments by selecting *Tools > Analysis of Variance* in the dialog of the ExperimentManager.

Output value *Average Patient LOS*

	Mean value	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	3:43:34.4524	1:05.0363	3:41:52.3807	3:44:47.0331	3:42:13.3913	3:44:55.5135
Exp 2	3:23:22.7185	58.4716	3:22:31.0219	3:24:59.5442	3:22:09.8396	3:24:35.5974
Exp 3	3:17:17.3577	1:20.3680	3:15:15.3782	3:18:39.1329	3:15:37.1872	3:18:57.5281
Exp 4	3:06:38.8923	25.2148	3:06:19.4052	3:07:21.4689	3:06:07.4646	3:07:10.3200
Exp 5	2:52:39.6154	36.8939	2:52:04.8010	2:53:38.1918	2:51:53.6310	2:53:25.5999
Exp 6	2:51:58.2653	33.2121	2:51:21.7695	2:52:43.6553	2:51:16.8698	2:52:39.6607

Outline

- Stakeholder
- Stakeholder needs
- Stakeholder Requirements
- System Decomposition
- System Architecture
- System Modeling and Simulation
- **Verification and Validation**
- Conclusion

System Verification and Validation

Verification

Model is right

1. Inspection of simulation logic using walk-throughs and slow runs (**inspection**).
2. Performing consistency checks on model outputs (**demonstration**).
3. Examination of the change in model's output in response to different conditions (**analysis**).
4. Testing the variation in model's output using multiple simulation runs (**analysis**).

Validation

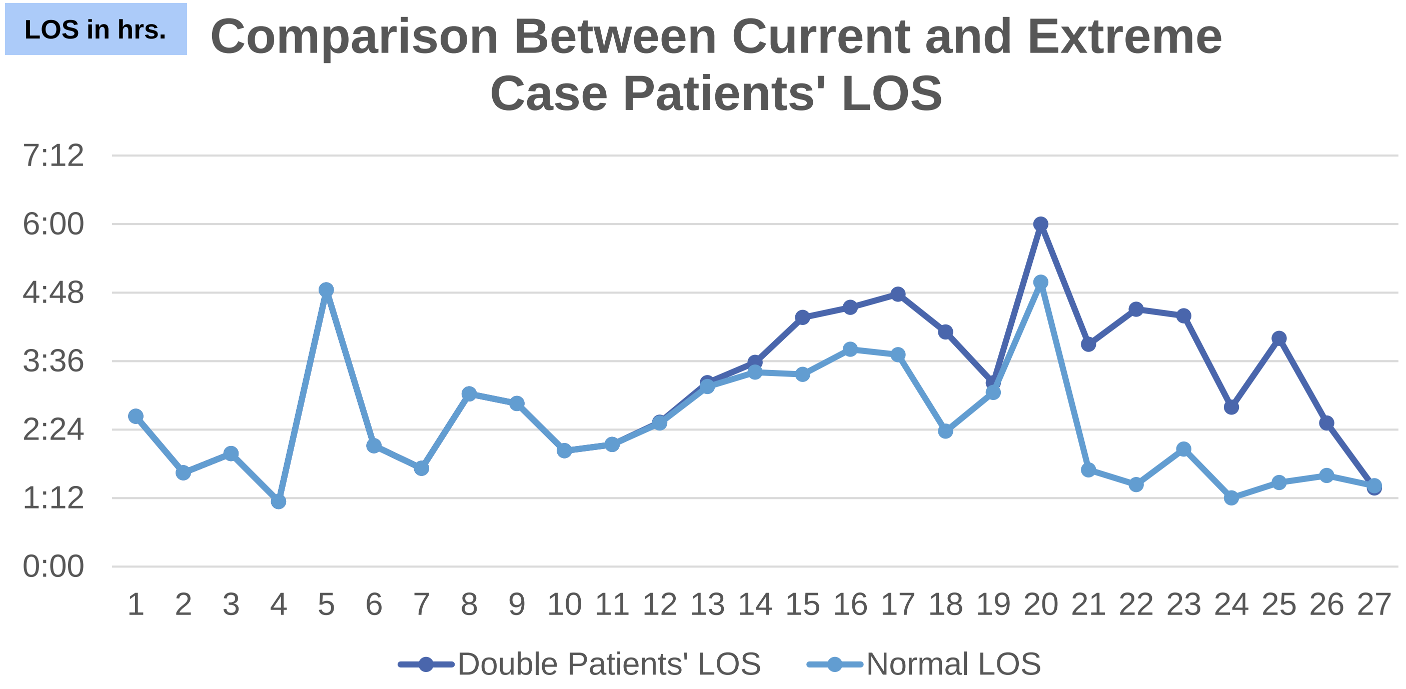
Right model is built

1. Comparing model's output behavior with Epic and Picasso data.
2. Validation by observing the real system.
3. Validation with ED and Simulation Experts.

Robert G. Sargent, 2005

Model Verification – Extreme Condition Testing (Model B)

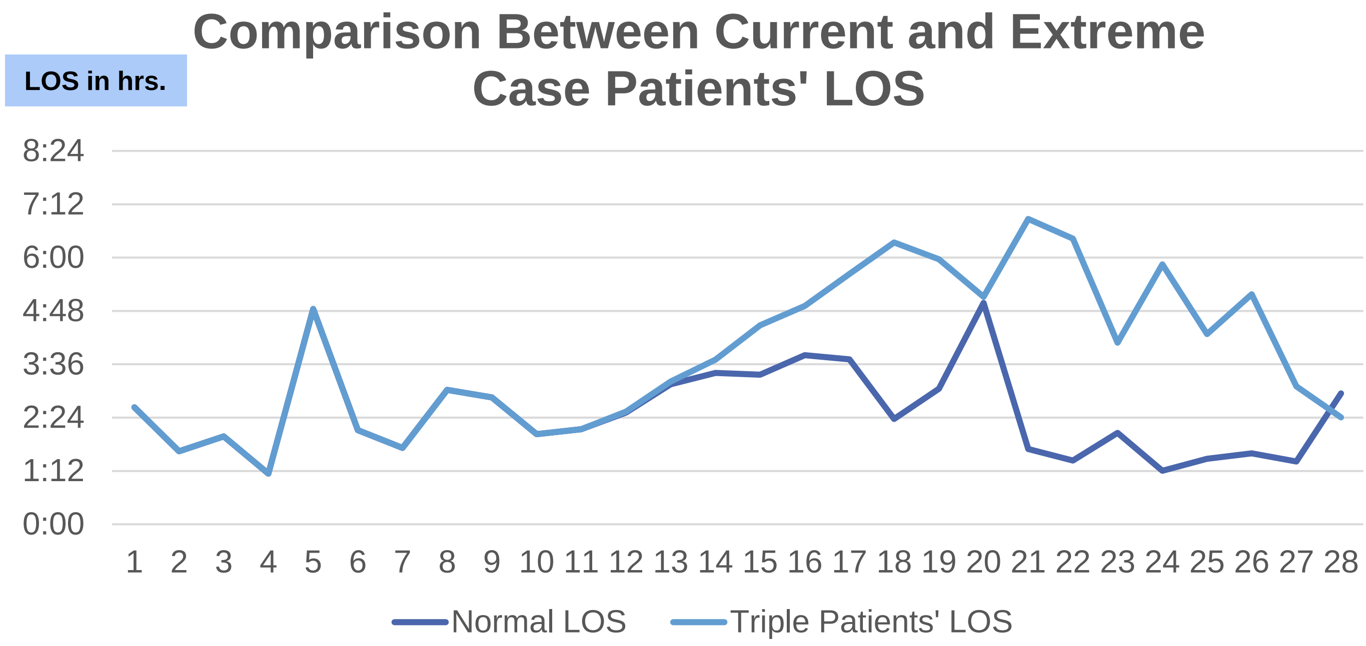
Number of patients arriving to the ED was doubled on 2/1/2014 for three hours between 9 AM and 12 PM using Model B.



The LOS starts increasing at noon, and then it goes back into normal value on 2/2/2014 at 3 AM

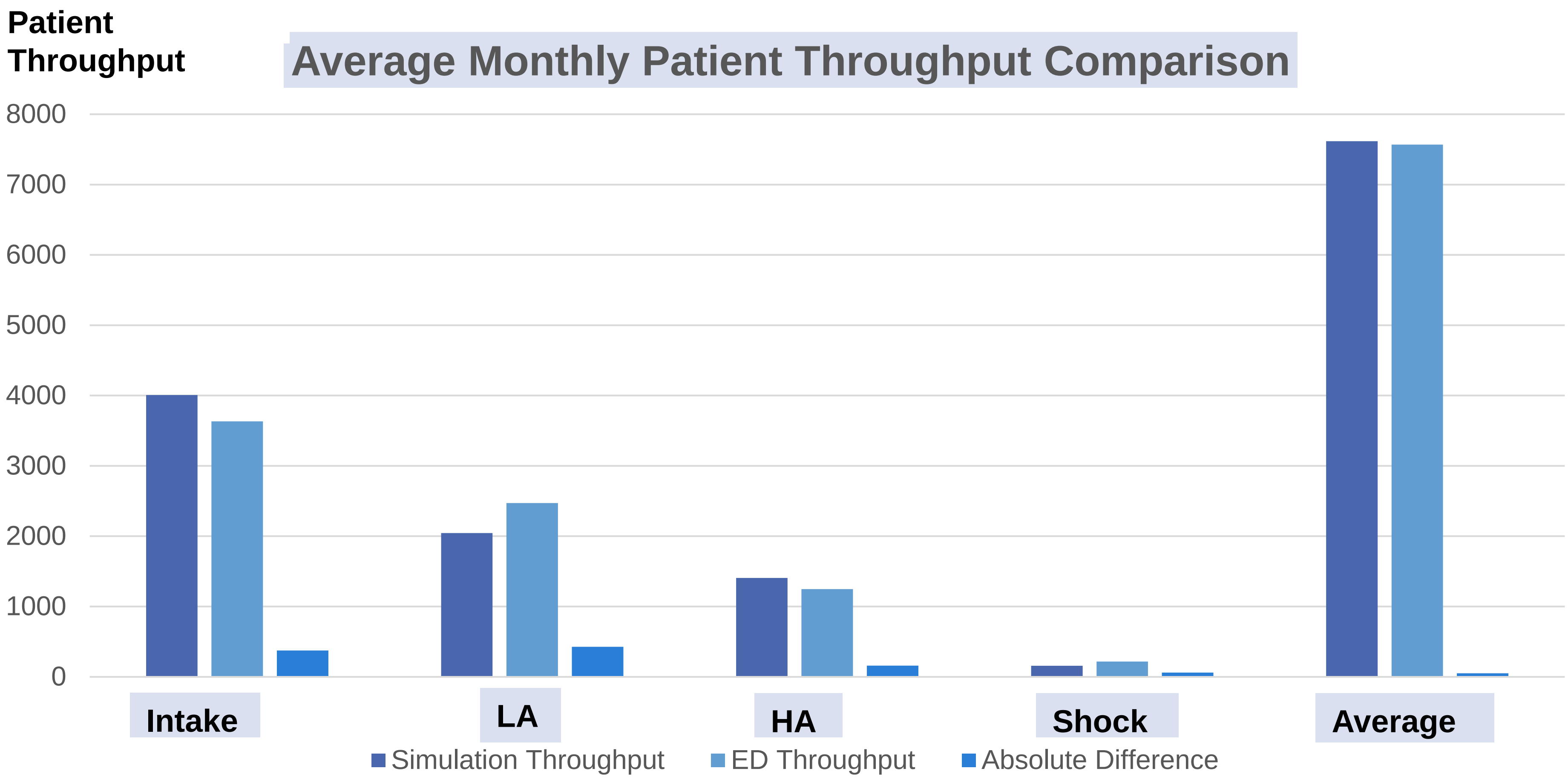
Model Verification – Extreme Condition Testing (Model B)

Number of patients arriving to the ED was tripled on 2/1/2014 for three hours between 9 AM and noon using Model B.

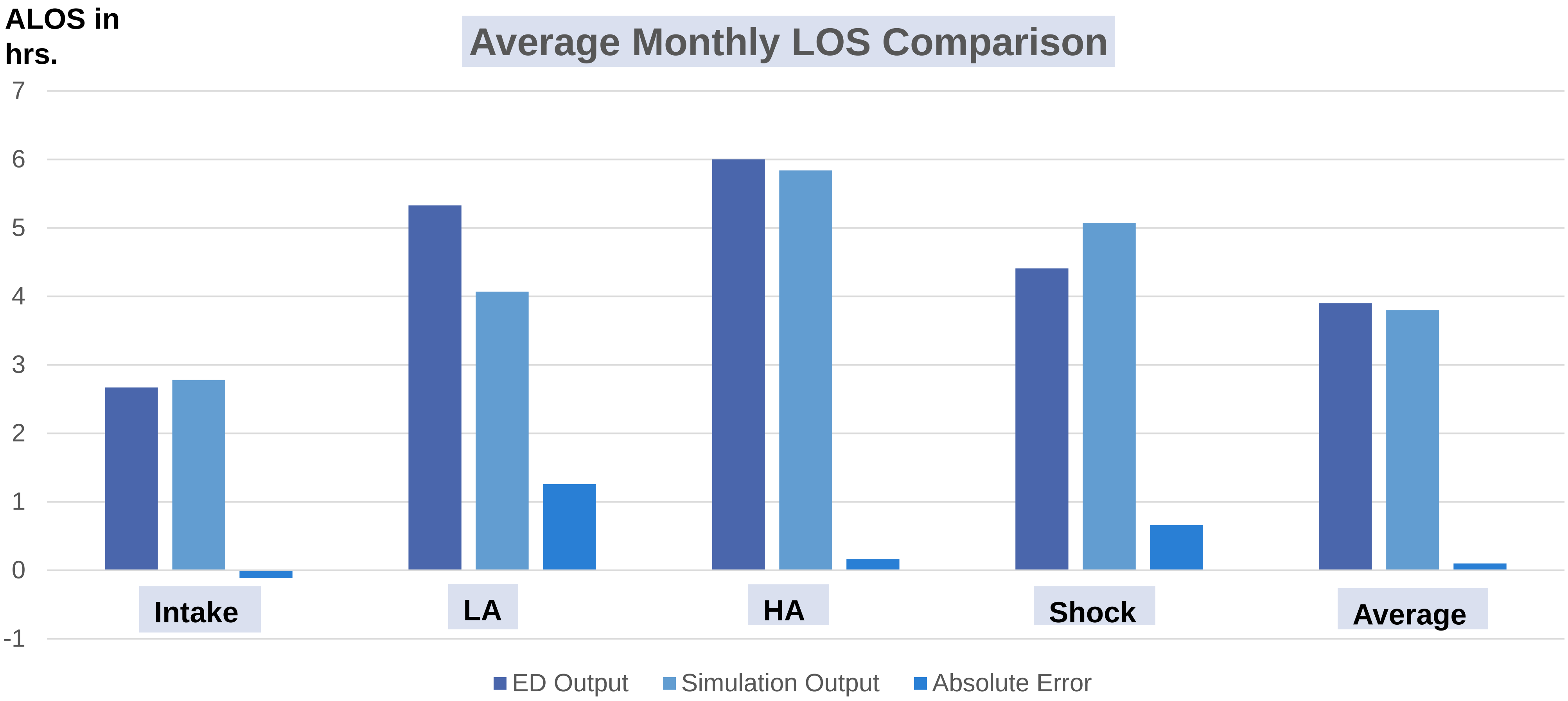


The LOS starts increasing at noon, and then it goes back into normal value on 2/2/2014 at 5 AM

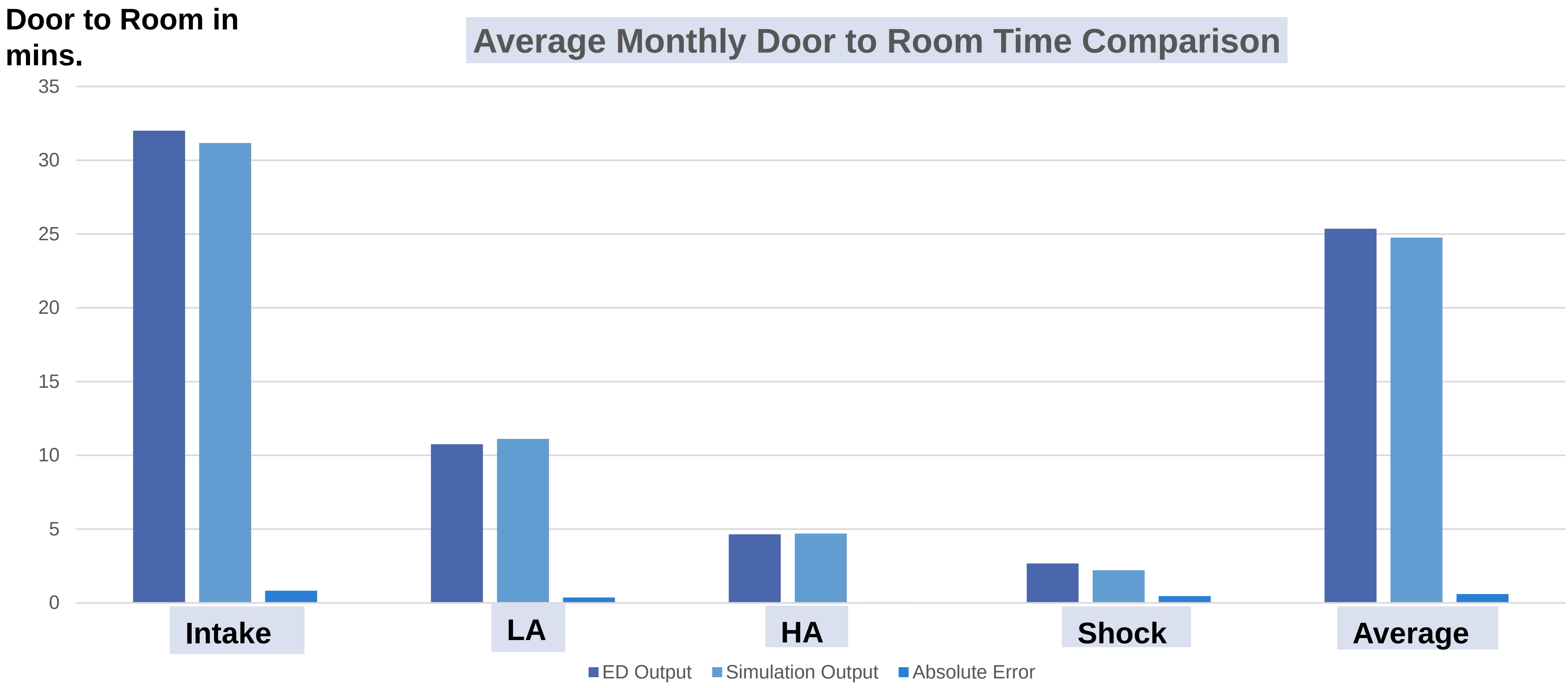
Model Validation – Output Behavior Comparison (Model B)



Model Validation – Output Behavior Comparison (Model B)



Model Validation – Output Behavior Comparison (Model B)



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Conclusion

A system engineering (SE) driven approach to health care delivery representation was proposed

The SE approach was successfully implemented to drive the modelling of ED process at a mid-size Emergency Department, namely Eskenazi

A two level fidelity modeling was used to capture patient flow as well as resource utilization

DES was used to create the higher fidelity simulation model, and predict LOS, room utilization, staff utilization, etc.

What-if scenarios were conducted to explore more optimal solutions through resource re-allocation

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Thank you

Open for Discussion…….

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