Discrete Event Simulation as a Tool for Cost Estimating

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National Nuclear Security Administration

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Protect the Nation by maintaining **a safe, secure, and effective** nuclear weapons stockpile

Reduce global **nuclear threats**

Provides the U.S. Navy with militarily effective **nuclear propulsion**

The NNSA is a semi-autonomous agency within the U.S. Department of Energy responsible for enhancing national security through the military application of nuclear science.

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NNSA's Office of Programming, Analysis, and Evaluation (PA&E)

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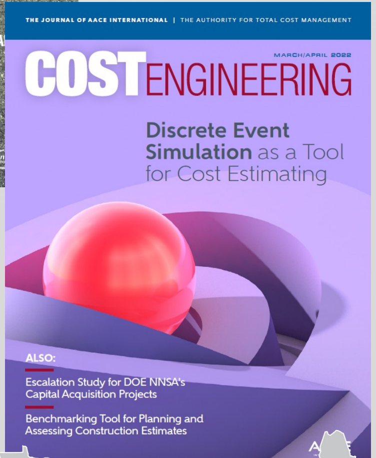
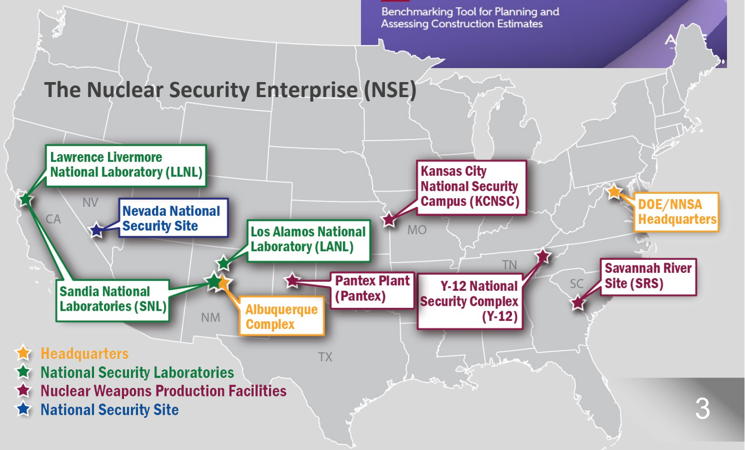
- 2011: Established to focus on cost estimating on early-stage weapons acquisitions
  - Subsequently broadened to other analytical disciplines (e.g. schedule estimating, risk analysis, etc)
- 2019: NNSA centralized cost estimating into two offices and established PA&E to lead:
  - Programmatic cost estimation
  - Execution of all Analysis of Alternatives (AoAs)
  - Programming process of annual Planning, Programming, Budgeting, and Evaluation (PPBE)
- PA&E provides analytical decision support throughout acquisition and budgeting
  - Promotes data-driven decisions and managing portfolio risk in budget-constrained environments
  - Promotes credibility in cost estimating and long-term planning through objective, unbiased, and technically sound analyses and tools.
- PA&E leads:
  - Agency's programmatic cost community which includes 8 national labs and production sites
  - Continuous improvement and innovation in analytical models, tools, and processes
  - Hosting annual Cost Estimating Community of Practice (CECOP) symposium
  - Active collaboration with external cost communities (NASA, DoD's CCRG, ICEAA, AACE, etc.)





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6th Annual Cost Estimating Community of Practice (CECOP) Symposium
August 2 – 3, 2022 in the Washington, DC Metro Area
To register: **CECOP@nnsa.doe.gov**

Discrete Event Simulation (DES)

- Model real-world systems as logic-based events
  - For a series of events the simulation moves sequentially through each event
  - Discrete not continuous
  - Events occur at discrete times; no system changes between events
- Address "What if…"
  - Manufacturing Processes
  - Logistics
  - Combat
- Multiple Vendors
  - AnyLogic, Arena, ExtendSim, FlexSim, Innoslate, SimEvents, and Jaam Sim (open source)

Cost Estimating & Facility Sizing

- The Office of Programming Analysis and Evaluation (NA-MB-90) uses Cost Estimating Relationships for NNSA capital acquisition projects

Example Multiplicative Functional Form Cost Estimating Relationship (CER)

Independent Variables

$$\text{TEC in BY\$/GSF} = a\,GSF^{b}\,Hazcat^{c}\,EquipComp^{d}$$

$$\text{OPC as \% TEC} = D\,GSF^{e}\,Hazcat^{f}\,EquipComp^{g}$$

Technical Cost Drivers

GSF – Gross Square Feet
Hazcat – Hazard Category Bin
*EquipComp – Equipment Complexity**

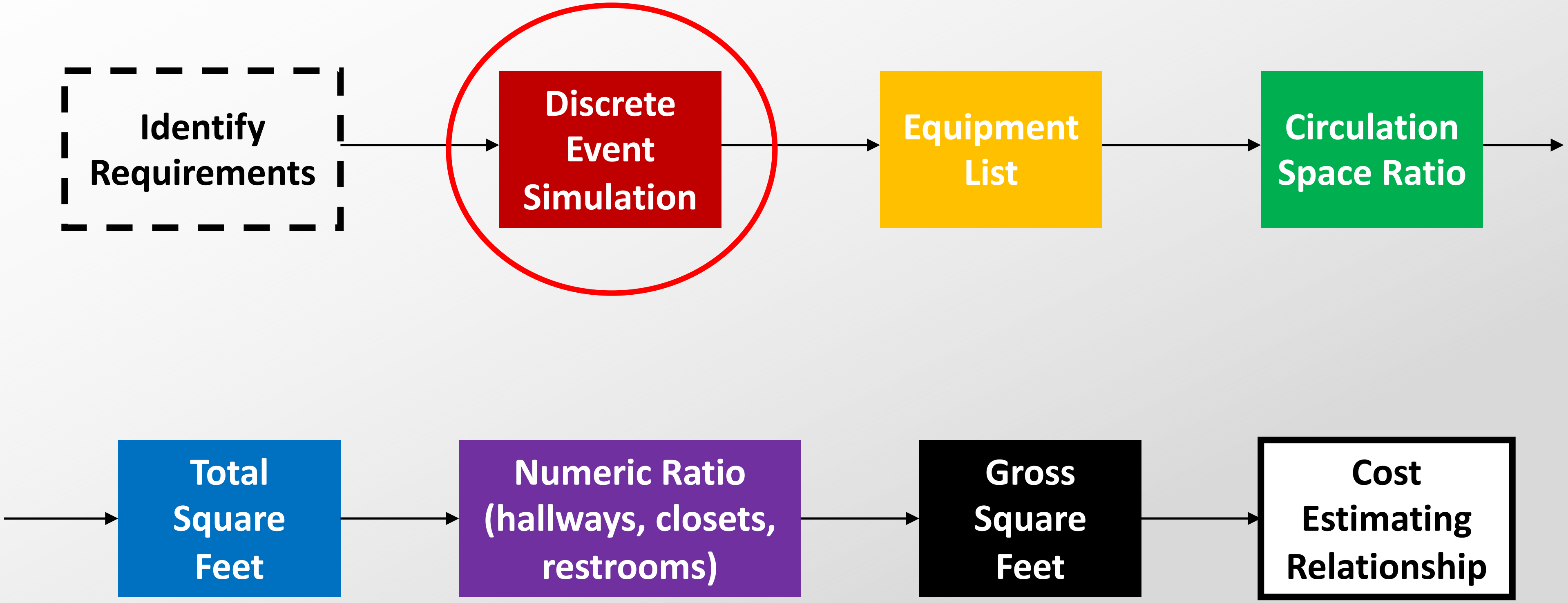
**Only for New Construction with or without Process Equipment*

- Hazard Category and Equipment Complexity are defined by program requirements

- A method for determining facility size (GSF) is necessary

TEC=Total Estimated Cost
OPC=Other Project Cost
BY = Base Year

Discrete Event Simulation in a Cost Estimate



Good data is necessary at all steps!

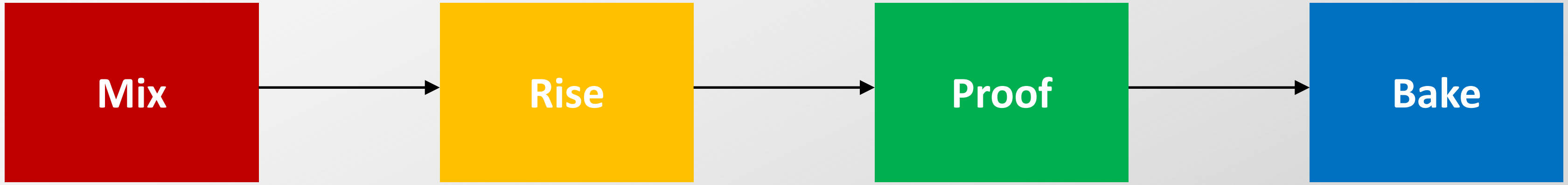
Application of DES to Facility Sizing

- The Office of Programming Analysis and Evaluation (NA-MB-90) has applied DES to facility sizing in support of cost estimates:
  - Plutonium Pit Production Model (2017)
    - 2016 National Defense Authorization Act required that NNSA have the capability to produce 80 pits per year
  - Depleted Uranium Production Model (2021)
    - 2021 Stockpile Stewardship and Management Plan described the need for a depleted uranium processing capability
  - Pit Disassembly and Processing Model (2022)
    - 2022 Plan to Reduce Global Nuclear Threats describes the need for a pit disassembly and processing capability
- This presentation will demonstrate using DES to develop a facility sizing estimate for a sample capital acquisition using MATLAB SimEvents software

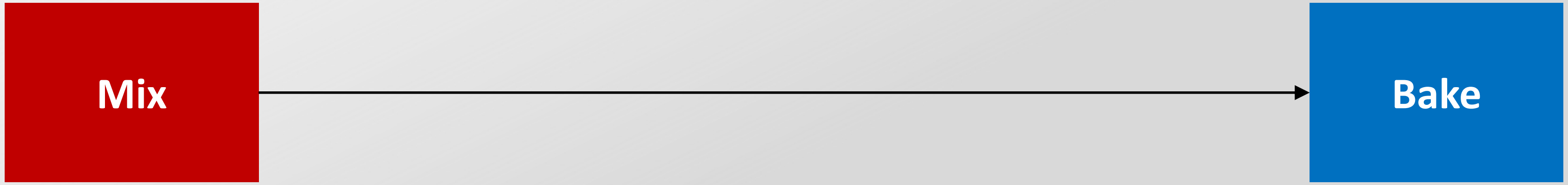
Building a Bakery

- Lofty Bread & Cookie Treats
  - Goal: Produce 100 bread batches and 120 cookie batches per week

- Bread Process



- Cookie Process



Bakery Process Data

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Bread	Minimum	Mode	Maximum	Equipment
Mix	0.45	0.5	0.75	Mixer
Rise	14	16	24	Refrigerator
Proof	1.75	2	2.25	Proofing Oven
Bake	0.45	0.5	2	Oven
Cookie	**Minimum**	**Mode**	**Maximum**	**Equipment**
Mix	0.8	1	2	Mixer
Bake	0.2	0.25	0.5	Oven

All times shown are in hours
Work Hours: M-F, 8AM-5PM

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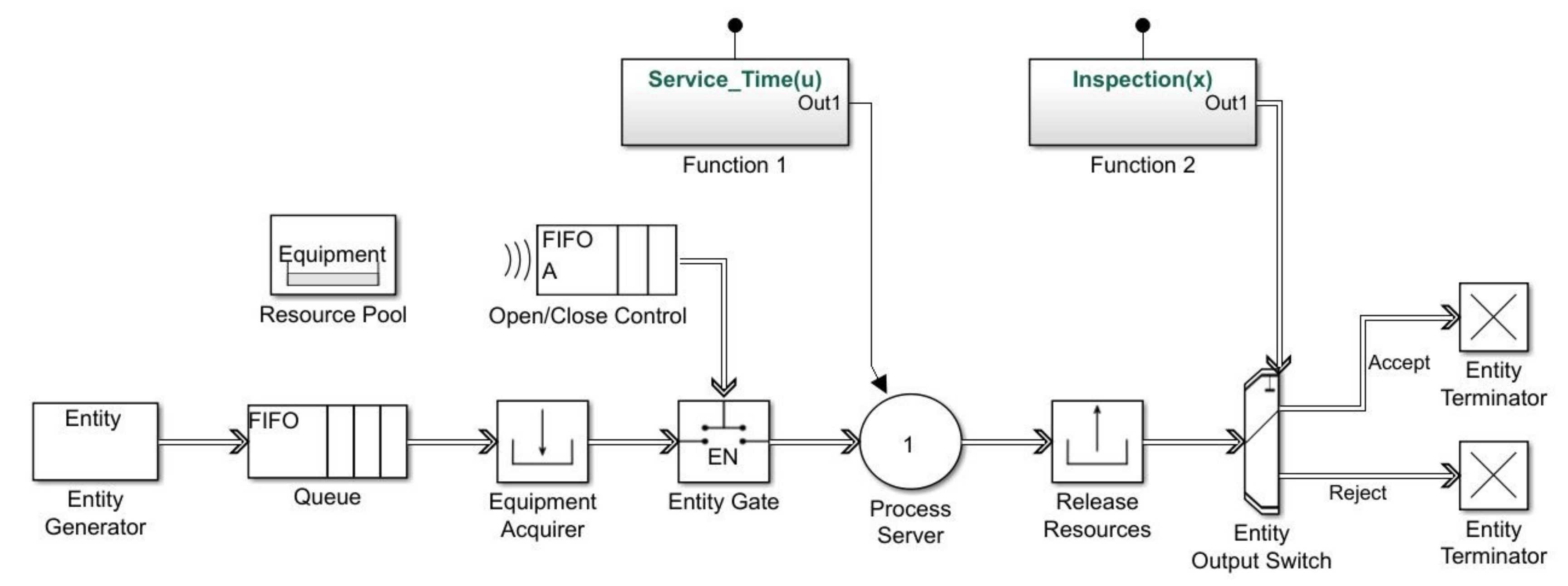
Building a Model

- A representative single operation is shown below:



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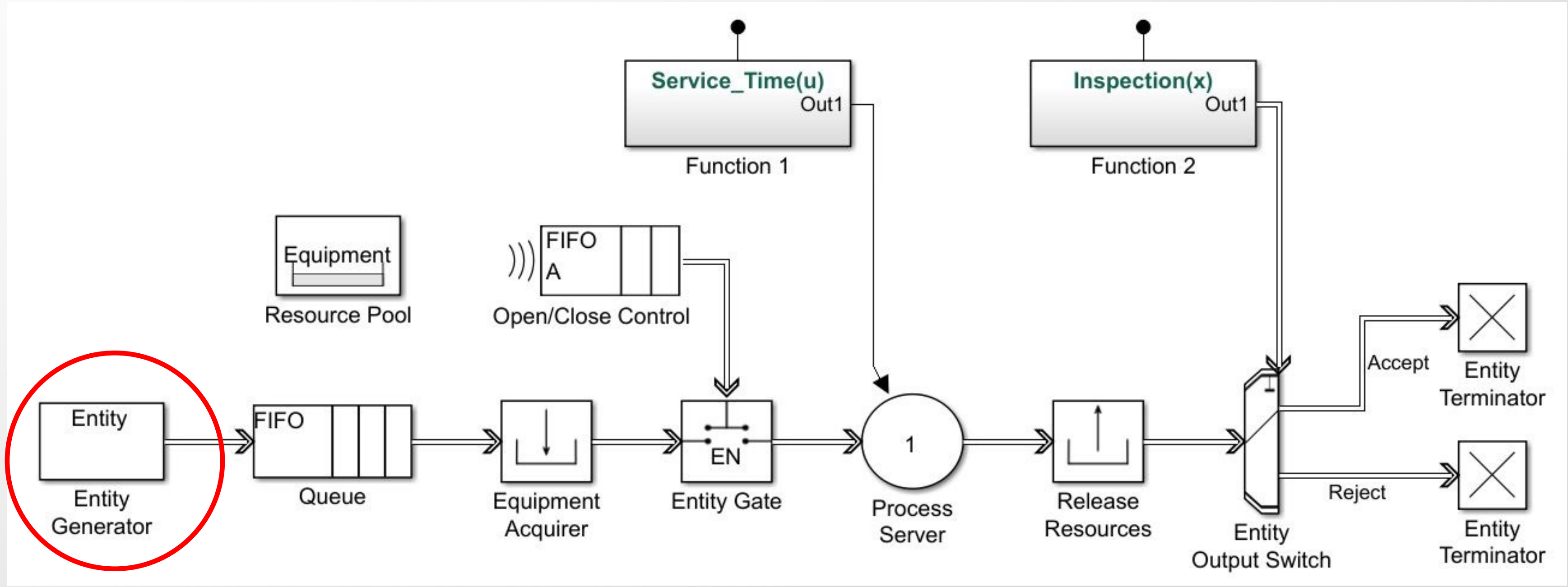

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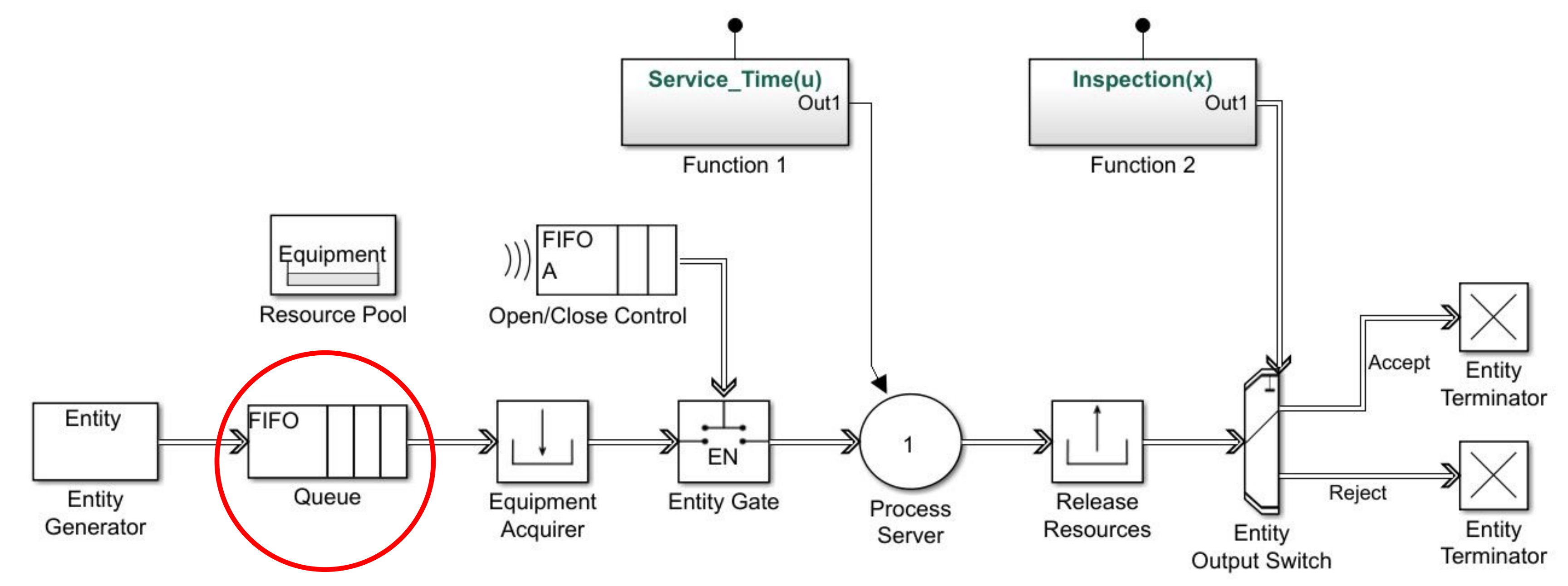

Building a Model

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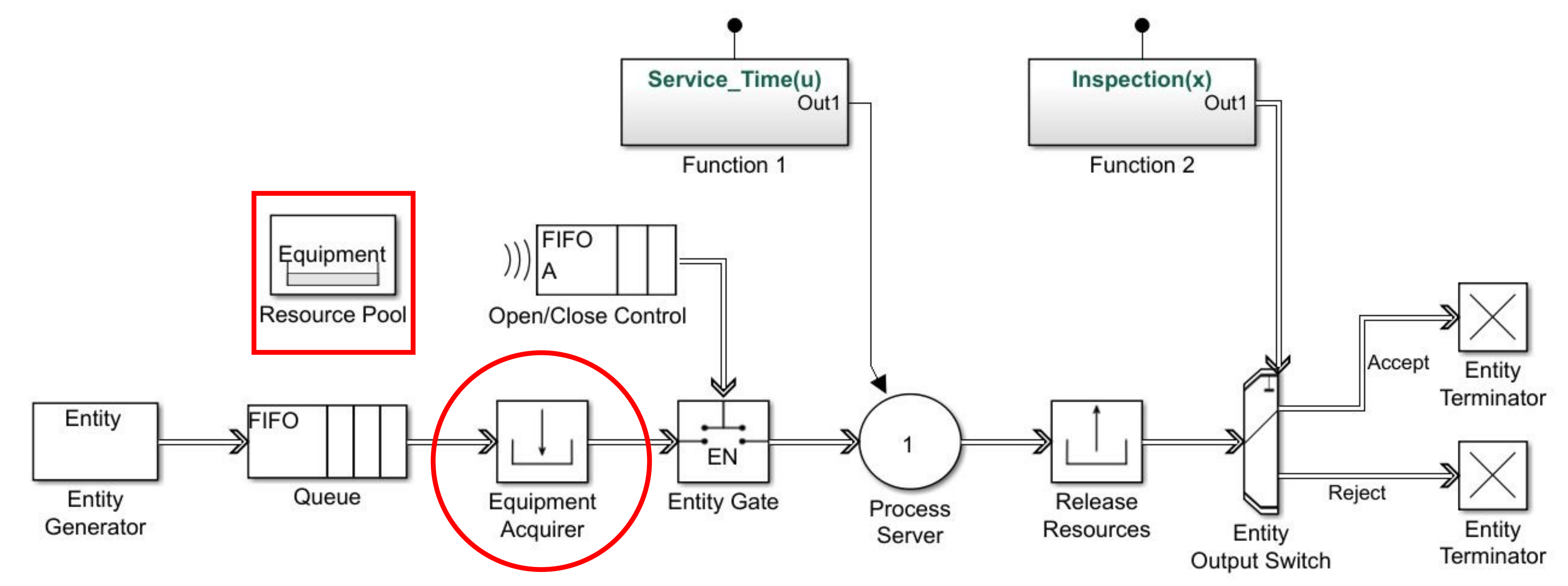

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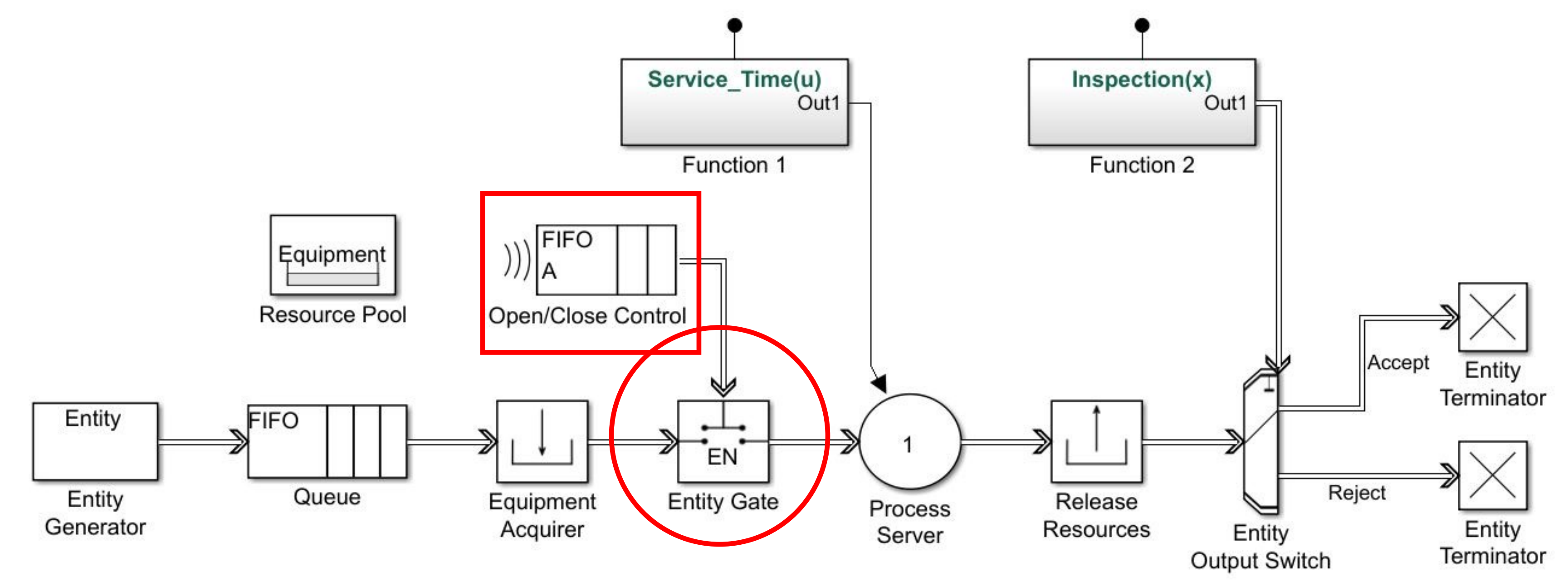

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Building a Model

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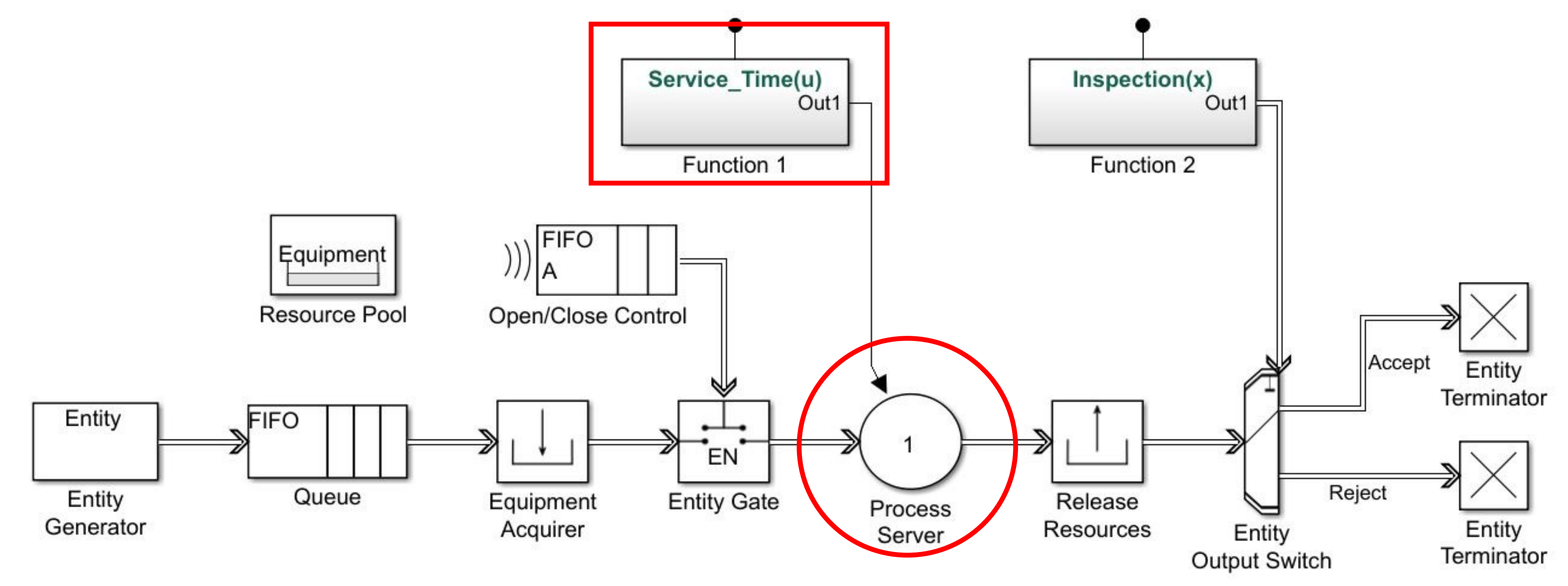

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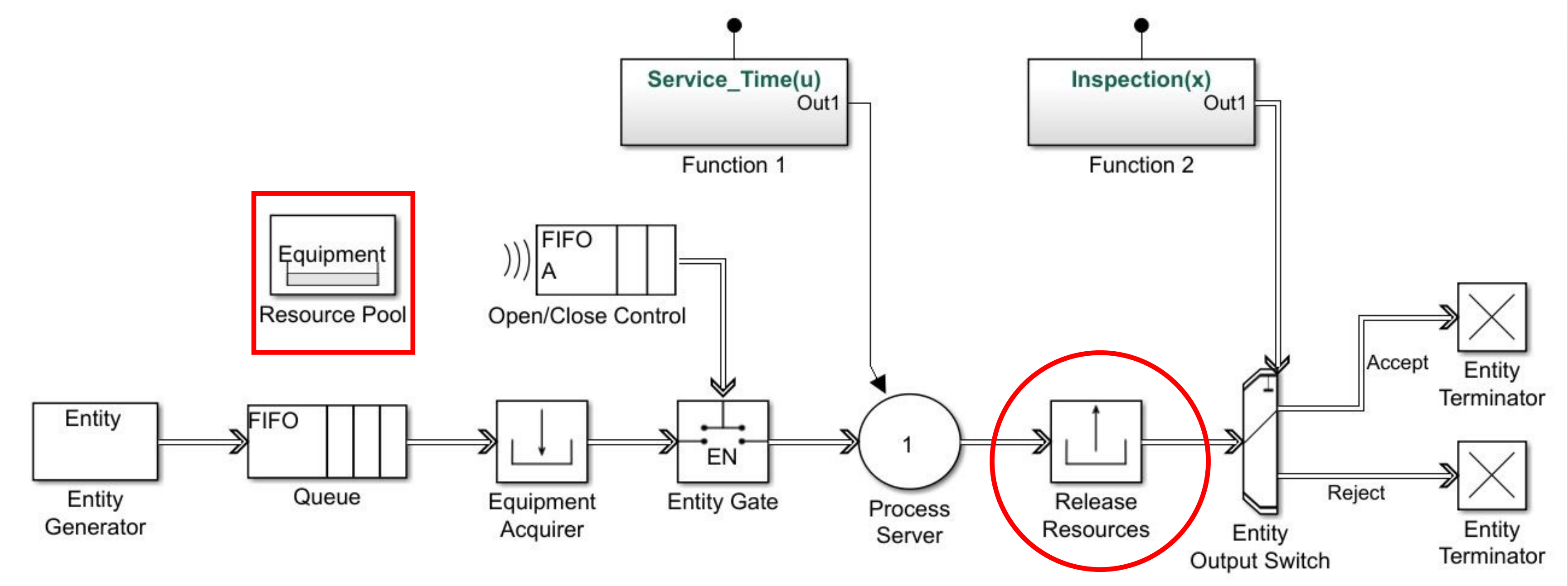

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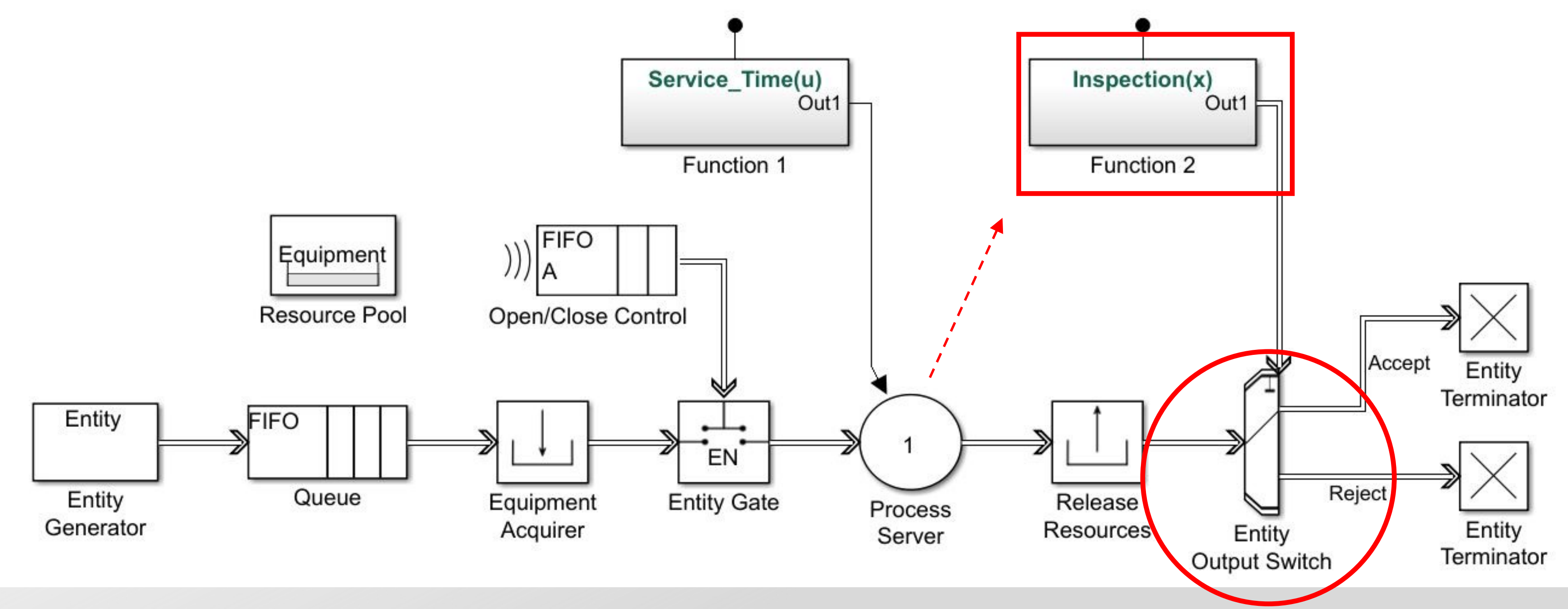

Building a Model

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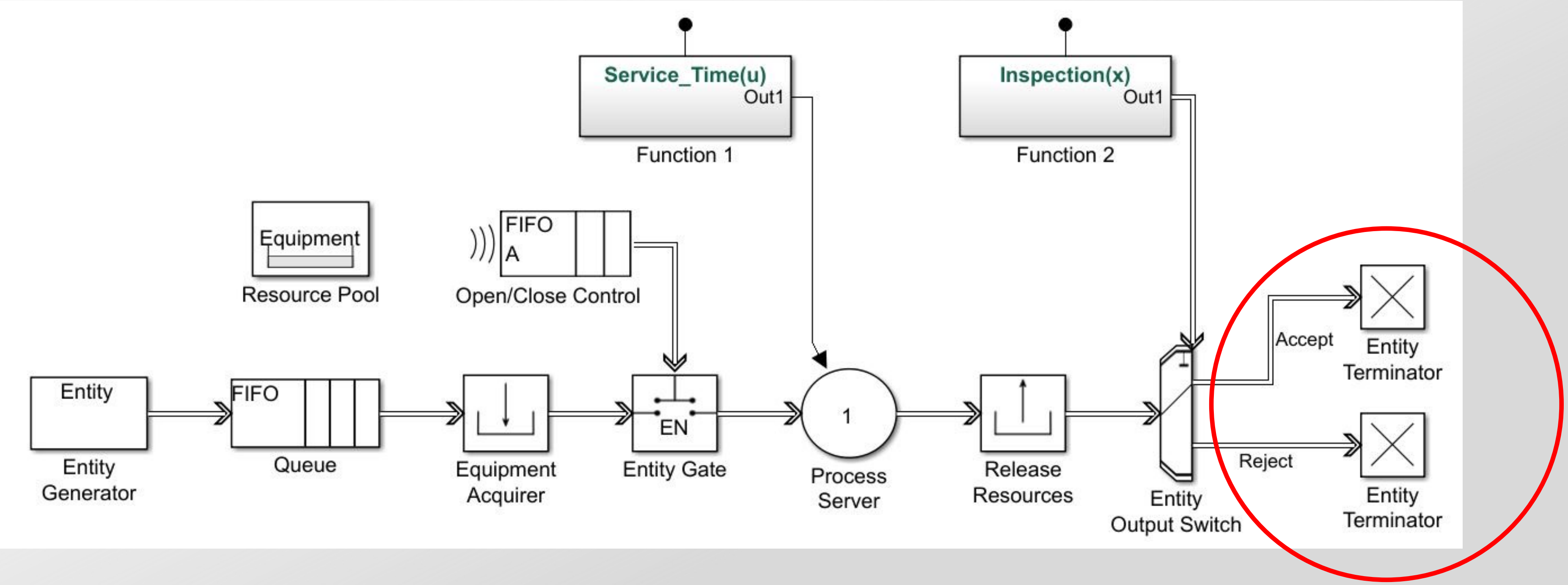
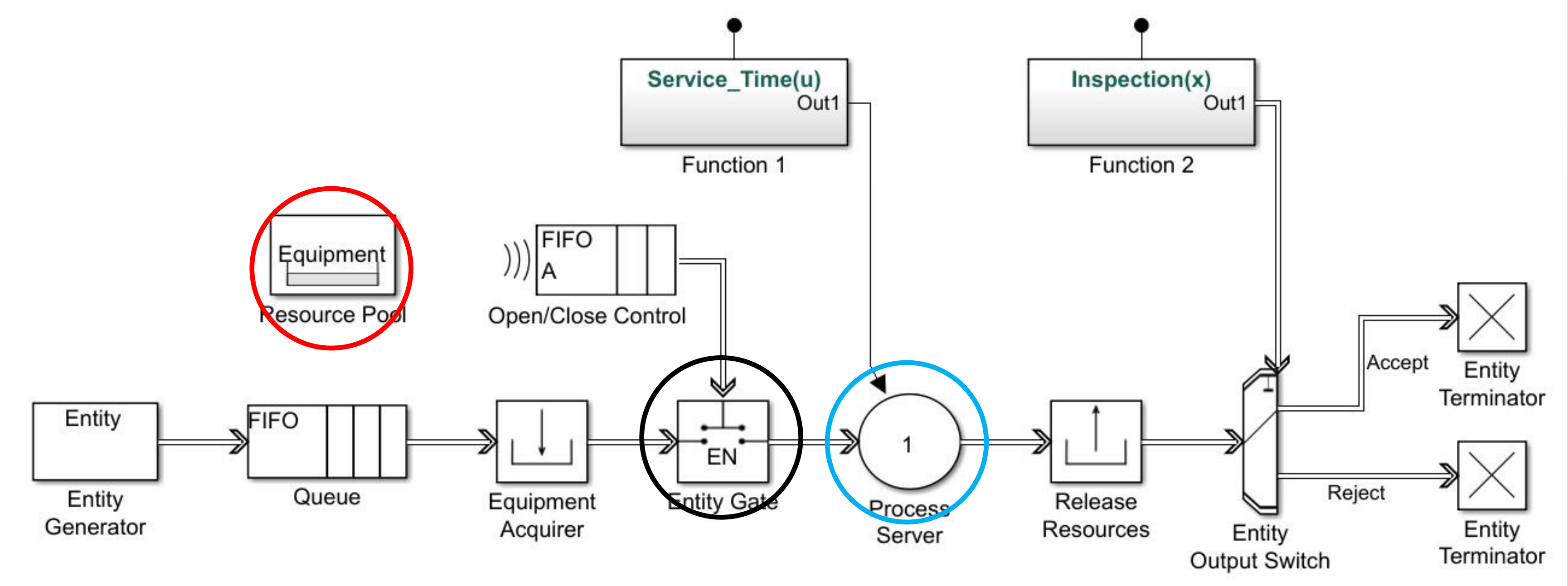
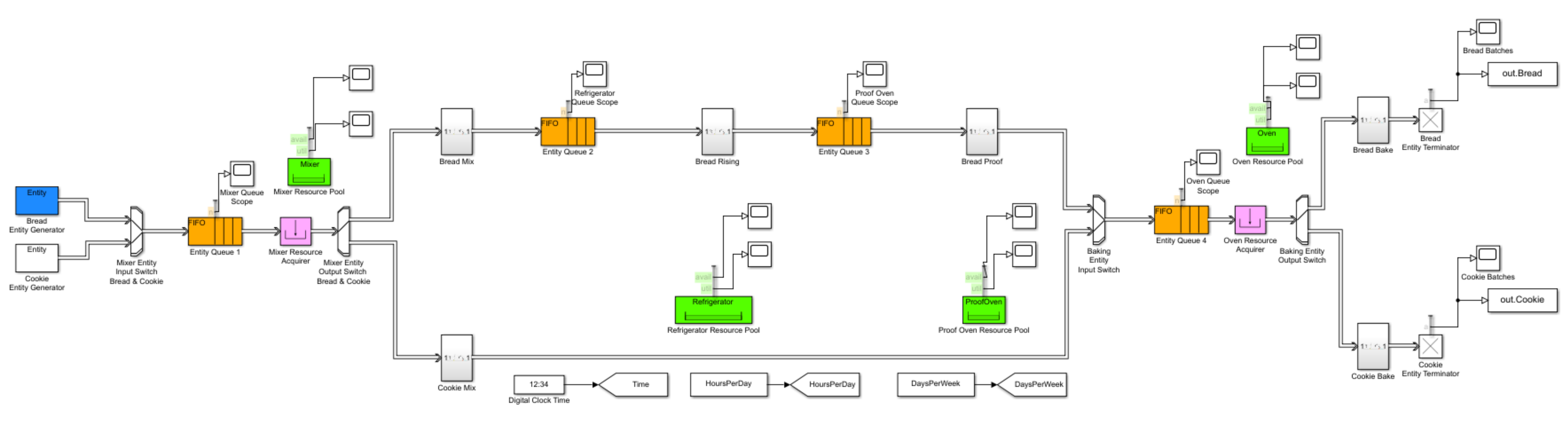


Build Model to Appropriate Level of Detail

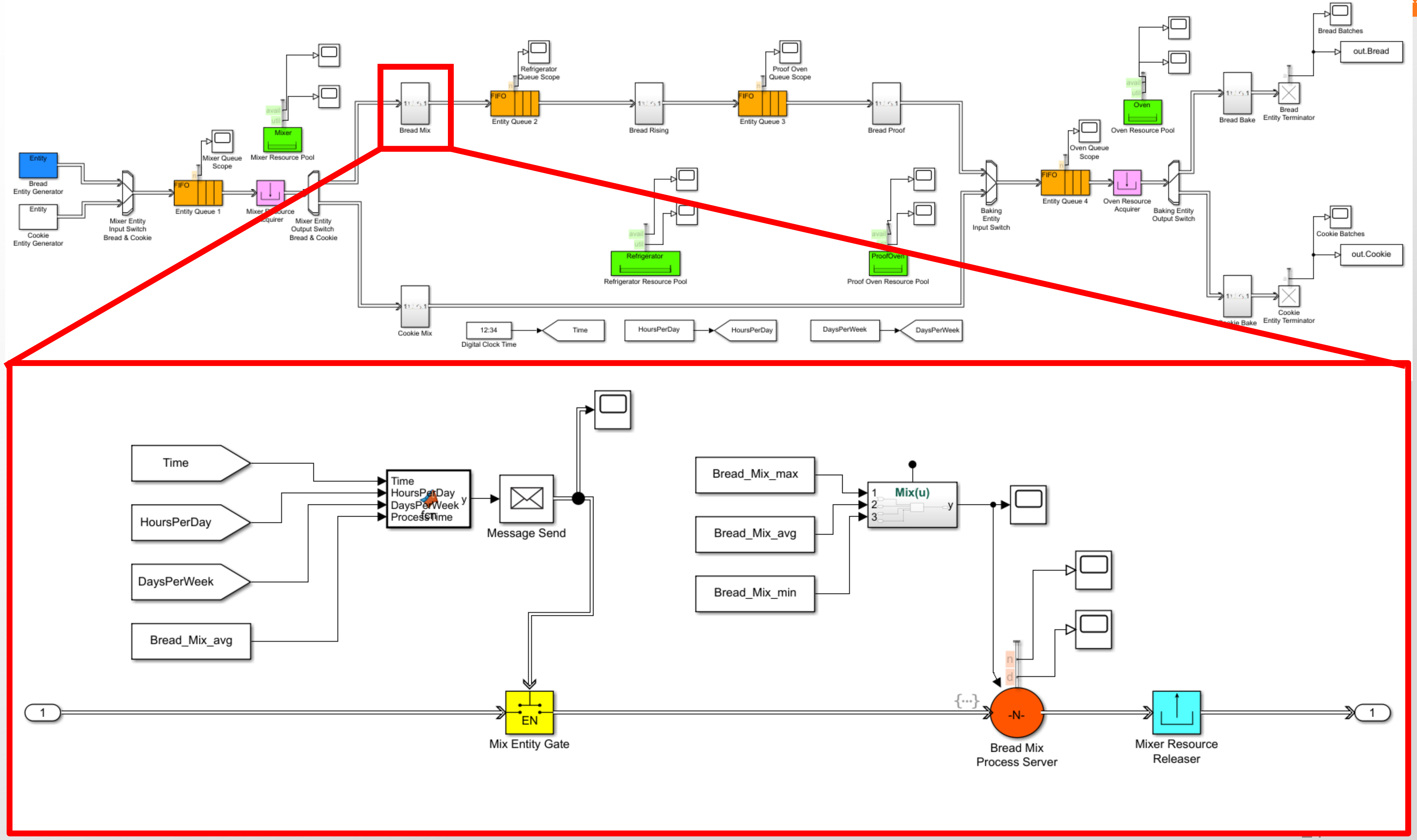
- Resource Pool: Equipment, Feedstock Material, Employees
- Entry Gates: representing when a facility is operating vs closed
- Process Server: Stochastic process time, equipment maintenance & failure during operation



MATLAB SimEvents Bakery



MATLAB SimEvents Bakery



Variable Values in Excel

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	A	B
1	Week	1
2	HoursPerDay	8
3	DaysPerWeek	5
4	Period_Bread	1
5	Period_Cookie	1
6	Mixer_quantity	1
7	Refrigerator_quantity	1
8	ProofOven_quantity	1
9	Oven_quantity	1
10	Bread_Mix_capacity	1
11	Bread_Mix_max	0.75
12	Bread_Mix_avg	0.5
13	Bread_Mix_min	0.45
14	Bread_Refrigerate_capacity	1
15	Bread_Refrigerate_max	24
16	Bread_Refrigerate_avg	16
17	Bread_Refrigerate_min	14
18	Bread_Proof_capacity	1
19	Bread_Proof_max	2.25
20	Bread_Proof_avg	2
21	Bread_Proof_min	1.75
22	Bread_Bake_capacity	1
23	Bread_Bake_max	2
24	Bread_Bake_avg	0.5
25	Bread_Bake_min	0.45
26	Cookie_Mix_capacity	1
27	Cookie_Mix_max	2
28	Cookie_Mix_avg	1
29	Cookie_Mix_min	0.8
30	Cookie_Bake_capacity	1
31	Cookie_Bake_max	0.5
32	Cookie_Bake_avg	0.25
33	Cookie_Bake_min	0.2

	A	B
1	Week	1
2	HoursPerDay	8
3	DaysPerWeek	5
4	Period_Bread	1
5	Period_Cookie	1
6	Mixer_quantity	1
7	Refrigerator_quantity	1
8	ProofOven_quantity	1
9	Oven_quantity	1
10	Bread_Mix_capacity	1
11	Bread_Mix_max	0.75
12	Bread_Mix_avg	0.5
13	Bread_Mix_min	0.45
14	Bread_Refrigerate_capacity	1
15	Bread_Refrigerate_max	24
16	Bread_Refrigerate_avg	16
17	Bread_Refrigerate_min	14

MATLAB Script: Parameters, Read Inputs, Run, Write Outputs


```
% Clean up before beginning
clear; % clear Workspace
clc;   % clear Command Window

% Gather model parameter values from Excel input file
Table1=readtable('Input.xlsx','ReadRowNames',true);

% Load model
mdl = 'Bakery_01';

%isModelOpen = bdIsLoaded(mdl); % Optional
%open_system(mdl);                % Optional; opens model window
load_system(mdl);               % Optional; use this instead of
open_system to load without opening Simulink Editor

%Random number generator-Seed selection
seed=1234;
rng(seed);

% Prepare to write results to output file
filename = 'Bakery_01_output.xlsx';
if exist(filename, 'file')==2
    delete(filename);
end

record_array = [];

% Iterate over years
start_week = 1;
end_week = 1;
nWeeks = (end_week - start_week) + 1;
 %Iterating Simulation
for i = 1:nWeeks
    thisweek = start_week + i - 1;
    thisweekStr = strcat('Year',num2str(thisweek));

    % Select data for this year
    thisweekdata = Table1(:,i); % Index i selects the ith column
of data. Datatype is "table"
 % Define servertime triangular distributions
    %Operating Hours and Days
    HoursPerDay = table2array(thisweekdata('HoursPerDay', 1));
    DaysPerWeek = table2array(thisweekdata('DaysPerWeek', 1));
```

Continue in next column

```
%Period for Entities
    Period_Bread = table2array(thisweekdata('Period_Bread', 1));
    Period_Cookie = table2array(thisweekdata('Period_Cookie', 1));
    %Equipment
    Mixer_quantity = table2array(thisweekdata('Mixer_quantity', 1));
    Refrigerator_quantity = table2array(thisweekdata('Refrigerator_quantity', 1));
    ProofOven_quantity = table2array(thisweekdata('ProofOven_quantity', 1));
    Oven_quantity = table2array(thisweekdata('Oven_quantity', 1));
    %Bread Process Times
    Bread_Mix_capacity = table2array(thisweekdata('Bread_Mix_capacity', 1));
    Bread_Mix_max = table2array(thisweekdata('Bread_Mix_max', 1));
    Bread_Mix_avg = table2array(thisweekdata('Bread_Mix_avg',1));
    Bread_Mix_min = table2array(thisweekdata('Bread_Mix_min', 1));
    Bread_Refrigerate_capacity = table2array(thisweekdata('Bread_Refrigerate_capacity', 1));
    Bread_Refrigerate_max= table2array(thisweekdata('Bread_Refrigerate_max',1));
    Bread_Refrigerate_avg = table2array(thisweekdata('Bread_Refrigerate_avg', 1));
    Bread_Refrigerate_min = table2array(thisweekdata('Bread_Refrigerate_min', 1));
    Bread_Proof_capacity = table2array(thisweekdata('Bread_Proof_capacity', 1));
    Bread_Proof_max = table2array(thisweekdata('Bread_Proof_max', 1));
    Bread_Proof_avg = table2array(thisweekdata('Bread_Proof_avg', 1));
    Bread_Proof_min= table2array(thisweekdata('Bread_Proof_min',1));
    Bread_Bake_capacity = table2array(thisweekdata('Bread_Bake_capacity', 1));
    Bread_Bake_max = table2array(thisweekdata('Bread_Bake_max', 1));
    Bread_Bake_avg = table2array(thisweekdata('Bread_Bake_avg', 1));
    Bread_Bake_min= table2array(thisweekdata('Bread_Bake_min',1));
    %Cookie Process Times
    Cookie_Mix_capacity = table2array(thisweekdata('Cookie_Mix_capacity', 1));
    Cookie_Mix_max = table2array(thisweekdata('Cookie_Mix_max', 1));
    Cookie_Mix_avg = table2array(thisweekdata('Cookie_Mix_avg', 1));
    Cookie_Mix_min= table2array(thisweekdata('Cookie_Mix_min',1));
    Cooke_Bake_capacity = table2array(thisweekdata('Cookie_Bake_capacity', 1));
    Cookie_Bake_max = table2array(thisweekdata('Cookie_Bake_max', 1));
    Cookie_Bake_avg = table2array(thisweekdata('Cookie_Bake_avg', 1));
    Cookie_Bake_min= table2array(thisweekdata('Cookie_Bake_min',1));
    %Perform simulation
    out = sim(mdl);
    %Write simulation data to file
    record_row = [thisweek];

    varNames = {'Time','Bread'};
    dummytable = table(out.Bread.Time, out.Bread.Data, 'VariableNames',varNames);
    writetable(dummytable, filename, 'Sheet', thisweekStr, 'Range', 'A1');

    varNames = {'Time','Cookie'};
    dummytable = table(out.Cookie.Time, out.Cookie.Data, 'VariableNames',varNames);
    writetable(dummytable, filename, 'Sheet', thisweekStr, 'Range', 'C1');
end
```

Verify & Validate

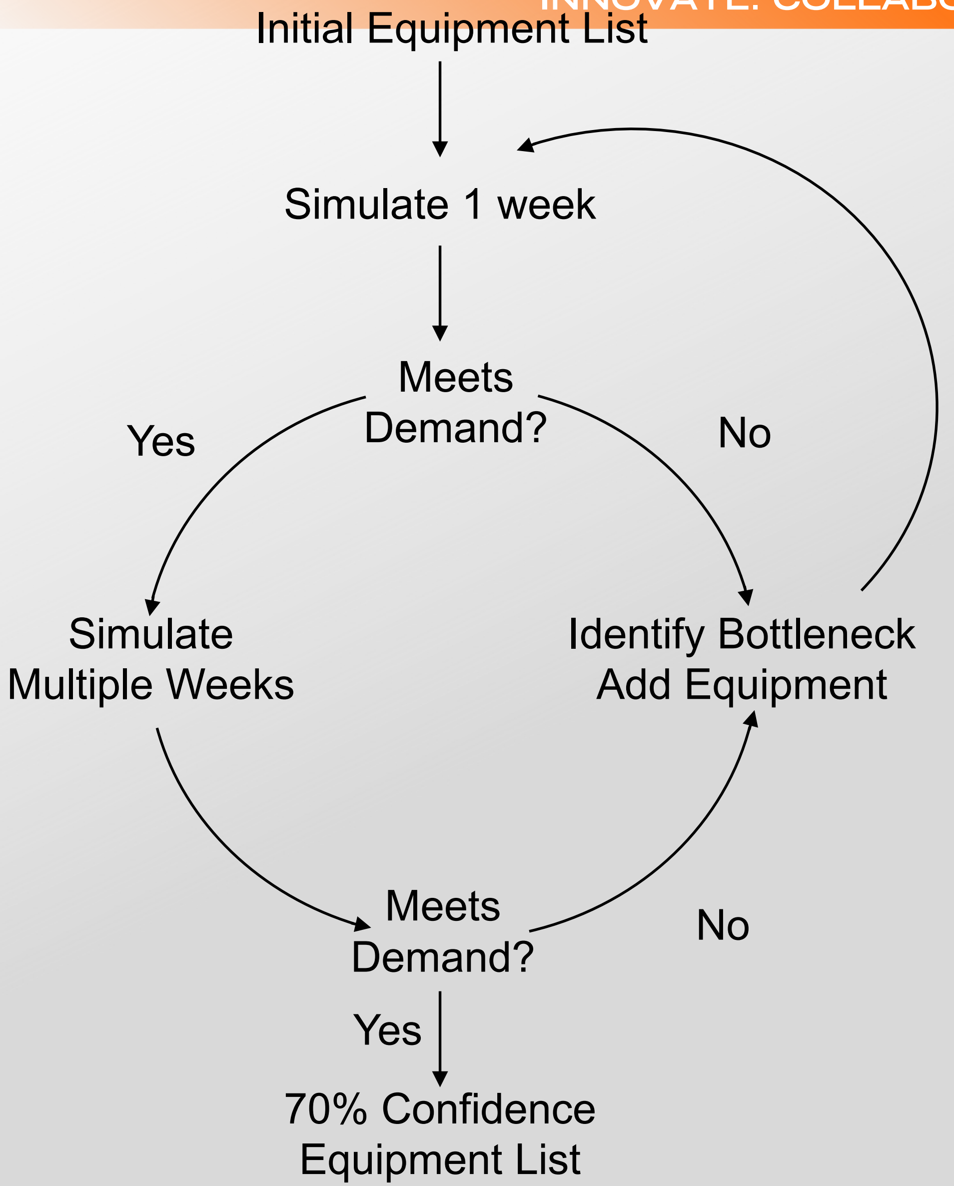
Extremely Important: provides justification to accept results

- Verification: Does the logic behave as desired?
  - Fixing Programming Bugs
  - Logic Errors
- Validation: Is the model representative of the actual process of interest?
  - Is current production data available?
  - Is historical data available?
  - Are there existing models to check against?
- Bakery Validation
  - Current facility with 1 Mixer, 1 Refrigerator, 1 Proofing Oven, and 1 Baking Oven

V&V	Bread	Cookie
Current Production	21	21
Simulated Production	20	19

Identify Equipment List at Confidence Level

- Desired Bakery Weekly Throughput:
  - 75 batches of bread
  - 120 batches of cookies
  - How much equipment is required to meet this production?
- 70% Confidence Level
  - For 10 simulation weeks, meet the demand of bread and cookies in 7 out of 10 weeks
- Iterative Process
  - Identifying equipment quantities that meet demand



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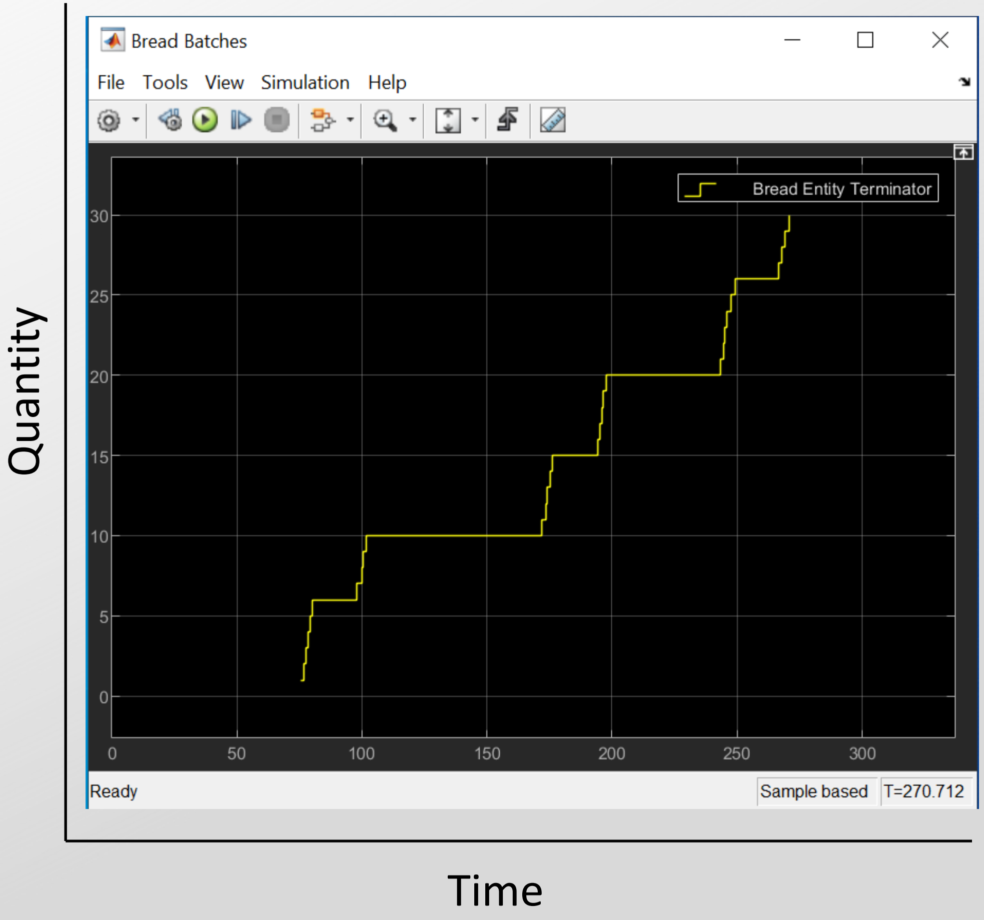
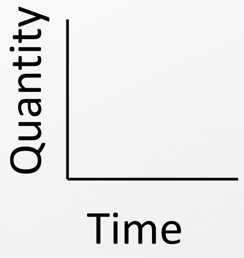
MATLAB SimEvents Bakery Run #1 Output

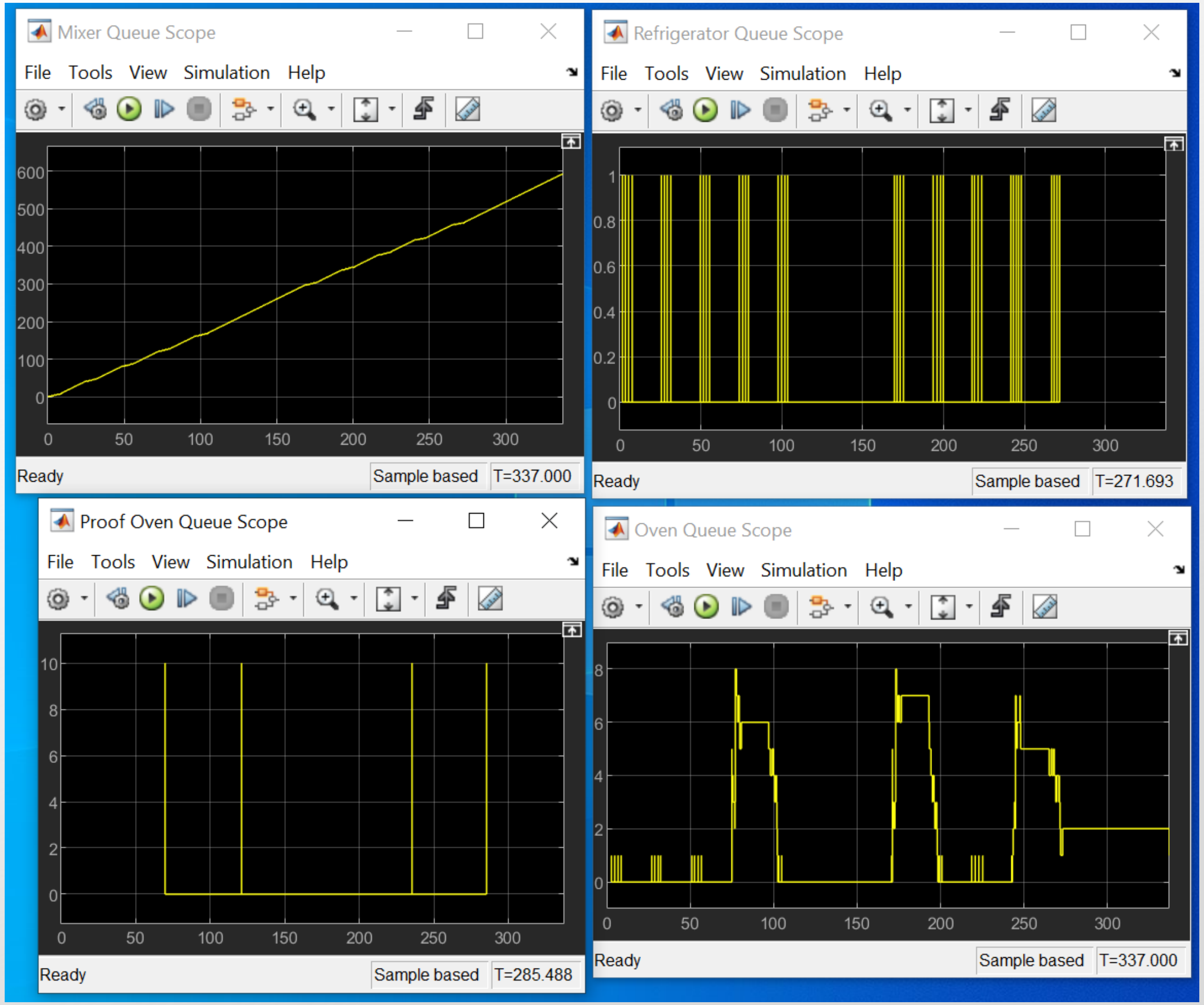
6	Mixer_quantity	1
7	Refrigerator_quantity	1
8	ProofOven_quantity	1
9	Oven_quantity	1

	A	B	C	D
1	t_warm=	168	t_warm=	168
2		10		19
3		10		19
4	Product	20	Product	19
5	Time	Bread	Time	Cookie
6	75.60794409	1	3.2034764	1
7	76.73851796	2	5.128213905	2
8	77.69685876	3	7.293529163	3
9	78.44845143	4	25.30654363	4
10	79.37346208	5	27.32734867	5
11	80.16593012	6	29.13869873	6
12	98.05689448	7	31.18848648	7
13	99.92120884	8	49.28242657	8
14	100.6321039	9	51.40651215	9
15	101.6982577	10	52.9586998	10
16	171.9939642	11	55.1790734	11



MATLAB SimEvents Bakery Run #1 Queues





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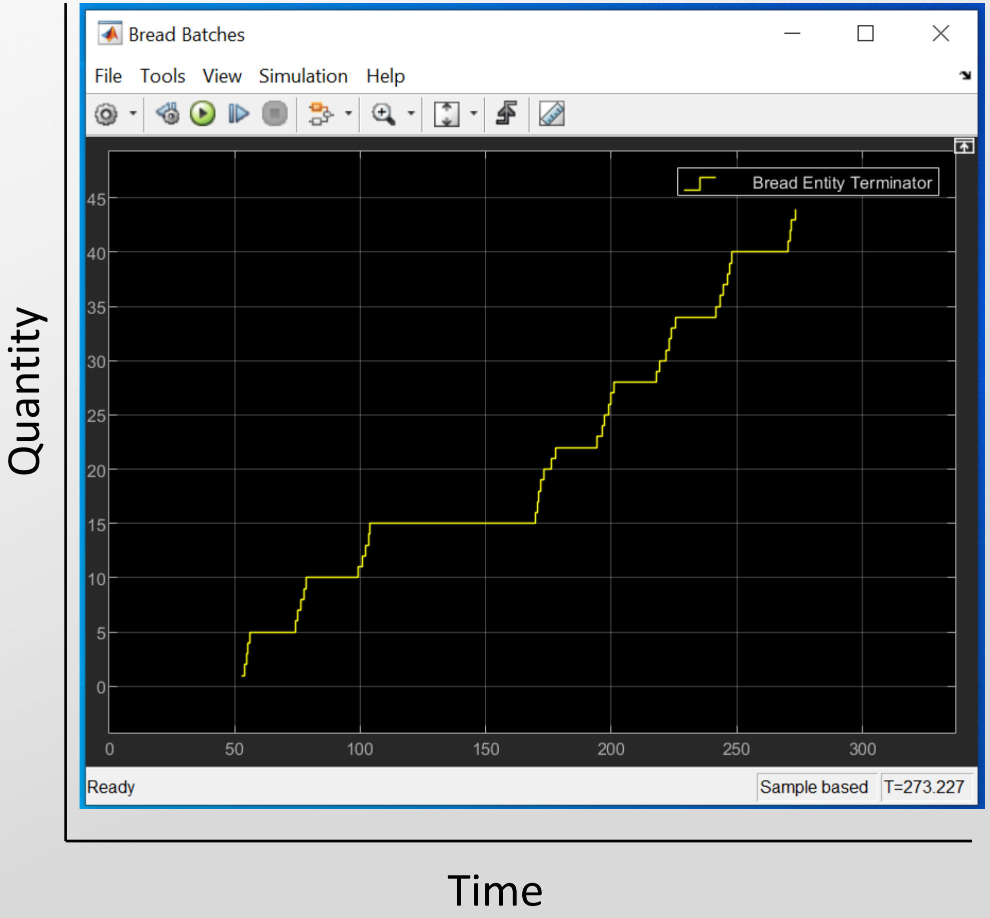
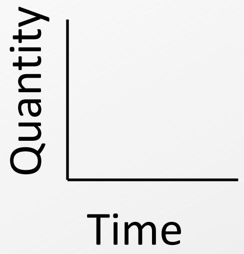
MATLAB SimEvents Bakery Run #2 Output

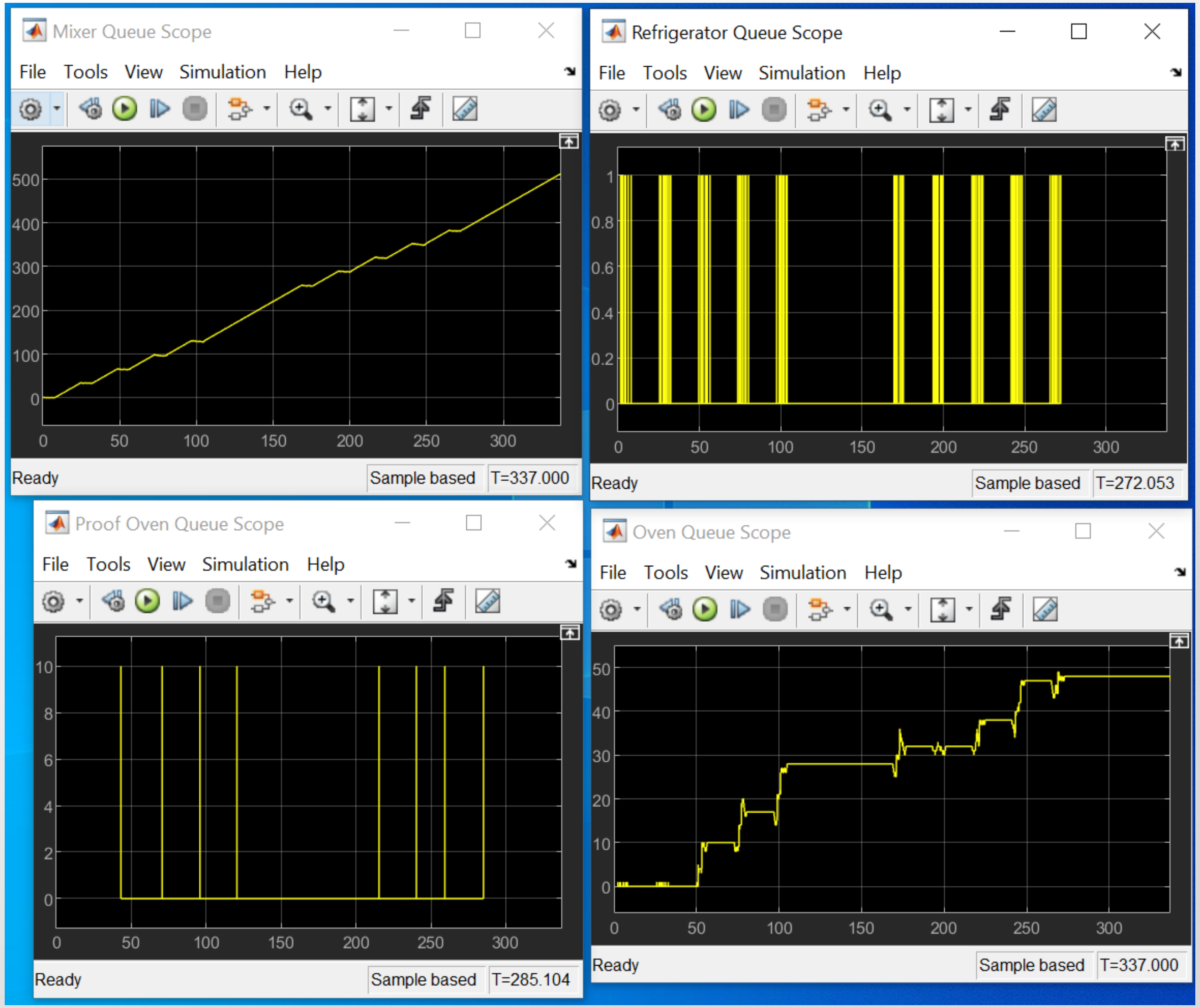
6	Mixer_quantity	2
7	Refrigerator_quantity	1
8	ProofOven_quantity	1
9	Oven_quantity	1

	A	B	C	D
1	t_warm=	168	t_warm=	168
2		15		26
3		15		26
4	Product	29	Product	32
5	Time	Bread	Time	Cookie
6	52.81731327	1	2.593027273	1
7	53.71575441	2	3.984856835	2
8	54.58663199	3	4.29688136	3
9	55.15574435	4	5.913165483	4
10	56.17619392	5	6.416165804	5
11	74.2012672	6	7.665318182	6
12	75.05705421	7	25.330161	7
13	76.12422933	8	26.22187866	8
14	77.497405	9	27.65010131	9
15	78.49568266	10	28.26573207	10
16	99.30517511	11	29.2545878	11



MATLAB SimEvents Bakery Run #2 Queues





Finding Appropriate Equipment List

Equipment Quantity				Queue Length				Product		
Mixer	Refrigerator	Proof Oven	Oven	Mixer	Refrigerator	Proof Oven	Oven	Bread	Cookies	Notes
-	-	-	-	-	-	-	-	100	120	Production Goal
1	1	1	1	600	0	0	0	20	19	Add 1 Mixer
2	1	1	1	500	0	0	50	29	32	Add 1 Oven
2	1	1	2	500	0	0	0	38	41	Add 1 Mixer
3	1	1	2	450	0	0	0	51	60	Add 1 Mixer
4	1	1	2	350	40	0	10	51	82	Add 1 Refrigerator
4	2	1	2	350	0	0	90	57	61	Add 1 Oven
4	2	1	3	350	0	0	0	75	82	Add 1 Mixer
5	2	1	3	275	0	15	10	86	97	Add 1 Oven
5	2	1	4	275	0	10	0	85	106	Add 1 Proof Oven
5	2	2	4	275	0	0	0	99	101	Add 1 Mixer
6	2	2	4	220	5	0	0	100	124	Meets Production

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Confidence Level

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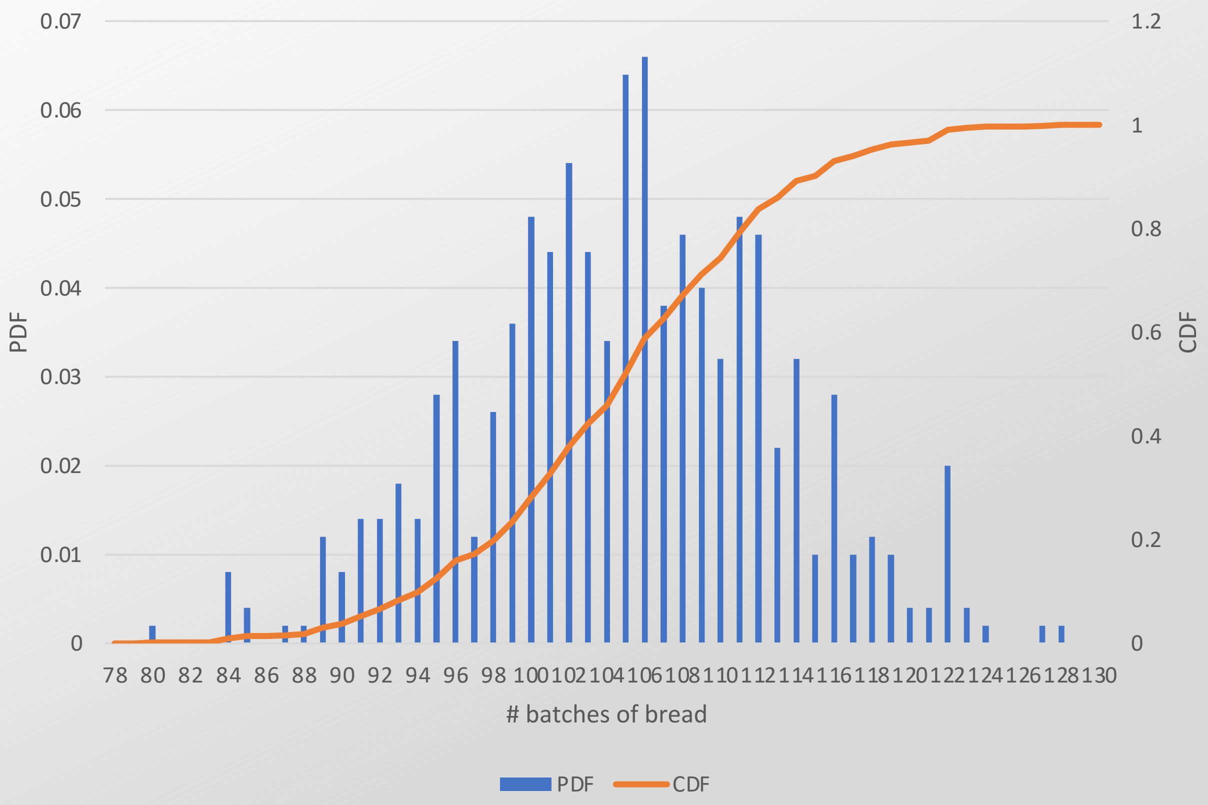
Equipment	Quantity
Mixer	6
Refrigerator	2
Proof Oven	2
Oven	4

Bread	Cookies
100	120



Meets production demand at 70% Confidence Level

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Deterministic vs Stochastic

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- If you do not account for random events (stochastic), the model will underestimate the quantity of equipment required.
- What if only the average process time were known?

Bread	Minimum	Mode	Maximum	Equipment
Mix	0.45	0.5	0.75	Mixer
Rise	14	16	24	Refrigerator
Proof	1.75	2	2.25	Proofing Oven
Bake	0.45	0.5	2	Oven
Cookie	**Minimum**	**Mode**	**Maximum**	**Equipment**
Mix	0.8	1	2	Mixer
Bake	0.2	0.25	0.5	Oven

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Deterministic vs Stochastic

Equipment	Deterministic	Stochastic
Mixer	5	6
Refrigerator	2	2
Proof Oven	2	2
Oven	3	4

70% Confidence Level

Conclusion

- DES can provide defensible equipment lists to support facility sizing development for cost estimates

- Principles for effective use of DES
  - Build model to appropriate level of detail
  - Sufficient time & resources allocated to model development
  - Including stochastic events is preferable
  - Verify & Validate model
  - Use confidence levels as appropriate

- Significant detail is necessary

Backup

Contact

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- Zachary Matheson, Zachary.Matheson@nnsa.doe.gov
- Thomas Cook, Thomas.Cook@nnsa.doe.gov
- Gabriel Sandler, Gabriel.Sandler@nnsa.doe.gov

Modeling Equipment Downtime