Solutions Manual

Discrete-Event System Simulation

Fifth Edition

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Contents

Foreword

There are over three hundred exercises for solution in the text. These exercises emphasize principles of discrete-event simulation and provide practice in utilizing concepts found in the text.

Answers provided here are selective, in that not every problem in every chapter is solved. Answers in some instances are suggestive rather than complete. These two caveats hold particularly in chapters where building of computer simulation models is required. The solutions manual will give the instructor a basis for assisting the student and judging the student's progress. Some instructors may interpret an exercise differently than we do, or utilize an alternate solution method; they are at liberty to do so. We have provided solutions that our students have found to be understandable.

When computer solutions are provided they will be found on the text web site, `www.bcnn.net`, rather than here. Solutions in addition to those noted below may be developed and added to the book's web site.

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Chapter 1

Introduction to Simulation

1.1

	SYSTEM	ENTITIES	ATTRIBUTES	ACTIVITIES	EVENTS	STATE VARIABLES
	Small appliance repair shop	Appliances	Type of appliance Age of appliance Nature of problem	Repairing the appliance	Arrival of a job Completion of a job	Number of appliances waiting to be repaired Status of repair person busy or idle
a.	Cafeteria	Diners	Size of appetite Entree preference	Selecting food Paying for food	Arrival at service line Departures from service line	Number of diners in waiting line Number of servers working
b.	Grocery store	Shoppers	Length of grocery list	Checking out	Arrival at checkout counters Departure from checkout counter	Number of shoppers in line Number of checkout lanes in operation
c.	Laundromat	Washing machine	Breakdown rate	Repairing a machine	Occurrence of breakdowns Completion of service	Number of machines running Number of machines in repair Number of Machines waiting for repair

	SYSTEM	ENTITIES	ATTRIBUTES	ACTIVITIES	EVENTS	STATE VARIABLES
d.	Fast food restaurant	Customers	Size of order desired	Placing the order Paying for the order	Arrival at the counter Completion of purchase	Number of customers waiting Number of positions operating
e.	Hospital emergency room	Patients	Attention level required	Providing service required	Arrival of the patient Departure of the patient	Number of patients waiting Number of physicians working
f.	Taxicab company	Fares	Origination Destination	Traveling	Pick-up of fare Drop-off of fare	Number of busy taxi cabs Number of fares waiting to be picked up
g.	Automobile assembly line	Robot welders	Speed Breakdown rate	Spot welding	Breaking down	Availability of machines

1.3 Abbreviated solution:

Iteration	Problem Formulation	Setting of Objectives and Overall Project Plan
1	Cars arriving at the intersection are controlled by a traffic light. The cars may go straight, turn left, or turn right.	How should the traffic light be sequenced? Criterion for evaluating effectiveness: average delay time of cars. Resources required: 2 people for 5 days for data collection, 1 person for 2 days for data analysis, 1 person for 3 days for model building, 1 person for 2 days for running the model, 1 person for 3 days for implementation.
2	Same as 1 above plus the following: Right on red is allowed after full stop provided no pedestrians are crossing and no vehicle is approaching the intersection.	How should the traffic light be sequenced? Criterion for evaluating effectiveness: average delay time of cars. Resources required: 2 people for 8 days for data collection, 1 person for 3 days for data analysis, 1 person for 4 days for model building, 1 person for 2 days for running the model, 1 person for 3 days for implementation.
3	Same as 2 above plus the following: Trucks arrive at the intersection. Vehicles break down in the intersection making one lane impassable. Accidents occur blocking traffic for varying amounts of time.	How should the traffic light be sequenced? Should the road be widened to 4 lanes? Method of evaluating effectiveness: average delay time of all vehicles. Resources required: 2 people for 10 days for data collection, 1 person for 5 days for data analysis, 1 person for 5 days for model building, 1 person for 3 days for running the model, 1 person for 4 days for implementation.

1.4 Data Needed

Number of guests attending

Time required for boiling water

Time required to cook pasta

Time required to dice onions, bell peppers, mushrooms

Time required to saute onions, bell peppers, mushrooms, ground beef

Time required to add necessary condiments and spices

Time required to add tomato sauce, tomatoes, tomato paste

Time required to simmer sauce

Time required to set the table

Time required to drain pasta

Time required to dish out the pasta and sauce

Events

Begin cooking

Complete pasta cooking } Simultaneous
Complete sauce cooking }

Arrival of dinner guests

Begin eating

Activities

Boiling the water

Cooking the pasta

Cooking sauce

Serving the guests

State variables

Number of dinner guests

Status of the water (boiling or not boiling)

Status of the pasta (done or not done)

Status of the sauce (done or not done)

1.5 Event

Deposit

Withdrawal

Activities

Writing a check

Cashing a check

Making a deposit

Verifying the account balance

Reconciling the checkbook with the bank statement

1.12 (a) 1971 with 1200 attendees

(b) 1972

(c) From Dec. 8, 1971 to Jan. 17, 1973, 1.11 years

(d) DC, Southeast, West

1.15 The pupose of the WSC Foundation is to develop and manage a fund to help insure the continuance and high quality of the WSC.

Chapter 2

Simulation Examples in a Spreadsheet

For additional solutions check the course web site at `www.bcnn.net`. *The numbers resulting from a student's spreadsheet simulation may differ from the results here, depending on the random numbers used.*

In the spreadsheet solutions, the columns labeled "RD Assignment" are for manual solutions using the random digits in Table A. 1. You can ignore these columns when solving the problem in Excel, and instead use the methods in the textbook.

2.1

Customer	Interarrival Time (Minutes)	Clock Arrival Time	Service Time (Minutes)	Clock Time Service Begins	Waiting Time in Queue (Minutes)	Clock Time Service Ends	Time Customer Spends in System (Minutes)	Idle Time of Server (Minutes)
1		0	25	0	0	25	25	
2	0	0	50	25	25	75	75	0
3	60	60	37	75	15	112	52	0
4	60	120	45	120	0	165	45	8
5	120	240	50	240	0	290	50	75
6	0	240	62	290	50	352	112	0
7	60	300	43	352	52	395	95	0
8	120	420	48	420	0	468	48	25
9	0	420	52	468	48	519	99	0
10	120	540	38	540	0	578	38	21
Average			45		19		112	

(a) The average time in the queue for the 10 new jobs is 19 minutes.

(b) The average processing time of the 10 new jobs is 45 minutes.

(c) The maximum time in the system for the 10 new jobs is 112 minutes.

2.2 Profit = Revenue from retail sales - Cost of bagels made + Revenue from grocery store sales - Lost profit.

Let Q = number of dozens baked/day

$S = \sum_i 0_i$, where 0_i = Order quantity in dozens for the ith customer

$Q - S$ = grocery store sales in dozens, $Q > S$

$S - Q$ = dozens of excess demand, $S > Q$

$$\text{Profit} = \$5.40 \min(S, Q) - \$3.80Q + \$2.70(Q - S) - \$1.60(S - Q)$$

Number of Customers	Probability	Cumulative Probability	RD Assignment
8	.35	.35	01-35
10	.30	.65	36-65
12	.25	.90	66-90
14	.10	1.00	91-100

Dozens Ordered	Probability	Cumulative Probability	RD Assignment
1	.4	.4	1-4
2	.3	.7	5-7
3	.2	.9	8-9
4	.1	1.0	0

Pre-analysis

$$
\begin{aligned}
E(\text{Number of Customers}) &= .35(8) + .30(10) + .25(12) + .10(14) \\
&= 10.20
\end{aligned}
$$

$$E(\text{Dozens ordered}) = .4(1) + .3(2) + .2(3) + .1(4) = 2$$

$$E(\text{Dozens sold}) = \bar{S} = (10.20)(2) = 20.4$$

$$
\begin{aligned}
E(\text{Profit}) &= \$5.40\text{Min}(\bar{S}, Q) - \$3.80Q + \$2.70(Q - \bar{S}) - \$1.60(\bar{S} - Q) \\
&= \$5.40\text{Min}(20.4, Q) - \$3.80Q + \$2.70(Q - 20.4) \\
&\quad -\$0.67(20.4 - Q)
\end{aligned}
$$

$$E(\text{Profit}|Q = 0) = 0 - 0 + \$1.60(20.4) = -\$32.64$$

$$
\begin{aligned}
E(\text{Profit}|Q = 10) &= \$5.40(10) - \$3.80(10) + 0 - \$1.60(20.4 - 10) \\
&= -\$0.64
\end{aligned}
$$

$$
\begin{aligned}
E(\text{Profit}|Q = 20) &= \$5.40(20) - \$3.80(20) + 0 - \$1.60(20.4 - 20) \\
&= \$15.36
\end{aligned}
$$

$$
\begin{aligned}
E(\text{Profit}|Q = 30) &= \$5.40(20.4) - \$3.80(30) + \$2.70(30 - 20.4) - 0 \\
&= \$22.08
\end{aligned}
$$

$$
\begin{aligned}
E(\text{Profit}|Q = 40) &= \$5.40(20.4) - \$3.80(40) + \$2.70(40 - 20.4) - 0 \\
&= \$11.08
\end{aligned}
$$

The pre-analysis, based on expectation only, indicates that simulation of the policies $Q = 20, 30$, and 40 should be sufficient to determine the policy. The simulation should begin with $Q = 30$, then proceed to $Q = 40$, then, most likely to $Q = 20$.

Initially, conduct a simulation for $Q = 20, 30$ and 40. If the profit is maximized when $Q = 30$, it will become the policy recommendation.

The problem requests that the simulation for each policy should run for 5 days. This is a very short run length to make a policy decision.

$Q = 30$

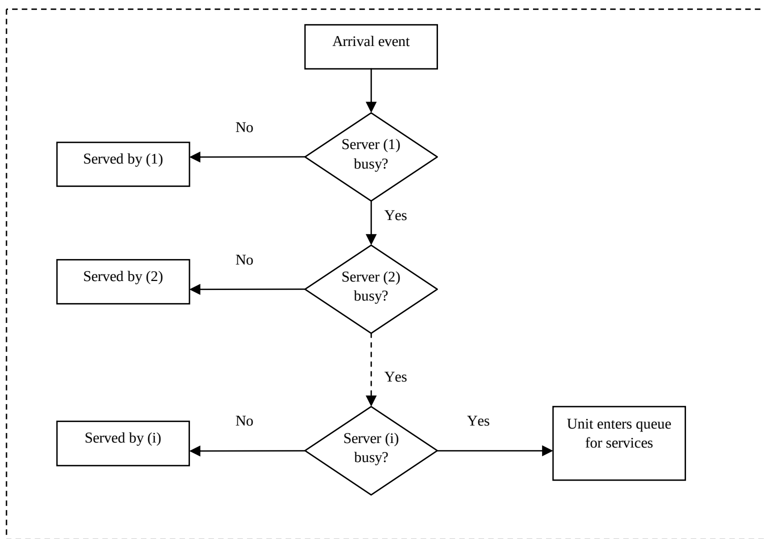
Day	RD for Customer	Number of Customers	RD for Demand	Dozens Ordered	Revenue from Retail $	Lost Profit $
1	44	10	8	3	16.20	0
			2	1	5.40	0
			4	1	5.40	0
			8	3	16.20	0
			1	1	5.40	0
			6	2	10.80	0
			3	1	5.40	0
			0	4	21.60	0
			2	1	5.40	0
			0	4	21.60	0
				21	113.40	0

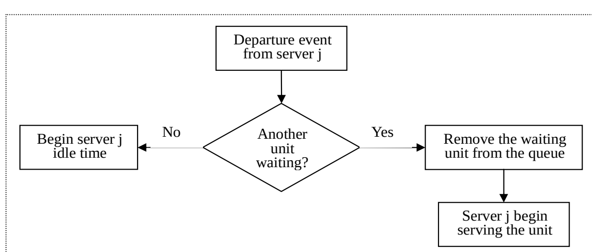
For Day 1,

Profit = \$113.40 − \$152.00 + \$24.30 − 0 = \$14.30

Days 2, 3, 4 and 5 are now analyzed and the five day total profit is determined.

2.3 For a queueing system with i channels, first rank all the servers by their processing rate. Let (1) denote the fastest server, (2) the second fastest server, and so on.





2.4

Time Between Calls	Probability	Cumulative Probability	RD Assignment
15	.14	.14	01-14
20	.22	.36	15-36
25	.43	.79	37-79
30	.17	.96	80-96
35	.04	1.00	97-00

Service Time	Probability	Cumulative Probability	RD Assignment
5	.12	.12	01-12
15	.35	.47	13-47
25	.43	.90	48-90
35	.06	.96	91-96
45	.04	1.00	97-00

First, simulate for one taxi for 5 days.
Then, simulate for two taxis for 5 days. } Shown on simulation tables

Comparison

Smalltown Taxi would have to decide which is more important—paying for about 43 hours of idle time in a five day period with no customers having to wait, or paying for around 4 hours of idle time in a five day period, but having a probability of waiting equal to 0.59 with an average waiting time for those who wait of around 20 minutes.

One Taxi

Day	Call	RD for Time between Calls	Time between Calls	Call Time	RD for Service Time	Service Time	Time Service Begins	Time Customer Waits	Time Service Ends	Time Customer in System	Idle Time of Taxi
1	1	15	-	0	01	5	0	0	5	5	0
	2	01	20	20	53	25	20	0	55	25	0
	3	14	15	35	62	25	55	20	80	45	0
	4	65	25	60	55	25	80	20	105	45	0
	5	73	25	85	95	35	105	20	140	55	0
	6	48	25	110	22	15	140	30	155	45	0
	⋮										
	20	77	25	444	63	25	470	25	495	50	0
2											
⋮											

Typical results for a 5 day simulation:

Total idle time = 265 minutes = 4.4 hours

Average idle time per call = 2.7 minutes

Proportion of idle time = .11

Total time customers wait = 1230 minutes

Average waiting time per customer = 11.9 minutes

Number of customers that wait = 61 (of 103 customers)

Probability that a customer has to wait = .59

Average waiting time of customers that wait = 20.2 minutes

Two taxis (using common RDs for time between calls and service time)

					Taxi 1			Taxi 2						
Day	Call	Time between Calls	Call Time	Service Time	Time Service Begins	Service Time	Time Service Ends	Time Service Begins	Service Time	Time Service Ends	Time Customer Waits	Time Customer in System	Idle Time Taxi 1	Idle Time Taxi 2
1	1	-	0	5	0	5	5				0	5		
	2	20	20	25	20	25	45				0	25		
	3	15	35	25				35	25	60	0	25		35
	4	25	60	25	60	25	85				0	25	15	
	5	25	85	35	80	35	120				0	35		
	6	25	110	15				110	15	125	0	15		50
	⋮													
	20	20	480	25	480	25	505				0	25	10	
2														
⋮														

Typical results for a 5 day simulation:

Idle time of Taxi 1 = 685 minutes

Idle time of Taxi 2 = 1915 minutes

Total idle time = 2600 minutes = 43 hours

Average idle time per call = 25.7 minutes

Proportion of idle time = .54

Total time customers wait = 0 minutes

Number of customers that wait = 0

2.5 For manual simulations, RNN_x is a random normal number from Table A. 2. For spreadsheet simulations, it is generated from the appropriate VBA function as described in Chapter 2. Similarly for RNN_y and RNN_z.

$$\begin{aligned} X &= 100 + 10RNN_x \\ Y &= 300 + 15RNN_y \\ Z &= 40 + 8RNN_z \end{aligned}$$

Typical results...

	RNN_x	X	RNN_y	Y	RNN_z	Z	W
1	-.137	98.63	.577	308.7	-.568	35.46	11.49
2	.918	109.18	.303	304.55	-.384	36.93	11.20
3	1.692	116.92	-.383	294.26	-.198	38.42	10.70
4	-.199	98.01	1.033	315.50	.031	40.25	10.27
5	-.411	95.89	.633	309.50	.397	43.18	9.39
⋮							

After generating the 50 values of W, you can use a bar chart in Excel to develop the histogram.

2.6

Value of B	Probability	Cumulative Probability	RD Assignment
0	0.2	0.2	1-2
1	0.2	0.4	3-4
2	0.2	0.6	5-6
3	0.2	0.8	7-8
4	0.2	1	9-0

Value of C	Probability	Cumulative Probability	RD Assignment
10	0.1	0.1	1-10
20	0.25	0.35	11-35
30	0.5	0.85	36-85
40	0.15	1	86-1

Customer	A	B	C	D
1	79.23	2	30	2
2	113.04	3	30	32
3	58.53	0	20	1.46
4	99.68	0	20	2.49
5	87.15	0	10	4.36
6	91.05	1	40	0.83
7	66.97	1	30	0.7
8	104.88	3	30	0.5
9	61.6	1	30	0.61
10	98.92	3	30	0.4
Average	86.1	1.4	27	4.53

2.7

Lead Time (Days)	Probability	Cumulative Probability	RD Assignment
0	.166	.166	001-166
1	.166	.332	167-332
2	.166	.498	333-498
3	.166	.664	499-664
4	.166	.830	665-830
5	.166	.996	831-996
			996-000 (discard)

Assume 5-day work weeks.

$$D = \text{Demand}$$
$$D = 5 + 1.5(RNN)(\text{ Rounded to nearest integer})$$

Week	Day	Beginning Inventory	RNN for Demands	Demand	Ending Inventory	Order Quantity	RD for Lead Time	Lead Time	Lost Sales
1	1	18	-1.40	3	15				0
	2	15	-.35	4	11				0
	3	11	-.38	4	7	13	691	4	0
	4	7	.05	5	2				0
	5	2	.36	6	0				4
2	6	0	.00	5	0				5
	7	0	-.83	4	0				4
	8	13	-1.83	2	11				0
	9	11	-.73	4	7	13	273	1	0
	10	7	-.89	4	3				0
⋮									

Typical results
Average number of lost sales/week = 24/5 = 4.8 units/weeks

2.8 Material *A* (200kg/box)

Interarrival Time	Probability	Cumulative Probability	RD Assignment
3	.2	.2	1-2
4	.2	.4	3-4
5	.2	.6	5-6
6	.2	.8	7-8
7	.2	1.0	9-0

Box	RD for Interarrival Time	Interarrival Time	Clock Time
1	1	3	3
2	4	4	7
3	8	6	13
4	3	4	17
⋮			
14	4	4	60

Material *B* (100kg/box)

Box	1	2	3	⋯	10
Clock Time	6	12	18	⋯	60

Material *C* (50kg/box)

Interarrival Time	Probability	Cumulative Probability	RD Assignment
2	.33	.33	01-33
3	.67	1.00	34-00

Box	RD for Interarrival Time	Interarrival Time	Clock Time
1	58	5	3
2	92	3	6
3	87	3	9
4	31	2	11
⋮	⋮	⋮	⋮
22	62	3	60

Clock Time	*A* Arrival	*B* Arrival	*C* Arrival
3	1		1
6		1	2
7	2		
9			3
11			4
12		2	
⋮			