Digital Companion Appendix A: TP Model without Patient Crossovers

The model without crossovers is identical for the nurse step, but lends itself to a much easier formulation of the provider step as the sequence of patients is fixed regardless of the scenario.

$$Min. \quad \frac{1}{S}\left(\alpha\left[\sum_{k}\sum_{s}\left(\left(z_{J_k,s}^{k,finish}-\sum_{k=1}^{J_k}\tau_{j,s}^{P_k}\right)\right)\right]+\beta\left[\sum_{s}\sum_{i=1}^{n}\left(y_{i,s}^{start}-15X_i\right)+\sum_{s}\left(\sum_{k}\sum_{j=1}^{J_k}\left(z_{j,s}^{k,start}-t_{j,s}^{k}\right)\right)\right]\right) \quad (1)$$

Subject to.

$$y_{i,s}^{start}=0 \quad \forall s\in S, i=1,2 \quad (2)$$

$$z_{0,s}^{k,finish}=0 \quad \forall k\in K, s\in S \quad (3)$$

$$X_i=0 \quad i=1,2 \quad (4)$$

$$y_{3,s}^{start}\geq \min\left(y_{1,s}^{finish}, y_{2,s}^{finish}\right) \quad \forall s\in S \quad (5)$$

$$N_{3,s}^{max}\geq \max\left(y_{1,s}^{finish}, y_{2,s}^{finish}\right) \quad \forall s\in S \quad (6)$$

$$N_{i,s}^{max}\geq \max\left(N_{i-1,s}^{max}, y_{i-1,s}^{finish}\right) \quad \forall i\in 4..I, s\in S \quad (7)$$

$$y_{i,s}^{start}\geq \min\left(N_{i-1,s}^{max}, y_{i-1,s}^{finish}\right) \quad \forall i\in 4..I, s\in S \quad (8)$$

$$y_{i,s}^{finish}=y_{i,s}^{start}+\tau_{i,s}^{N} \quad \forall i\in I, s\in S \quad (9)$$

$$y_{i,s}^{start}\geq 15X_i \quad \forall i\in I, s\in S \quad (10)$$

$$t_{j,s}^{k}=y_{f[j,k],s}^{finish} \quad \forall k\in K, j\in J_k, s\in S \quad (11)$$

$$z_{j,s}^{k,start}\geq t_{j,s}^{k} \quad \forall k\in K, j\in J_k, s\in S \quad (12)$$

$$z_{j,s}^{k,finish}=z_{j,s}^{k,start}+\tau_{j,s}^{P_k} \quad \forall k\in K, j\in J_k, s\in S \quad (13)$$

$$z_{j,s}^{k,start}\geq z_{j-1,s}^{k,finish} \quad \forall k\in K, j\in J_k, s\in S \quad (14)$$

$$X\geq 0, INT;\ y^{start}, y^{finish}, z^{start}, z^{finish}\geq 0$$

Digital Companion Appendix B: Computational Results for Lognormally Distributed Nurse and Provider Service Times

B1. Computational Performance as Service Time Variance Increases

Optimality Gaps for Medium (8 patients per provider) and Large Instances (10 patients per provider) with Lognormally Distributed Service Times with and without Lower Bounds Created by Solving 100 Groups of 10-Scenario Problems

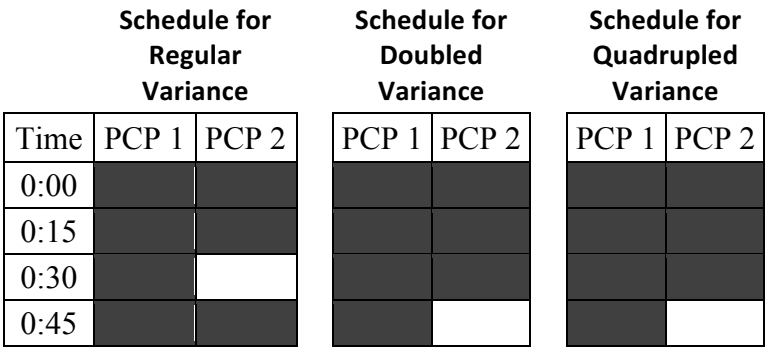
Without Scenario-Groups Lower Bounds			
Gaps	Regular Variance	Doubled Variance	Quadrupled Variance
Medium Instances	12.71%	10.64%	7.12%
Large Instances	22.41%	18.39%	11.15%
With Scenario-Groups Lower Bounds			
Gaps	Regular Variance	Doubled Variance	Quadrupled Variance
Medium Instances	3.81%	3.66%	3.44%
Large Instances	5.05%	5.14%	4.32%

B2. Schedule Sensitivity to Service Time Variance and Idle vs. Wait Time Cost Ratio

The optimal schedules displayed below show 1) when idle time is prioritized with a cost ratio of 4, fewer empty slots are needed as variability increases, and 2) as a heavier weight is placed on wait time, with cost ratios of 2 and 1, more slack is added and variability does not affect the optimal schedule.

Schedules for Small Instances (5 patients per provider) with Lognormally Distributed Service Times for different Cost Ratios (4 (0.8:0.2 idle time/wait time), 2 (0.67:0.33 idle time/wait time) and 1 (0.5:0.5 idle time/wait time)) and for different Service Time Variance

Cost Ratio of 4



1:00							
1:15							
1:30							

Cost Ratio of 2

	Schedule for Regular Variance		Schedule for Doubled Variance		Schedule for Quadrupled Variance	
Time	PCP 1	PCP 2	PCP 1	PCP 2	PCP 1	PCP 2
0:00						
0:15						
0:30						
0:45						
1:00						
1:15						
1:30						

Cost Ratio of 1

	Schedule for Regular Variance		Schedule for Doubled Variance		Schedule for Quadrupled Variance	
Time	PCP 1	PCP 2	PCP 1	PCP 2	PCP 1	PCP 2
0:00						
0:15						
0:30						
0:45						
1:00						
1:15						
1:30						
1:45						
2:00						

Wait time vs. Idle Time(min) for Small Instances (5 patients per provider) with Lognormally Distributed Service Times for different Cost Ratios (4 (0.8:0.2 idle time/wait time), 2 (0.67:0.33 idle time/wait time) and 1 (0.5:0.5 idle time/wait time))

	CR1			CR2			CR4		
	Mean	Median	90th Percentile	Mean	Median	90th Percentile	Mean	Median	90th Percentile
	Regular Variance								
Wait	3.69	1.7	9.3	9.44	6.4	21.2	10.35	7.2	23.52
Idle	56.39	55.5	78	36.08	34.5	54.5	34.92	33.5	53.55
	Objective Function: 74.84			Objective Function: 79.56			Objective Function: 76.57		
	Doubled Variance								
Wait	5.59	2.7	14.31	10.05	6.1	23.92	14.41	9.6	32.62
Idle	61.12	60.25	89.5	46.06	43	73	38.32	34.5	65
	Objective Function: 89.07			Objective Function: 94.90			Objective Function: 90.14		
	Quadrupled Variance								
Wait	7.98	3.4	20.51	13.3	7.25	33.03	17.79	10.7	43.22
Idle	66.9	64	103.05	49.93	44.5	85.1	43.23	36.5	80.05
	Objective Function: 106.81			Objective Function: 110.89			Objective Function: 104.75		

B3. Effect of Crossovers

Wait time vs. Idle Time (min) for Small Instances (5 patients per provider) with Lognormally Distributed Service Times for Models with and without Crossovers for different Cost Ratios

Cost Ratio of 4 (0.8:0.2 weights on idle time/wait time)

	No crossover			Crossover		
	Mean	Median	90th Percentile	Mean	Median	90th Percentile
	Regular Variance					
Wait	10.56	7.1	24.21	10.35	7.2	23.52
Idle	37.28	35.5	58	34.92	33.5	53.55
	Objective Function: 80.77			Objective Function: 76.57		
	Doubled Variance					
Wait	17.07	11.35	39.62	14.41	9.6	32.62
Idle	41.08	37	69.5	38.32	34.5	65
	Objective Function: 99.87			Objective Function: 90.13		
	Quadrupled Variance					
Wait	21.75	13.65	50.55	17.79	10.7	43.22
Idle	48.95	41	89	43.23	36.5	80.05
	Objective Function: 121.82			Objective Function: 104.75		

Cost Ratio of 1 (0.5:0.5 weights on idle time/wait time)

	No crossover			Crossover		
	Mean	Median	90th Percentile	Mean	Median	90th Percentile
	Regular Variance					
Wait	4.46	2	11.41	3.69	1.7	9.3
Idle	57.02	56.5	79	56.39	55.5	78

	Objective Function: 79.32			Objective Function: 74.84		
	Doubled Variance					
Wait	7.51	3.5	19.13	5.59	2.7	14.31
Idle	62.83	61	92	61.12	60.25	89.5
	Objective Function: 100.38			Objective Function: 89.07		
	Quadrupled Variance					
Wait	12.08	5.4	31.21	7.98	3.4	20.51
Idle	70.04	66	108.05	66.9	64	103.05
	Objective Function: 130.44			Objective Function: 106.81		

Percentages of Crossovers for Instances with Lognormally Distributed Service Times

Instance	Crossover Percentage
Small instance, regular variance	5.35%
Small instance, doubled variance	10.34%
Small instance, quadrupled variance	13.40%
Medium instance, regular variance	7.49%
Medium instance, doubled variance	12.39%
Medium instance, quadrupled variance	13.70%
Large instance, regular variance	8.95%
Large instance, doubled variance	18.64%
Large instance, quadrupled variance	15.13%

B4. Effect of Decreasing the Length Appointment Time slots

Our model considers 15min appointment slots; that is, patients will only be given appointments at the quarters of the hour (e.g. 8AM, 8:15AM, 8:30AM, etc.). Below, we first compare the performance of these 15min slot appointments to 5min slots (e.g. 8AM, 8:05AM, 8:10AM, etc.) As an extreme case, we also consider the continuous appointment problem, where patients can be given appointments at any time (e.g. 8:03AM).

Wait Time vs. Idle Time for Small Instance (5 patients per provider) with Lognormally Distributed Service Times with 5-minute vs. 15-minute Appointment Intervals

	5 minutes Appointment			15 minutes Appointment		
	Mean	Median	90th Percentile	Mean	Median	90th Percentile
Wait	9.91	6.6	23.3	10.35	7.2	23.52
Idle	34.53	33	53.5	34.92	33.5	53.55
	Objective Function: 75.07			Objective Function: 76.57		

Wait Time vs. Idle Time for Small Instances (5 patients per provider) with Lognormally Distributed Service Times with Continuous vs. 15-minute Appointment Intervals

	Continuous Appointment			15 minutes Appointment		
	Mean	Median	90th Percentile	Mean	Median	90th Percentile
	Regular Variance					
Wait	10.45	7	24.4	10.35	7.2	23.52
Idle	33.68	32	53	34.92	33.5	53.55
	Objective Function: 74.8			Objective Function: 76.57		
	Doubled Variance					
Wait	13	8.2	31.93	14.41	9.6	32.62
Idle	39.15	35.5	64.55	38.32	34.5	65
	Objective Function: 88.64			Objective Function: 90.13		
	Quadrupled Variance					
Wait	15.79	9.05	39.81	17.79	10.7	43.22
Idle	44.86	38	82	43.23	36.5	80.05
	Objective Function: 103.36			Objective Function: 104.75		