Modeling Variability of Intensive Care Unit Demand: a Comparative Cost Analysis and Performance Evaluation of Fixed versus Variable Beds structures with a simulation approach.

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Abstract

Introduction. High demand, limited intensive care unit (ICU) beds, and costs pose a sustainability challenge in healthcare. Simulation modelling helps examine ICU bed assignment policies.[1] Our study compares the performance of two management strategies: fixed versus variable bed availability. Estimating length of stay (LOS) is a complex process [2, 3] due to ICU daily uncertainties: we developed an ICU LOS prediction model integrated into a complex simulation model.

Materials and Method. Anonymized data of adult patients from *AmsterdamUMCdb* (2003-2016) were used. Admission rate (AR) was estimated from elective and urgent patients cumulative AR. Using coefficients for four-time slots and days of the week, we estimated the lambda parameter of a Poisson distribution and simulated random admissions. The best fixed-bed ICU was which one minimises costs: a Monte Carlo (MC) simulation was performed on a bed occupancy algorithm (Image 1), a stochastic bootstrapping LOS simulation[4]. ICU bed cost was 1425 Euros/day, with fixed costs 0.43.[5] In a closed system, a patient unsuccessfully demanding ICU was considered rejected. According to literature, each urgent life saved costs 111,035 Euros [6] delayed elective procedures costs 1,000 Euros, resulting in 21,927.22 Euros per rejected patient. MC simulation produces the outcomes: $RejectionIndex = \frac{\text{Patients Rejected}}{\text{Days Simulation}}$ and $FreeFreeBedsIndex = \frac{\text{Hours Free Beds}}{\text{Days Simulation}}$. The optimal number of beds has been determined by minimising the product of these values and their associated expenses. LOS prediction was obtained from a regression random forest model and a stochastic approach. MAE, MSE and RMSE confronted different models in a subset test.

A complex model that incorporates optimal variation in the number of beds within a range of 0.875 to 1.125 times the calculated ideal bed capacity was built. A probability score executed every 24 hours allowed for the opening or closing of variable beds seven days in advance. The prediction model was based on an MC simulation that considered the estimation of remaining LOS for admitted patients, the estimation of incoming patients for the next seven days, and a stochastic estimation of LOS for these patients. Another MC simulation was used to optimize this probability cut-off to minimise costs. The results in terms of costs of fixed and variable bed simulations were compared using an MC simulation.

Results. The admission ratio was 0.19 patients/hour. Elective-to-urgent admission ratio was 2.70. The best number which minimises ICU beds in the fixed model was n=42 (Image 2) which resulted in a cost of €1865.276±€2488.486 for rejected patients and €7,412.416±€1,592.51 for unused beds (total daily cost of €9,277.692±€2,954.429). The random forest regression model showed a bad test accuracy (0.40) without overfitting. After probability coefficient optimisation, Variable-Beds ICU resulted in a total daily cost of €10,728.200±€4,296.201.

Conclusion. In a healthcare system that daily faces the presence of limited resources, a variable-bed intensive care model that meets patient needs while allowing for well-planned resource allocation can offer advantages.

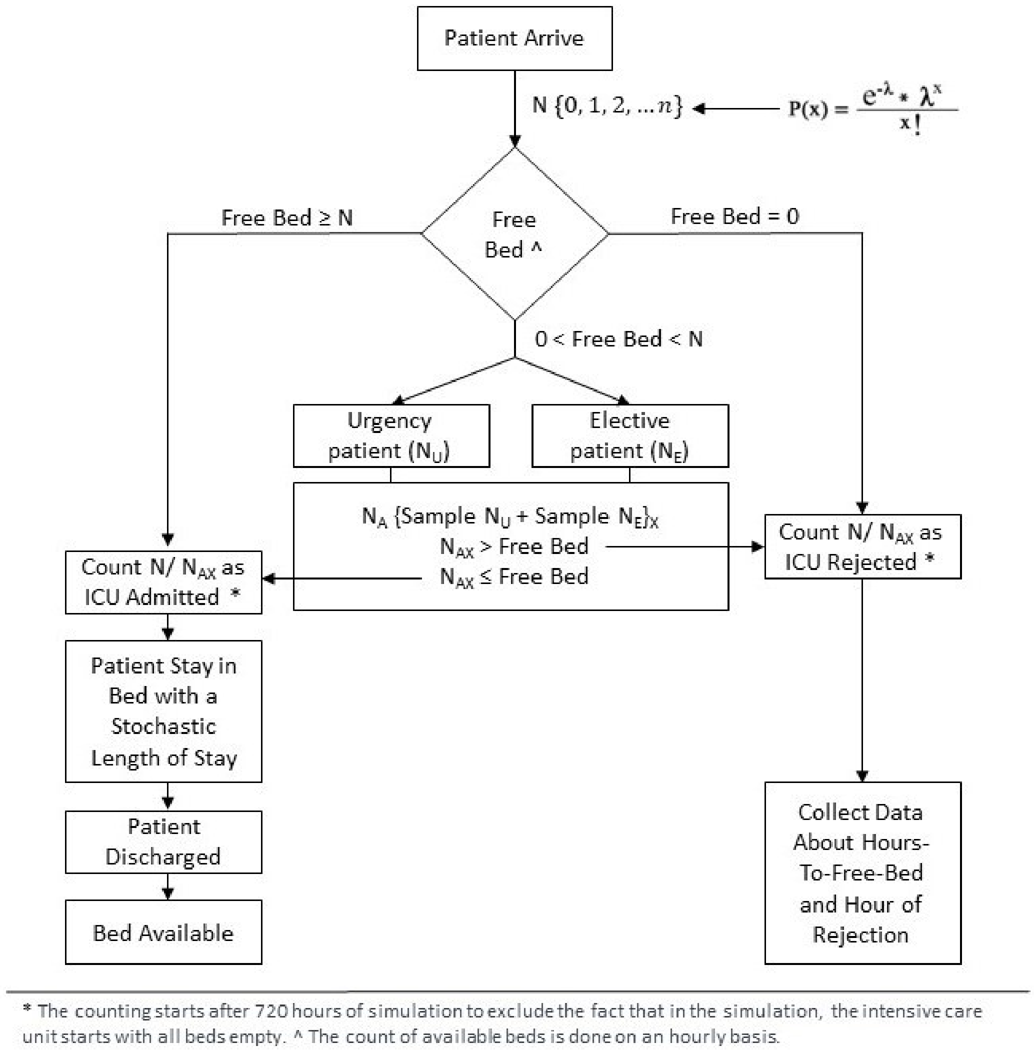

Figure 1: The algorithm considers an admission rate based on an hourly probability distribution following a Poisson distribution with lambda derived from the array of admission coefficients 1 2. The length of stay (LOS) is modeled stochastically by bootstrapping from the LOS distribution in the database. This type of simulation allows for the extraction of two parameters considered for cost analysis: the number of patients rejected from the intensive care unit and the number of hours that each intensive care bed remains unused. Firs 30 simulation days were not considered in the result considering that ICU started with all beds empty.

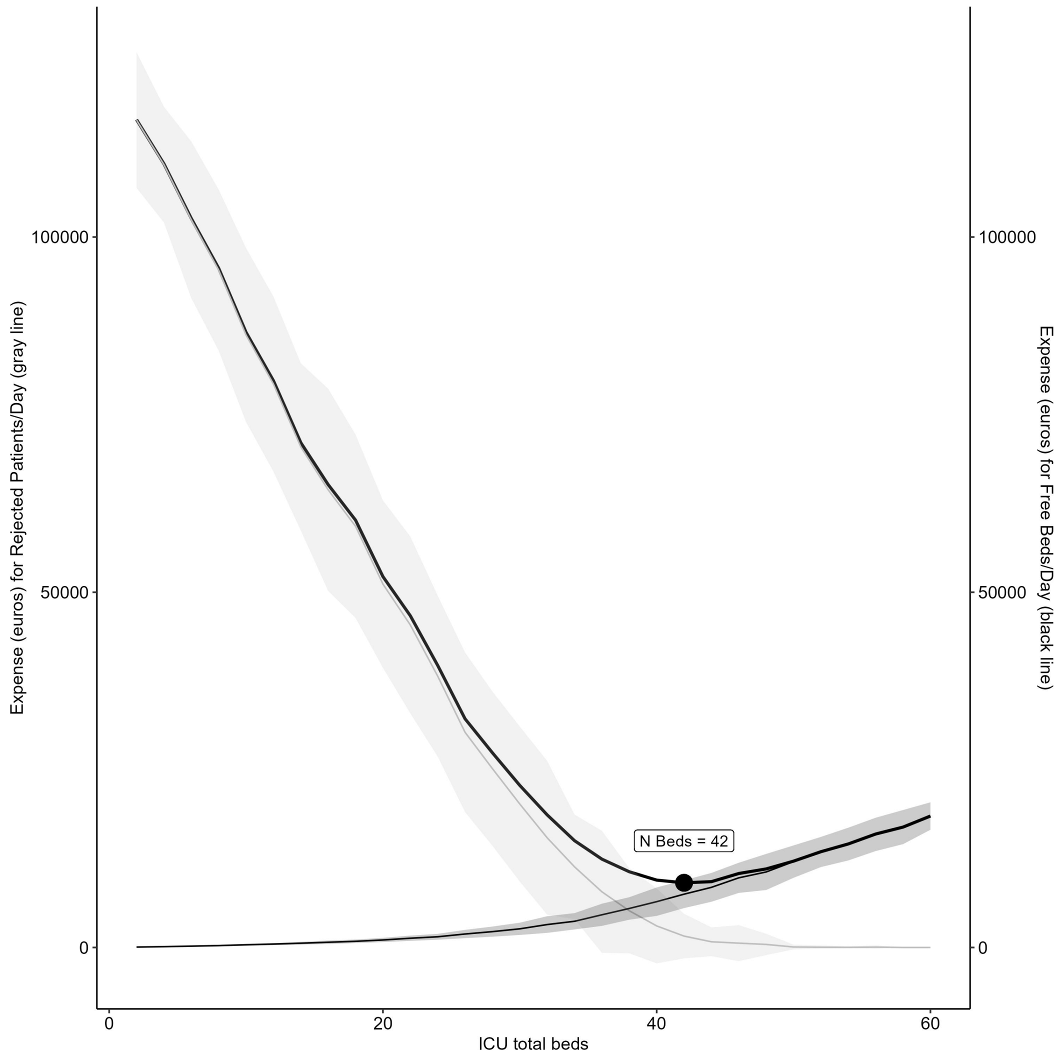

Figure 2: Simulation to find the best number of beds minimizing costs for rejected patients and unused beds.The simulation considers a number of beds ranging from 2 to 60, a simulation duration of 60 days (1440 hours), and a total number of simulations set to S = 100. Cost were based on cost table 4 in appendix. N = 42 beds minimize cost. Raw data are available in appendix table 5 and 3.

References

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Appendix

Files used for the simulation are available with public access in the GitHub repository.

Table 1: Coefficient for Elective Admission Rate

1	2	3	4	5	6	7
0.12	0.12	0.12	0.12	0.12	0.01	0.01
0.57	0.57	0.57	0.57	0.57	0.04	0.04
0.24	0.24	0.24	0.24	0.24	0.02	0.02
0.02	0.02	0.02	0.02	0.02	0.00	0.00

Table 2: Coefficient for Urgency Admission Rate

1	2	3	4	5	6	7
0.06	0.06	0.06	0.06	0.06	0.06	0.06
0.06	0.06	0.06	0.06	0.06	0.06	0.06
0.07	0.07	0.07	0.07	0.07	0.07	0.07
0.06	0.06	0.06	0.06	0.06	0.06	0.06

Table 3: Simulation to find the best number of beds minimizing costs for rejected patients and unused beds: the frequency. The simulation considers a number of beds ranging from 2 to 60, a simulation duration of 60 days (1440 hours), and a total number of simulations set to S = 100. Cost were based on cost table4

Bed Number	Rejected patients/Bed/Day	Hour available Bed/Day
2	5.3113 ± 0.3400	2.247 ± 0.9178
4	5.0252 ± 0.2901	4.4963 ± 1.5558
6	4.6708 ± 0.3925	7.3942 ± 2.228
8	4.348 ± 0.4036	10.3475 ± 3.1471
10	3.9313 ± 0.4358	14.856 ± 3.9299
12	3.6167 ± 0.4388	18.7368 ± 4.355
14	3.2132 ± 0.4194	23.4892 ± 5.7418
16	2.9375 ± 0.5069	28.759 ± 7.5265
18	2.7035 ± 0.4596	34.0033 ± 7.5753
20	2.3327 ± 0.4198	41.3173 ± 9.186
22	2.0702 ± 0.4432	50.9442 ± 11.3079
24	1.742 ± 0.4031	58.9408 ± 12.6252
26	1.3813 ± 0.4000	74.237 ± 17.8239
28	1.1478 ± 0.3866	87.3702 ± 21.8234
30	0.9207 ± 0.3887	102.7528 ± 26.3909
32	0.704 ± 0.3855	126.3383 ± 35.7823
34	0.5173 ± 0.262	144.3507 ± 35.1673
36	0.3572 ± 0.3059	180.197 ± 47.7418
38	0.2355 ± 0.2131	215.0863 ± 48.4461
40	0.1383 ± 0.1877	252.5145 ± 61.2839
42	0.073 ± 0.1116	293.7988 ± 59.9283
44	0.0365 ± 0.072	331.49 ± 62.0244
46	0.0277 ± 0.0902	383.9862 ± 64.9582
48	0.0195 ± 0.0534	416.2918 ± 77.7093
50	0.0031 ± 0.0118	473.3305 ± 69.7185
52	0.0018 ± 0.0088	526.467 ± 64.9048
54	0.0009 ± 0.005	570.0527 ± 70.53
56	0.0024 ± 0.0089	623.4448 ± 71.7614
58	0.0000 ± 0.0000	663.6752 ± 73.4481
60	0.0000 ± 0.0000	724.5952 ± 59.104

Table 4: Coefficients of costs related to a patient rejected from the intensive care unit and to an unoccupied bed for 24 hours.

fixCost (euros)	rejcost (euros)
612.75	21,927.22

Table 5: Simulation to find the best number of beds minimizing costs for rejected patients and unused beds: the expense.The simulation considers a number of beds ranging from 2 to 60, a simulation duration of 60 days (1440 hours), and a total number of simulations set to S = 100. Cost were based on cost table4. N = 42 beds minimize cost.

Bed Number	Expense for Rejected patients/Day	Expense for Hour available/Day
2	116462.79 ± 7455.07	57.37 ± 23.43
4	110187.95 ± 6361.20	114.80 ± 39.72
6	102418.41 ± 8606.36	188.78 ± 56.88
8	95339.57 ± 8849.79	264.18 ± 80.35
10	86203.23 ± 9556.48	379.29 ± 100.34
12	79303.46 ± 9620.74	478.37 ± 111.19
14	70455.82 ± 9195.92	599.71 ± 146.60
16	64411.22 ± 11114.10	734.25 ± 192.16
18	59280.25 ± 10077.31	868.15 ± 193.41
20	51148.90 ± 9204.22	1054.88 ± 234.53
20	45393.01 ± 9717.19	1300.67 ± 288.70
24	38197.22 ± 8839.45	1504.83 ± 322.34
26	30288.81 ± 8770.16	1895.36 ± 455.07
28	25168.80 ± 8477.38	2230.67 ± 557.18
30	20187.66 ± 8522.05	2623.41 ± 673.79
32	15436.77 ± 8452.59	3225.58 ± 913.57
34	11343.68 ± 5745.30	3685.45 ± 897.86
36	7831.67 ± 6706.98	4600.65 ± 1218.91
38	5163.86 ± 4673.36	5491.42 ± 1236.89
40	3033.27 ± 4116.82	6447.01 ± 1564.65
42	1600.69 ± 2447.29	7501.05 ± 1530.04
44	800.34 ± 1579.53	8463.35 ± 1583.56
46	607.85 ± 1978.80	9803.65 ± 1658.46
48	427.66 ± 1170.04	10628.45 ± 1984.02
50	67.12 ± 258.93	12084.72 ± 1780.00
52	38.76 ± 193.69	13441.36 ± 1657.10
54	18.65 ± 109.73	14554.16 ± 1800.72
56	52.21 ± 195.34	15917.33 ± 1832.16
58	0.00 ± 0.00	16944.46 ± 1875.22
60	0.00 ± 0.00	18499.82 ± 1509.00

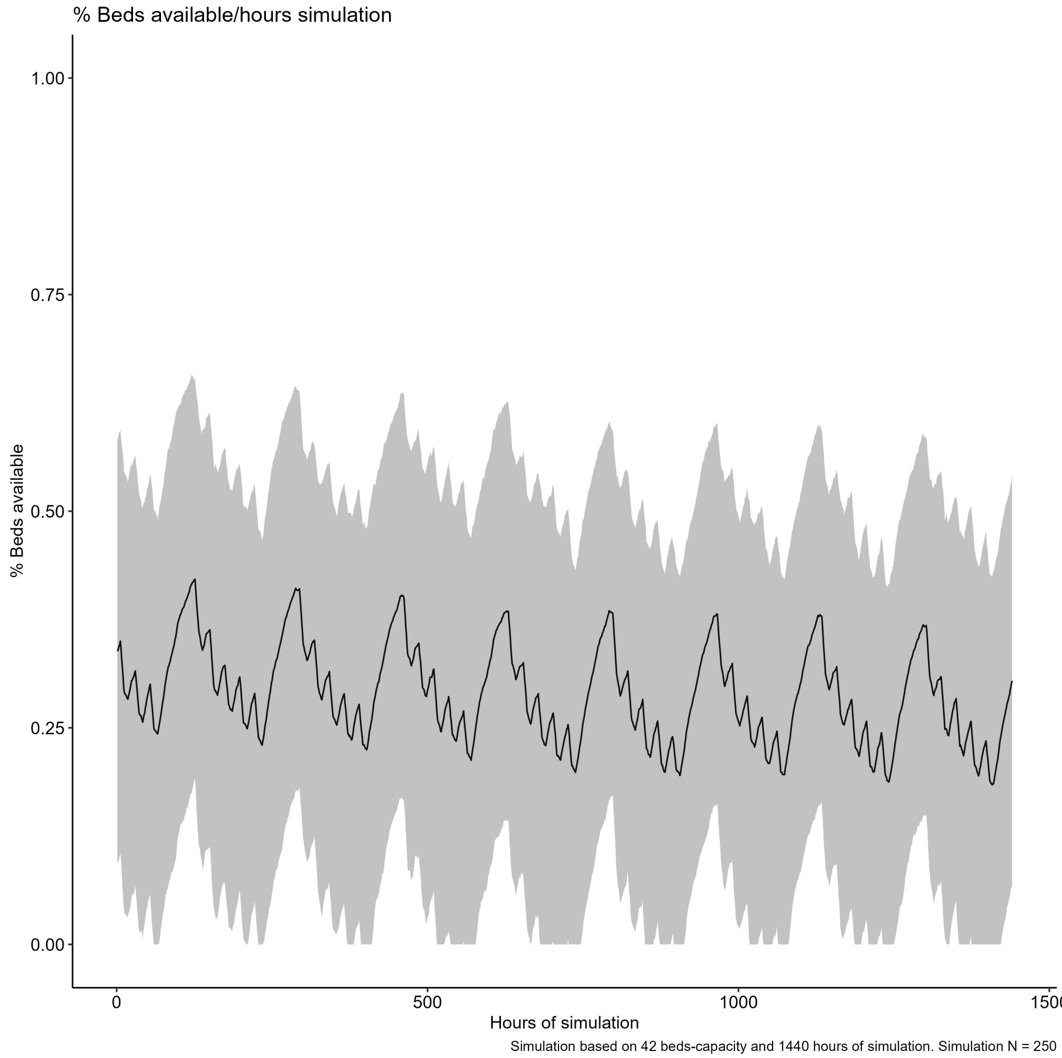

Figure 3: 250 simulations of a 42 fixed-bed ICU for sixty days. It is possible to observe changes in bed occupancy for cyclic difference in admission coefficients.

Table 6: Simulation to find the best coefficient for IntellICU Algorithm to minimize costs. 0.0, which imply simple opening af variable beds result in less cost.

IntellICU Coefficient	Expense for Rejected patients/Day	Expense for Hour available/Day
0.00	4531.6262 ± 3396.3089	6050.6594 ± 1350.5841
0.10	4590.0988 ± 3951.3727	6026.4133 ± 1080.6000
0.20	5934.9685 ± 4063.8637	5465.3045 ± 1082.9104
0.30	5934.9685 ± 4451.7935	5345.8182 ± 1260.7002
0.40	7930.3459 ± 5018.0512	5207.4303 ± 1285.3426
0.50	6527.0036 ± 4225.9267	5172.0270 ± 1091.4006
0.60	7645.2920 ± 5410.9119	4931.9482 ± 1300.4846
0.70	9180.1977 ± 6072.5584	4724.7110 ± 1265.2407
0.80	8712.4169 ± 6372.4852	4492.4702 ± 1302.9215
0.90	9691.8329 ± 6066.0916	4406.9831 ± 1116.7737
1.00	15926.4735 ± 7112.5519	3211.4057 ± 777.4318

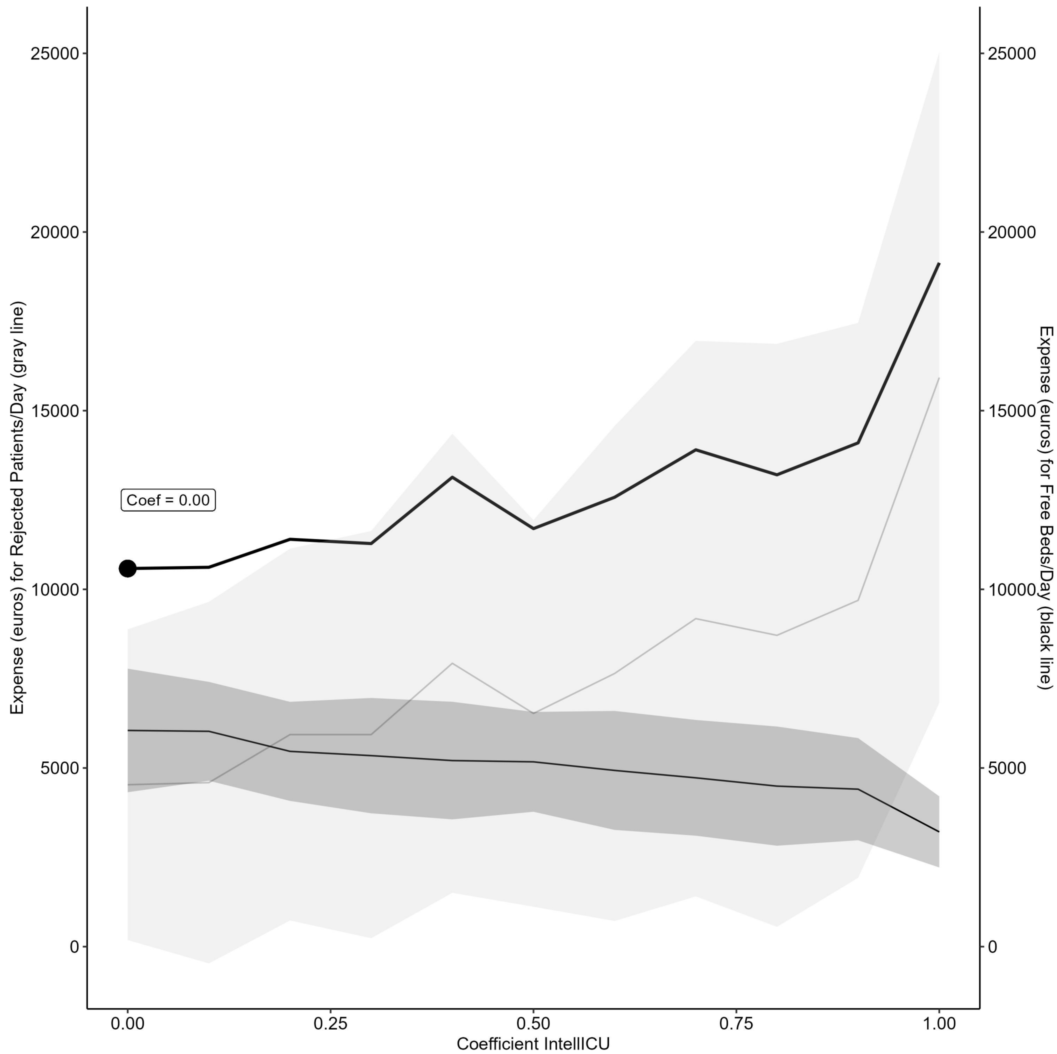

Figure 4: Simulation to find the best IntellICU coefficient to minimizing costs for rejected patients and unused beds.The simulation considers a number of beds ranging from 37 to 47, a simulation duration of 60 days (1440 hours), and a total number of simulations set to S = 100. Cost were based on cost table6 in appendix. IntellICU Coefficient = 0.00 minimize cost.

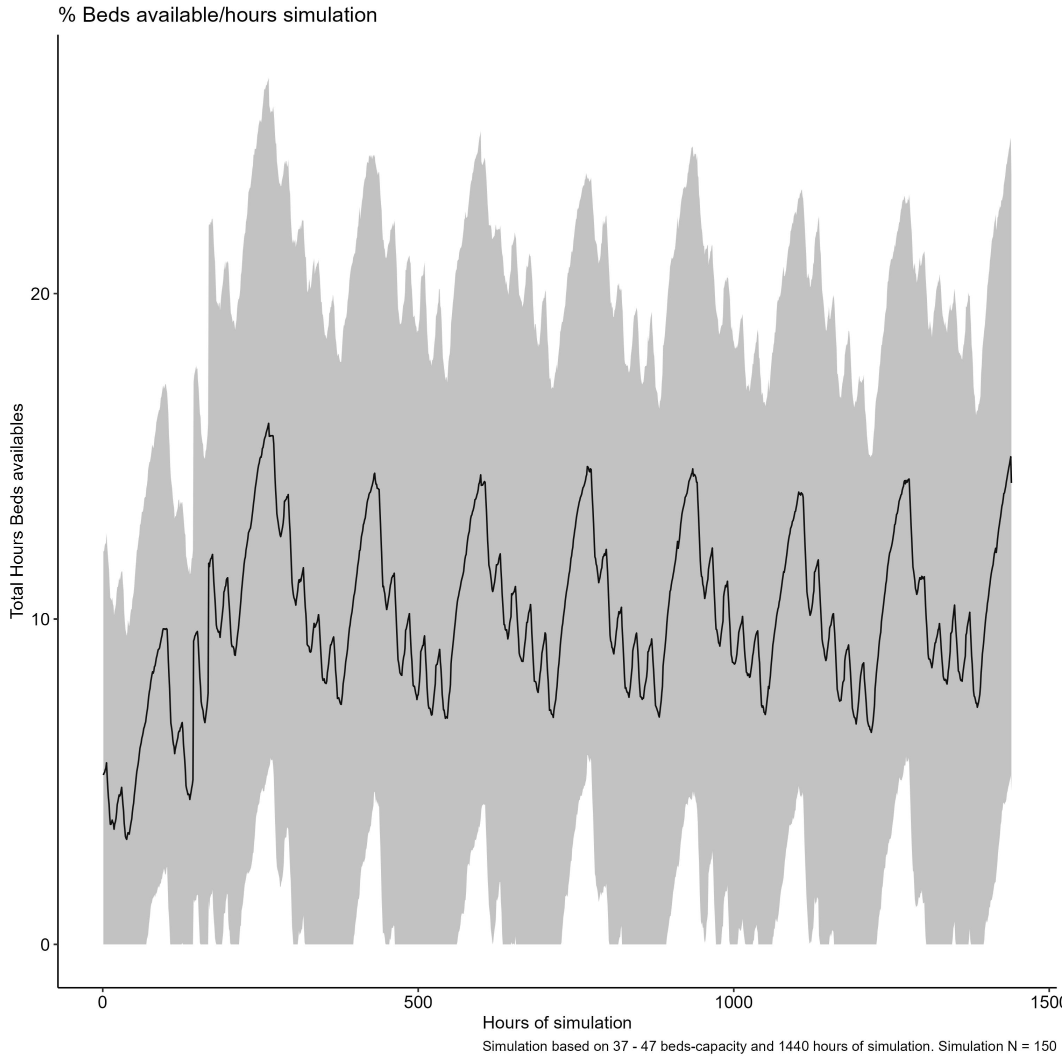

Figure 5: 150 simulations of a variable-bed ICU for sixty days with cut-off coefficient of 0.00. It is possible to observe changes in bed occupancy for cyclic difference in admission coefficients.