Project 2

BAN403 – Simulation of Business Processes

Candidates: 136, 149, 158

Task 1 – Analyzing the Current Process Design

1. System Flowchart

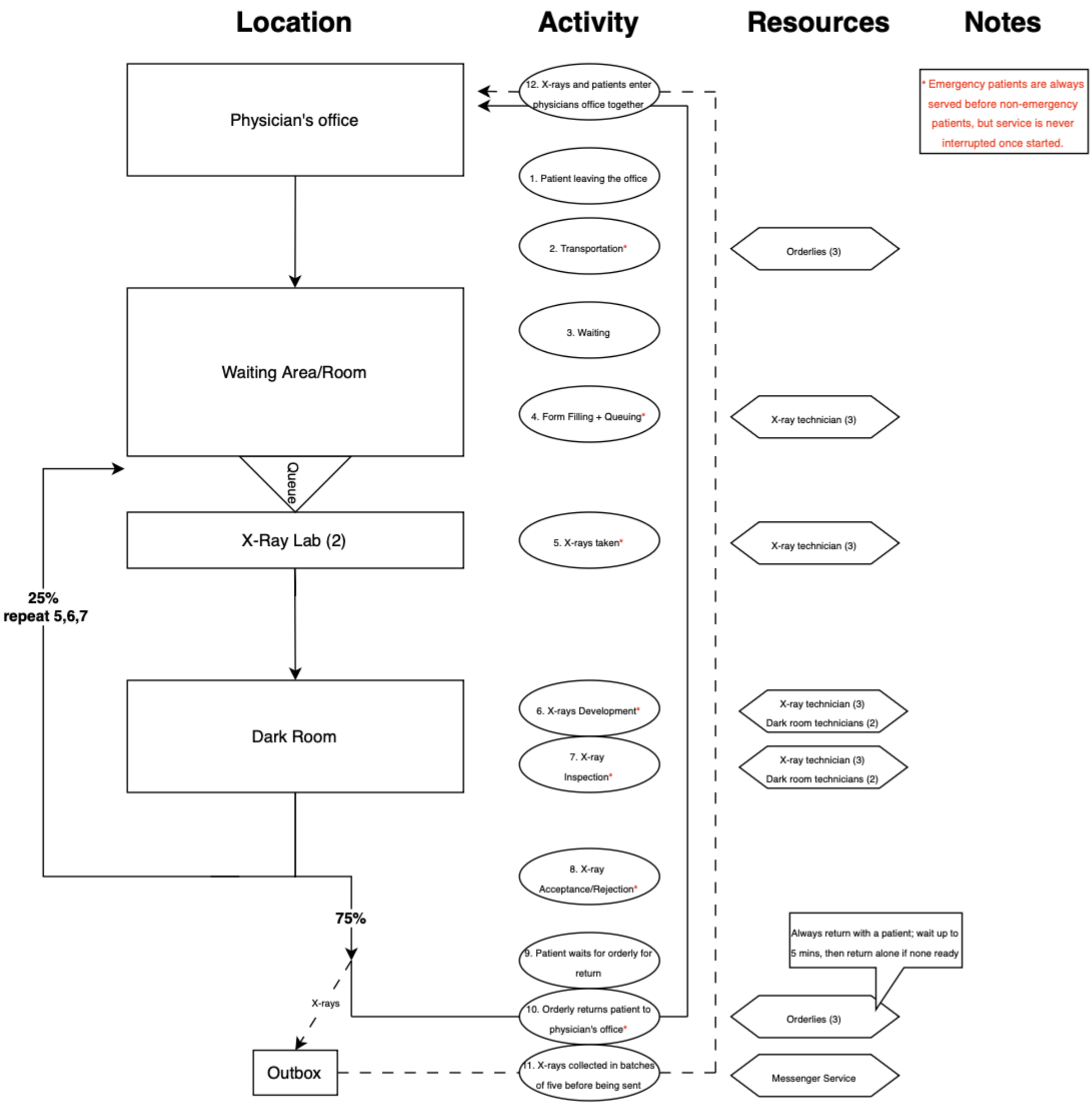

Figure 1 - Flowchart of the Current X-Ray Process at County Hospital

2. Simulation Model Development

To analyze the input data for the arrival process and various activities, we used Python. Specifically, we examined the distribution of inter-arrival times for non-emergency and emergency patients, as well as the service times for activities four and seven. We calculated the inter-arrival times by determining the time differences between consecutive arrival times in the sample data file.

	Non-Emergency Patients	Emergency Patients					Activity 4	Activity 7
		Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**		
Distribution	Log-Normal	Exponential	Weibull	Log-Normal	Exponential	Weibull	Triangular	Log-Normal
Parameters	Location: -0.920 [min] Scale: 5.375 [min] Normal Standard Deviation: 0.728	MinValue: 0.006 [min] Mean: 11.562 [min]	Location: 0.060 [min] Scale: 10.356 [min] Shape: 0.945	Location: -0.185 [min] Scale: 6.752 [min] Normal Standard Deviation: 1.050	MinValue: 0.350 [min] Mean: 12.620 [min]	Location: 0.037 [min] Scale: 10.473 [min] Shape: 0.963	MinValue: 3 [min] MaxValue: 6 [min] Mode: 5 3[min]	Location: -0.389 [min] Scale: 1.939 [min] Normal Standard Deviation: 0.563

Table 1 – Inter-Arrival Distributions for Non-Emergency and Emergency Patients

To enable the model to distinguish between different orderlies, each has their own Seize object, along with specific attributes and thresholds for activities requiring an orderly. The orderlies have two attributes, *inLab* and *inWard*, both set to one if true. Before each transportation process, these attributes are set to zero; upon completion, the relevant attribute is set to one. These attributes control the thresholds: when *inWard* is one, the threshold *ToLab* is open, and when *inLab* is one, the threshold *ToWard* is open. These thresholds are linked to *SeizeToLab* and *SeizeToWard*, respectively.

When a patient is transported to the X-ray lab, the accompanying orderly receives the attribute *inLab* = 1. At this stage, the entity is duplicated: the version with the orderly (from now on just referred to as the orderly) is sent to a queue called *OrderlyWaiting*, while the duplicate continues through the X-ray process. This ensures that constraints related to orderlies waiting to transport patients back to the ward are respected. Upon arriving at the waiting area, the orderly enters the *OrderlyWaiting* queue. They will leave this queue and be seized by a patient if one is in the *ReturnQueue* or arrives within five minutes. If no patient appears during that time, the orderly returns to the ward alone.

If the orderly reneges, it is assigned *inLab* = 0 and enters an *EntityConveyor*, representing the five-minute walk back to the ward. After that, the orderly is assigned *inWard* = 1 and released, making them available for transporting a new patient to the lab. However, if there is a patient in the *ReturnQueue*, the entity enters a server controlled by a threshold called *SomeOneInQueue*, activated when a patient is waiting in the *ReturnQueue*. If the server opens, the orderly resource is released and can be seized to transport the patient back to the ward.

To manage simultaneous events in JaamSim, releasing the orderly resource during patient pickup at the lab required two servers and two queues instead of one. When multiple orderlies were waiting and a patient arrived before any had reneged, both orderlies could exit the *OrderlyWaiting* queue before the first was assigned, leaving the second idle and unassigned. Utilizing a second queue and server resolved this by capturing the unassigned orderly, maintaining the correct five-minute renege time, and keeping them properly within the system.

Emergency patients are prioritized over non-emergency patients throughout the entire process using the Priority parameter in each queue. Within the lab activities, there is also an internal prioritization, where patients further along in the process are prioritized over those earlier in the sequence, ensuring patients move through the lab area as quickly as possible.

To simulate the parallel activities ten and eleven, patient entities are duplicated. In the messenger service, X-ray entities are batched in groups of five before being transferred to the ward. We assume this is a fax service that can send one batch at a time without delay between the completion and the start of a new batch. Meanwhile, patient entities wait for an available orderly to transport them from the lab to the ward. After transport, both the X-ray and patient entities wait in their respective queues until the other arrives. Once both are present, they are merged before the next activity begins. This ensures that resources are not occupied while patients wait in queues for the next step.

Resource pools are used to differentiate between resources and facilitate adjustments when improving the process. We selected entity delays as they can handle multiple entities simultaneously and allow overtaking, which suits our stochastic service times.

According to the process description, during normal operating hours, orderlies must always bring a patient from the ward when picking someone up from the X-ray area. However, during the night shift, no new patients arrive, so eventually, there will be no patients left in the ward to transport to the X-ray area. As a result, orderlies could become idle while patients remain in the lab, waiting to be taken back to the ward. To address this inefficiency, we implemented a solution allowing orderlies to go to the lab without bringing a patient if no one is waiting in the ward, it is outside regular opening hours, and at least one patient in the lab needs transport back. Finally, we assume that multiple X-rays cannot be processed in the dark room at the same time. A screenshot of our JaamSim-model can be found in the Appendix (Figure A1).

3. Process Nature Identification

A terminating process typically begins and ends in an empty state (Laguna & Marklund, 2018). In this case, the X-ray unit operates during regular hours from 8:00 a.m. to 8:00 p.m., providing a natural endpoint once a fixed amount of time elapses. This division into discrete time units (i.e., a working day) indicates that the process is structured to start and finish within a specific and limited period (Laguna & Marklund, 2018). Therefore, the X-ray process at County Hospital can be theoretically classified as a terminating process.

Also, the X-ray unit is part of a regular medical unit, not an emergency department. Emergency units are often modeled as nonterminating systems because they must deal with patients continuously and do not have a set end time each day (Batt et al., 2019). In contrast, the X-ray unit at County Hospital stops admitting new patients at 8:00 p.m., and any patients remaining in the system are processed until completion, with no cases carrying over to the next day.

The performance of terminating processes is usually analyzed by running multiple independent simulations and using statistical methods to estimate cycle times, throughput, and resource utilization (Laguna & Marklund, 2018). If the process continued without a natural endpoint, and patients remaining after 8:00 p.m. were processed the following day, it would likely be nonterminating due to the lack of a clear termination when a new day begins.

4. Preliminary Simulation Analysis

Average Cycle Time	Input Rate	Output Rate
159.882 min	3.875 / Hour	1.677 / Hour

Table 2 – Average Cycle Time, Input Rate and Output Rate for a One-Day Simulation

	TransportToLab	FillForm	TakeXRay	DevelopXRay	Inspection	TransportToWard
Utilization	66.14%	50.32%	85.99%	96.90%	15.55%	42.75%
	MessengerTransfer	**Orderly1**	**Orderly2**	**Orderly3**	**XRayTech1**	**XrayTech2**
Utilization (at 8 p.m.)	5.92%	88.64% (99.43%)	81.60% (98.96%)	75.48% (98.32%)	98.70%	98.99%
	XrayTech3	**XrayRoom1**	**XrayRoom2**	**DRTech1**	**DRTech2**	**DarkRoom1**
Utilization	98.89%	66.51%	63.28%	58.77%	54.60%	97.58%

Table 3 – Activity/Resource Utilization as Percentage of Total Time

	TransportLabQueue	WaitingArea	WaitingX-Ray	WaitingDevelop
Queue Length	25.23	31.17	0.84	42.13
	InspectionQueue	**ReturnQueue**	**PatientWardQueue**	**Sum**
Queue Length	0.24	0.05	1.83	101.25

Table 4 – Average Queue Length per Queue (in Number of People)

We simulated a full day, starting at 8:00 a.m. and ending at 8:00 a.m. the next day, covering a 24-hour period. The process is not stable because the input rate (3.875 patients per hour) exceeds the output rate (1.677 patients per hour), meaning the condition $\lambda = R_i = R_o$ does not hold. Consequently, the system cannot empty itself, preventing meaningful determination of a steady throughput rate. The average cycle time was 159.882 minutes at the end of our simulation, and it includes those patients who have completed the entire X-ray process and exited the system. This average is expected to increase the longer we run the simulation, as newly arriving patients face increasingly long queues due to the system's congestion (see Figure A2 in Appendix). This circumstance applies to all simulations that are unstable and have remaining patients in the system at the end of the run and should be considered when reporting average cycle times in the following tasks. The average number of people across all queues is approximately 101, which is high. The longest queue, about 42 people, forms before the development step for the X-rays. Additionally, long queues of 25 people on average form in front of transportation to the lab and 31 people in front of the waiting area before filling out the form. The three X-ray technicians work nearly 100% of the time, while the two dark room technicians work only about 59% and 55%, suggesting that the dark room may be a bottleneck due to its limited availability.

Several serious issues are evident. Even if no new patients are accepted after 8 p.m., processing those already in the queue would take a long time, potentially requiring employees scheduled from 8 a.m. to 8 p.m. to work far into the night or even longer to complete the day's workload. Theoretically, the process is terminating, as the model uses discrete time steps, and the system description suggests an end. Practically, however, based on activity time distributions, it has elements of a non-terminating process, as unfinished work continues through the night and into the next day. It is clear without further analysis that the system is under-resourced. To improve it, more staff and/or equipment are likely needed. If this setup remains unchanged for several days, the queues will continue to grow larger each day.

5. Replication Justification

The number of simulation runs is chosen to collect sufficient data for statistical analysis, giving reliable conclusions about process information (Laguna & Marklund, 2018). For determining the number of replications needed, we use the formula $n = \left(\frac{Z_{\frac{\alpha}{2}} * s}{d}\right)^2$, where $Z_{\frac{\alpha}{2}}$ is the z-value from the standard normal distribution based on the chosen confidence level, s is the sample standard deviation of the average cycle time, d is the desired half-width of the confidence interval, and n is the number of replications required. Since the observations (average cycle time per patient) are independent and identically distributed, the sample mean follows a normal distribution when the sample size is sufficiently large. Given that the population standard deviation is unknown, the sample standard deviation s can be used as an approximation if the sample size is at least 30 (Laguna & Marklund, 2018). JaamSim uses different random seeds for each simulation run by default, ensuring that the samples are independent.

To estimate the sample standard deviation, we simulated the process 30 times from an empty state over one work week per simulation, from Monday 8 a.m. until Saturday 8 a.m. We stopped the simulation at this time to include the Friday night shift and due to a lack of information about weekend opening hours or arrival rates. This resulted in a standard deviation of approximately 31.76 minutes. We selected a 95% confidence level with a corresponding z-value of 1.96, commonly used in practice. For the confidence interval half-width d, we chose 2.5 minutes, resulting in a total width of five minutes, which is reasonable given the standard deviation. Solving for $n = \left(\frac{1.96*31.76}{2.5}\right)^2$ yields $n \approx 620$ replications (see *task2-5_Night-Logic_calc.xlsx*).

6. Statistical Output Analysis

Based on the results from 620 replications, the average cycle time was 305.108 minutes (approximately 5.1 hours), with a margin of error of ≈ 3.34 minutes. The 95% confidence interval for the cycle time (301.76-308.45 minutes) means the true average is expected to fall within this range in 95 out of 100 repeated trials. As seen in Table 5, the difference between inflow and outflow shows the same characteristics as in Task 4, and we cannot compute a meaningful throughput rate.

	Monday	Tuesday	Wednesday	Thursday	Friday
Inflow	**3.765**	**3.853**	**3.793**	**3.598**	**3.857**
Upper Bound	3.786	3.874	3.817	3.619	3.878
Lower Bound	3.744	3.833	3.770	3.577	3.836
Error Term	0.021	0.020	0.023	0.021	0.021
Outflow	**1.757**	**1.846**	**1.846**	**1.847**	**1.846**
Upper Bound	1.767	1.856	1.856	1.857	1.856
Lower Bound	1.747	1.836	1.836	1.837	1.836
Error Term	0.010	0.010	0.010	0.010	0.010

Table 5 – Inflow and Outflow of Patients per Hour, with 95% Confidence Intervals

	TransportToLab	FillForm	TakeXRay	DevelopXRay	Inspection	TransportTo-Ward
Utilization	**64.54%**	**44.20%**	**89.38%**	**98.44%**	**15.16%**	**46.63%**
Upper Bound	64.72%	44.26%	89.43%	98.46%	15.20%	46.73%
Lower Bound	64.37%	44.14%	89.33%	98.42%	15.12%	46.53%
Error Term	0.18%	0.06%	0.05%	0.02%	0.04%	0.10%
	MessengerTransfer	**Orderly1**	**Orderly2**	**Orderly3**	**XRayTech1**	**XrayTech2**

Utilization	**6.07%**	**88.77%**	**81.97%**	**75.84%**	**99.73%**	**99.73%**
Upper Bound	6.08%	88.87%	82.13%	76.03%	99.75%	99.74%
Lower Bound	6.05%	88.67%	81.82%	75.65%	99.72%	99.71%
Error Term	0.02%	0.10%	0.15%	0.19%	0.02%	0.01%
	XrayTech3	**XrayRoom1**	**XrayRoom2**	**DRTech1**	**DRTech2**	**DarkRoom1**
Utilization	**99.69%**	**66.77%**	**66.78%**	**56.99%**	**56.78%**	**98.44%**
Upper Bound	99.71%	66.84%	66.85%	57.05%	56.85%	98.46%
Lower Bound	99.68%	66.71%	66.72%	56.92%	56.72%	98.42%
Error Term	0.02%	0.06%	0.07%	0.07%	0.07%	0.02%

Table 6 – Activity/Resource Utilization as Percentage of Total Time, with 95% Confidence Intervals

	TransportLabQueue	WaitingArea	WaitingX-Ray	WaitingDevelop
Queue Length	**24.29**	**68.41**	**0.74**	**180.21**
Upper Bound	24.53	69.59	0.74	180.85
Lower Bound	24.05	67.23	0.73	179.58
Error Term	0.24	1.18	0.00	0.64
	InspectionQueue	**ReturnQueue**	**PatientWardQueue**	**Sum**
Queue Length	**0.24**	**0.06**	**1.77**	**275.48**
Upper Bound	0.24	0.06	1.77	276.97
Lower Bound	0.24	0.06	1.77	273.99
Error Term	0.00	0.00	0.00	1.49

Table 7 – Average Queue Length per Queue (in Number of People), with 95% Confidence Intervals

The assumption that the system is empty every morning does not hold under the current process design. Comparing the cycle time with the results from Task 4 reveals an increase of more than 140 minutes. This increase is not due to varying arrival times across different days but is caused by a backlog of patients still in the system each morning. Despite the simulation including a night shift with the same resources as the day shift, which may be realistic for a hospital, queue lengths continue to grow, leading to longer average queue times over five days. However, the utilization of activities and resources shows no significant differences between Task 4 and Task 6. As discussed earlier, the process is theoretically terminating. However, the queue lengths and backlog from previous days give the process non-terminating characteristics.

7. Performance and Bottlenecks

The bottlenecks in the process are the X-ray technicians (3) and the dark room (1). This is evident from the utilization rates of these resources, which are very close to 100 % (Table 6), and the excessively high queue lengths before activities requiring these resources, which drop to almost zero for the first activity not requiring these (Table 7).

Although the orderlies have a utilization of nearly 100% during the opening hours (Table 3) and the average queue length for lab transport is 24.29 (Table 7) – a number that peaks way higher during opening hours since no patients are added to the queue between 8 p.m. and 8 a.m. – orderlies are not the bottleneck. The bottleneck activities cannot process more patients than they currently do, so increasing the inflow to the lab waiting room from the ward would not reduce cycle time. Furthermore, the average number of patients waiting to return to the physicians' office is nearly zero (Table 7), indicating sufficient orderly capacity for this task.

Increasing the number of X-ray technicians and dark rooms will reduce cycle time and increase output flow. Addressing both bottlenecks simultaneously will yield even better results. However, whether these are the only constraints preventing the system from achieving a steady state is unlikely; with the severe backlog observable, other resources likely become bottlenecks once the current ones are resolved. As things stand, the number of X-ray technicians and darkrooms is the bottleneck in the system.

Task 2 – Suggest and Evaluate a New Process Design

1. Process Redesign Proposal

In this task, we present several possible changes to the current process and explain how each change could impact performance, such as reducing the average cycle time. Each proposed change is evaluated based on three criteria: time to implement, difficulty or costs, and potential to improve the process.

Developing X-ray images requires both a dark room technician and an X-ray technician. Since X-ray technicians are nearly fully utilized (Table 6), delegating the entire task to dark room technicians, who have around 57% utilization (Table 6), should help balance the workload between the two roles. Implementing this change would free up over one-third of the X-ray technicians' total workload, thereby speeding up other X-ray activities. This assumes that the dark room technicians have the necessary skills to develop images independently and that the activity duration remains unchanged without an X-ray technician present. Nonetheless, the solution is quick to implement, cost-free, and improves performance.

Additionally, hiring more X-ray technicians could similarly enhance productivity in lab activities and reduce cycle time. Although costly, this approach is effective and quick to implement. Whether freeing up X-ray technicians from developing images alone sufficiently resolves the bottleneck or hiring more technicians is necessary will depend on observed performance after implementation. Given the current state, it is reasonable to assume that more X-ray technicians are needed for the process to function well, as merely freeing up one-third of their workload is likely insufficient.

The number of dark rooms is a critical bottleneck, as increasing their availability would speed up the X-ray process for patients. Transforming an existing room (e.g., an X-ray room) into a dark room is the fastest and most likely least costly approach. This should improve the process performance, as developing X-ray images takes longer on average than capturing them. However, it is unlikely that this solution will stabilize the system. Achieving a well-functioning system would likely require adding more X-ray and dark rooms, suggesting that the long-term solution involves expanding the hospital, either by restructuring its layout or constructing a new wing, rather than solely converting an X-ray room into a dark room. Given the current setup and patient flow, expanding the hospital is the only realistic way to achieve a well-functioning system, despite the high cost and time investment this would demand.

Currently, X-rays are transferred in batches of five, causing patients to wait for their images before returning to the physician's office. The average queue length at this stage is 1.77 patients (Table 7), indicating a relatively short waiting time. The ideal batch size should match the expected number of patients (and their X-rays) entering the *ReturnQueue* during the combined time they are expected to spend in the queue and transported to the physician's office. It is worth considering whether the messenger service is necessary at all. Orderlies could carry the patients' documents, potentially making the messenger service redundant. This change is quick to implement, could moderately reduce cycle time, and would free up resources.

Another important aspect is optimizing the use of orderlies and possibly hiring an additional one. Although orderlies are not currently the bottleneck, they might become one with improved efficiency in X-ray activities. The discrepancy in the average queue lengths – patients waiting for transport to the lab (24.29) versus from the lab (0.06) (Table 7) – suggests a need to reduce the time an orderly waits to transport a patient back. The optimal waiting time can be found through trial and error and may need adjustment as improved X-ray activities lead to more frequent arrivals at the *ReturnQueue*. It is, however, unclear whether optimized instructions for the three orderlies, without hiring another one, will be sufficient to prevent the buildup of the *TransportToLab* queue during opening hours after other improvements. Optimizing orderly instructions can be done overnight, cost-free.

Upgrading to modern technology could make activities six and eleven (Figure 1) and their related resources expandable. With digital image development, images are developed in negligible time and can be uploaded instantly to the physician's office after inspection. Although costly, this technological upgrade could free up resources, such as dark rooms and their technicians, and reduce the need for other solutions, helping to offset expenses. It is assumed that the new technology and equipment would increase the success rate of the X-ray machines from 75% to 90%, significantly improving system flow and cycle times. Whether this alone can make the system stable is uncertain without simulation, but it should be possible with additional X-ray resources. Overhauling the system's technology is a vast, long-term solution that offers an alternative to expanding the hospital to achieve a well-functioning system.

<table>
<tr><th>Short-Term Improvements</th><th>Long-Term Improvements</th></tr>
<tr><td>Optimize orderly instructions</td><td rowspan="2">Expand the X-ray unit to accommodate enough resources to achieve an average cycle time of 2 hours</td></tr>
<tr><td>Let X-ray technicians leave during development</td></tr>
<tr><td>Orderlies take over messenger transport</td><td rowspan="2">Overhaul technology and equipment, and replace newly redundant resources with ones in need, to achieve an average cycle time of 90 min</td></tr>
<tr><td>If necessary: Increase the number of X-ray technicians</td></tr>
</table>

Table 8 - Suggested Short-Term and Long-Term Improvements for the X-Ray Process

2. Redesign Performance Evaluation

We redesigned the current process and developed three different solutions, which are presented below. Hypothesis tests were used to assess whether the changes led to significant improvements, as shown in the file *hypothesis testing.xlsx*. The first solution (*Short-Term*) applies our proposed short-term improvements into the original model. During testing, our theory that X-ray technicians would no longer be bottlenecks after being relieved from activity six (Develop X-ray) was confirmed, eliminating the need to hire additional staff. The other short-term measures were to replace the messenger transfer to orderly transport and optimize the instructions given to orderlies (Table 8).

Implementing these changes results in an average cycle time of 1136 minutes (Table 9). The increase in average cycle time compared to Task 1.6 is due to accumulated queues, as more long-waiting patients are now being processed and included in the cycle time. A more relevant measure for comparing the performance of two unstable systems is the total outflow of patients. Notably, a statistically significant increase from 436 to 443 (Table 9) can be observed, indicating the changes are somewhat effective, especially given their cost-free nature. Thus, we recommend that the hospital management implement these quick solutions as soon as possible.

In addition, we developed two long-term models that built upon the short-term improvements. The first long-term model (*Expand*) retains the structure of the original system but adjusts the number of resources needed to achieve a system with an average cycle time of two hours, as confirmed by the results (Table 9). To accomplish this, the hospital would need to add one orderly, three X-ray technicians, two X-ray rooms, three dark room technicians, and two dark rooms. The substantial increase in required resources underscores that the original system is heavily under-resourced. Nevertheless, this first long-term model represents a well-functioning process where staff can expect to finish no later than 11 p.m. (Table 14).

The second long-term (*Overhaul*) model incorporates our proposal for a technological overhaul and adjusts resources to offer a faster solution than the *Expand* model, achieving an average cycle time of less than 90 minutes (Table 9). This reduction is due to fewer activities for patients and a lower chance of needing to redo them. In this version, dark rooms and dark room technicians are removed, and one dark room is converted into an X-ray room. Additionally, one orderly and two extra X-ray technicians are hired. Without detailed cost and timeframe data for the two long-term solutions, we cannot determine which is superior. However, it is reasonable to assume the technological *overhaul* may be preferable, as it results in statistically lower cycle time, raising customer satisfaction and reducing overtime hours for staff to complete the process each night.

	Current	Short-Term	Expand	Overhaul		Current	Short-Term	Expand	Overhaul
Cycle Time	**305.108**	**1136.353**	**120.412**	**86.717**	**Total Patients**	**436.329**	**443.405**	**900.608**	**900.608**
Upper Bound	308.451	1146.290	121.311	87.420	Upper Bound	437.326	444.399	902.876	902.876
Lower Bound	301.764	1126.416	119.513	86.014	Lower Bound	435.332	442.411	898.340	898.340
Error Term	3.344	9.937	0.899	0.703	Error Term	0.997	0.994	2.268	2.268

Table 9 – Cycle Time and Total Patients Processed, with 95% Confidence Intervals

	Monday	Tuesday	Wednesday	Thursday	Friday
Inflow	**3.765**	**3.853**	**3.793**	**3.598**	**3.857**
Upper Bound	3.786	3.874	3.817	3.619	3.878
Lower Bound	3.744	3.833	3.770	3.577	3.836
Error Term	0.021	0.020	0.023	0.021	0.021
Short-Term					
Outflow	**1.826**	**1.878**	**1.872**	**1.884**	**1.881**
Upper Bound	1.836	1.888	1.881	1.893	1.891
Lower Bound	1.817	1.869	1.862	1.874	1.872
Error Term	0.010	0.010	0.009	0.010	0.009
Expand					
Outflow	**3.764**	**3.854**	**3.793**	**3.598**	**3.859**
Upper Bound	3.785	3.875	3.816	3.619	3.880
Lower Bound	3.742	3.833	3.769	3.576	3.838
Error Term	0.021	0.021	0.024	0.021	0.021
Overhaul					
Outflow	**3.764**	**3.854**	**3.793**	**3.598**	**3.858**
Upper Bound	3.785	3.875	3.817	3.619	3.879
Lower Bound	3.743	3.833	3.770	3.577	3.837
Error Term	0.021	0.021	0.023	0.021	0.021

Table 10 – Inflow and Outflow of New Process Designs, with 95% Confidence Intervals

Short-Term	TransportToLab	FillForm	TakeXRay	DevelopXRay	Inspection	TransportToWard
Utilization	**64.77 %**	**55.28 %**	**81.59 %**	**99.63 %**	**15.52 %**	**47.85 %**
Upper Bound	64.94 %	55.43 %	81.75 %	99.64 %	15.56 %	47.95 %
Lower Bound	64.60 %	55.13 %	81.43 %	99.63 %	15.48 %	47.75 %
Error Term	0.17 %	0.15 %	0.16 %	0.01 %	0.04 %	0.10 %
Expand	**TransportToLab**	**FillForm**	**TakeXRay**	**DevelopXRay**	**Inspection**	**TransportToWard**
Utilization	**49.26 %**	**40.79 %**	**55.53 %**	**56.68 %**	**28.77 %**	**51.91 %**
Upper Bound	49.37 %	40.89 %	55.64 %	56.80 %	28.88 %	52.02 %
Lower Bound	49.16 %	40.68 %	55.41 %	56.56 %	28.66 %	51.80 %
Error Term	0.10 %	0.11 %	0.11 %	0.12 %	0.11 %	0.11 %

Overhaul	TransportToLab	FillForm	TakeXRay	Inspection	TransportToWard
Utilization	**49.44 %**	**41.67 %**	**54.04 %**	**22.66 %**	**51.18 %**

Upper Bound	49.54 %	41.78 %	54.14 %	22.73 %	51.28 %
Lower Bound	49.34 %	41.57 %	53.93 %	22.59 %	51.07 %
Error Term	0.10 %	0.11 %	0.10 %	0.07 %	0.10 %

Table 11 – Activity Utilization of New Process Designs, with 95% Confidence Intervals

Short-Term	**Orderly1**	**Orderly2**	**Orderly3**	**XRayTech1**	**XrayTech2**	**XrayTech3**
Utilization	**89.01 %**	**81.67 %**	**75.52 %**	**74.50 %**	**74.49 %**	**74.44 %**
Upper Bound	89.12 %	81.83 %	75.71 %	74.68 %	74.66 %	74.61 %
Lower Bound	88.91 %	81.52 %	75.33 %	74.33 %	74.32 %	74.27 %
Error Term	0.10 %	0.15 %	0.19 %	0.17 %	0.17 %	0.17 %

	XrayRoom1	**XrayRoom2**	**DRTech1**	**DRTech2**	**DarkRoom1**
Utilization	**74.79 %**	**74.76 %**	**57.60 %**	**57.55 %**	**99.63 %**
Upper Bound	74.97 %	74.94 %	57.67 %	57.62 %	99.64 %
Lower Bound	74.61 %	74.58 %	57.54 %	57.49 %	99.63 %
Error Term	0.18 %	0.18 %	0.07 %	0.07 %	0.01 %

Expand	**Orderly1**	**Orderly2**	**Orderly3**	**Orderly4**	**XRayTech1**	**XrayTech2**	**XrayTech3**	**XrayTech4**
Utilization	**57.59 %**	**55.82 %**	**54.54 %**	**53.10 %**	**43.82 %**	**43.81 %**	**43.81 %**	**43.81 %**
Upper Bound	57.73 %	55.97 %	54.69 %	53.28 %	43.95 %	43.93 %	43.94 %	43.93 %
Lower Bound	57.45 %	55.68 %	54.38 %	52.93 %	43.69 %	43.68 %	43.69 %	43.68 %
Error Term	0.14 %	0.14 %	0.16 %	0.17 %	0.13 %	0.13 %	0.13 %	0.13 %

	XrayTech5	**XrayTech6**	**XrayRoom1**	**XrayRoom2**	**XrayRoom3**	**XrayRoom4**	**DRTech1**	**DRTech2**
Utilization	**43.76 %**	**43.76 %**	**43.28 %**	**43.24 %**	**43.19 %**	**43.17 %**	**46.75 %**	**46.71 %**
Upper Bound	43.88 %	43.88 %	43.41 %	43.38 %	43.32 %	43.30 %	46.89 %	46.86 %
Lower Bound	43.63 %	43.63 %	43.15 %	43.11 %	43.06 %	43.04 %	46.60 %	46.57 %
Error Term	0.13 %	0.13 %	0.13 %	0.13 %	0.13 %	0.13 %	0.15 %	0.15 %

	DRTech3	**DRTech4**	**DRTech5**	**DarkRoom1**	**DarkRoom2**	**DarkRoom3**	**DarkRoom4**
Utilization	**46.65 %**	**46.65 %**	**46.57 %**	**50.51 %**	**50.48 %**	**50.45 %**	**50.38 %**
Upper Bound	46.80 %	46.80 %	46.72 %	50.67 %	50.63 %	50.60 %	50.54 %
Lower Bound	46.51 %	46.50 %	46.43 %	50.36 %	50.32 %	50.30 %	50.23 %
Error Term	0.14 %	0.15 %	0.14 %	0.15 %	0.16 %	0.15 %	0.15 %

Overhaul	**Orderly1**	**Orderly2**	**Orderly3**	**Orderly4**	**XRayTech1**	**XrayTech2**	**XrayTech3**
Utilization	**54.82 %**	**54.12 %**	**53.28 %**	**52.22 %**	**45.76 %**	**45.77 %**	**45.73 %**
Upper Bound	54.94 %	54.25 %	53.43 %	52.39 %	45.88 %	45.90 %	45.86 %
Lower Bound	54.70 %	53.99 %	53.14 %	52.05 %	45.63 %	45.65 %	45.60 %
Error Term	0.12 %	0.13 %	0.14 %	0.17 %	0.13 %	0.13 %	0.13 %

	XrayTech4	**XrayTech5**	**XrayRoom1**	**XrayRoom2**	**XrayRoom3**
Utilization	**45.73 %**	**45.72 %**	**48.06 %**	**48.02 %**	**48.01 %**
Upper Bound	45.85 %	45.85 %	48.19 %	48.15 %	48.14 %
Lower Bound	45.60 %	45.60 %	47.92 %	47.88 %	47.87 %
Error Term	0.13 %	0.13 %	0.13 %	0.14 %	0.14 %

Table 12 – Resource Utilization of New Process Designs, with 95% Confidence Intervals

Short-Term	**TransportLabQueue**	**WaitingArea**	**WaitingX-Ray**	**WaitingDevelop**	**InspectionQueue**	**ReturnQueue**	**Sum**
Queue Length	**23.991**	**0.244**	**1.738**	**244.954**	**0.083**	**0.062**	**270.990**
Upper Bound	24.228	0.246	1.777	246.241	0.083	0.063	272.462
Lower Bound	23.755	0.242	1.699	243.668	0.082	0.062	269.519
Error Term	0.236	0.002	0.039	1.286	0.000	0.001	1.471
Expand	**TransportLabQueue**	**WaitingArea**	**WaitingX-Ray**	**WaitingDevelop**	**InspectionQueue**	**ReturnQueue**	**Sum**
Queue Length	**4.285**	**0.048**	**0.277**	**1.612**	**0.131**	**2.036**	**8.256**
Upper Bound	4.387	0.049	0.282	1.658	0.133	2.070	8.383
Lower Bound	4.183	0.047	0.271	1.565	0.130	2.001	8.130
Error Term	0.102	0.001	0.006	0.046	0.002	0.035	0.126

Overhaul	**TransportLabQueue**	**WaitingArea**	**WaitingX-Ray**	**InspectionQueue**	**ReturnQueue**	**Sum**
Queue Length	**3.848**	**0.067**	**0.733**	**0.058**	**1.819**	**6.467**
Upper Bound	3.937	0.068	0.754	0.058	1.844	6.567
Lower Bound	3.758	0.066	0.713	0.057	1.795	6.367
Error Term	0.090	0.001	0.021	0.001	0.024	0.100

Table 13 – Queue Lengths of New Process Designs, with 95% Confidence Intervals

Expand	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
Minutes Overtime	**143.259**	**166.825**	**158.523**	**131.142**	**166.291**
Upper Bound	146.561	170.822	162.682	134.418	170.319
Lower Bound	139.956	162.829	154.364	127.866	162.264
Error Term	3.302	3.997	4.159	3.276	4.028
Overhaul	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
Minutes Overtime	**99.716**	**113.082**	**108.368**	**85.038**	**113.553**
Upper Bound	102.618	116.275	111.586	87.514	116.774
Lower Bound	96.814	109.888	105.149	82.561	110.332
Error Term	2.902	3.194	3.218	2.476	3.221

Table 14 – Average Minutes of Overtime per Day, with 95% Confidence Intervals

List of References

Batt, R. J., Kc, D. S., Staats, B. R., & Patterson, B. W. (2019). The effects of discrete work shifts on a nonterminating service system. *Production and Operations Management*, *28*(6), 1528–1544.

Laguna, M., & Marklund, J. (2018). *Business process modeling, simulation and design*. Chapman and Hall/CRC

Appendix

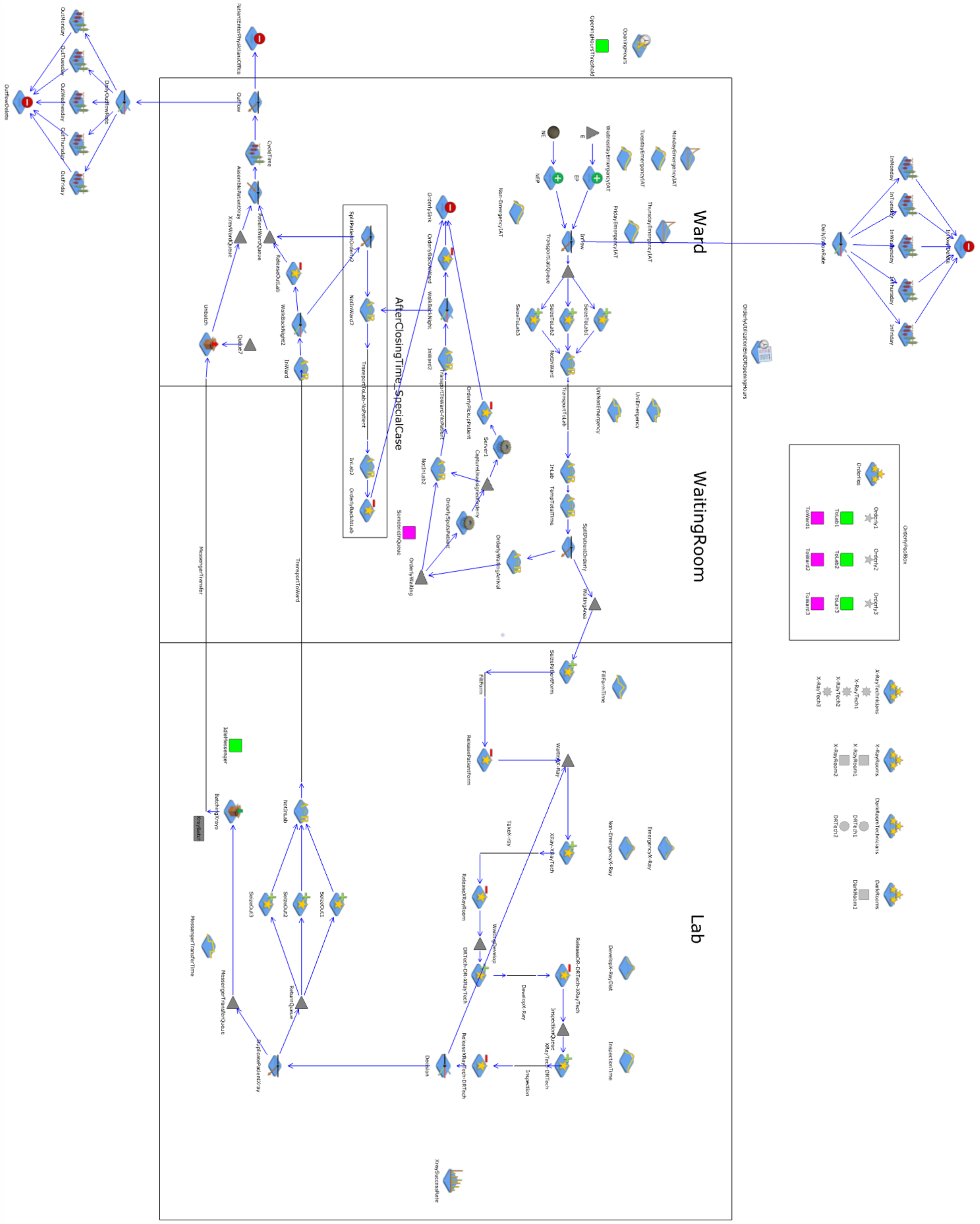

Figure A1 – Current Process Design in JaamSim

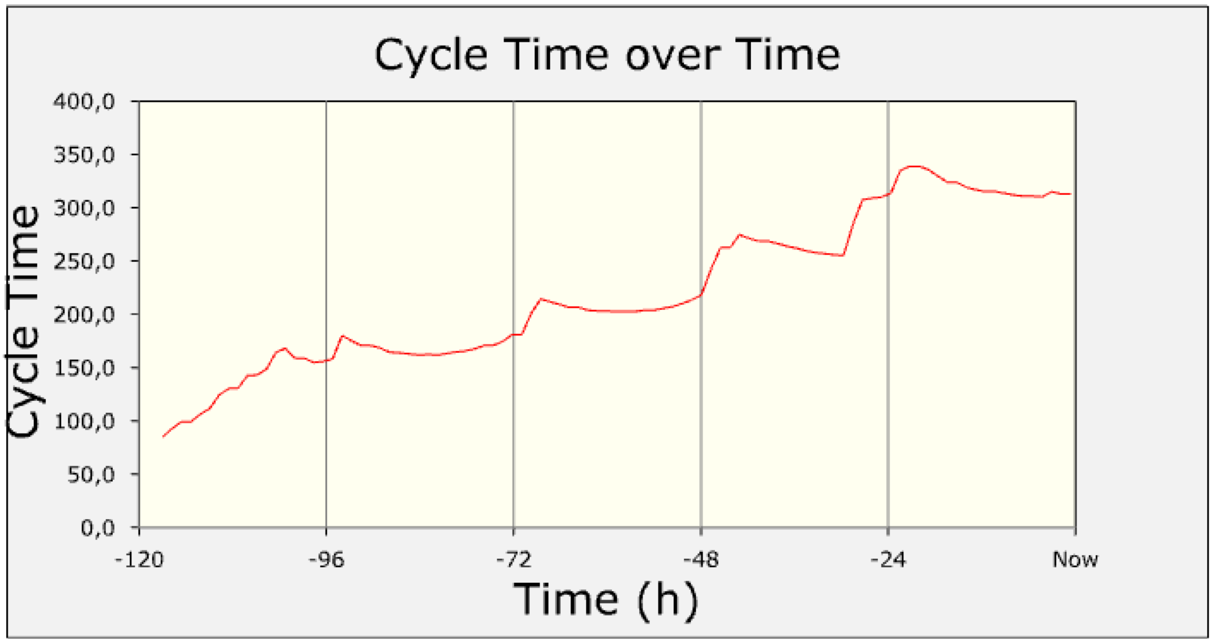

Figure A2 – Cycle Time Over Time