Modeling and Analysis of the Rotor Blade Refurbishment Process at the Corpus Christi Army Depot

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Abstract: Much of the Army's equipment is coming to the end of its planned life cycle. At the same time, the Department of Defense and the Army are facing severe budget reductions for the foreseeable future. As a result, the planned modernization and acquisition of new equipment will be delayed. The Army is now forced to keep and maintain current equipment as opposed to retiring old systems and buying new ones. With the increased investment in the current systems, the organizations and depots that maintain and refurbish the Army's equipment are becoming increasingly valuable assets. Corpus Christi Army Depot (CCAD) is the Army's only facility for repair and overhaul of rotary wing aircraft. CCAD receives approximately 10 rotor blades per day for the Black Hawk helicopter. Each blade is routed through a detailed inspection and rework process consisting of approximately 67 sequential operations which take approximately 45 days per blade. Recently CCAD has expanded and reorganized the rotor blade refurbishment facility which provides an opportunity to re-examine processes, adjust positioning of work stations, and improve efficiency. In this research we develop a discrete-event simulation model of the CCAD rotor blade refurbishment process in order to identify inefficiencies and examine "what if" scenarios to improve key performance metrics. The key performance metrics used to analyze model input include throughput, work in progress, mean queue time, mean queue size, and workstation utilization. The baseline model revealed that there were two crucial bottlenecks that severely limited the throughput and overall performance of the refurbishment process. Adjusting the capacities of these workstations was very effective in reducing the number of blades in WIP and reducing the impact of the queues in front of these stations, but failed to increase the throughput to the desired amount. Additionally, we found that the loss of one whirl tower's production would not be a significant factor for CCAD's performance in terms of throughput since operating with only one whirl tower did not significantly impact metrics of interest for the process.

Keywords: Simulation, Depot Maintenance, Sequential Manufacturing, Work in Progress (WIP), Throughput, Bottleneck Analysis, Discrete-event Simulation

1. Modeling and Analysis of Army Rotor Blade Refurbishment Process

Much of the Army's equipment is coming to the end of its planned life cycle. At the same time, the Department of Defense and the Army are facing severe budget reductions for the foreseeable future. As a result, the planned modernization and acquisition of new equipment will be delayed. The Army is now forced to keep and maintain current equipment as opposed to retiring old systems and buying new ones. With the increased investment in the current systems, the organizations and depots that maintain and refurbish the Army's equipment are becoming increasingly valuable assets.

1.1 Background

Starting in 1961, what became Corpus Christi Army Depot (CCAD), the Army Aeronautical Depot Maintenance Center began operations on a retired Naval Air Station with the mission to return rotary wing aircraft and components to the Department of Defense and its organizations with the highest quality, lowest cost, and in the shortest time. CCAD sets these goals for its mission and is also challenged by Army Demands in three different areas. The first area is performing "overhaul, repair, modification, retrofit, and modernization for Army and DOD rotary wing aircraft. Secondly, CCAD provides "hands-on training for Reserve, National Guard, active duty, and friendly foreign military personnel" (Military, 2011). The last area is that CCAD provides maintenance support for other depots that include "on-site maintenance teams, crash damage analysis, and chemical technical support" (Military, 2011).

All the U.S. Armed Forces benefit from the contributions of CCAD. The Depot is a major contributor to the repair and maintenance of helicopters as well as engines and components. While CCAD is not the only depot for the Army, it is the Army's only facility for repair and overhaul of rotary wing aircraft. Among the various major aircraft components processed at the Depot, CCAD receives approximately 10 rotor blades per day for the Black Hawk helicopter. Each blade is routed through a detailed inspection and rework process consisting of approximately 67 sequential operations which take approximately 45 days per blade. Recently CCAD has expanded and reorganized the rotor blade refurbishment facility which provides an opportunity to re-examine processes, adjust positioning of work stations and improve efficiency.

1.2 Model Motivation

As the government's budget is decreasing, there is growing pressure to improve process efficiency at all Army Depots. In addition to the opportunity presented by the expanded rotor blade refurbishment facility, CCAD has also identified blade refurbishment as one of their more inefficient processes and is motivated to conduct an in-depth analysis. Lastly, because CCAD operates on a cost reimbursable basis, there is intense interest in ways to increase throughput and reduce work in progress (WIP). CCAD desires to increase throughput by around 33% while also significantly decreasing their WIP.

1.3 Problem Statement

Develop a model of the CCAD rotor blade refurbishment process in order to identify bottlenecks and inefficiencies as well as examine "what if" scenarios to improve key performance metrics.

1.4 Literature Review

Previous research reveals a multitude of engineering efficiency concepts, ways to identify and reduce bottlenecks, and ways to increase the efficiency of a manufacturing process. Some of the research we discovered can be directly applied to benefit CCAD. Allahverdi and Soroush found that it is most efficient to treat set up times and cost separately from processing times and cost since it will speed up the changeover from building to building (Allahverdi, 2006). Additionally, Johnson found that it is more effective to have multiple assembly cells as opposed to assembly lines (Johnson, 2005). CCAD could be interested in this subject since they are in the development of moving their process to a new building and these factors can help increase efficiency.

One of CCAD's main interests is to eliminate or at least alleviate some of the bottlenecks from their existing rotor blade refurbishment process. Lin Li and his associates found a new data driven, short-term method of detecting bottlenecks that looks at production line blockage and the lack of a queue in front of a process for pinpointing limiting factors (Li, Chang, 2009). In order to mediate these bottlenecks, Hector Vergara and David Kim found a new buffer placement method based on simulations and workstation interactions that proved to be more effective than the previous algorithms that were popular in use (Vergara, 2009). These two methods will be exceptionally useful for CCAD to identify future bottlenecks as well as quickly reduce them based on the simulation data from our project.

The two biggest concerns for CCAD with this refurbishment process are throughput and the number of blades that are work in progress (WIP). We identified a method called CONWIP (constant WIP) that uses a series of constraints on a system that can be tightened or relaxed in order to reduce WIP, and subsequently costs, without sacrificing on-time delivery rates (Luh, 2000). More research provided a method developed by Jingshan Li and his colleagues that replaced a two-machine line with one equivalent machine that kept throughput the same but increased the value of several other performance measures (Li, Blumenfeld, 2009). These methods can be used to adjust our model so that we can create an alternative that will produce the best value scores without making changes to the process itself.

2. Methodology

The methodology employed to analyze and model the rotor blade refurbishment process is highlighted in Figure 1 below. Stakeholder analysis was conducted to refine the problem statement and identify scenarios and production metrics of interest. The process was then mapped out in all 67 steps and the requisite supporting data was gathered. Next, the model was populated with all of the workstations and their associated data such as process times and capacities as a discrete-event simulation. Discrete-event simulation is often used for manufacturing and service systems, similar to our CCAD process. CCAD's process can be modeled by a discrete-event simulation due to the discrete-change state of the variable within the system. Discrete-change refers to the number of blades as a whole number within each workstation upon arrival and completion. The number of UH-60 blades within the system is a discrete variable, since they arrive and leave from workstations as complete units, whereas a continuous variable could travel in separate parts. After a few more adjustments, the model was sent to our client at CCAD for validation to make sure it was an accurate representation of the real-life process in terms of the performance measures they are concerned with. Once the model was authenticated, the alternative scenarios that would indicate the impacts of these bottlenecks on the whole process were then created. The methodology is illustrated in more detail below as well as graphically in the following figure.

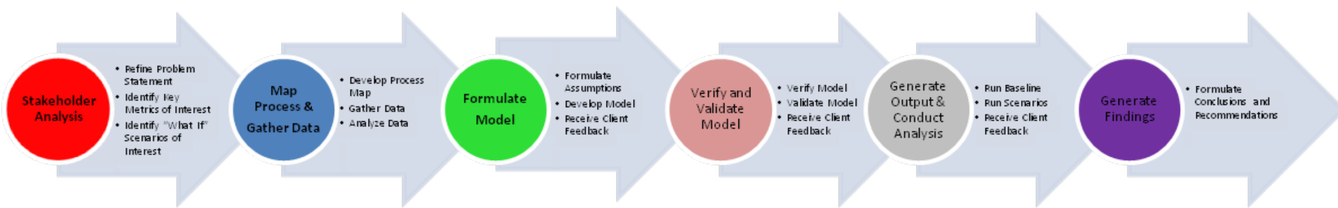


Figure 1. Methodology Flow Chart

2.1 Stakeholder Analysis

The key stakeholders for the problem include CCAD, Army Material Command (AMC), Army Aviation units, and of course the pilots and soldiers that use and rely on the Black Hawk helicopter. AMC is headquarters for all of the Army's depots and since CCAD is the largest aviation repair facility, the efficiency of the systems in place there is important to AMC. Stakeholder input for this effort was gathered primarily through interviews and observation. A member of the Capstone team was able to observe the UH60 blade process for three weeks during a summer internship. During this time, interviews were conducted with management and shop floor employees. Additional interviews were conducted throughout the Capstone project. The key outputs of this stakeholder analysis were performance metrics and scenarios of interest.

2.1.1 Key Performance Metrics.

There are numerous manufacturing performance metrics mentioned in engineering literature (Ignizio, 2009). During stakeholder interviews with key CCAD industrial engineering staff members, we were able to identify the key performance metrics of interest. Table 1 below highlights the UH60 rotor blade refurbishment key performance metrics of interest to CCAD.

Table 1. Key Performance Metrics

Performance Metric	Definition	Relative Priority
Throughput	The number of refurbished blades that exit the system (per month).	High
WIP (Work in Progress)	The average number of blades in the system at a given time	High
Mean Queue Time	The average amount of time a blade spends waiting to be serviced at each station.	Medium
Mean Queue Size	The average number of rotor blades waiting to be serviced at each station.	Medium
Workstation Utilization	The percent of work time a given station was actually processing a blade.	Low

2.1.2 Model Scenarios

CCAD management is interested in identifying current process bottlenecks as well as the impacts of potential modifications to the existing UH60 blade process and their impact on the performance metrics discussed above. Specifically, CCAD would like to explore the impact of adding extra shifts to their current bottlenecks in order to determine how best they can relieve the buildup behind them. CCAD is interested in examining four scenarios which are depicted in Table 2 below.

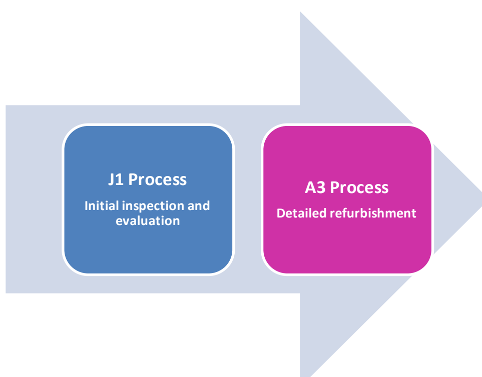
Table 2. Alternative Scenarios

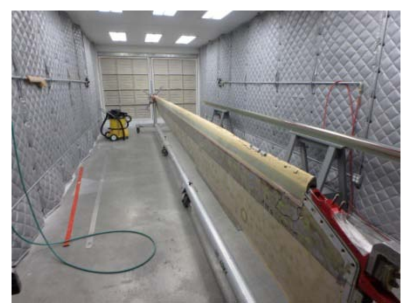
Scenario	Definition
Baseline	As-is process which we will use to determine which stations will be adjusted as well as comparing the outputs to verify the improvement in the performance metrics.
2nd Shift	Increasing the capacities of the bottlenecks from the baseline scenario to determine the impact on the overall process.
3rd Shift	Increasing capacities of the bottlenecks from the 2nd shift scenario to determine the effect of adding yet another shift to the workstations that are holding up the process.
1 Tower	A modification of the baseline model with one whirl tower inoperable to determine the downstream impacts caused by tower availability.

2.2 Map Existing Process and Gather Data

In general, each UH60 rotor blade undergoes 67 sequential operations during the refurbishment process. These operations are grouped into two major phases: Inspection (J1 Process) and Refurbishment (A3 Process). The J1 process is the initial inspection that all UH-60 blades experience. It is here where they are also divided by the severity of the need of refurbishment. The J1 process includes 17 stations such as electrical test, moisture removal, and bolt removal. The A3 process is where the blade individuality is identified. This means that each blade's A3 process could be different. There are 50 steps in A3 process which include bond repair, NDT, and static balance. A typical UH60 rotor blade spends approximately 45 days negotiating the entire refurbishment process. Figure 2 below provides a high level overview of the entire process.

An employee conducts a mechanical evaluation or tap test during the J1 process





The NDT, a form of X-Ray used in the A3 process

Figure 2. J1/A3 Processes

2.2.1 ProModel Data Requirements

Several key elements of data are necessary to accurately model the process, including the names and number of each workstation in the blade refurbishment process, as well as their capacities, or the number of blades each can process at a time. Next, we needed the process time, or how long it takes each workstation to perform its function, in hours. In order to correctly funnel blades into the process, we also needed to know CCAD's blade arrival rate. In this case, the unit of measurement was blades per week. Sometimes, blades have to wait before entering a workstation that gets backed up, so we also needed data on queue capacities. Finally, we needed an estimate of the percentages of blades that either are too damaged to process (J1 fallouts), or are "special case" blades that need specific attention. This would affect the route each blade takes through the system.

The next process was to gather and clean the data as it came in from CCAD. Data collection was iterative. We often realized the need for additional data to clarify certain aspects of the system. Eventually we held all the sufficient data to populate the model.

3. Model

In order to make the model flexible and user friendly, we moved the data to a Microsoft Excel document, and imported the spreadsheet to ProModel. With the data linked from a common spreadsheet, our stakeholders will be able to alter the route and time information in the model, without having to dig through the code.

IDEF0 is a function modeling system that helps to explain our simulation. The inputs are the constants that enter the process as we set prior to beginning which include the arrival rate and workstation capacity. The simulation was a discrete-event that was controlled by the blade routing rules and fallout rates. The outputs feature the primary methods of value modeling for our scenarios. Overall, the IDEF0 provides a framework for our ProModel simulation of the blade refurbishment process.

Perhaps the most important aspect of the model is the processing aspect, or how the blades move throughout the system. Each station assumes a first in, first out queuing discipline, and when a blade is done at a station, it moves immediately to the next station's queue. At each shop, the blade waits for a prescribed time according to a uniform distribution, centered on the data from CCAD's internal studies and cadet time studies. With the exception of the X-Ray machine, a blade is processed one time at each station.

Figure 3 below demonstrates how the IDEF0 derives the ProModel Simulation and how that creates our model output for the CCAD UH60 blade process.

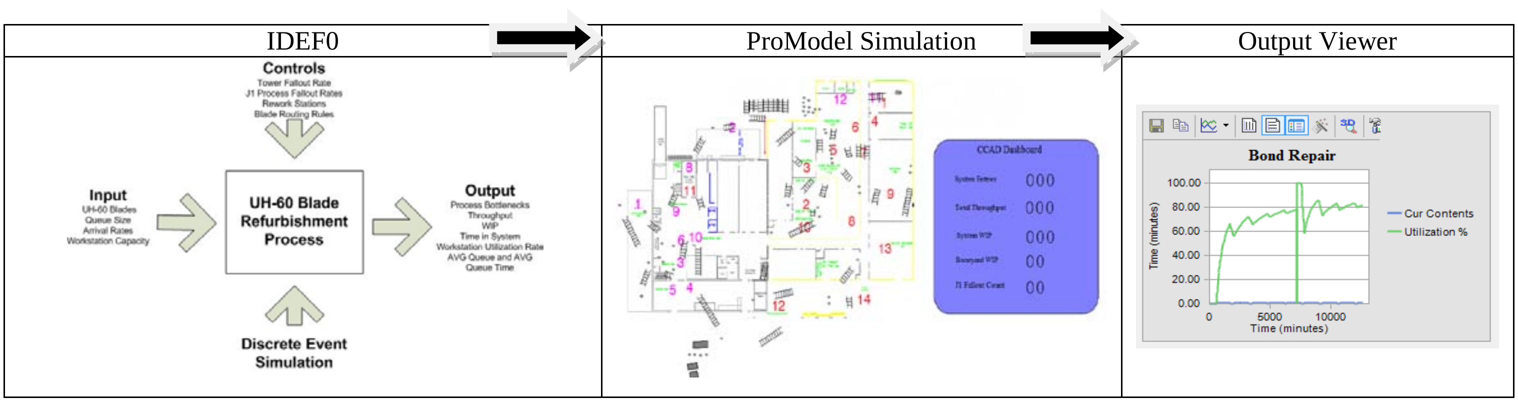


Figure 3. Input to Output Process

3.1 Verification and Validation of Model

After we laid out the process step-by-step and assigned the time parameters for each station, we needed to verify and validate the model. It is common practice in systems engineering to conduct model verification and validation. Verifying the model ensures that we build the model correctly, while the validation justifies if we built a model reflecting CCAD. Techniques like tracing and top-down design are used to verify a model. Validation includes comparing a model with the actual system (CCAD), performing sensitivity analysis, and testing against historical data.

During our model verification process, we started out with a top-down design by starting with a big picture approach. We used this approach to breakdown the model into the small, modular details. For CCAD, this could be seen in the re-inspection, bone yard discards, and different queues for specific stations. This is described as step wise refinement. To further verify our model, we traced and debugged different features of the model. We accomplished this by running the model to see if there was anything wrong with the make-up of the model. This helped us in checking for a reasonable throughput because some of the model debugging was a direct correlation to the output.

Validation provides us the best outlook to determine if our model was similar to CCADs process. Testing against historical data occurs by looking at our value measures and CCAD's historical averages, as provided by them. Sensitivity analysis occurs when we use identified value measures and their weights to compare our model scenarios. We then ran the model for a year's time and saw that our outputs were close to the actual monthly outputs of CCAD. Having a similar number of throughputs and the same bottlenecks further validates our model.

3.2 Model Output and Analysis

Once the model was validated, we ran all four of our scenarios to determine how valuable each change to the process is to CCAD, compared to the baseline, in terms of its effect on the key performance metrics. For the sake of simplicity and significance, the scores for average queue time and size were calculated using only the queues of stations with workstation utilization rates greater than 80%, which we deemed as bottlenecks. Similarly, the workstation utilization value measure was used to count the number of bottlenecks that scenario had rather than calculate an average utilization rate for that scenario. Figure 4 below shows our value modeling process. The top rows for each scenario are just the raw scores or the output straight from our model. The second rows show that value measure's utility on a scale from 0-100 based on each measure's specific scoring model whether it be continuous or discrete. The last rows reflect the measure's score relative to all the other measures as per the weights we found during our Stakeholder Analysis. The weighted scores for each value measure are added together to create a utility score for each scenario on a scale from 0-100. The scores for each scenario are shown in the table below.

Scenario		Throughput	WIP	Avg Queue Time	Avg Queue	Workstation Utilization	Total Value
Baseline	Raw Score	176	270	9.7	3.33	2	25.72
	Utility	34.67	22.54	24.20	16.75	35	
	Weighted Score	9.24	5.41	5.16	3.57	2.33	
2nd Shift	Raw Score	200	125	1.385	0.54	1	85.36
	Utility	66.67	100	92.80	86.50	80	
	Weighted Score	17.78	24.00	19.80	18.45	5.33	
3rd Shift	Raw Score	199	126	0.24	0.105	0	90.09
	Utility	65.33	100	99.51	97.38	100	
	Weighted Score	17.42	24.00	21.23	20.77	6.67	
1 Tower	Raw Score	176	284	9.88	3.405	2	21.69
	Utility	34.67	9.07	22.32	14.88	35	
	Weighted Score	9.24	2.18	4.76	3.17	2.33	

Figure 4. Alternative Value Scoring Model

4. Conclusions

The baseline model revealed that there were two crucial bottlenecks that severely limited the throughput and overall performance of the refurbishment process. Adjusting the capacities of these workstations was effective in reducing the impact felt as a result of these inadequacies although it was not as effective as we had expected. While we did see a significant decrease in WIP, our 2nd and 3rd shift scenarios only improved throughput by about 14%. The most significant change these scenarios brought was that it almost entirely eliminated our queues in front of our bottlenecks. Additionally, we found that the loss of one whirl tower's production would not be a significant factor for CCAD's performance in terms of throughput since operating with only one whirl tower did not cause a serious blockage for the process. Although these scenarios showed that adding working shifts to the current process will generate more throughput, more of the current process will have to be adjusted if CCAD is to reach their desired amount, such as taking in more blades per day.

4.1 Future Research

The first change we recommend for future work is to adapt the model to include resources and shifts. Resources in this case include people and the robots that transport the blades from station to station. We would also be interested in knowing more about CCAD's quality control system, and the engineers that inspect the special case blades. Finally, with the blade shop expanding into a new facility in the coming years, we are interested in running scenarios with the changes the new location brings.

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