Proceedings of the 2003 Systems and Information Engineering Design Symposium  
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PROCESS FLOW SIMULATION FOR THE FABRICATION OF COMMERCIAL NUCLEAR FUEL ASSEMBLY SUBCOMPONENTS

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KEYWORDS: Discrete-event simulation, manufacturing applications, nuclear power industry, process batching, production scheduling, spreadsheet simulation interfaces

ABSTRACT

Framatome ANP (FANP) recently merged with Siemens Power Corporation to form one of the world’s largest suppliers of fuel assemblies for commercial nuclear power plants. This merger offers the potential for cost reductions and logistical improvements through the integration of FANP’s two North American fuel fabrication facilities. According to plan, the current production uranium fuel rods and assemblies at Lynchburg, VA, will move to the Richland, WA, and the current production of spacer grids at Richland will move to Lynchburg. As a result, the number of different grids and the overall throughput of all grids at Lynchburg will double. This paper describes a simulation study commissioned by FANP to determine the impact of the consolidation at Lynchburg. Discrete-event simulation was applied first to study the existing grid fabrication process. A baseline model was developed that captures current process flows. This stochastic model was calibrated using data collected on the production floor, verified using deterministic line-of-balance calculations, and validated against historical throughput data. The baseline model was then extended to incorporate the new facility layout, equipment additions, and anticipated load. The enhanced model was used to predict potential bottlenecks and to refine resource and process modifications needed to manage the additional load effectively within the fabrication schedule constraints. To provide a tool for continuing operations management, use cases were developed and spreadsheet interfaces were implemented which allow FANP engineers to explore evolving operational scenarios.

1 BACKGROUND

Parts of Framatome Technologies recently merged with the nuclear divisions of Siemens Power Corporation to form the joint venture Framatome Advanced Nuclear Power (ANP) with United State headquarters in Lynchburg, VA. The combined work forces, technology, and market share project FANP as the world leading supplier of nuclear fuel and fuel services. The success of any business merger lies in the successful consolidation of the work force and technology with the intent of lowering costs, maximizing output, and improving quality. A major consolidation effort between the two companies falls within the nuclear fuel manufacturing. The nuclear spacer grid is an in-house manufactured subcomponent of the nuclear fuel assembly, the source of heat for the generation of electrical power in the power plant. The spacer grid is a critical component of the fuel assembly as it provides structural support as well as enhancing the heat transfer characteristics of the fuel assembly. Ideally, a manufacturing model holistically describes, predicts, and controls the joint spacer grid manufacturing process.

During the merger process, fuel fabrication must continue without interruption. Due to the dependency of the nuclear fuel assembly production on the spacer grid manufacturing, delays or unexpected problems in the spacer grid
manufacturing causes schedule slippages in the entire fuel fabrication process.

Section 2 presents a seven step model used during the simulation study. Section 3 presents two techniques for model validation. A deterministic line of balance model and the FANP historical production schedule provide comparison against the simulation results. Section 4 discusses the potential bottlenecks occurring within the manufacturing process and the impacts of adding additional process resources on the production time. Section 5 presents a more formal optimization procedure for identifying the bottleneck areas within the system. Section 6 presents a brief use case analysis for further simulation usage and experimentation by FANP engineers. Section 7 presents a personnel analysis and Section 8 summarizes.

2 SUCCESSFUL STEPS OF A SIMULATION STUDY

![Figure 1: Seven step model for a successful simulation model (adopted from Law and McComas, 23)](image)

The first phase of the project is the elicitation of the FANP goals and axiological components. Describing the goals of the system is the most critical step in the study as an engineer is unable to solve a problem that is poorly defined (Gibson, 5).

The development of a high level or conceptual description of the system is needed. One must define the processes used in the system, the behavior of the individual processes, and the process routing between stations.

A simulative model is only as accurate as the underlying data representative of the actual model. In addition, machines and processes can be characterized precisely, while human actions and human interactions with machines are much more difficult to characterize. For this reason, data collection is one of the most important and crucial steps in developing the model. There are two extreme methods in gathering data: 1) collect generalized statistics quickly and efficiently, 2) collect vast amounts of information on each process creating highly precise statistics. The latter may prove more effective in creating an accurate model, while also being extremely time consuming and dramatically decreasing the forward momentum of the overall project. Initially, the capstone team believed that supreme accuracy was not required to achieve an accurate model, and that the overall goal was to obtain general results and reflections of the effects of the integration. For that reason, and to meet critical deadlines, a compromise between speed and accuracy in collecting data was necessary.

Conceptual validation determines how accurate the model represents the real world from the perspective of the model users (Hu et al., 595). If the model is not an accurate representation of the real system, any conclusions from the model are erroneous. The simulation will always be an approximation despite the time and energy spent on the model building. The model should be sufficient to meet the specified objectives (Law and McComas, 22). If the model is not valid, iteration through the project objectives and data collection occurs to discover the errors in capturing the conceptual model.

Programming the model occurs within Arena 7.0. Arena 7.0 is one of the more accepted and tested discrete event simulation programs specifically designed for simulating in manufacturing, enabling better decisions, improving processes, and avoiding costly mistakes (Swets and Drake, 201). Validation of the programmed model involves comparing the simulation output to other benchmarks and modeling techniques. Validation of the conceptual and programmed model provides confidence that the simulation output is accurate in predicting the manufacturing system behavior. Experiments performed within the model focus on the feasibility of future production schedules involving the additional Siemens Power Corporation grid designs as well as assessing the impact of additional process resources on the production time.

The last step involves documenting the model and creating use cases for further simulation experimentation and study. Interfaces generated between Microsoft Excel and Arena 7.0 promote usability and usage by non-simulation experts.
3 MODEL VALIDATION

Validation is the “process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.” (Hu, San, and Wang, 595). Prior to the usage of the model results in a decision making process, careful steps must be taken to validate the accuracy of the model.

3.1 Deterministic Study

A deterministic model does not account for any uncertainty in the manufacturing process. The deterministic study is highly simplified and calculates the “line of balance” or operational load for each station over a given production interval given an average production and setup time for a station (Hopp and Spearman, 640). The deterministic calculation provides an overall view of the process to act as a model of comparison against the results from the stochastic discrete event simulation model.

The operational load or line of balance for a specific manufacturing process is calculated with the following equation:

\[
\text{Processing Time} + \text{Setup}_{\text{Like Grids}} + \text{Setup}_{\text{Unlike Grids}} \quad (1)
\]

The first term is the total raw processing time, for a specific station, over the entire production schedule. Some stations batch the spacer grids in groups of two, six, or eight for processing and this is taken into affect when calculating the raw processing time. Thus the raw processing time is found by the following equation:

\[
\text{Processing Time Batch} \times \{\text{Quantity} / \text{Batch Size}\} \quad (2)
\]

The second term in (1) is the setup time between similar spacer grids. For example, a machine may require five minutes to load another spacer grid type which is the same as the previously processed spacer grid. The last term is the setup time between spacer grids of unlike type. The following example further illustrates the line of balance calculations.

3.1.1 Deterministic Study Sample Study

Three grid types, Grid A, Grid B, and Grid C are produced in quantities of 100, 50, and 25 respectively. Each grid is processed through three processes, process I, process II, and process III. Each station has one machine operating. Table 1 summarizes the needed information for the line of balance calculation.

<table>
<thead>
<tr>
<th>Process</th>
<th>Process</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid Type A</td>
<td>Grid Type B</td>
<td>Grid Type C</td>
</tr>
<tr>
<td>Raw Processing Time</td>
<td>Raw Processing Time</td>
<td>Raw Processing Time</td>
</tr>
<tr>
<td>Setup Like Grids</td>
<td>Setup Like Grids</td>
<td>Setup Like Grids</td>
</tr>
<tr>
<td>Setup Unlike Grids</td>
<td>Setup Unlike Grids</td>
<td>Setup Unlike Grids</td>
</tr>
<tr>
<td>Total Time</td>
<td>Total Time</td>
<td>Total Time</td>
</tr>
</tbody>
</table>

Table 2 and Figure 2 summarize the line of balance calculations as expressed in equations (1) and (2).

Table 2: Breakdown of Operational Load

<table>
<thead>
<tr>
<th>Grid Type</th>
<th>Process I</th>
<th>Process II</th>
<th>Process III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Processing Time</td>
<td>833</td>
<td>2000</td>
<td>1000</td>
</tr>
<tr>
<td>Setup Like Grids</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Grid Type B</td>
<td>Raw Processing Time</td>
<td>417</td>
<td>1000</td>
</tr>
<tr>
<td>Setup Like Grids</td>
<td>0</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>Grid Type C</td>
<td>Raw Processing Time</td>
<td>208</td>
<td>500</td>
</tr>
<tr>
<td>Setup Like Grids</td>
<td>0</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>Setup Unlike Grids</td>
<td>60</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Total Time</td>
<td>1518</td>
<td>3715</td>
<td>1800</td>
</tr>
</tbody>
</table>

Figure 2: Graphical Breakdown of Operational Load

Process II has the highest operational time over the production schedule and is the restraining resource or bottleneck process. The throughput of the system is restrained by the processing capacity of process II (Roser et. all, 949). The figure shows that the setup times are rather insignificant relative to the raw processing time. As Process I is able to process grids at an average rate of over twice as fast, a rather large queue is expected to emerge at Process II. Process III will be highly under-utilized as it receives a grid from process II, processes the part, and must further
wait for Process II to supply another part. The starvation of process III may be a concern if the station is the most costly to operate and maintain. Increasing the system throughput requires increasing the operational capacity of process II which may involve reducing the processing time or batching the spacer grids for processing. This type of analysis may be applied to the FANP system over the production schedule spanning the next two years.

3.1.2 FANP Deterministic Study

Figure 3 displays the line of balance for the joint FANP grid manufacturing process over the next two years. The line of balance calculations were performed as shown in the previous example.

Figure 3 reveals several potential bottlenecks and thus restraining resources. It is important to note that Cleaning A and Cleaning C are separate processes using the same resource creating a re-entrant queue. Thus the total operational load over the Cleaning A and C resource is shown as the last vertical bar. The Weld A process, running only one eight hour shift per day, is the limiting resource or bottleneck process. However, FANP typically operates the Weld A process for two shifts a day thus decreasing the operational load required per eight-hour shift by two. Figure 4 displays such a scenario.

The operational load on the Weld A process, over one shift, is now comparable to the operational load of other stations. Thus, doubling the processing availability of the Weld A process potentially shifts the restraining resource to the Cleaning A and C process, Inspection C process, and the Assembly A and Assembly B areas. Increasing the Weld A capacity further through the addition of another machine, as FANP has indicated as a possible scenario, may have little impact on the overall increase in throughput as the system bottleneck shifts to another station. The deterministic model acts as a point of comparison for the simulation model.

3.1.3 Simulation Production Schedule Baseline Results

A visual plot of the expected times for grid completion based on the production schedule and the results from the simulation provides a level of validation for the simulation results. The completion time for the production schedule is based on the historical performance of the system and represents an accurate measure of system performance. Ideally, the two lines contained within the plot coincide. A visual inspection of Figure 5 verifies that as expected the lines do not perfectly overlap however are remarkable close for a discrete event simulation study. This discrepancy may arise in that the simulation produces grids immediately while the productions schedule logs completion of grids in batches and the simulation does not account for holidays such as Christmas where the manufacturing system is down. This provides further validation for the results of the simulation as the simulation is accurately predicting the behavior of the manufacturing process.
4 PROCESS ANALYSIS

FANP is interested in the impact of a new resource for the Weld A process on the system throughput, believing that the Weld A process is the system bottleneck. As stated previously, in order for the throughput of the system to improve, the throughput of the bottleneck has to be improved (Roser et. all, 949). If the Weld A process, as described in the deterministic model, is running for two shifts a day, the additional resource may not impact on the system cycle time and throughput. The addition of a new resource may shift the bottleneck elsewhere within the system and not have any impact on the system performance.

The discrete event simulation was executed with an additional Weld A resource operating two shifts per day. Thus the total resource capacity at the Weld A station is two machines operating for two shifts a day. Figure 6 shows the baseline simulation model with the Weld A station operating with one resource for two shifts a day. Another line, almost perfectly coinciding with baseline simulation, shows the effect of doubling the capacity at the Weld A station. The production finishes in almost exactly the same amount of time and the slope of the line, representing the system throughput (number of parts out divided by a given period of time), is nearly identical. The additional resource has no effect. The simulation results agree with the outcome of the deterministic study providing further validation for the discrete event simulation model.

The bottleneck has shifted to another station within the system. The deterministic model suggests stations Cleaning A and C, Assembly A and B, as well as Inspection C. The simulation was executed with the additional Weld A resource and an additional Cleaning resource. The overall cycle time is reduced by 14% over the life of the production schedule and has a significant impact on increasing throughput as shown in Figure 6 and Table 3.

The simulation was executed again with the previously added resources and an additional resource at the Inspection C station. The additional inspection resource has no significant impact until approximately day 450 when the Siemens grids begin production. The sequence of steps for the Siemens grids differs than the sequences taken by the FANP grids. Thus the additional inspection resource during Siemens grid production drastically decreases cycle time in conjunction with the additional cleaning and weld resources. It is important to note the placement of additional resources is recommended solely on reducing the cycle time while various other considerations such as costs, floor space, etc. may factor into the decision. Due to the difficulty in quantifying such criterion, they are not considered.

Assembly A and Assembly B were given another resource each. The additional resources have a drastic impact on the throughput and the cycle time of the system. Figure 6 and Table 3 summarize the bottleneck analysis.

Table 3: % Production Time Improvement in Additional Resources

<table>
<thead>
<tr>
<th>Additional Resource</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Baseline</td>
<td>N/A</td>
</tr>
<tr>
<td>Production Schedule</td>
<td>+4.61%</td>
</tr>
<tr>
<td>Weld A</td>
<td>-0.05%</td>
</tr>
<tr>
<td>Weld A, Cleaning</td>
<td>-14.11%</td>
</tr>
<tr>
<td>Weld A, Cleaning, Inspection C</td>
<td>-28.24%</td>
</tr>
<tr>
<td>Weld A, Cleaning, Inspection C, Assembly</td>
<td>-48.80%</td>
</tr>
</tbody>
</table>

The additional resources were added in an ad hoc manner. It is of interest to determine the placement of one additional resource to minimize the total production time in a systematic procedure.
5 SIMULATION OPTIMIZATION

The Arena software package comes bundled with OptQuest, a simulation optimization package. A common issue faced by individuals interested in the operation and design of manufacturing systems is selecting the control parameters to optimize the performance of the system (Rogers, 1142). The general format of an optimization requires two elements within Arena. The first element of the optimization problem begins with the objective function, the function in which one wishes to minimize or maximize. The second element requires defining and restraining the controls within the objective function. The constraints involve a non-negative control value (Rogers, 1143). The number of station resources may not be zero.

It is desirable to determine where to allocate additional resources among the manufacturing system to minimize the total production time. The optimization problem formulated by OptQuest begins with the objective function to minimize the total production time. Five stations were considered for the addition of another resource based on the potential bottleneck areas revealed from the simulation and the deterministic model. The five stations and the variables in the optimization are Cleaning, Assembly A, Assembly B, Inspection C, and Weld A, which represent the number of resources available for usage at the particular station. All resources other than the Weld A process run for one eight-hour shift while the Weld A process runs for two eight-hour shifts. All of the variables were required to equal one or more thus forcing at least one resource at any given station. The optimization determined the optimal location of an additional one, two, or three resources. The optimization problem is summarized in Table 4.

<table>
<thead>
<tr>
<th>Additional Resources</th>
<th>Optimal Additional Resource Location</th>
<th>% Decrease Production Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>1</td>
<td>Assembly A</td>
<td>11.7</td>
</tr>
<tr>
<td>2</td>
<td>Cleaning, Inspection C</td>
<td>20.7</td>
</tr>
<tr>
<td>3</td>
<td>Cleaning, Inspection C, Weld A</td>
<td>28.3</td>
</tr>
</tbody>
</table>

Table 5 summaries the optimization results. The optimal location of one additional resource is Assembly A. This result may be counter-intuitive compared to our previous analysis, however several bottlenecks exist within the simulation and the addition of one additional resource shifts the bottleneck to another station without a significant decrease in the production time. The Assembly A is the initial process and an additional resource at this station brings more grids into the system for processing at a faster rate.

6 PERSONNEL ANALYSIS

The goal of the personnel analysis was to determine the optimal level of staffing from a throughput and labor-utilization standpoint.

The first step was implementing labor as a resource set in the simulation model. Next, the model was verified using existing data and very little error was observed. This verification is shown in Figure 7.

After verifying that the model retained its accuracy with the addition of the resource set, the model was run several times with different levels of staffing to determine the optimal level of staffing, as determined by the level that produces the greatest throughput and the level of labor utilization closest to 75%.
It was found that both before and after the consolidation efforts took place, eight employees working on non-batching processes proved to have the greatest levels of throughput and utilization. This concurs with the facility’s current staffing levels, so Framatome ANP should not alter staffing levels in preparation for the upcoming integration effort.

7 USE CASES AND FURTHER SIMULATION USAGE

FANP engineers are interested in working with the simulation model in the future to extract information and do quantitative studies that will be help them reduce their manufacturing costs and improve their logistics. In order to maximize the utility of the simulation model FANP suggested a number of scenarios, which the Capstone team translated into a set of casual use-cases. Unfortunately, not all these scenarios are currently feasible without the assistance of a simulation professional. Nevertheless, our team explains the current steps for implementing each of the suggested scenarios in a set of use-cases. The use-cases define the importance of the scenario, the steps on how to reach the objective of the scenario successfully and where the potential failures may exist. The use-cases consist of the following scenarios:

- Change number of people
- Modify schedule
- Modify process flow (add or delete processes)
- Add grid types
- Modify equipment

8 SUMMARY

Simulation yields valuable information describing the underlying behavior manufacturing systems. The simulation presents an accurate and valid model of the actual production system compared to a static "line of balance" model and verification against the FANP future production schedule based on historical behavior. In both cases, the simulation output matched the results from the historical behavior and the deterministic model. The ability of the model to represent the actual manufacturing system attaches a degree of confidence for future simulation and experimentation.

The simulation model provides a holistic model of the manufacturing system with the desire to predict any potential pitfalls in the joint FANP grid manufacturing process. The purchase of the additional Weld A resource was believed by FANP to be adequate in allowing the manufacturing system to handle the additional Siemens Power Corporation grid technology. The simulation study concluded that the Weld A resource is a bottleneck resource however shared the constraint with other manufacturing processes. These processes including the Assembly A and B, Cleaning A and C, and Inspection C stations. Without this knowledge, the joint process throughput would not significantly increase. The usefulness of the additional Weld A resource would be questioned, and valuable manufacturing time would be lost in attempting to discover the cause of the true system bottleneck. The simulation saves time and money in the integration effort and provides an excellent tool for future process experimentation and analysis.
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