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BEST PRACTICES FOR EFFECTIVE APPLICATION OF DISCRETE EVENT SIMULATION IN THE PROCESS INDUSTRIES

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ABSTRACT

The application of discrete event simulation in the process industries is commonly used for the analysis of reliability and maintenance improvements. However there have been increasing applications that go beyond this traditional area of application to include evaluations for chemical plant expansions, capital investment options, cycle time reduction and safety, in presence of failure prone components. This paper will present three case studies to demonstrate the use of discrete event simulation for such applications. The first case study demonstrates the use of discrete event simulation to identify critical failure modes for a plant characterized by discrete and continuous product flow. The second study involves the evaluation of capital expansion decisions in presence of different failures and identification of critical components affecting plant throughput. The third case study shows the use of simulation of verify the designed production capacity of a subsystem in presence of different failures and operational constraints. The goal of this paper is to show the potential of discrete event simulation for such problems, and to present examples of best practices for the scoping and execution of simulation projects in the process industries.

1 INTRODUCTION

The reliable operation of a chemical plant plays a critical role in its ability to meet the target production. For plants running at a "sold-out" condition, downtimes resulting from unplanned shutdowns can cause lost sales and unmet demand, translating directly to a decreased profit. These downtimes can affect the plant wide operations (for example, failure of steam supply causing entire plant to stop functioning), operations of a subsystem (for example, failure of material handling system affecting the raw material loading in a subsystem) or operations of a single unit (for example, a pump failure affecting a reactor operation). In order to ensure reliable operations, improvement efforts are usually carried out in order to identify critical components that can significantly affect plant production and devise change policies for the critical components. Such change policies include: effective inventory management of spares, preventive maintenance policies. Besides these reliability related improvement efforts, the reliability of different components must be taken into account during other application areas such as: evaluating the impact of capital investment or new system design decision and cycle time reduction projects as ignoring such information can lead to over-estimation of the production capacity because "new" and "improved" does not always translate into improved reliability.

The identification of critical reliability components and evaluating the performance of manufacturing system in presence of failure prone components is a non trivial task because:

- The complex system interactions and product flows in chemical plants make it difficult to access the direct impact of reliability of different components on plant production. The operational complexity is further compounded by discrete and continuous product flows at different production steps, batching/un-batching of product streams at different processing stages, and variability associated with different processing steps (excluding reliability).

- Different failures can have different impacts on plant production. The failures can either reduce the production capability of the unit or allow running the unit at reduced production capacity. In addition, the startup and shutdown protocols before and after repair are different.
- Lack of historical data for certain types of failures makes it difficult to model in the simulation (for example, rare events, reliability data for new components).

Selecting the right level of detail required for modeling (for example, selecting different failure types), type of failures (for example, component failures only, safety trips, operating discipline issues) is a learned art but in general it is related to the data that is required to answer specific questions and make decisions. Reliability analysis for large scale manufacturing systems take considerable amount of time, and such efforts are typically carried out as a part of Six Sigma improvement initiatives (Owen et al. 2006, 2006a). The Winter Simulation Proceedings are a rich source of information addressing how to have a successful simulation project, usually found in the introductory tutorial papers, for example, “Introduction to Simulation” by White and Ingalls (2009). Of the many quality success papers available in the past proceedings, the paper by Sadowski and Grabau (2003) has the clearest statement about getting the right data (information) from the model and the right time to make the right decision. Identifying the data required to make a decision, the quality of the data required and the consequences of a correct or incorrect decision is a more difficult task for stakeholders than specifying a problem. Asking about the data required to make the decision will often lead the stakeholders to greater clarity about what is the successful outcome of the project.

Discrete event simulation based analysis is widely considered a best practice for reliability and performance analysis of manufacturing system due to its ability to model such complex system dynamics with relative ease. The simulation models mimic the operational dynamics of a system, and can be leveraged to other improvement projects with little or no customization.

In this paper, we discuss three case studies on use of discrete event simulation for reliability and performance analysis of manufacturing systems. The first case study discusses the use of simulation for reliability analysis of a chemical plant and provides a methodology for identifying critical components. This case study is based on our earlier work (Sharda and Bury 2008). The second case study demonstrates the use of simulation to evaluate the impact of capital improvement opportunities and to identify critical components contributing towards plant downtimes. The third case study shows the use of simulation to verify the designed production capacity of a subsystem in presence of different failures and operational constraints.

2 CASE STUDY 1: IDENTIFICATION OF CRITICAL RELIABILITY COMPONENTS CONTRIBUTING TOWARD THE PRODUCTION LOSSES IN A CHEMICAL PLANT

The objective of this case study was to identify critical components whose failures contribute towards the production losses in a chemical plant at The Dow Chemical Company. The chemical plant considered here produces more than 15 different types of products, consists of ~40 different subsystems (such as reactors, wash tanks, refining system) and there are more than 250 different types of component failures, which occur in different subsystems. Based on historical data, 36% of the production losses were due to equipment failures. The production operations at this plant were characterized by production of multiple products, batching/ un-batching of product stream, discrete and continuous material flow and uncertainties associated with production processes. The work discussed here is based on our earlier work (Sharda and Bury, 2008). However, in this paper, we provide a modified approach for reliability analysis and provide an overview of key challenges encountered during this project

The operations of the chemical plant being considered here can be subdivided into following main steps. Note the combination of batch and continuous processing steps.

1. Raw material loading (batch)
2. Raw material mixing (batch)
3. Reaction (batch)
4. Intermediate storage 1 (batch)
5. Raw product washing- (continuous)
6. Drying (continuous)
7. Blending (continuous)
8. Intermediate storage 2 (continuous)
9. Final Packaging (continuous to batch)

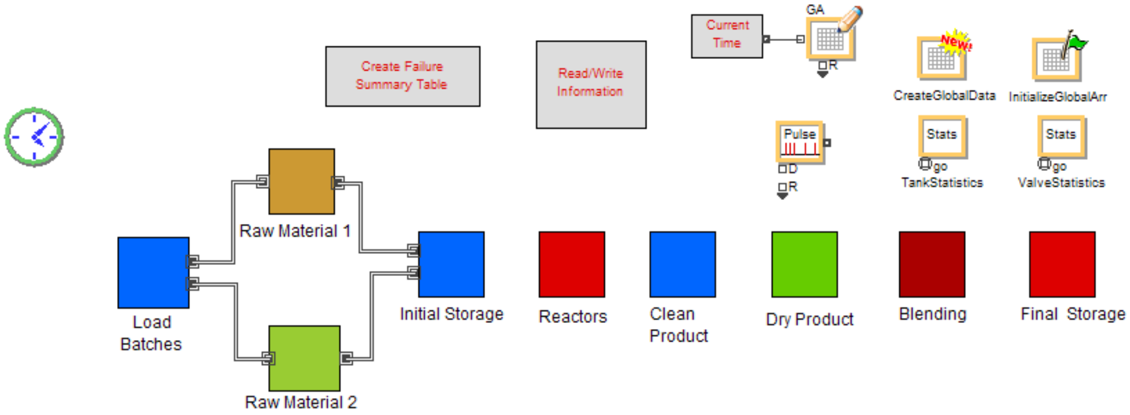

Figure 1: DES model for the chemical plant developed using ExtendSim (Sharda and Bury, 2008)

Figure 1 shows a snapshot of the DES model developed for the chemical plant using Imagine That, Inc.'s ExtendSim simulation software . The ExtendSim simulation tool allows for hierarchical modeling that promotes a clean and organized model structure that enhances understanding by the non-model developers. The data required for building the simulation model was readily available from on line systems. SAS's statistical software JMP and Averill M. Law & Associates' ExpertFit were used to generate distributions for different processing steps. The reliability data (distributions for time between failure (TBF) and Time to repair (TTR) of different failure components) was provided by the maintenance team.

Integrated databases within ExtendSim were used to store the information required for running the simulation model, information required for executing simulation logic and to store different statistics generated by the simulation model. These databases can be easily imported/exported from Microsoft Excel. We have found these databases greatly simplified the verification of the actual simulation logic and communication with the end users.

The user interface for the simulation model provided the following options for reliability analysis:

- Evaluating the impact of all the failure modes on plant throughput
- Evaluating the impact of failure of a certain subsystem (s) on plant throughput
- Evaluating the impact of failure of a certain component (s) on plant throughput

We created custom ExtendSim blocks to simulate the failure and repair of different components. In addition, we also created custom blocks to simulate the effect of change of inventory control policies of failure-prone components such as re-order point, stock level and time to reorder (see Sharda and Bury, 2008 for more details). These blocks simulated the process of tracking the spare part inventory for different component, ordering new spare parts at reorder point, and updating the spare inventory when the new spare parts arrive. If the component's spares were not available, the time to repair was adjusted to account for time to acquire additional spares.

The following approach was used to identify critical failure components:

- Evaluate the baseline production capability of the production plant considering all the failure modes. The baseline production capability represented the existing production capability of the plant.
- For each failure mode, evaluate the production capability of the production plant without considering the failure mode. This analysis provided the impact of removal of a given failure mode on the production capability of the plant.
- Identify critical failure modes using statistical analysis. We used t-test to compare the production level obtained by excluding certain failure with baseline production capability. A Pareto analysis for statistically different failure modes can be generated to provide guidelines for prioritizing improvement efforts.

The model predictions were validated against the data for daily production levels and average uptime rates for different products.

A significant barrier to successful execution of this study was scenario overload, or now that a simulation exists there are too many parameters to investigate. To efficiently execute the key task of identifying the critical components, we designed a systematic approach that first establishes the baseline production capability of the plant. The impact of each failure mode was then evaluated by running the simulation model by excluding that failure mode. Using Pareto analysis, the critical failures that have significant impact on production can then be identified. This reduces the number of possible simulation scenarios and generates data that are easier to understand and evaluate. The simulation modeling effort for this project also demonstrated the capability to conduct reliability analysis for systems with discrete and continuous product flow. The customized blocks developed for reliability analysis can also be used for other simulation projects. One of such example is provided next.

3 CASE STUDY 2: EVALUATING PRODUCTION IMPROVEMENT OPPORTUNITIES AND RELIABILITY ANALYSIS OF A CHEMICAL PLANT

In the previous case study, we provided an example of use of discrete event simulation to identify critical failure affecting plant throughput. In this study, we present a case study on the use of discrete event simulation to evaluate the proposed capacity expansion and reliability improvement opportunities at a chemical plant of The Dow Chemical Company. Similar to the previous case study, this case study also involved reliability analysis to identify critical failure modes affecting plant throughput. In addition, the impact of failure of different components was considered during the evaluation of different improvement opportunities. We leveraged the customized blocks and the analysis approach developed in previous case study to simulate the failure and repair of different components. A detailed discussion of this case study is in press (Sharda and Bury 2011).

Figure 2 outlines the high level overview of the production process. The entire production process can be divided into 5 major operations: raw material loading (continuous operation), material transfer (continuous operation), Operation 1 (batch operation), Operation 2 (batch operation) and final packaging (continuous operation). Operation 1 and Operation 2 involve completion of several sub steps. The plant produces 10 different types of products that are packaged in 5 different sizes. The processing time and transfer rates varied according to product type, and there was significant variation in processing times/rates within each product. When transitioning from one product type to next, a flush batch is sent to clean the entire production line. The raw product is first manually loaded into a Dump Station. From the Dump Station, a product batch is loaded into the Storage 1, where it is kept until the downstream equipment is available for the next operation. When the downstream equipment is available for the next operation, the batch is transferred for Operation 1. After Operation 1, the batch is transferred to immediate Storage 2 for storage. Storage 2 can hold multiple batches of product. The Operation 2 listed in Figure 2 is a batch operation and the equipment used to carry out the operation is used for both storage and processing. Different batches of the same product are stored in the Operation 2 equipment until (a) the equipment is full or (b) the production order is complete. If Operation 2 is being carried out, the intermediate batches are stored in Storage 2. After completion of Operation 2, final packaging is carried out which is also accompanied by quality control tests. The chemical plant operations were subjected to shutdowns (100-150 different shutdown events). The shutdowns occurred due to equipment failures, and other events such equipment cleaning, inspection, and quality control. Some failure events affected individual operations, whereas some failure events affected the entire plant operations. For each subsystem (for example, a Dump Station), there were multiple sources of failures (for example, failure of pump or gear box).

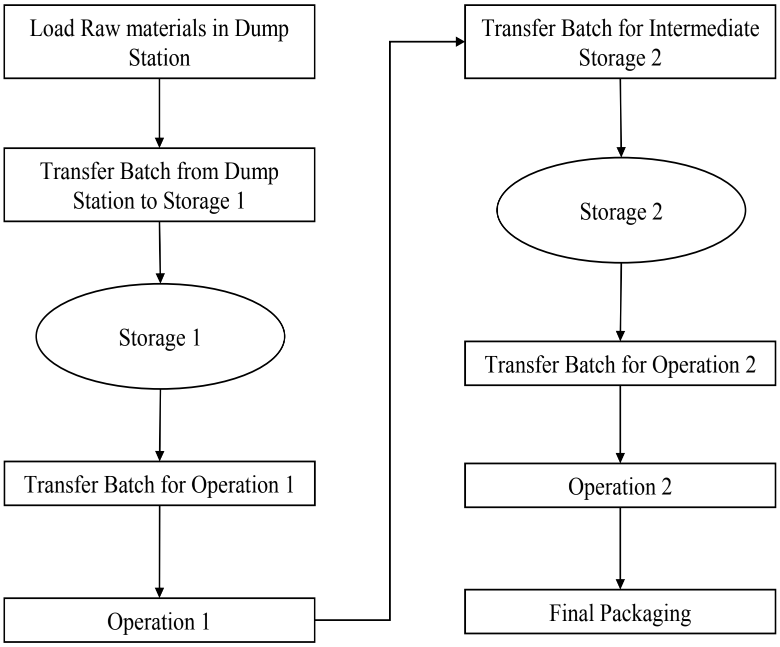

Figure 2: High level overview of the production process (Sharda and Bury 2011)

The main objectives for this study are outlined below:

- Evaluate the impact of different improvement opportunities including:
    - Variation in production batch size used for Operation 1
    - Evaluate the impact of automated transfer of batch from Dump Station to Storage 1
- Identify critical failures affecting the plant throughput and discuss change policies for critical components

The simulation model for the process was developed using ExtendSim®. We leveraged the custom blocks used for reliability analysis in the previous case study for this work. Most of the process data (such as transfer rates, cycle times) needed for model development was readily available from the automation systems. Additional information required for simulation model development (such as storage unit capacities, batch sizes) was provided by the subject matter experts. For failure and repair information of different shutdowns in the system, the previous 3 years of data was collected from different reports and Time between failure (TBF), and Time to repair distributions (TTR) were generated. The failure components were classified into different subsystems that correspond to individual equipment areas (for example, Operation 2 equipment failures). In addition to the failure modes, we also included other shutdowns (for example, downtimes associated with operating discipline issues, quality control tests) in our analysis. These downtimes were also a major contributing factor towards the plant downtime and the business team was interested in evaluating their impact on plant production.

We used JMP statistical software and ExpertFit distribution fitting software for data analysis and distribution fitting. JM® software was used to conduct preliminary data analysis in order to identify process shifts in the data, and identify significant outliers. Run charts are a useful tool to identify process shifts in the data. After checking the correctness of data with subject matter experts, the data was then imported in ExpertFit distribution fitting software for additional analysis (such as checking data independence) and distribution fitting.

After model development, the model logic was first verified with the subject matter experts. We used the following settings for running the simulation model:

- Simulation run length: 10 years
- Number of simulation runs: 25
- Warm up period: 30 day

These settings showed good model convergence. Law and Kelton (2000) and Banks et al. (2005) are good sources for on model convergence and efficiency. Different statistics such as operating times, transfer rates, daily production level, time between failure and time to repair of different components were verified against historical data and were found to be statistically consistent with actual data. Besides verifying these parameters, other key variables identified for validating simulation model output were average daily production rate of Operation 1 (for each product) and annual production. The analysis showed that the daily production rates of Operation 1 for different products were statistically indifferent from historical data.

To evaluate the impact of different improvement opportunities, the following scenarios were defined:

- Scenario I: Base case representing existing system
- Scenario II: Base case with addition of automated transfer of batch from Dump Station to Storage 1
- Scenario III: Base case with change in production batch size used for Operation 1 from X to Y lbs
- Scenario IV: Base case with change in production batch size used for Operation 1 from X to Z lbs, where Z>Y lbs
- Scenario V: Base case with change in production batch size used for Operation 1 from X to Z lbs and automated transfer of batch.

Figure 3 shows the Tukey's Honestly Significant Difference (HSD) test comparison of normalized annual production (lbs/year) for different scenarios. It can be clearly seen that increasing the batch size from X to Z lbs results in ~6% production increase. However, we can see that automating the transfer process from Dump Station to Operation 1 didn't have a significant impact on the production increase. This can be easily seen by comparing Base Case (I) with Scenario II, and Scenario IV with Scenario V.

After evaluating the different improvement opportunities, it was decided to use the parameters of Scenario IV for further analysis. The primary focus of reliability analysis was to identify the critical components that are significant contributors towards the production loss. The components identified from the analysis will be evaluated to identify "change policies" such as increase in spares, better preventive maintenance policies and/or new components.

We used the analysis methodology from the previous case study (discussed in Section 3) to identify critical failure components. After discussions with project team, it was decided to consider only certain failure components, instead of all the failure components. This decision was based on looking at multiple factors such as: the component area where a failure occurs, the duration/frequency of TBF and TTR. There were also certain failures that occur very infrequently, but can cause a significant production downtime and these were also included in the analysis. The main motive for considering specific failure modes was to reduce the scenario overload.

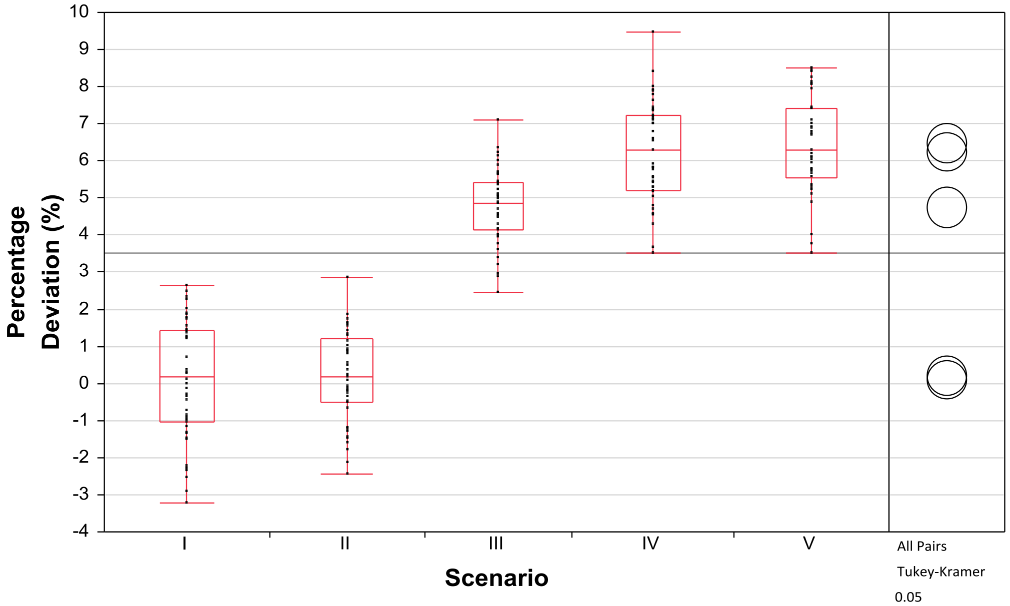

Figure 3: Comparison of annual production (lbs/year) obtained under different scenarios (Sharda and Bury 2011)

Figure 4 shows the normalized annual production (lbs/year) Dunnett's test comparison of different failures. We found that failure ID's 87 and 10 were statistically significant from other failures. The production gain of >1 % was significant for this plant, given the fact that the plant is running at a "sold out" capacity and producing high-margin products. Eliminating these failures would significantly improve the plant profitability.

The findings were discussed with a team of subject matter experts and production management. Solutions for the critical failures were developed in brainstorming sessions. These solutions were further evaluated for their cost effectiveness. One of the key contributions of this analysis was to quantify the production losses that will be accrued if the high impact failures are not eliminated. This provided the management with useful directions to improve the plant reliability.

4 CASE STUDY 3: EVALUATING THE DESIGNED PRODUCTION CAPACITY OF A MANUFACTURING SYSTEM IN PRESENCE OF DIFFERENT FAILURE MODES

In this case study, we present an example of use of discrete event simulation for evaluating the designed production capacity of a subsystem within a chemical plant. The key variables affecting the designed production capacity were different failure modes and operational constraints involving interlocks and restrictions on material flow. The objective of this study was to evaluate if the addition of a new production unit in the subsystem will achieve the desired production capability, and the subsystem production capacity would not limit the overall production capability of the plant.

Figure 5 shows the process overview of the section within a chemical plant. In the proposed system, a new unit (highlighted below) will be added to the existing 3 units. The production system receives a batch of raw product from upstream operations, and stores it in one of the two storage tanks (Storage 1-2). Each storage tank can hold one production batch required for running unit 1-4 operations. At any given time, there can be only 1 ongoing transfer from the storage tanks to the production units, and the transfer can only start if the storage unit's level is above a specific limit. If during the product transfer, the storage unit becomes empty, then the other storage unit is selected if its level is >0.

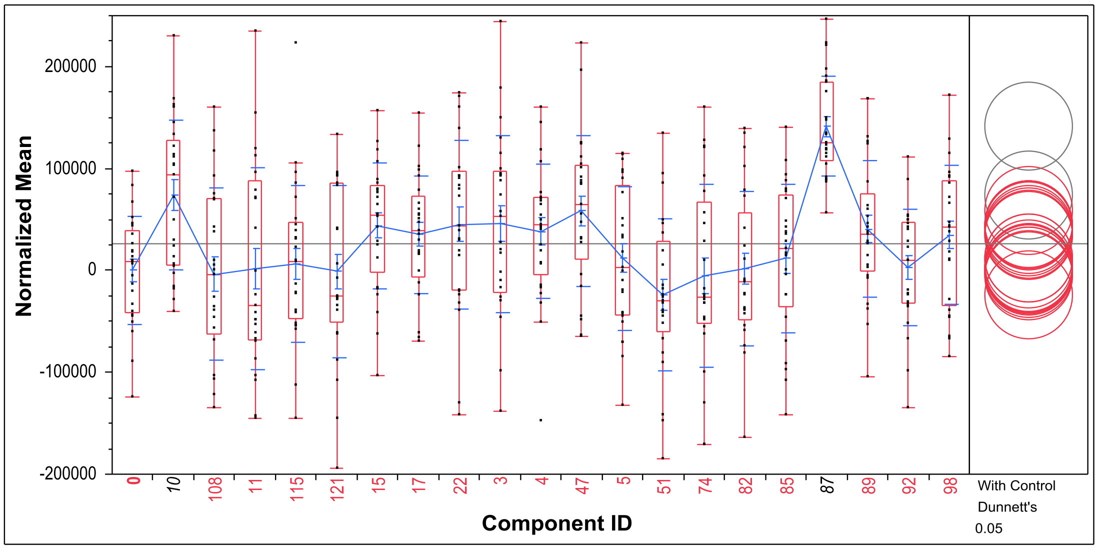

Figure 4: Normalized average annual production by eliminating a failure ID (Sharda and Bury, 2011)

Units 1-4 are batch processes and are composed of several sub-steps. At the end of the batch process, the product is transferred to downstream operations. The safe operating rules limit the concurrent states of the plant; the units 1, 2 and units 3, 4 cannot be in specific batch steps at the same time. In addition, unit 1 (or unit 2) can start its operation only when unit 2 (or unit 1) is in certain step or higher. Similar rules also hold true for operations of unit 3 and unit 4. The production capability of each unit is affected by different failures. The distribution of these failure modes was provided by the reliability team involved in the project.

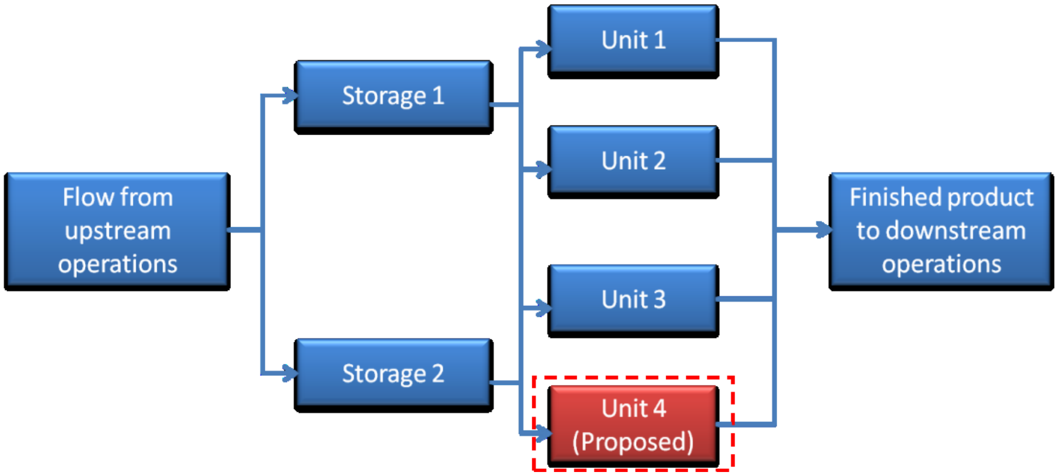

Figure 5: High level overview of the production process

Since the primary focus of this study was to evaluate the production capacity of the proposed system, we made the following simplifying assumptions:

- The product is always available in the storage units 1-2. This assumption implies that there is no starving from a bottleneck at the upstream operations and the product can always be transferred to the storage units at an adequate rate.

- The product can always be transferred from units 1-4 to downstream operations. This assumption implies that there is no blocking from a bottleneck at downstream operations.

The simulation model for the proposed system was developed using Extend® simulation software. We used the following simulation settings to evaluate the production capacity of the proposed system. These simulation settings showed good model convergence and a steady state behavior.

- Total simulation length: 10 year
- Warm up period: 1 month
- Number of simulation replications :10

The simulation results revealed that with the addition of new production unit (unit 4), the production capability of the new system will be higher than upstream and downstream operations. This was observed by significant wait times of units 1-4 for starting a new operation (indicating starving), and significant wait time for units 1-4 for unloading the finished product (indicating blocking). We evaluated the true production capacity of the new system by setting high upstream and downstream production rates. Our results show that the new system had ~7% higher production capacity than the upstream and downstream operations. These findings validate the hypothesis that the proposed system will not limit the production capability of the plant.

5 SUMMARY

The application of discrete event simulation in the process industries is commonly used for the analysis of reliability and maintenance improvements. However there have been increasing applications that go beyond this traditional area of application to include evaluations for chemical plant expansions, capital investment options, cycle time reduction and safety, in presence of failure prone components.

This paper presents three case studies to demonstrate the use of discrete event simulation for reliability analysis, evaluation of improvement efforts and to validate the design production capacity of a proposed system with addition of a new production unit. The first case study demonstrates the use of discrete event simulation to identify critical failure modes for a plant characterized by discrete and continuous product flow. The second study involves the evaluation of capital expansion decisions in presence of different failures and identification of critical components affecting plant throughput. The third case study shows the use of simulation of verify the designed production capacity of a subsystem in presence of different failures and operational constraints.

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