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EVALUATING INDUSTRY SPECIFIC ELECTRICAL DISTURBANCES USING A PROCESS MODELING AND SIMULATION TOOL

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Summary: **Electrical system-related disturbances cost the manufacturing industry several billion dollars per year in non-value-added expenses. In today's global economy, the need for elimination of these non-value-added expenses cannot be ignored. Elimination of these expenses requires the continued emphasis on developing robust electrical systems that work synergistically with today's world-class manufacturing systems. However, for most industrial companies to appreciate and invest in more electrically robust processes, electrical power variables must be presented in terms of their effects on improved plant productivity and profitability. Unit costs, throughput limits, and number of defects are parameters of interest to the process engineer and plant manager (decision-makers) rather than a voltage sag probability curve or magnitude-duration plot.**
This paper discusses two examples of using dynamic simulation as a new approach to translate the realities of electrical disturbances, well know to utility engineers, into productivity and cost impacts important to process engineers and plant managers. The first example is a discrete manufacturing process and the second example is a continuous manufacturing process. This paper will also discuss the major differences between both types of manufacturing processes.

1. INTRODUCTION

Dynamic simulation is the duplication of an actual system on the computer for the purposes of experimenting with the system without disrupting the actual production process. It is in essence a laboratory for the analysis of problems that have one of the following characteristics:
1. When a process behavior is not well understood,
2. When a prediction of future system behavior is required before investing any time or money in the actual system,
3. When the problem is too expensive for experimentation in the real world and,
4. When the system is too complex to understand the impact of one component of the system on the complete manufacturing system.

Dynamic simulation is therefore an ideal tool to analyze the impact of electrical disturbances on discrete and continuous manufacturing processes. Electrical disturbances and its associated characteristics (which are not well understood by most production personnel) can be modeled and measured by production performance metrics such as throughput time, cycle time, resource utilization and others. The ability to evaluate electrical disturbances and associated solution alternatives using dynamic simulation empowers production personnel to make informed economic decisions. Dynamic simulation can be considered one of the most powerful analysis tools for investigating complex processes or systems and for understanding the financial impacts of electrical disturbances on the manufacturing process. This tool bridges the gap between the power quality and production domain for new and innovative power quality solutions to improve overall production parameters.

2. SIMULATION CONCEPTS

2.1. Background

A basic premise to all management initiatives is the economic principle that we live in a world where labor and material resources are limited and its value is defined by the supply and demand for these resources. The supply and demand for limited resources generates its economic value. The objective of any organization is to use the limited resources to maximize the organizations economic value to its stakeholders. Thus, eliminating non-value-added costs is the underlying theme of all management initiatives. For instance, Just-In-Time eliminates costs associated with overproduction and unnecessary inventory storage and transportation. Concurrent engineering reduces the engineering design process time thereby getting new products to market faster and with fewer product development costs to recover. The central theme behind the lean enterprise concept is to continuously identify and eliminate non-value added activities throughout the entire value stream by understanding customer needs and redesigning the value chain to best meet or exceed those needs.

It is clearer now, than at any other point in the history of manufacturing, that the continuous elimination of non-value-added activities and costs is imperative to the continued growth of an organization. With that in mind, today's leading firms are constantly striving to identify sources of non-value added activities and develop innovative ways to eliminate them.

Eliminating mechanical based disruptions has been a key focus of production facilities as illustrated by the growth of the maintenance and reliability field. However, few organizations have recognized electrical disturbances as a major contributor of non-value added costs. It is estimated that electrical disturbances result in several billion dollars in production loses per year. For the last twelve years, EPRI PEAC has been working closely with the utility industry and their customers to help identify and eliminate non-value-added activities associated with electrical disturbances.

Every day, managers make difficult decisions that have both short- term and long-term impacts on the profitable success of their organizations. More often than not, these decisions are very complex. For most managers, anticipating all factors and factor interactions that impact the outcome of decisions is very difficult, if not impossible. Now, imagine a world where that manager has access to "perfect information" about the possible outcomes of decisions before they are made. While we will never have "perfect information," there does exist a tool that can evaluate potential outcomes of decisions and help to make the uncertainty of decisions more explicit. That tool is called dynamic simulation. This is in agreement with the MISSION program, an international consortium of industry, government, and academia, that organizations must implement and maintain pervasive simulation modeling to achieve a competitive edge in the next generation industry. The concept is that pervasive simulation throughout an organization will eliminate waste associated with the trial and error process of introducing goods and services to the customer. For example, EPRI PEAC recently completed a simulation project for a printed circuit board manufacturing company. The simulation identified several solutions to a power quality problem that was adversely affecting production. Simulation made it easier to perform cost benefit analysis and select the lowest cost alternative to improve plant performance and eliminate non-value-added costs.

The idea of spending more time and effort in the planning phase of a project, and using simulation to develop all of the possible scenarios is merely an extension of Deming's philosophy on quality: it is much less expensive to "do it right the first time" than to rework projects. The greatest potential for life cycle cost savings is in the planning stages of a project. Simulation helps to identify the most feasible economic alternative early in the design stage. Again, simulation encourages getting better information to make better economic decisions.

2.2. Pros and Cons of Simulation

Simulation is a valuable tool with increasingly new applications. Organizations are utilizing simulation not only for traditional design and implementation purposes but also for developing strategies, training, promotion, and marketing. However, like every other tool, simulation is not appropriate for all situations. The pros and cons of simulation discussed below may provide insight to the reader for identifying appropriate simulation applications. Simulation models have the advantage of being able to describe the following types of systems:

1. Systems that are currently not in existence,
2. Modified or altered systems that have not currently been modified or altered,
3. Systems that are too complex to be analytically modeled, and
4. Systems that have ill-defined critical variables that require experimentation.

Simulation allows one to experiment and make inferences regarding these systems in an environment that eliminates waste and subsequently reduces the cost of providing a product or service. Examples of waste reduction are the elimination of building prototypes, elimination of performing destructive tests, disrupting production, eliminating trial and error production modifications, and reducing personnel exposure to unsafe environments. As a by-product, simulation acts as a communication tool that forces members of an organization or team to provide input and coordinate plans.

The disadvantages of simulation are that it may be an expensive and time-consuming activity. If proper resources are not allocated to this activity, it will probably result in less than satisfactory information and project timing results. Even with the appropriate resources, simulation will not provide optimal solutions, but it will provide alternative satisfying solutions. Moreover, simulation modeling will not compensate for inadequate data, improper modeling, and faulty management requirements. Simulation modeling will not be able to provide process information to processes that have not been modeled.

2.3. Basic Steps of a Simulation Project

Simulation modeling has gone from utilizing basic programming languages such as FORTRAN, BASIC, C++, and others to utilizing menu driven software such as ARENA, PROMODEL, WITNESS, EXTEND, and others. This software evolution has made simulation programming easier, and to a certain degree, moved simulation modeling from the back rooms of academia to the forefronts of business decision making. However, this ease of programming is a double edged sword that has brought along with it a major concern; the development and use of inaccurate simulation models.

The primary objective of a simulation model is to **duplicate** the actual process on a computer such that it behaves under various anticipated circumstances similar to the actual process. If this is not achieved, then the computer model **cannot** be utilized as a predictive tool to evaluate the impact of process modifications. Typically, simulation models are utilized as a basis of allocating significant capital expenditures to improve process parameters. If the model is inaccurate, the implementation of solutions is in jeopardy.

The simulation community has developed basic steps to guide organizations through a simulation project by identifying tasks and issues to consider and their proper sequences to ensure a higher probability of a successful project. It is hoped that proper attention to these guidelines will significantly reduce the chances of a simulation model not representing the actual process. A review of the literature reveals a variety of these guidelines, which are more different in terminology and presentation than in basic requirements. The University of Tennessee, as a result of project experiences, as well as reviewing and interpreting other guidelines developed the following guidelines.

Step 1. Define Problem
— Identify the current problem of interest,
— Determine goals and objectives for the stated problem,
— Determine if simulation is best tool to achieve goals and objectives,
— Develop a project team of decision-makers and others familiar and affected by problem,
— Determine if simulation resources are available in-house,
— Develop a project plan.

Step 2. Define Problem Boundary
— Define explicitly the physical boundary to satisfy goals and objectives,
— Define the depth of analysis requires to satisfy goals and objectives.

Step 3. Determine Critical Variables
— Determine output metrics required to satisfy goals and objectives,
— Determine input variables necessary to achieve output metrics,
— Determine process variables necessary to achieve output metrics,
— Determine other variables that could impact output metrics,
— Link all the variables and metrics in a visual manner,
— Seek consensus from project group.

Step 4. Data Collection and Verification
— Determine data to be collected for input variables,
— Determine data to be collected for process variables,
— Determine data to be collected for other variables identified in step 3,
— Determine a strategy to collect data,
— Transform collected data into an appropriate format such as statistical distributions,
— Verify collected and transformed data for accuracy.

Step 5. Model Development
— Develop a flowchart of the process defined in step 2,
— Verify the flowchart for accuracy,
— Verify the flowchart data requirements against data collected in step 4,
— Develop a simulation program based on flow chart.

Step 6. Verification and Validation
— Establish agreement on the computer model logic among the project team members,
— Compare the model with the real system when real system exists,
— Compare the model with other similar systems if real system does not exist,
— Establish agreement among project team members that the model represents the real system.

Step 7. Experimentation
— Develop design of experiments to address goals and objectives,
— Determine a replication strategy,
— Perform experimentation.

Step 8. Output Translation
— Translate output into forms that others can understand,
— Develop simulation animation if required,
— Outline unexpected results and future concerns.

Step 9. Documentation
— Goals,
— Assumptions,
— Logic modules,
— End results,
— Opportunities

The above nine-step guideline is designed to assist individuals interested in simulation to ensure that the models are successful in adding value to the decision making process.

2.4. Discrete and Continuous Simulation Applications

Manufacturing applications can be divided into two broad types of process systems:
1. Discrete process manufacturing and,
2. Continuous process manufacturing.

A discrete process is described as a process that changes only at discrete points in time. For example, a discrete process performs activities on an entity and then when complete may transport the entity to another location for further processing. An example of a discrete process includes many manufacturing processes such as metal fabrication where the process includes drilling holes in a metal bar followed by grinding the bar prior to final assembly. Other examples of a discrete process are waiting in line for a bank teller or waiting to be served at a hospital emergency room. Another important feature of discrete processes is buffering or queuing. In discrete sub-processes within a system, an entity my be stored in a buffer area or queue waiting for the next discrete process step. This buffer area may be used to absorb the impact of an electrical disturbance as will be demonstrated further in this paper. Approximately 80 percent of all manufacturing processes are some type of discrete process.

The second type of process system is the continuous process. A continuous process is defined as a process that includes continuously changing entities. For example, petrochemical processes, paper machine processes, or plastic extrusion processes are examples of continuous process. An important feature of continuous processes is the very limited to no buffer area between sub-process elements in a continuous process. (Note: an exception would be a holding tank to smooth out process flow fluctuations.) For example, once a continuous process begins, the process must continue thro-

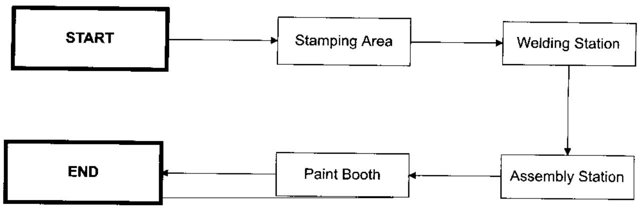


Figure 1. Metal Parts Production Process

ugh completion without interruption. For instance, once crude oil enters a petrochemical refinery process, the process must continue unabated through the continuous process, or significant costs may be incurred. The material flow system in a continuous process can be characterized as follows:

1. Large quantity and small variety of products are produced,
2. Very long, continuous production runs,
3. Equipment used is special purpose rather than general purpose,
4. Inventory of work-in-process is very low compared to output,
5. Swift movement of units through the facility is typical,
6. Very little to no buffer or waiting line proceeding sequences of individual sub-processes,
7. Materials are moved by connected pipes, material guides, webbing feeds, etc., and
8. Fixed costs tend to be high and variable costs tend to be low.

3. CASE STUDIES

3.1. Discrete Simulation Case Study for Metal Parts Production

Industry utilizes the basic process of converting raw sheets of metal into either consumer products or components for consumer products. Examples of industry that use this basic process are automobile, aerospace, appliances, computers, electronics, and building products. The specifics of the process design and configuration depend on the product design (shape and properties). The basic raw sheets of metal are transformed into value-added products through six different types of processes as defined below:

1. Casting/Molding force liquids or derivatives at high temperatures into a mold and then allowed to harden to the shape of the mold.
2. Forming forces raw materials by pressure into die or mold and then are allowed to take the shape of the die or mold.
3. Separating cuts or shears the material to achieve the desired shape of the product utilizing a variety of techniques such as tapping, milling, stamping, and others.
4. Conditioning utilizes mechanisms such as heat and chemicals to modify material property.
5. Assembly combines parts into a single component or products.
6. Finishing beautifies and/or protects the product.

A simplified version of an actual production line from the automobile parts manufacturer is presented in Figure 1. Small metal sheets are brought from the receiving inventory area to the stamping area. In this case, the part is stamped on a group of presses to obtain the desired shape of the product. The total time to process the part at the press ranges uniformly from 1.5 to 2.1 minutes depending on variations in the product. The part is then forwarded to the welding station. The welding station welds several smaller metal pieces to the stamped component. The mean time to weld parts is 1.4 minutes with a standard deviation of 0.8 minutes. This large standard deviation is due to the on job training of new employees. The parts are then forwarded to the assembly station where several small parts are assembled to the component. The time required to assembly the part ranges from 1.2 minutes to 1.9 minutes. Again the variation is due to the variety of product modifications. Finally, the parts are sent to painting. The painting booth is automated and set for parts to be in the paint booth for 1 minute.

A discrete event simulation model of the process was developed utilizing the ARENA software. The model simulated the process for one shift over one year. The objective of the simulation model was to predict the impact of electrical power disruptions in terms of the performance degradation of the production line. The model specifically wanted to evaluate the electrical power disruptions to the presses in the stamping area, as it currently is the bottleneck for the entire production line. Empirical data indicates that such presses are

Table 1. Simulation Results—Discrete Process

Metrics	Results without electrical disturbances	Results with electrical disturbances	Percent impact
Number of Parts Produced	66,644	65,111	–2.3
Average Time (min) in System	10,012	10,802	–7.9
Resource Utilization (%)			
Stamping	0.99	0.96	–3.1
Welding	0.55	0.51	–7.8
Assembly	0.86	0.80	–7.5
Painting	0.55	0.52	–5.7
Inventory Levels			
Stamping	6,648	7,257	–9.1
Welding	0.23	0.25	–8.6
Assembly	0.63	0.68	–7.9

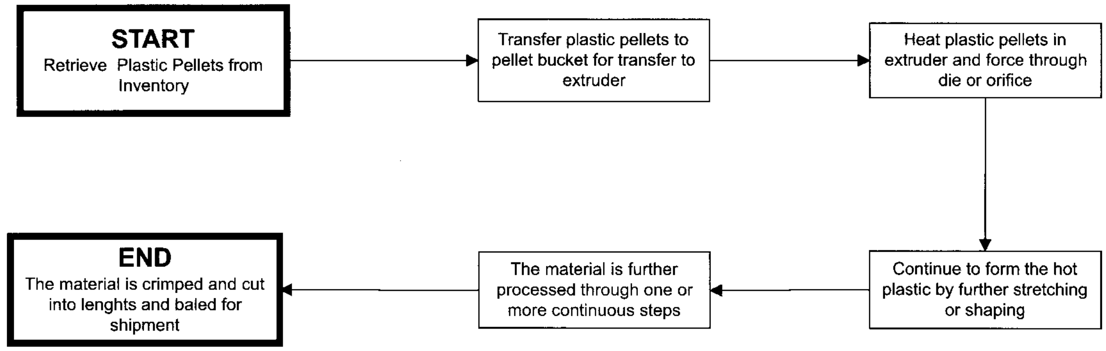


Figure 2. Process Flow Chart for Plastic Extrusion

exposed to 12 occurrences of electrical power disruptions per year. Each occurrence will shut the machine down from several minutes to a few hours. Production line performance was defined in terms of parts produced, throughput time, resource utilization, and inventory levels as illustrated in Table 1.

The simulation results present the degradation to the performance of the metal production line due to expected electrical disruptions to the stamping presses. The percent degradation numbers may be deceptive because these values represent the significant impact that electrical distributions have on the production line. For example, a 9.1 percent increase in inventory space requirement is a significant additional cost to the organization. This cost includes components such as facility cost ($70 per square foot), utilities cost (heating, cooling, lights), labor cost (additional labor to handle inventory), equipment cost (additional material handling equipment), and others. It is also evident from the simulation results that electrical disturbances degrade every critical performance metric of a production line. These degradations would significantly increase from the above results given the following realistic conditions:

1. Manufacturers face greater electrical disturbances than considered in this case study,
2. Electrical disturbances result in rework that then must be integrated into the production line,
3. Electrical disturbances result in scrap that must then be handled, and
4. Electrical disturbances impact all equipment rather than the stamping presses.

This case study has illustrated via dynamic simulation the significant impact electrical disturbances have on discrete manufacturing process.

3.2. Continuous Simulation Case Study for Plastic Extrusion Process

A continuous manufacturing process is typically found in high-volume, low-variety industries. An example of a continuous manufacturing process is the manufacturing of plastic wire using a plastic extrusion process.

This section of the paper discusses the impact of an electrical disturbance on a continuous manufacturing process by simulating a plastic extrusion process. A basic plastic manufacturing process used in making wire or other metallic profile shapes is called an extrusion process. Extrusion is something like operation of a sausage-stuffing machine or a hand-operated cake decorator. Dry powder, granular, or heavily reinforced plastics is heated and forced through an orifice in a die. The heart of the process is the extruder. The extruder plasticates (melts and mixes) the material and forces it through the die. Screw extruders are the most common, but ram or plunger types are also sometimes used. During the extrusion process, the polymer is compacted, heated, degassed, compressed, and plasticated by the action of the screw. In most extruder processes, the plastics go through the following five steps:

1. Extruder plasticates and forces material out through the die or orifice.
2. Die allows the hot molten or soft plastics to take shape.
3. Forming stretches or shapes the hot material.
4. Post-forming trims, cuts or further shapes the material.
5. Secondary processing further cuts or fabricates or assemblies.

A common extrusion process is to produce monofilaments. Monofilaments are produced using a multiorifice die. These dies contain many small openings from which the molten material emerges. The multiorifice is often much finer than the diameter of a human hair which requires the plastics to be made fluid. In many cases, the plastic extrusion from the multiorifices is extruded into a coagulation bath through the tiny holes of a spinneret. In the bath, the solution coagulates and becomes Acrilan acrylic fiber. The fiber is then washed, dried, crimped and cut into lengths, and baled for shipment to textile mills where it is converted into carpeting, wearing apparel, and many other products.

Figure 2 provides an outline of the manufacturing process.

A simulation model of the continuous process was developed utilizing the ARENA software with the same assumptions as stated for the discrete case. For each process shown in Figure 2, the mean process time and standard deviation, including outages, setups, rework, and other routine disruptions are incorporated in the simulation. The model specifically wanted to evaluate the electrical power disruptions to the extruder, as it currently is the bottleneck for the entire continuous production line. Production line performance is illustrated in Table 2.

The simulation results present the degradation to the performance of the plastic extrusion production line due to expected electrical disruptions. For example, a 9.2 decrease in yearly production and a 6.8 percent increase in time that the continuous part must stay in the system, represents additional

Table 2. Simulation Results—Continuous Process

Metrics	Results without electrical disturbances	Results with electrical disturbances	Percent impact
Number of Coils Produced	209	189	-9.2
Average Time (min) in System	576	615	-6.8
Resource Utilization (%)			
Extruder	1.0	0.93	-6.4

costs to the organization. It is evident from the simulation results that electrical disturbances degrade critical performance metrics of a continuous production line. These degradations would significantly increase from the above results for the same reasons as stated in the discrete case. This case study illustrated the impact of electrical disturbances on a continuous process utilizing dynamic simulation

3.3. Results and Information Content

As stated previously, the continuous manufacturing process is characterized by having very little to no buffer or waiting time proceeding sequences of individual sub-processes. For example, in a discrete manufacturing process, a transportation step and a waiting or queue step follow discrete process steps. The waiting or queue step provides elasticity in the manufacturing process. Whereas, in a continuous process, there is very limited to no waiting or queue step that provides elasticity in the manufacturing process. Having no elasticity in the manufacturing process is one major contributor to the differences in the financial impact associated with continuous versus discrete manufacturing processes.

The best way to understand the important difference between discrete and continuous manufacturing process is to visualize a single entity and imagine the entity being transported throughout both manufacturing processes. In a discrete process, the entity is transported to the first process where it waits in a queue prior to some transformation-taking place on the entity. Once the process is complete, the entity is then transported to another process, where again, it waits in a queue prior to the second transformation process. These steps, transportation, waiting, and process continue through each step until final process. However, in a continuous process, the entity is transferred to the first process unabated (no waiting in a queue) where some transformation is performed on the entity then transported to the subsequent process. In a continuous process, the entity experiences little to no waiting in a queue between processes but rather a continuous process occurs. This continuous process results in no elasticity being available in the manufacturing systems to absorb any disturbances. As a result, if a disturbance does occur, it affects all processes upstream of the occurrence. This difference between a discrete and continuous process is shown simplistically in Figure 3. As shown, the most significant difference between a discrete and a continuous manufacturing process is that very little to no waiting time occurs between process steps in a continuous process, again as shown in Figure 3.

The cycle time (CT) for a typical discrete process is defined using Formula 1 where the random variable T_i is the transportation time for process i, W_i is the waiting time for process i, and P_i is the time for process i through process n. The cycle time for a typical continuous process is shown in Formula 2.

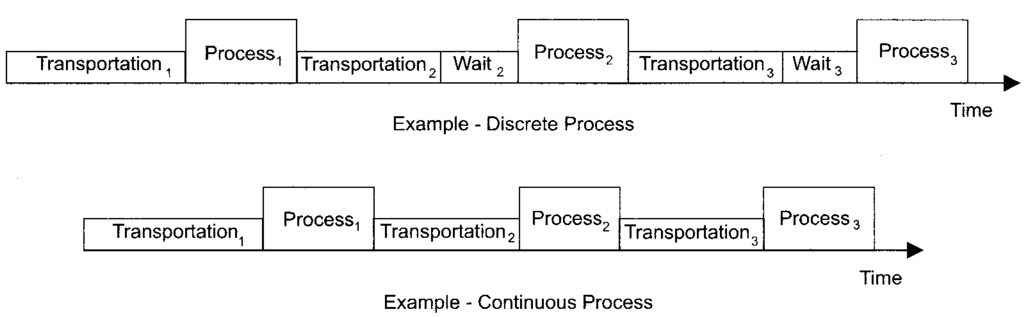
Formula 1: $$CT = \sum_{i=1}^{n} T_i + W_i + P_i$$

Formula 2: $$CT = \sum_{i=1}^{n} T_i + P_i$$

Higher cycle time results in increased costs, inventory, work-in-process, and bottlenecks.

Random disturbances manifest themselves in large bottlenecks and queue times. These disturbances may last for extended periods, possibly throughout the production cycle. This compounding affect of random disturbances is the single largest contributor to increased cycle time. The com-

Figure 3. Comparison of Discrete and Continuous Manufacturing Process



pounding result is a consequence of the linear combination of random numbers, that is, a linear combination of sequential manufacturing operations whose process times are described by statistical distributions. The mean of a linear combination of two random variables, say X_1 and X_2, is given as $E(Y) = E(X_1) + E(X_2)$; however, the variance calculation is $V(Y) = V(X_1) + V(X_2) + 2Cov(X_1, X_2)$ where $Cov(X_1, X_2)$ is the covariance of X_1 and X_2. The covariance is used to describe the degree of association between X_1 and X_2. For many sequential manufacturing operations, a strong covariance exists between random variables, which results in increasing the overall system variance. For a continuous process, the covariance between two random variables approaches 1.

The location of an electrical system disturbance within a sequential manufacturing process is also a significant contributing factor that results in increasing system variation. For example, if an electrical system disturbance occurs at the first workstation, it has a greater impact on the WIP and cycle time variation than an equivalent disturbance later in the process. This affect is primarily due to the linear combination of the covariance terms in the downstream processes. Therefore, excess variation early in a manufacturing process results in the propagation of covariance in downstream stations.

The production process impact of an electrical system disruption can be significant, as demonstrated in this study. In addition, the economic impact of random disruptions and the associated non-value activities required for continued operation can also have a significant impact on the firm's profit-and-loss statement.

4. CONCLUSION

Electrical system-related disturbances are estimated to cost the manufacturing industry several billion dollars per year in lost productivity and overall process performance. This paper discusses a new approach for defining the performance and financial aspects associated with electrical system disturbances in a sequential manufacturing environment using a mathematical simulation and modeling technique. By modeling an actual manufacturing system and running a simulation to determine key variables that effect performance, a company can make more informed economic decisions concerning the best alternative to optimize the manufacturing process.

This paper discusses the importance of incorporating a power quality program to minimize random manufacturing failures thereby reducing production time and cost. Unscheduled downtimes are one of the largest and most disruptive sources of variation. Sensitive electronic equipment shutdown, resulting from voltage sags, can significantly effect a production system's cycle time, throughput, work in process, and equipment utilization.

The conclusion provided by this study is summarized below:

1. Electrical system disturbances result in a marketable increase in the average cycle time, a primary performance measurement of a manufacturing operation.
2. Continuous processes contain little to no elasticity to absorb electrical disturbances.
3. Electrical system disturbances cause a significant decrease in the average yearly production.
4. Electrical system disturbances have significantly larger and longer impacts as the utilization of the manufacturing facility increases.
5. Electrical system disturbances result in increasing the overall system variability.
6. Electrical system disturbances located early in the manufacturing process have a greater influence on the system variability then do affects further downstream.
7. Electrical disturbance mitigation components should first be considered for bottleneck equipment followed by equipment located early in the manufacturing process.
8. Under-utilized facilities will see limited impact from electrical system disturbances.