INTEGRATING DISCRETE-EVENT SIMULATION WITH STATISTICAL PROCESS CONTROL CHARTS FOR TRANSITIONS IN A MANUFACTURING ENVIRONMENT

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ABSTRACT

We present a model that integrates real-time process control charting with simulation modeling to illustrate the effects and benefits of SPC charts for quality improvement efforts. The integrated model is particularly significant in addressing transition issues arising from changes in the input material. A case study based on a medical manufacturing industry process is used to illustrate the approach.

1 INTRODUCTION

Simulation has proven to be a potent tool in the design/redesign, development, evaluation and operation of manufacturing systems prior to its installation. When simulation models are well designed, analyzed, and tested, robust systems will often result. Modeling and analysis of the intended manufacturing system via simulation often helps to construct a better system through elimination of unforeseen bottlenecks, improvement of resources utilization and optimization of system resources. Through better appreciation and understanding of the system, the analyst can experiment with different scenarios and unknown situations.

Statistical process control (SPC) is a widely used process monitoring technique, especially in discrete process industries, for the continuous improvement of products and processes. SPC in the form of control charts (e.g., Shewhart charts and CUSUM charts) is useful in improving product quality by continually checking the "stable-state" system. When there is a departure from the stable-state of statistical control (due to certain special events) and detected by the control chart, the engineers or analyst then look for the assignable causes and try to eliminate them.

While simulation models provide a "realistic" platform for better understanding of the new or redesigned system operation, the product and process quality dimensions of the manufacturing system are often overlooked. The fact is that quality control techniques are critical activities in manufacturing industries when maintaining and improving product quality is a priority. In this paper, we use a case study to illustrate the integration of on-line control charts with simulation modeling.

The remainder of this paper is organized as follows. In Section 2, we introduce the company used in the case study. Section 3 provides a description of the process. The use of SPC techniques for process monitoring is illustrated in Section 4. In Section 5, we discuss the development of the simulation model to represent for the production process. The integration of SPC technique with the simulation model is then described in Section 6. A summary and discussion of future work is provided in Section 7.

2 COMPANY BACKGROUND

GAMMEX-RMI is a worldwide organization, developing products for improved healthcare for over 25 years. GAMMEX was incorporated in 1969, as a manufacturer of laser alignment devices for use in medical imaging and oncology treatment. In 1987, Radiation Measurements, Inc. (RMI) of Middleton, WI was acquired. RMI had proven itself to be a major innovator of quality control devices for radiology, ultrasound, and mammography.

Working closely with universities and medical physicists worldwide, GAMMEX-RMI now develops and refines more efficient and effective testing tools for quality assurance.

In this paper, we illustrate the proposed simulation integration with SPC using an industrial process at GAMMEX-RMI. We have coded the actual data given here to protect the company's confidentiality.

3 THE TISSUE MIMICKING PROCESS

GAMMEX-RMI produces tissue mimicking products, often known as phantoms, for several human components

including brain, bones, lungs, breasts, etc. The phantoms are typically used in quality assurance programs for medical departments such as radiation oncology, ultrasound, and mammography to meet FDA requirements on test instrument specifications.

GAMMEX-RMI most frequently produces a phantom called Electron Solid Water. These products are primarily used for radiation beam calibrations including photon, gamma ray, and electron beams. The product slabs comes in different sizes, as shown in Figure 1. In this paper, we will focus on the Electron Solid Water production process.
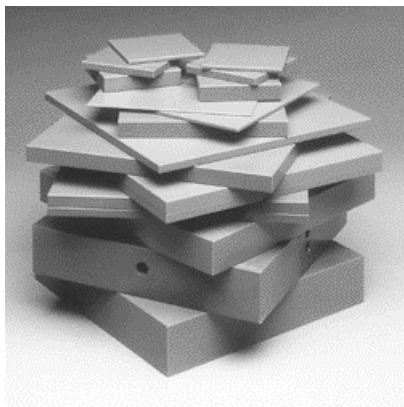

Figure 1: The Final Electron Solid Water Slabs

3.1 Process Flow

Figure 2 gives a flowchart of the basic tissue mimicking process (TMP). It first involves mixing appropriate amounts of resin, filler and hardener ingredients based on the prescribed recipe. One of the primary components in the recipe is a plastic polymer called PolyMicroSphere (PMS). The PMS batches are often preheated the day before use to reduce the moisture content. Once the recipe is prepared, it is put into a vacuum chamber to blend for approximately 50 minutes. Next, the sluggish product mix is evacuated from the container bowl into steel mold slabs of different sizes as well as cylinder molds to make test rods. These molds are then sent to a waiting area to dry and harden. Next, the molds are cured in heated ovens. Once cured, the test rods are measured at a local computer tomography (CT) scanning lab to determine the CT number. Meanwhile, the mold slabs wait in a temporary storage area for the CT number report to return. If the CT number for the batch is not within the specification limit the product is scrapped. If the CT number is within the specification limits, the operators will proceed to de-mold the slabs, cut them into required dimensions, and give them a final trim to make the completed product. These finished slabs are then examined by quality control personnel for flaws before packaging and shipping.

3.2 Transitions in Input Material and the Effect on Quality

The most important quality characteristic of the output product is the CT number. Each TMP product has an acceptable range for its CT number. The CT number specification limit for Electron Solid Water is 31 ± 5 (in Hounsfield Units, HU). Among the ingredients used in the TMP, the PMS material is known to have a direct impact on the CT number. The lightness of the PMS material and its tendency to absorb moisture make it difficult to work with.

Further, the PMS material is shipped to GAMMEX-RMI in barrels. A new barrel of PMS has to be opened, on average, every twenty days. Through experience, it was known that there is a tremendous amount of barrel-to-barrel difference in the PMS material. Such variation in PMS barrels has made the transition from barrel to barrel problematic. Often, the current recipe using a new barrel of PMS will make unacceptable slabs, i.e., the CT number will be out of specification. Within each barrel, the size of the PMS tends to vary which has potential impact on the product mix and thus the CT number reading. In addition, these PMS barrels are often contaminated by impurities.

As a result of these material issues, systematic adjustments to the recipe for the transition from one barrel to the other and sometimes from batch to batch are an integral part of the production process. To compensate these unknown variations, information about the CT number is fed back to determine the amount of adjustment in the recipe, if necessary. The need for feedback adjustments has opened doors to monitoring and control of the TMP process.

4   SPC FOR THE TISSUE MIMICKING PROCESS

Control charting is a useful SPC tool in product and process improvement work. Grant and Leavenworth (1996) and Montgomery (1997) are two references that contain an in-depth study of various control chart methods. The typical control chart plots the measured averages of the quality characteristic from the process versus time (or batch number). A center line is drawn on the chart to represent the process average of the quality characteristic that correspond to the in-control state. To serve the purpose of continually checking the stable-state system, the upper control limit (UCL) and lower control limit (LCL) are also plotted. When a point falls outside the control limits, there is statistical evidence that the process is out of control. Then corrective actions can be commenced to look for the assignable cause.
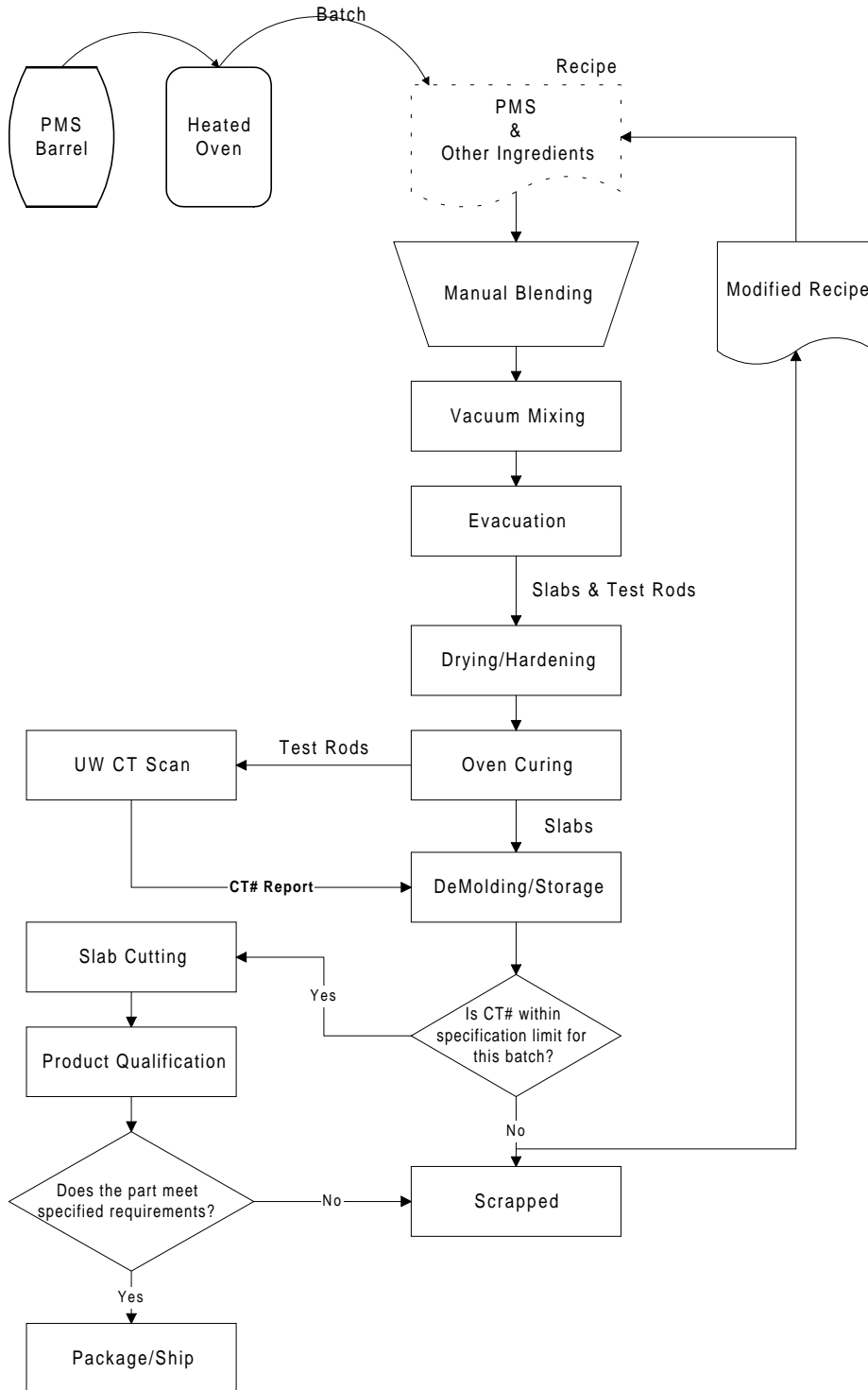
Figure 2: The Tissue Mimicking Process Flowchart

For the Electron Solid Water process, a CT measurement is acquired for each batch of the product. We note that CT number is the critical variable data used to qualify the acceptability of this tissue mimicking product. Therefore, it is important to closely monitor the production process in terms of the output quality characteristic CT numbers. As such we employed the control chart methods for individual measurements, the X and MR chart to gain an understanding of the process location and variability.

The centerline and control limits for the X and MR charts are determined from the following equations. Let x_1, x_2, …, x_n be the CT measurement for n batches. Then, the center line, $\bar{x}$, for the X chart is given by

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}. \tag{1}$$

In order to obtain an estimate of the process variability, the charting method uses the moving range of two successive observations. The moving range is

$$MR_i = \left| x_i - x_{i-1} \right|, \quad i = 1, 2, …, n-1.$$

The average of the moving ranges, $\overline{MR}$ (or the centerline for the MR chart), is

$$\overline{MR} = \frac{\sum_{i=1}^{n-1} MR_i}{n-1}. \tag{2}$$

Using $\overline{MR}$, the control limits for the X chart are

$$UCL_X = \bar{x} + 3\frac{\overline{MR}}{d_2}$$
$$LCL_X = \bar{x} - 3\frac{\overline{MR}}{d_2} \tag{3}$$

where $d_2 = 1.128$, since the moving range uses two consecutive observations. Similarly, the control limits for the MR chart are

$$UCL_{MR} = D_3\overline{MR}$$
$$LCL_{MR} = D_4\overline{MR} \tag{4}$$

where, $D_3 = 0$ and $D_4 = 3.27$.

To illustrate the use of these equations, we construct the X and MR chart of the CT numbers using two recent PMS barrels. Barrel 168 consists of 33 batches of CT data while barrel 169 has 21 batches of CT data. Using Equations (1) and (2), the $\bar{x}$ and $\overline{MR}$ values for barrel 168 are 39.42 and 1.16 respectively. Using this information and

Equation (3), the upper and lower control limits for X chart are 32.52 and 26.33. From Equation (4), the upper and lower control limits for X chart are 3.8 and 0. The CT numbers for barrel 168 are now plotted on the control chart as shown in Figure 3. Batch numbers 9, 19, and 26 registered out of control for this barrel.

Notice that the production seemed to experience a mean shift in the middle of the barrel usage. The shift can readily be explained by a reduction in PMS ingredient as noted in the production records. This is revealing in that a decision to adjust the amount of PMS adjustment should always be made with caution. A poor adjustment made to the PMS amount could be more detrimental than helpful.
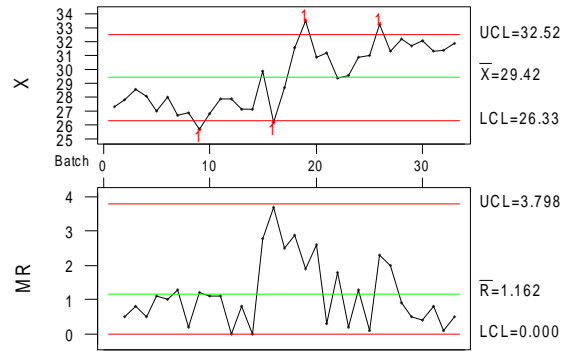

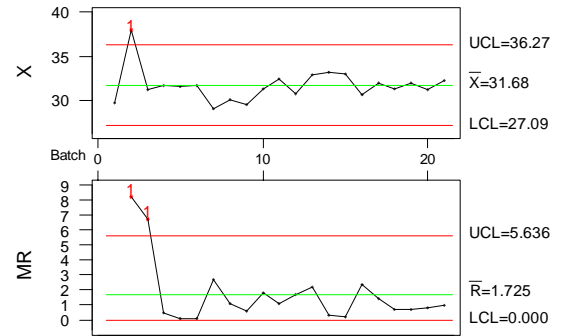Figure 3: X and MR Chart of CT Numbers for Barrel 168

Figure 4: X and MR Chart of CT Numbers for Barrel 169

A similar procedure is followed to construct the X and MR chart for barrel 169. Figure 4 shows the control charts of individual measurements of CT numbers for barrel 169. Except for the first few batches, the CT numbers fluctuate around the centerline, which is very well centered to the specification. No PMS "tuning" seemed necessary for this "good" production barrel.

Because of large variation expected in the barrels of PMS ingredient, adjustments to the recipe (or PMS ingredient) are necessary to ensure good quality transitions from barrel to barrel. The transitional problem is, however, difficult and complex. There is variability in the PMS

ingredient even within barrels. Other complicating factors affecting the variability of CT numbers are CT measurement procedure, mix evacuation process, and curing process, etc. For the transition from barrel 168 to 169, we only observed a slight increase in the mean CT numbers. To better monitor the process, it would be beneficial to maintain control charts for both within and between barrels.

5 SIMULATION OF THE TISSUE MIMICKING PROCESS

In this section, we introduce the ProModel simulation package and describe the modeling of the tissue mimicking process. An introductory tutorial on ProModel simulation is given by Benson (1997). The simulation model constructed for the TMP is based on the process model described in Figure 2. Since the focus of this investigation is on modeling integration, we give little attention to analyzing the TMP model and its system performance.

5.1 ProModel Background

ProModel is a simulation and animation tool designed to model manufacturing systems. It is easy to learn and use for engineers and managers. Because of its intuitive and straightforward approach to modeling, it has been widely used in academic engineering and business curricula to teach modeling and analysis concepts without having to teach computer programming.

The basic ProModel building blocks are: location, entities, path networks, resources, processing, arrivals. Many systems can be modeled by using appropriate configuration of these basic blocks. Moreover, ProModel also provides complete programming capability for modeling special situations. There are built-in language features such as if-else logic, Boolean expressions, variables, attributes, arrays, and access to external spreadsheet and text files (ProModel 1995).

5.2 External Subroutines

The capacity of ProModel to handle complex systems can be extended using external subroutines. ProModel allows interfacing with external subroutines located in 32 bit Windows DLL files. This feature is very useful for extensive simulation needs such as file input/output, performing statistical analysis, or making interactive sessions.

ProModel provides the capability to access to external subroutines coded using a programming language such as Visual Basic or Visual C/C++. The subroutines may be linked dynamically to the model and called from anywhere inside the model at runtime. The external subroutine that allows for the run-time model interface is *XSUB*. ProModel Corporation also provided the necessary DLL file to interact with XSUB and control simulation at runtime. This will be discussed in detail in Section 6.

5.3 Tissue Mimicking Process Application

Figure 5 shows the simulation model that we created for the TMP at GAMMEX-RMI. The model consists of the following elements.

Locations. This is done by putting some pictures from the *location graphics window* to the *layout window*. The names of the locations may be changed in the *location edit table* as needed. Eleven locations are identified for the TMP as shown in Figure 5: Manual Blending, Vacuum Mixing, Evacuation, Hardening, Oven Curing, UW (CT) Scan, Demolding/Storage, Cutting, Waste, Product Qualification, and Final Product Storage.

Entities. Anything that a model processes is called an *Entity*. Parts, products, people or even paperwork should be modeled as an entity. Each entity has a name. In logic and expressions, an entity can be referred to by name. In our model, we have one entity, which symbolizes a test rod from each production batch.

Processing. Processing is defined in the Processing Editor. *Processing* defines the routing of entities through the system and the operations that take place at each location they enter. Once entities have entered the system, as defined in the Arrivals table, processing specifies everything that happens to them until they exit the system.

Arrivals. An arrival occurs whenever new entities are introduced into the system. An arrival record is defined by specifying the number of new entities per arrival, frequency of the arrivals, location of the arrival, time of the first arrival, total occurrences of the arrival in the Arrivals editor.

Variables. There are two types of variables in ProModel: local and global. Local variables are available within the logic that declared them. Global variables are defined by the user to represent changing numeric values. Here, the variable name *CTnumber* is used to record the CT numbers from an external data file.

External Files. External files may be used during the simulation to read data into the simulation or write data as output from the simulation. Files can also be used to specify such things as operation times, arrival schedules, shift schedules, and external subroutines. All external files used with a model must be listed in the External Editor, which is accessed from the Build menu. Here, we used three external files. One file is for reading data (CT number), the second is for writing the result, and the third file is the DLL file used in the *XSUB* subroutine.

From the constructed TMP simulation model, we can perform simulation runs for a specified length of time. When simulation is completed, users can view the model statistics and reports. Because the proposed SPC technique is a part of the TMP, the model construction till this point is not yet

fully completed. In the next section, we will demonstrate the integration of control charts into the simulation model as an important function of the TMP process.
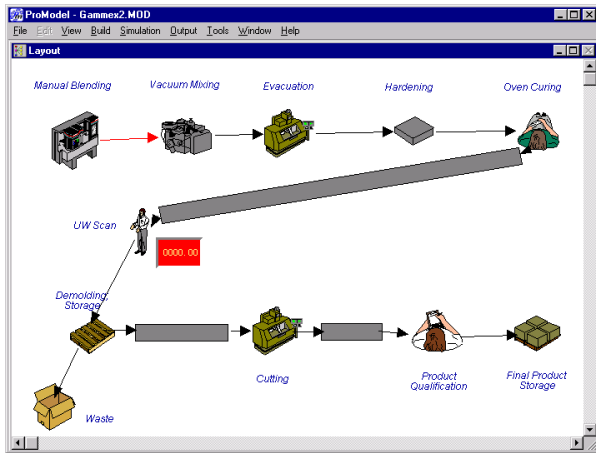

Figure 5: Simulation Layout for the Tissue Mimicking Process

6   INTEGRATING SPC WITH PROMODEL USING EXCEL

The quality of TMP products depends on meeting the CT number specification. The monitoring and control of CT number accuracy is a critical activity for the tissue mimicking process. This reflects the importance of implementing SPC techniques in many manufacturing operations. From the perspective of simulation model design and analysis of manufacturing systems, there are potential benefits to integrate SPC techniques (in the form of control charts). With the graphical and object-oriented capabilities in current simulation software packages, integrating simulation models with on-line control charts can provide a great visualization aid for teaching and training shop-floor personnel the importance of each process step and the functionality and use of control charts. Parallel to the simulation modeling objectives, analysts can also experiment with the use of control charts at various process steps and play out many scenarios for idea generation, discussion, and eliminate any unforeseen obstacles and problems. Such knowledge and information would lead to more efficient implementation of SPC, which in turn would improve the manufacturing operations.

The goal of integrating SPC with the tissue mimicking process simulation model is to be able to plot and show the corresponding control charts for the CT number data during the simulation run. In Figure 6, we proposed a method for achieving this goal. The Data File block provides the necessary CT number for both programs. The XSUB routine acts as a link between ProModel and Microsoft Excel. A DLL file called "exemenu.dll" is used in the *XSUB* subroutine for executing the Excel program during the simulation run.
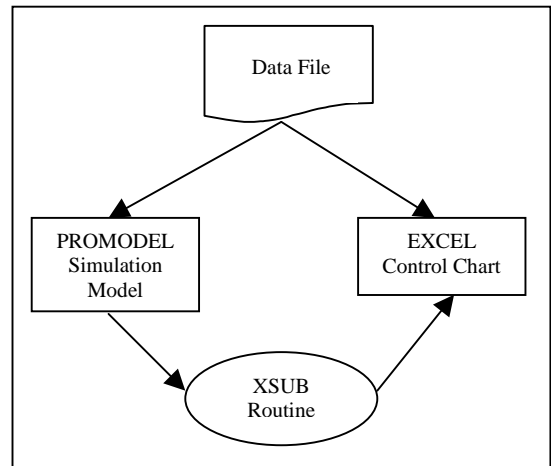

Figure 6: Block Diagram for Program Interface

An external Excel program is used to construct and plot the necessary control charts, in this case X and MR chart. To automate and control the mechanical charting task, Visual Basic for Applications (see, e.g., Webb 1996) is used. We have successfully written the Visual Basic code necessary for the construction of X and MR chart and the interfacing with the ProModel program. A screen capture of the charts in action is shown in Figure 7. The figure shows the X and MR chart and their control limits which were calculated using Barrel 231 data prior to the simulation run. The dashed vertical lines signify the start of the simulation run where CT numbers are plotted for each batch.

Using the XSUB function provided in the ProModel software, we have successfully interfaced the model simulation with the control charting. Figure 8 shows a screen capture of the program interface.
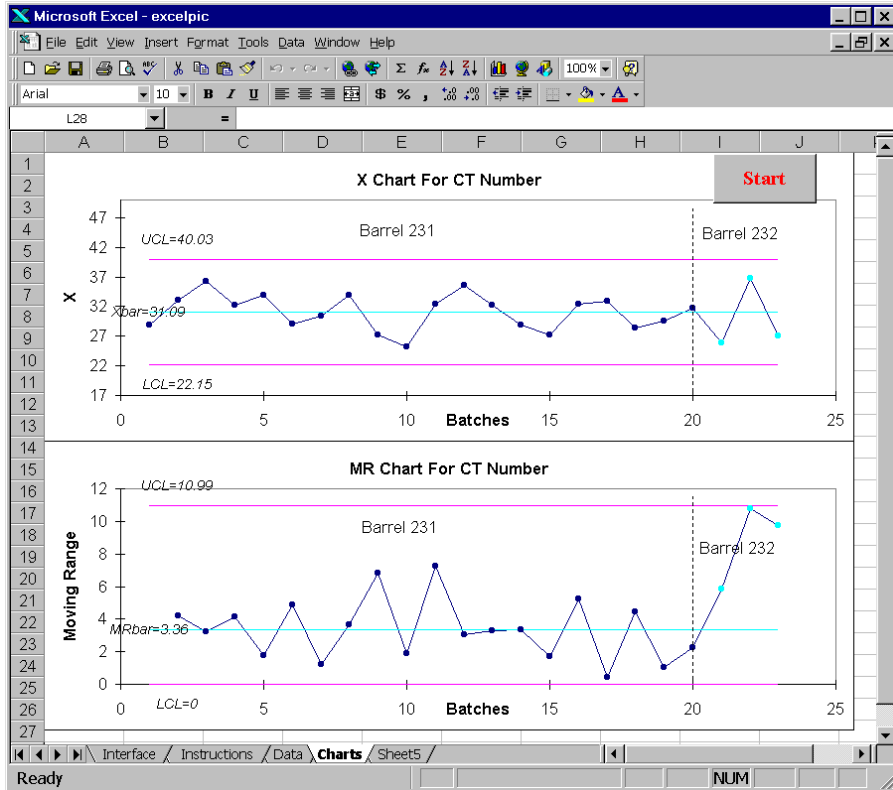
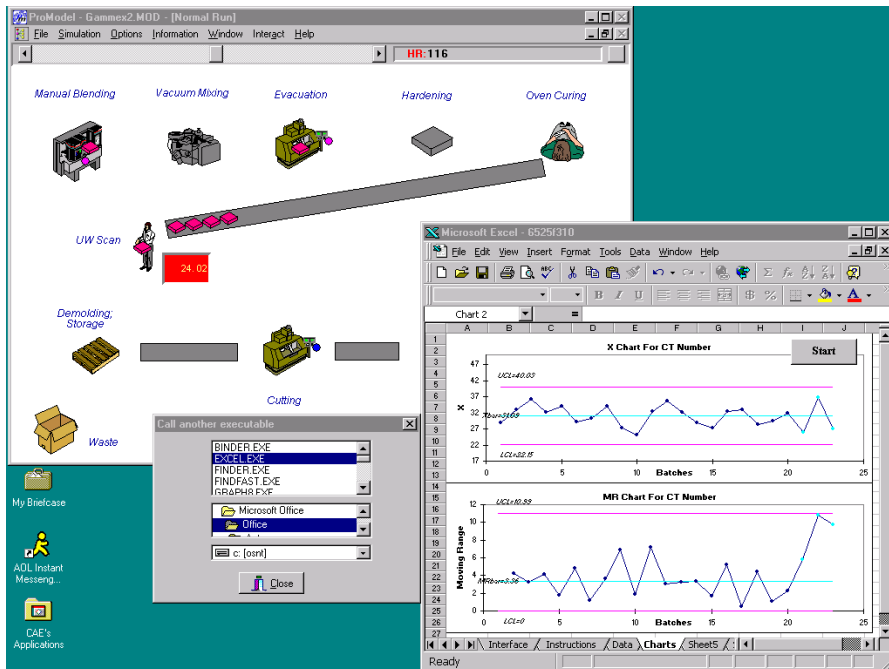Figure 7: Microsoft Excel On-line Control Chart Program

Figure 8: Simulation Model and On-line Control Chart Interface

The X and MR chart window shows the plotting of a CT number for some new barrel. As the data for the CT number becomes available, the model program plots the individual observation and its moving range on the charts. A representative user session proceeds as follows.

Step 1: During the simulation run, when a CT number is available at the UW Scan Lab, the screen will prompt for the execution of the Excel program.

Step 2: The Excel program is executed and by pressing the "Start" button on the spreadsheet, the corresponding CT number is plotted on the control chart.

Step 3: The Excel program closes.

Step 4: Repeat Step 1 for the next available CT number.

7   SUMMARY AND CONCLUDING REMARKS

Simulation is useful in providing insight to the dynamics of a system under study. It lacks, however, in a conceptualization of how SPC techniques could be of value to the system. In this paper, we integrated two on-line SPC control charts within the construction of a simulation model. We demonstrated the application of this integrated model on a manufacturing and assembly process at GAMMEX-RMI.

Our approach has potential value on several levels. On one level it can help the people of GAMMEX-RMI to train and educate their workforce on the process and the output product. On another level it can help characterize and improve system performance. On yet another level it can help determine the effectiveness of the most appropriate control chart method for the system model. We hope that this approach will bring about a greater awareness of the potential benefits and applications to simulation users and the research community.

Based on this investigation, we have identified two areas of future work.

- One disadvantage of the proposed interface procedure is that the Excel program interface that plots the control chart needs to be closed before the next available CT number. The upcoming ProModel software edition will have dynamic feature implementation capabilities. With such new capabilities, we hope to program the SPC interface directly into the simulation model using ProModel. This feature will make the integration implementation nearly seamless.

- We suspect that low levels of autocorrelation may be present in the CT data. However, the basic control charts used here rely on assumptions of independent and normally distributed observations. This presents an opportunity to investigate the possibility of using EWMA chart as well as X and MR chart for the residuals.

ACKNOWLEDGEMENTS

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