Proceedings of the 1990 Winter Simulation Conference
Osman Balci, Randall P. Sadowski, Richard E. Nance (eds.)

A CASE STUDY: SIMULATION OF PACKAGING LINE CONTROL LOGIC

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ABSTRACT

Kraft General Foods has been utilizing simulation techniques for the past several years. In our simulation of high speed packaging lines, one area that has provided efficiency improvements is the evaluation of control logic. This paper presents a case study in the form of a mystery. After a discussion of the packaging line's designed strategy and control logic, we will use simulation to illustrate why this logic concept did not actually work. The line operators had disabled portions of the disfunctional logic and were controlling the line in an altered sequence from the original design. The paper discusses the reasons for the operators' actions as well as an equitable solution.

1. INTRODUCTION

Since 1986, General Foods (now a division of Kraft General Foods) has been developing the use of simulation in evaluating and improving the efficiency of high speed packaging lines. Off-the-shelf simulation packages have not provided the accuracy required to analyze the complex detail of our lines. We have developed a generic simulation shell with Pritsker Corporation that is currently being used in several of our plants. This paper addresses the use of simulation to evaluate and improve the control logic of the line.

How do we define control logic? It is made up of two distinct parts, human logic and programmed logic. The human logic would include a multitude of management and operator decisions: when to take a troubled machine out of service for repair, how to adjust Filler speeds to insure that label weights are met, and the start-up sequencing of multiple lines. Programmed logic refers to the use of photo-eyes and programmable controls as part of the packaging line's operating system. The photo-eyes are positioned on the line to react when product "backs up" in front of the eye (the eye is covered) or "clears" the area in front of the eye (the eye is uncovered). Programmed logic is set into action when an eye is covered or uncovered for a specified length of time (a delay before taking action). The logic could start or stop machines, change speeds, activate surge systems, stop conveyors, or respond in a variety of other line functions.

This paper concentrates on the simulation of programmed logic. The case study included here has been disguised and simplified for proprietary reasons, but the essence of the study is intact. As packaging lines have been modernized with programmed logic, there have been opportunities to reduce crewing and to standardize logic decisions. A main drawback has been the difficulty of an observer to evaluate errors in the design or application of the control logic. Changes to the line may have caused the logic to be obsolete for the new conditions. The strategy of the logic design may not be known to the line operators or management. The programmer responsible for maintenance of the line controls talks in a language of "ladder logic". We have used simulation to gain an understanding of the programmed logic for discussion with both the programmer and line management. The simulation allows faults in the logic to become readily observable and permits an experimentation procedure to improve the logic.

The case study reviews a packaging line used to fill bottles. The simplified version of the line includes only three machines, two Surge Tables, and eight Photo-eyes. A discussion of the strategy of even this simplified line becomes quite complex. However, an understanding of the line is required to evaluate why the production operators disabled the logic for actual factory floor conditions. We will examine both the design and actual strategy in detail. Several solutions will be discussed and presented.

2. DESCRIPTION OF THE "BOTTLE LINE"

The bottling line in Figure 1 fills bottles, combines the bottles in a 3-pack package, applies a label, and transfers the 3-pack to downstream operations (case packing, palletizing, etc.) There are two surge tables on the line: 1) between the Filler and Combiner and 2) between the Combiner and Labeler. When the conveyor between the Combiner and Filler becomes

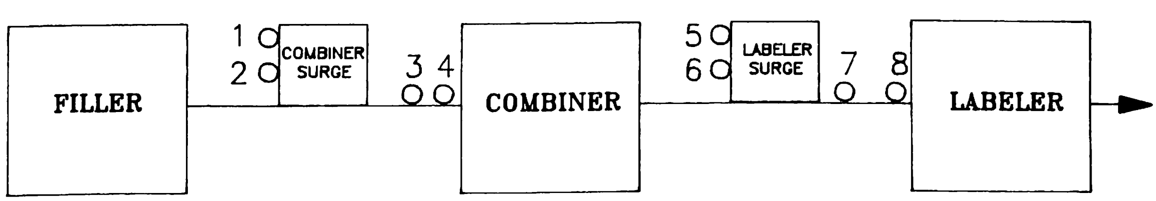

Figure 1. The "Bottle Line"; Photo-eye Locations are Represented by Circles

full (for example, if the Combiner is stopped for a period of time), the Surge Table will allow the Filler to continue operating. The excess bottles will be transferred to the Surge Table. When the Combiner resumes operations, the Surge Table can feed back bottles onto the Conveyor. The system is designed to speed up the Combiner when bottles are on the Surge Table so the table can be emptied. The Labeler Surge works in a similar manner.

Table 1 lists some of the operating characteristics of the line's machines, conveyors, and surge tables.

Table 1. Operating Characteristics

MACHINE SPEEDS		
Filler - 600 Bottles/Minute		
Combiner -	Low Speed	200 3-Packs/Minute (600 Bottles/Minute)
	High Speed	220 3-Packs/Minute (600 Bottles/Minute)
Labeler -	Low Speed	200 3-Packs/Minute
	Medium Speed	230 3-Packs/Minute
	High Speed	250 3-Packs/Minute

CONVEYOR/SURGE TABLE CAPACITY	
Filler to Combiner Conveyor	360 Bottles
Combiner Surge Table	1200 Bottles
Combiner to Labeler Conveyor	580 3-Packs
Labeler Surge Table	1000 3-Packs

3. PROCESS CONTROLS

There are eight photo-eyes indicated in Figure 1. Table 2 indicates the actions taken as each photo-eye is covered or uncovered. The photo-eye location is described in terms of the number of backed up bottles or 3-packs needed to cover the photo-eye.

Let's "walk through three examples of line flow to illustrate how the controls work:

3.1 Normal Operation

- Filler starts operating at 600 bottles/minute; the remainder of the line is empty and idle.
- Bottles flow on the "Filler to Combiner" Conveyor
- When the bottles reach the Combiner in-feed, they are backed up waiting for the Combiner to begin operating
- When 180 bottles back up on the Conveyor, Photo-eye #3 is covered; the Combiner is turned on at low speed, 200 bottles/minute
- The Combiner begins grouping bottles into 3-packs. The 3-packs flow onto the "Combiner to Labeler" Conveyor
- When the 3-packs reach the Labeler in-feed, they are backed up waiting for the Labeler to operate
- When 530 3-packs are backed up, Photo-eye #7 is covered. The Labeler starts up at the medium speed of 230 3-packs/minute
- The line speed is 200 3-packs per minute. Since the Labeler is running faster than the input speed, Photo-eye #7 becomes uncovered. The Labeler then changes to low speed, 200 3-packs/minute
- The line continues to run without change as long as the Filler, Combiner, and Labeler continue to operate.

3.2 Back-Up Conditions

- Suppose the Labeler breaks down for an extended period with the line in "Normal Operation"
- 3-packs would back up at the Labeler
- When 1580 3-packs back up on the Conveyor and Labeler Surge Table, the Combiner is blocked
- With the Combiner blocked, bottles back up on the "Filler to Combiner Conveyor"
- When 1560 bottles back up on the Conveyor and Combiner Surge Table, the Filler is blocked

Table 2. Photo-eye Actions

PHOTO-EYE #	LOCATION	COVERED	UNCOVERED
1	1560 Bottles on Comb. Surge	Block Filler	Unblock Filler
2	470 Bottles on Comb. Surge	Comb. to HS	Comb. to LS
3	180 Bottles on Conveyor	Comb. to LS	No Action
4	60 Bottles on Conveyor	No Action	Comb. Off
5	1580 3-Packs on Labeler Surge	Block Comb.	Unblock Comb.
6	630 3-Packs on Labeler Surge	Labeler to HS	Labeler to MS
7	530 3-Packs on Conveyor	Labeler to MS	Labeler to LS
8	60 3-Packs on Conveyor	No Action	Labeler Off

- The line will continue to be blocked until the Labeler begins to operate.

3.3 Recovery

- The Labeler begins to operate. Since Photo-eye #6 was covered when the Conveyor was filled, the Labeler is signaled to start in high speed, 250 3-packs per minute.
- As the Labeler begins to process 3-packs, Photo-eye #5 is uncovered; the Combiner is unblocked
- The Combiner starts in high speed, 220 3-packs per minute because Photo-eye #2 has been covered
- As the Combiner is unblocked, it processes 3-packs to eventually uncover Photo-eye #1, which unblocks the Filler. The Filler begins operation at 600 bottles/minute, its only speed
- Then things get interesting. The Combiner is operating 60 bottles/minute faster than the Filler. It takes 18 minutes to reduce the number of bottles on the Combiner Surge Table to 470. At that level, Photo-eye #2 is uncovered, so the Combiner is set to low speed, 200 3-packs/minute
- The Labeler continues in high speed until Photo-eye #6 is uncovered. When 630 3-packs remain on the "Combiner to Labeler" conveyor, the Labeler changes to medium speed. From the time the Labeler begins operating, it takes 24 minutes to uncover Photo-eye #6. Even though the Labeler is producing at 50 3-packs/minute above the speed of the Filler, the Combiner is emptying out its Surge Table at 220 3-packs/minute. After the Combiner slows to 200 3-packs/minute, the Labeler Surge Table takes 6 more minutes to reach the level of Photo-eye #6.

4. BOTTLE-LINE STRATEGY

The controls on the bottle line are programmed to follow a flow strategy. The Filler represents the key machine on the line. The line's efficiency is tied to the Filler. As long as the Filler operates, the line is producing filled bottles. If the Filler is down for mechanical reasons or blocked by downstream problems, that time cannot be made up. The main strategy of the line is to protect the Filler from downstream blockages.

When the line is operating in "normal" conditions, the speeds of the Combiner and Labeler are matched exactly to the Filler. The Combiner could experience downtime for three reasons: mechanical downtime for repair, downstream blockages, or upstream starvation. When the Combiner is down for any of these reasons, the Combiner Surge Table provides a buffer to allow the Filler to continue operating while the stoppage is resolved. When the Combiner returns to operation, it will run at a higher speed to reduce the bottle inventory on the Surge Table. When the Surge Table is emptied, the Combiner will return to "low speed" matching the Filler speed once again.

The Labeler can be stopped for mechanical repair or upstream starvations. In this case study, it is assumed there are no downstream blockages. When the Labeler goes down, the Labeler Surge Table provides a buffer to allow the Combiner to continue operating. When the Labeler becomes operational, it will run at a high speed to empty the Surge Table system in preparation for future Labeler breakdowns.

5. SIMULATION

While a quick glance at the bottle line diagram in Figure 1 might give the appearance of simplicity, the three machines and linking Conveyors/Surge Tables are subject to a complex series of controls, speed changes, and random downtimes. Simulation can capture the dynamic nature of the line for analysis and experimentation. The model used for this simulation provides a combination of discrete and continuous concepts that provide an accurate representation of high speed packaging lines. The remainder of this paper will demonstrate how simulation was used to analyze the bottle flows on this line and to explain the mystery concerning the operators' disabling of the control logic.

6. THE PROGRAMMED LOGIC AS DESIGNED

Using simulation plots, we will examine how the line was designed to operate. A simulation has been run for 480 minutes (one shift). The machines are subject to random downtimes as represented by exponential curves with the means indicated in Table 3.

First, let's look at Figure 2 to examine a simulation plot of the Filler. The X-AXIS represents the time line for zero to 480 minutes. The Y-AXIS shows the speed of the Filler. When the Filler operates, it can only operate at one speed, 600 bottles/minute. When it is down, the Y-AXIS indicates the reason for downtime: blocked or repair. It is assumed the Filler is never starved for bottles or formula. In this example simulation, the Filler ran at 90.9% efficiency. It was down 39 minutes for repairs, 8.1%; it was down 5 minutes due to downstream

Table 3. Definition of Random Downtimes

	Mean Time Between Failures	Mean Time to Repair
Filler	28.5 minutes	1.5 minutes
Combiner	59.0 minutes	1.0 minutes
Labeler	19.0 minutes	1.0 minutes

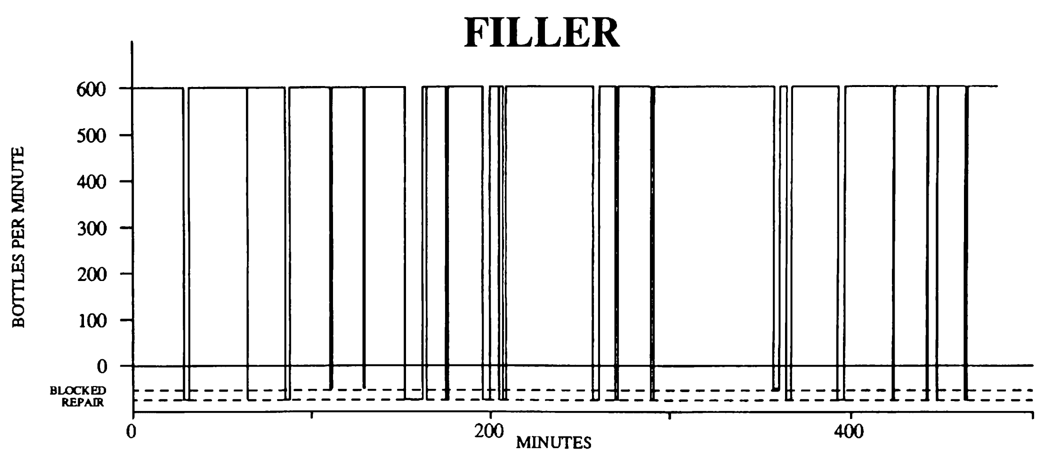

Figure 2. Simulated Operation of the Filler

blockage, 1%. The plot shows the duration and timing of each of these occurrences. There were 18 times that the Filler was down for repairs. There were only three occasions when the Filler was down due to downstream blockages. As we examine simulation plots further down the line, we will be looking to understand the reasons for the downstream blockage. The repair downtime cannot be alleviated through use of this simulation analysis.

Figure 3 examines the inter-relationships among the Filler, Combiner Surge Table, and Combiner. The Combiner Surge Plot indicates the total number of bottles on the Surge Table and on the Conveyor itself. When 1560 bottles are in residence, Photo-eye #1 is covered and the Filler is blocked. We can see the three occurrences of the Filler being blocked due to the Combiner Surge Table being full. The Combiner Surge Plot illustrates the "normal" Conveyor inventory (approximate-

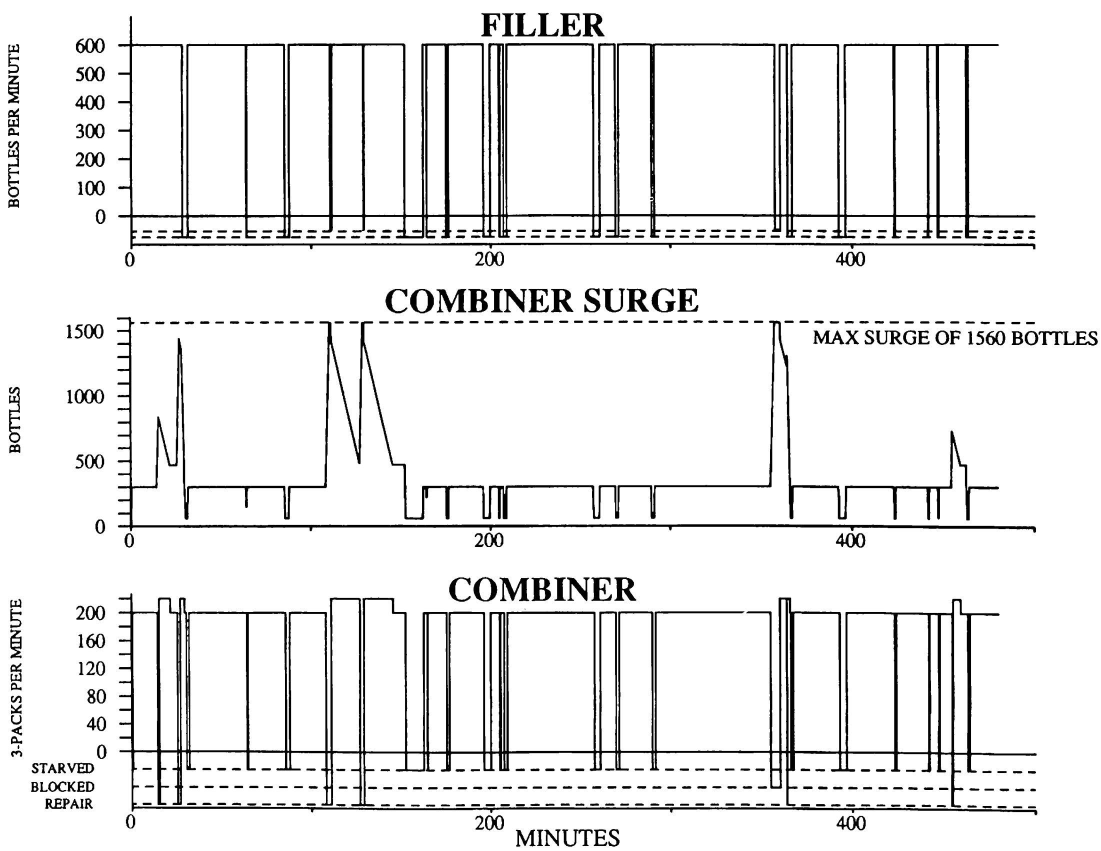

Figure 3. The Backup Level of the Combiner Surge Affects the Operation of the Filler and Combiner

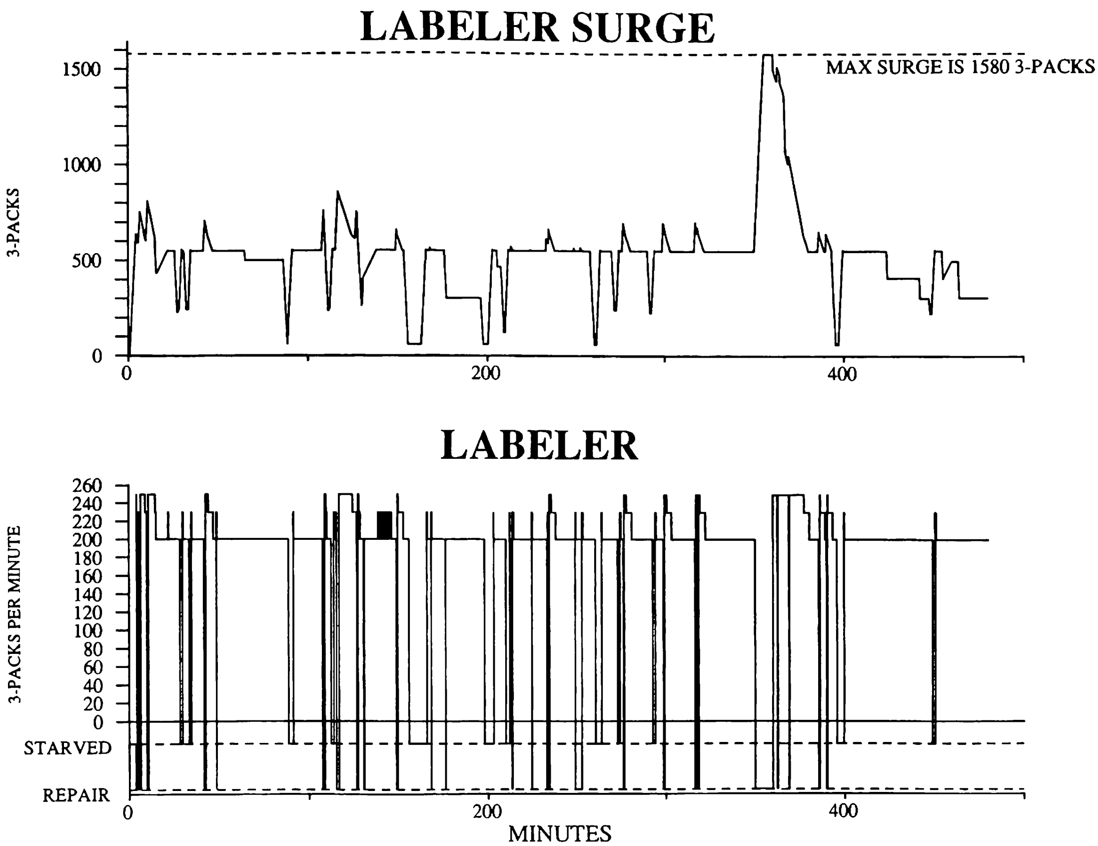

Figure 4. The Labeler Changes Speeds as the Level Varies in the Labeler Surge

ly 300 bottles) as well as the loading levels when backups occur. The bottom plot in Figure 3 shows the process speeds of the Combiner. Note the two speeds: 200 and 220 3-packs/minute. Comparing the Combiner Plot to the Combiner Surge Plot, the Combiner goes to high speed whenever the bottle level in the Combiner Surge exceeds 470 bottles. The Combiner is starved when the bottle backup falls below 60 bottles. Notice that two of the Combiner repair downtimes caused minor blockages at the Filler.

Figure 4 includes the Labeler and the Labeler Surge Table. Note the three process speeds of the Labeler are based on the inventory of the Labeler Surge. The Labeler is starved when the backup is less than 60 3-packs. The Labeler is starved 13 times in this example. At time 350 minutes, the Labeler encounters a major downtime repair of 10 minutes. The Labeler Surge is filled to 1580 3-packs and the Combiner is blocked (refer back to Figure 3). The Combiner is blocked long enough to fill the Combiner Surge and block the Filler.

A review of Figure 2 through Figure 4 shows how the bottle line was designed to operate. While an initial appraisal may find fault with some of the operating speeds and photo-eye locations, generally the design satisfies the line strategy: protect the Filler from downstream blockages.

7. FACTORY FLOOR ACTUAL CONTROLS

Somehow, from the design and installation phase to the actual day-to-day running of the line, the control concepts changed. The line operators took over the line's decision logic by disabling several of the photo-eyes. The effect is seen clearly in the synergy between the Labeler and Labeler Surge as shown in Figure 5. Reviewing these Plots, we can see the Labeler runs only at the high speed of 250 3-packs/minute. Both low and medium speed have been eliminated. Also, the Labeler is not signalled to start until the Surge becomes almost full (1500 3-packs).

The problem with the operator's change in the line logic is that it is counter to the strategy of protecting the Filler from downstream blockages. The design strategy attempts to keep the Labeler Surge at a low level so that Labeler downtimes can be fully buffered by the Labeler Surge. The operators' logic has the Surge filling up on a cyclical basis. If a Labeler failure occurs while the Surge is full, there is no buffer protection. The Combiner is blocked which leads to a blockage of the Filler.

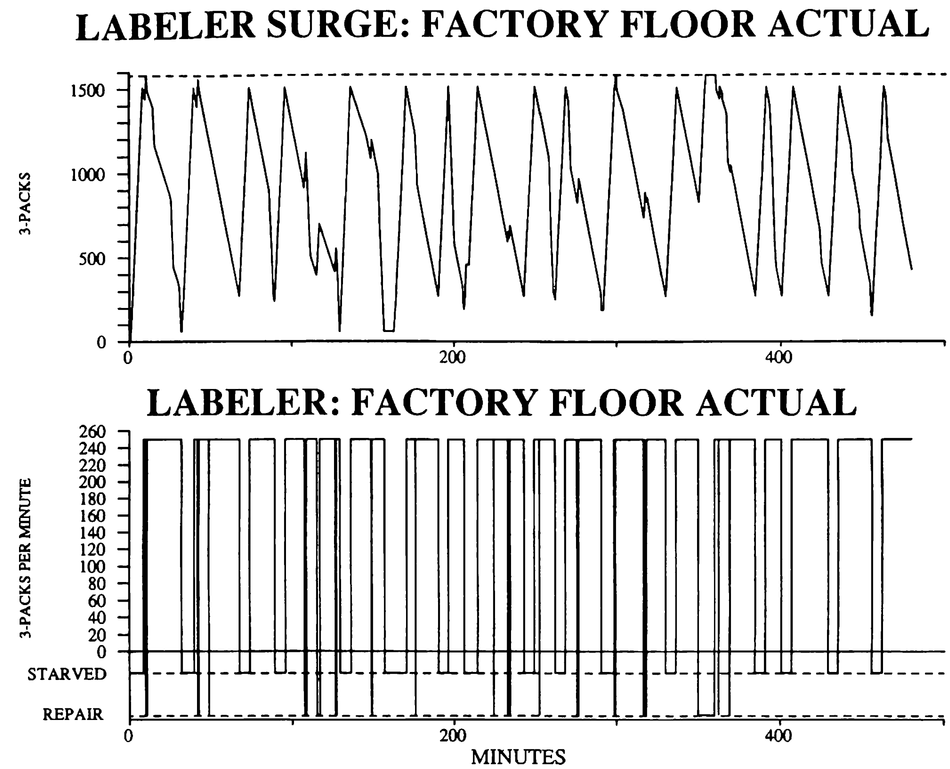

Figure 5. Simulation of Actual Factory Floor Logic

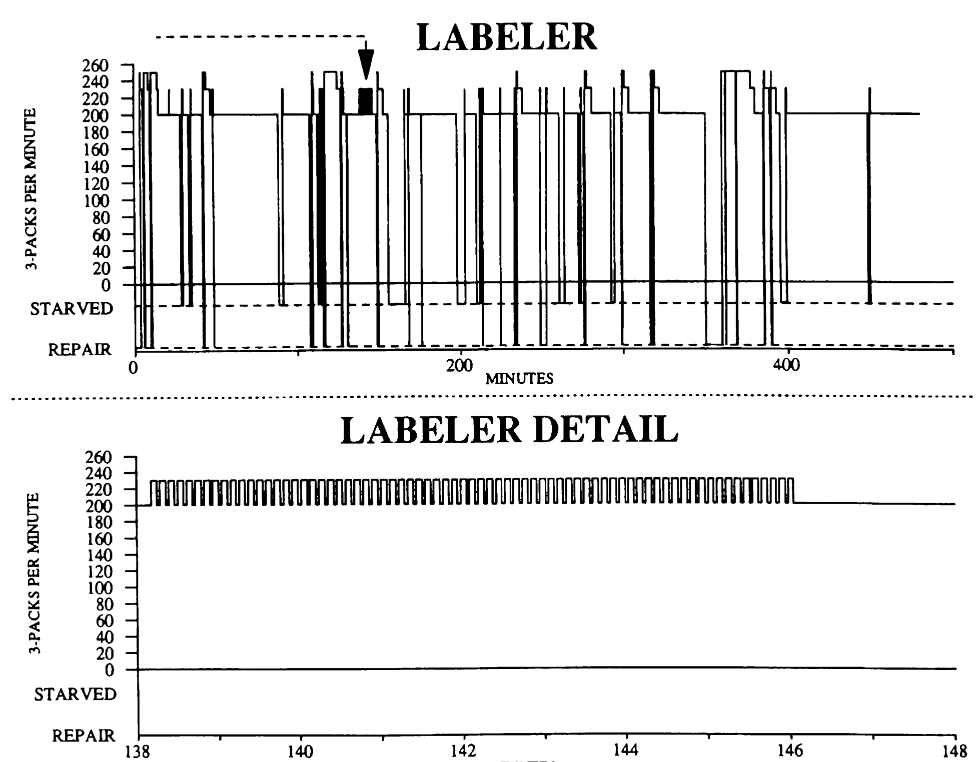

Figure 6. Rapid Cycling

8. WHY DID THE OPERATORS CHANGE THE LOGIC?

We interviewed the operators to discover why they changed the line's logic: why did they disable the design logic and substitute their own concepts? The operators claimed that the line logic caused the Labeler to operate at three speeds; low, medium, and high speed. They noticed that when the Labeler was operated at low and medium speeds, at various times during the shift, the Labeler would act erratically. It would spray glue and labels on the 3-packs, requiring substantial cleaning and adjustments. The operators stated that when the Labeler operated at only high speed, no problems occurred. Therefore, they altered the line logic to insure the Labeler would operate only in high speed.

Next, we interviewed the maintenance crew. We asked why the operators believed the Labeler would not operate in low and medium speeds. Maintenance said they had fully examined the Labeler and felt it worked without problems at each of the three speeds. They believed the operators had changed the line logic to allow themselves rest periods between Labeler runs. "If they wait until the Labeler Surge fills up, they have several minutes to relax before they have to run the labels. If they let it run in the lower speeds, then they have to stand there and watch the Labeler all the time."

9. WHO WAS RIGHT?

The answer to this dilemma is revealed in Figure 6. The Labeler Plot on top is the original "design logic" Labeler Plot shown in Figure 4. An arrow points to a dark block occurring at approximately TIME = 140 minutes. This section is magnified to a 10 minute period in the plot below. Here we can see that the black block is really a series of speed changes, known as rapid cycling. There are only seconds between changes from medium to low and then back to medium again. It is this rapid cycling that causes the erratic behavior of the Labeler.

Refer back to Figure 4 to see how this rapid cycling occurs. The cycling exists when the Labeler Surge is below 630 3-packs. If it was above this level, Photo-eye #6 would be covered, and the Labeler would operate in high speed. A second factor in causing the rapid cycling is seen in Figure 3. The Combiner is reducing the inventory on the Combiner Surge by operating at the high speed of 220 3-packs/minute.

Given these conditions, let's follow what has happened to the labeler's control logic. It all centers on Photo-eye #7. When #7 is covered, it causes the Labeler to operate in medium speed; when uncovered the Labeler operates in low speed. In these conditions, the 3-packs are delivered from the

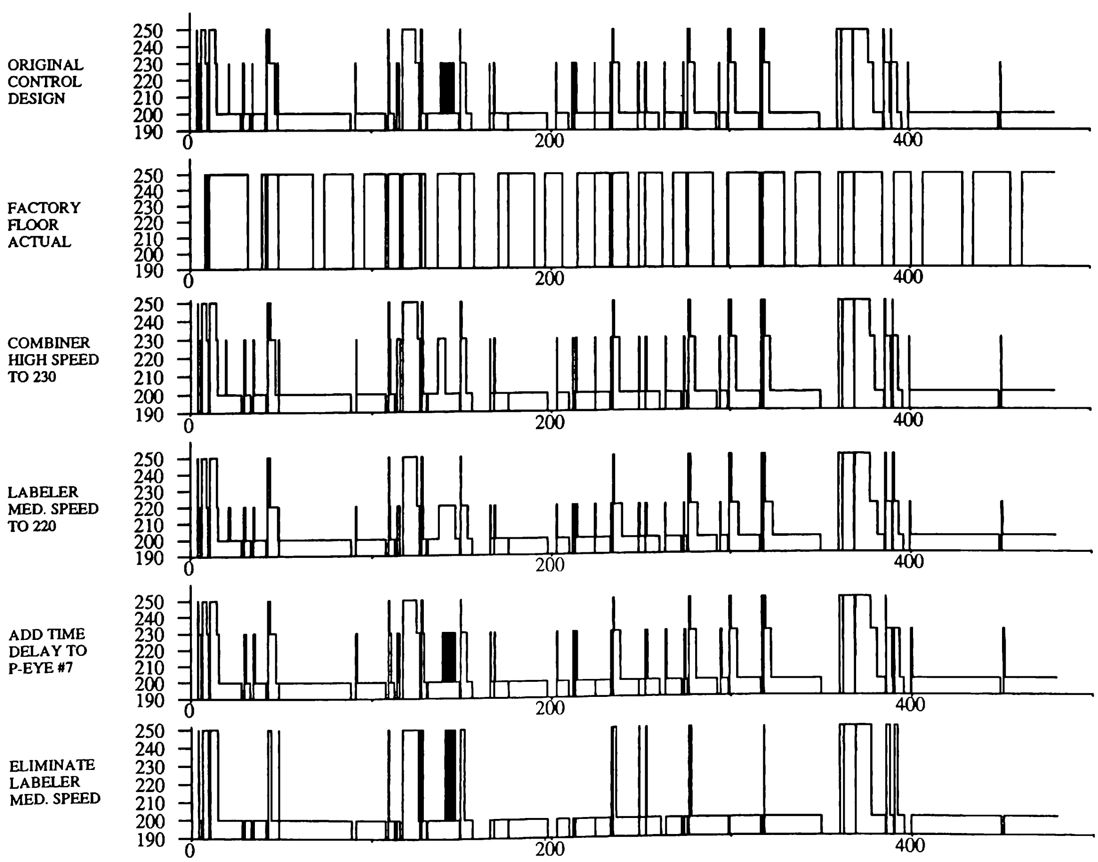

Figure 7. Comparing Simulated Labeler Control Concepts

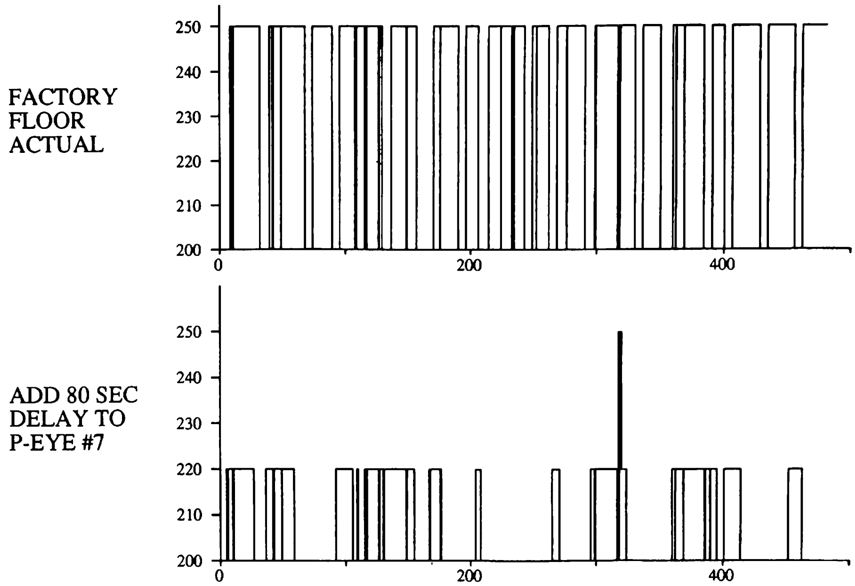

Figure 8. Comparing the Actual Labeler Logic to a Simulated Improvement

Combiner at 220 3-packs/minute. When Photo-eye #7 is uncovered, the input of 220-3 packs/minute exceeds the low Labeler speed of 200 3-packs per minute. So, the 3-packs begin to back up, covering Photo-eye #7. The Labeler shifts to the medium speed of 230 3-packs per minute. Now, the Labeler is faster than the input speed. The 3-pack backup is reduced and Photo-eye #7 is uncovered; the Labeler shifts back to low speed. Rapid cycling.

Who was right? The operators were right. They recognized that the Labeler was not operating properly when the line logic was used. They did not recognize the issues involved, but they knew it occurred sporadically. They knew that once in a while, for no known reason, the Labeler operated erratically. They found through their own experimentation that a way to fix the problem was to operate the Labeler only at high speed. Then, they explained their success by claiming that the labeler could only operate correctly at high speed. The only problem is that the Filler experiences more blocked time using the operators' rules.

10. RECOMMENDED CHANGES

In order to fix the problem, we have to add a second sub-strategy. Our first strategy is to protect the Filler from down-stream blockages. In addition, we need to insure that the Labeler does not rapid cycle. Our objective is to identify ways to maintain Labeler speeds of several minutes duration while still allowing Labeler Surge to be close to empty as a buffer protection. Here are some likely concepts:

- Change the high speed of the Combiner to 230 3-packs per minute to match the Labeler's medium speed. This would avoid the rapid cycling condition.
- Change the medium Labeler speed to 220 3-packs per minute to match the Combiner's high speed
- Change the delay time on Photo-eye #7 so that the Labeler remains in medium speed for several seconds before switching back to low.
- Eliminate the medium speed. Just use low and high speeds.

The results of these experiments are shown in Figure 7 along with plots of the original design and the factory floor actual. Only the top portion of the Labeler Plots are shown for comparison.

Eliminating the medium Labeler speed and adding a 30 second delay to uncovering Photo-eye #7 still has substantial rapid cycling. The Plots changing the Combiner speed to 230 or the Labeler medium speed to 220 do not include rapid cycling; however, they are less stable than the "Factory Floor Actual" Plot illustrating the operators' rules.

One more series of experiments is needed. Add delay time to uncover the action of Photo-eye #7 and compare it to the number of speed changes. The operators' logic had 37 changes. Trying a variety of delay times from 2 seconds to 3 minutes, we find an optimal number of speed changes occurs at 80 seconds: 35 changes. This is even better than the operators' logic and maintains the initial Filler efficiency of 90.9%. Figure 8 compares the Labeler Plots for these two logic concepts.

Adding the 80 second delay appears to satisfy the line strategy and the operators' requirements.

11. CONCLUSION

The "real-life" case study was somewhat more complex than the example presented here. The logic issues were the same: the operators had correctly disabled the controls to allow the Labeler to function without rapid cycling. However, the solution contained some additional complications outside of the scope of this case study. In the "real-life" case, a new layout of the line was considered necessary to implement a series of equipment and logic rearrangements.

In the discussion of the packaging line's logic, it can be seen that simulation provides an important tool in improving a line's efficiency through evaluation. It is also clear that the analysis phase is complex and requires ample time for both experimentation and presentation.