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META-MODELS FOR BUFFER SIZING IN HIGH-SPEED PACKAGING SYSTEMS

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ABSTRACT

Buffer sizing is a critical decision when designing high-speed packaging lines for fast-moving consumer goods. Strategically placed buffers provide benefits, but there is not a simple equation for increased system efficiency. Discrete-event simulation tools are commonly used to offer estimates for single scenarios. We introduce an approach using meta-models to inform systems engineers where to place buffers and how to size them. The model captures the decreasing marginal benefits of buffer, including interactions between buffer sizes in different locations.

1 INTRODUCTION

High-speed packaging lines for consumer goods operate at speeds exceeding 300 packs per minute and include several distinct machine centers involved in filling, labeling, packing, and unitizing the products. At these high speeds, jams and other short duration micro-stops are frequent and difficult to eliminate; system designers include buffers in specific locations to insulate the bottleneck machine from other machine stoppages. When these systems are close-coupled, meaning downtime events on one machine immediately stop the whole system, system availability is simply the product of all machine availabilities in series.

Buffers have two key parameters. First is size, expressed as units of time a micro-stop can last before blocking or starving other machines. Second is overspeed, or the percent speed difference between the machine and the bottleneck. Overspeed is critical for buffers to recover after a downtime event and be ready to buffer the next event. When a line includes buffers, there is no simple calculation to determine system availability from individual machine availabilities.

Discrete-event simulation is commonly used to calculate system availability for a given buffer configuration, but it is not a simple tool to deploy for system designers. We have developed meta-models to empower system designers to answer frequent questions like “how much buffer should we plan for?” and “where is it most effective?”.

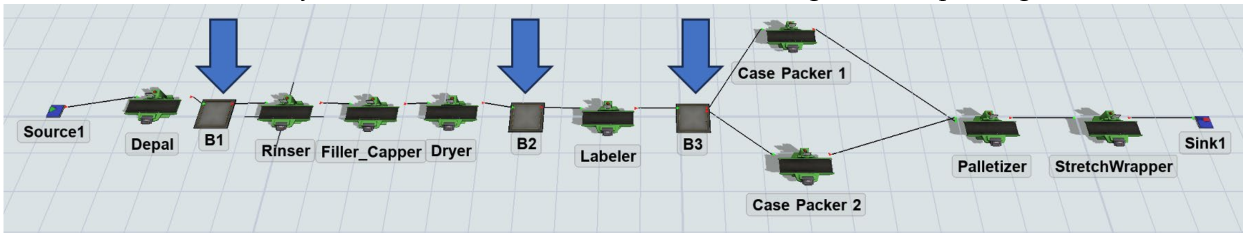
2 V-THEORY & ESTIMATING SYSTEM PERFORMANCE

Packaging system designers use a design paradigm known as V-Theory. The “V” refers to choosing a bottleneck machine, or the bottom of the “V”, and sizing buffers and machine speeds to insulate the bottleneck from micro-stops. Typical buffer size recommendations are to provide 2 to 3 minutes of buffer time at the bottleneck rate, or 1.5x the estimated mean time to repair (MTTR) if available. To effectively clear the buffers, a speed differential is required. The differential is typically 10% to 15% of the speed of the machine nearer the bottleneck or set such that it can be cleared in 1.0x the estimated mean time between failure (MTBF) if available. Using these rules of thumb, systems engineers can quickly size a system.

Discrete-event simulation models are commonly built to support packaging system design. During detailed design, we build models that closely match the system and are not optimized for running a lot of scenarios quickly. To improve model performance, early in the process, we use a flowchart level of detail that can capture parallel machines, batching, and packing, without including all the automation and control devices on the line.

3 EXPERIMENTAL DESIGN

We developed an approach for meta-modeling the buffer sizing problem on a specific project where the bottle filler runs 450 bottles per minute. The system included three buffers, one immediately upstream of the filler, one immediately downstream, and one between the labeling and case-packing machines.



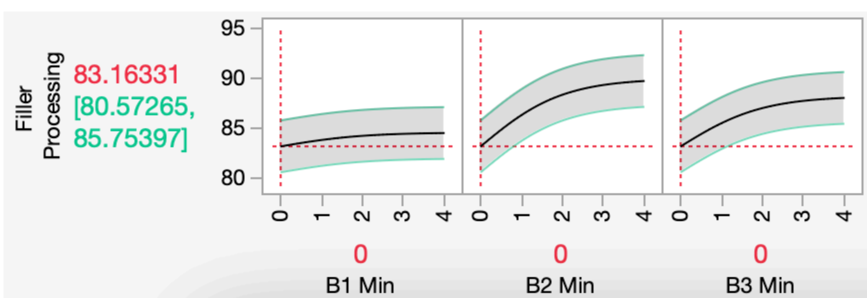
Buffers have a non-linear effect on system availability. The bottleneck machine sets a ceiling on system throughput that improvements from buffers can't exceed, and we know from experience that buffer effectiveness diminishes as sizes increase, both individually and collectively.

Our model included three factors, the buffer time for each of the three buffers indicated in the screenshot, and two responses, the bottleneck processing percent and throughput. We used a fully-crossed design with several interior points, varying each buffer from 0 minutes to 4 minutes in increments of 30 seconds. This resulted in 3 variables, with 9 levels each, or 729 scenarios. We ran 10 replications, using common random numbers, for each scenario.

4 META-MODELS AND RESULTS

We fit a mixed effects model using standard least squares in JMP. The model included factors for the three buffers and all 2nd order effects. The factors used the logistic transformation to account for the non-linearity bounded at 100% system availability. The replication number was included as a random effect. The fitted model has an R^2 of 0.708, however the residuals plot still shows some non-linearity. We also fit a model using the Neural platform in JMP and achieved a similar R^2, but prefer the standard least squares due to explainability and ease of implementing the prediction formula.

The fitted model captures the non-linear relationship between system availability and buffer size. It also captures the interaction of Buffer 2 and Buffer 3. Increasing the size of B2 diminishes the effectiveness of additional buffer at B3, and vice versa.



5 FUTURE WORK

Future work will focus on education and training for system designers to interpret the results of meta-models. We will also focus on collecting better historical data for machine performance. Finally, we plan to expand our experimental design to include overspeed between machines and sensitivity (or noise) for machine performance. We anticipate this more expansive experimental design can provide feedback to the common rules of thumb used in the packaging industry.