Modeling and Simulation of 500 mL Packaged Drinking Water Packaging Line

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Abstract

Packaged drinking water plants depend on synchronized filling, capping, date coding, labelling, and shrink-wrapping operations to maintain production rate, product quality, and dispatch readiness. This study presents a case-based discrete-event simulation and virtual commissioning study of the 500 mL packaged drinking water packaging section at Tashi Beverages Limited, Bhutan. Operational data collected from the plant, including station processing times, weekly downtime estimates, rework assumptions, production target, rated capacity, buffer capacity, and effective operating time, were used to parameterize a Siemens Tecnomatix Plant Simulation model. The model was validated using a plant-derived benchmark range of 920 to 1150 cases over a 7.67-hour reduced simulation window. Ten baseline replications produced a mean throughput of 1028.4 cases, a standard deviation of 77.84 cases, a coefficient of variation of 7.57%, and a relative precision of 5.41%. Simulation experiments showed that increasing buffer capacity from 1 to 500 bottles produced only about 1.5% throughput improvement and was not statistically significant, whereas reducing the processing time of the filler, sealer, and date coder gave a much stronger improvement up to a practical threshold region of 0.75-0.67 s/bottle. PLC logic was developed in Siemens TIA Portal using a finite-state-machine concept, and a PC-based HMI/SCADA-oriented interface was developed in WinCC Runtime Advanced for overview monitoring, alarms, trends, reporting, and data logging. The TPS model was then linked with the PLC logic through S7-PLCSIM Advanced to demonstrate a virtual commissioning testbed. The work is presented as a plant-specific engineering study and digital-twin-oriented prototype, not as a complete industrial digital twin or fully validated plant deployment.

Keywords: *Packaged Drinking Water, Tecnomatix Plant Simulation, TIA Portal, PLC, HMI, Finite State Machine, Bottleneck Analysis, Overall Equipment Effectiveness*

1. INTRODUCTION

Packaging lines are critical sections of beverage manufacturing because they convert filled products into distributable units while maintaining throughput, quality, traceability, and product presentation. The performance of a packaging line depends not only on the rated speed of individual machines but also on machine interaction, buffer behavior, downtime, rework, blocking, starvation, and control coordination. Direct experimentation on an operating industrial line can be costly and disruptive; therefore, simulation provides a safer approach for analyzing system behavior before physical changes are attempted (Law, 2015; Robinson, 2014).

Discrete-event simulation (DES) has been widely applied in manufacturing and packaging systems to evaluate throughput, resource utilization, bottlenecks, work-in-progress (WIP), buffer requirements, and production improvement scenarios. Prior packaging studies have shown that bottleneck behavior is affected by machine speeds, short stoppages, conveyor logic, and accumulator configuration, and that line-level performance cannot always be improved by modifying one machine in isolation (Alarcón et al., 2013; Javadi et al., 2023). Recent food-industry studies also show that DES can support decision-making when production costs, rework, breakdowns, and changing production conditions interact in complex ways (Loacker et al., 2024).

In the Bhutanese context, local published technical documentation on packaged drinking water packaging lines is limited, while station-level operating data, control logic, downtime behavior, and integration details are normally proprietary. This makes it difficult to study the combined effect of station speed, downtime, buffering, quality loss, and control coordination using realistic local data. The present work therefore uses the Tashi Beverages Limited case as an applied engineering study rather than as a general model for all beverage plants.

This study addresses that applied engineering gap by developing a DES-based case model of the 500 mL packaged drinking water packaging section at Tashi Beverages Limited. The model was used to evaluate throughput, station performance, OEE-related indicators, WIP, buffer-capacity sensitivity, and machine-speed sensitivity. In addition, a supervisory PLC and SCADA framework was developed using Siemens TIA Portal to demonstrate state-based control, alarm handling, operator monitoring, and virtual commissioning of the modeled line. The main contributions of the study are:

- Development of a case-specific DES model of a local 500 mL packaged drinking water packaging line using plant-provided operational data.
- Benchmark-based validation of throughput, including explicit reporting of variation, relative precision, and one below-range replication.
- Simulation-based comparison of buffer-capacity expansion and bottleneck-machine speed improvement.
- Development of PLC logic using a finite state machine structure and SCADA screens for overview, alarms, trends, and reports.
- Demonstration of a virtual commissioning framework linking process simulation with supervisory automation logic.

The study is limited to a case-study contribution. It does not claim a new DES algorithm, a universal packaging-line model, full mathematical optimization, or a complete digital twin. Rather, it presents a structured engineering study that combines process simulation, plant-based KPI analysis, PLC/SCADA-oriented control development, and virtual commissioning. The study also explicitly identifies the additional data and validation work required before industrial deployment.

2. STUDY AREA

The study was based on the 500 mL packaged drinking water packaging section at Tashi Beverages Limited, located near the Pasakha Industrial Estate, Phuentsholing, Bhutan. The selected section begins after bottle rinsing and includes filling, capping or sealing, date coding, labelling, shrink wrapping, and movement toward storage. The product is packed in cases of 24 bottles. The study area was selected because the line represents a practical multi-station packaging system with measurable throughput, station speeds, downtime, and quality-loss assumptions.

The boundary of the study excludes upstream water treatment, bottle blowing, rinsing, raw-material supply logistics, warehouse dispatch, detailed operator allocation, and laboratory quality testing. The source object in TPS therefore represents pre-rinsed bottles entering the filling section. These exclusions were made to keep the model focused on the packaging section for which station parameters were available; they also limit the interpretation of the output to the selected packaging boundary rather than the entire plant.

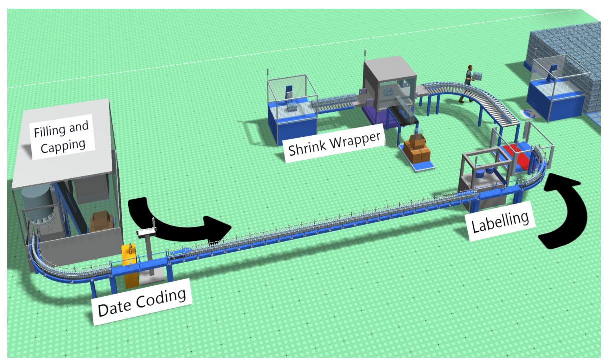

Fig. 1: *Process boundary of the modeled 500 mL packaging line.*

3. LITERATURE REVIEW

3.1 Discrete-event simulation in manufacturing and packaging systems

DES is suitable for manufacturing systems in which state changes occur at discrete points in time, such as product arrival, process completion, machine failure, repair completion, transfer, blocking, and release. It is particularly useful when analytical methods become difficult due to stochastic downtime, buffers, queues, and interactions among stations (Banks et al., 2010; Law, 2015; Robinson, 2014).

Packaging lines are strongly influenced by accumulation, speed mismatch, short stops, and station dependencies. Alarcón et al. (2013) used simulation to analyze a beer packaging line and showed that speed changes, accumulator use, and conveyor logic affected overall efficiency. Javadi et al. (2023) used simulation to identify and reduce bottlenecks in a food manufacturing system, showing that line improvement requires understanding interactions between machines rather than observing individual stations only. These studies support the use of DES for the present case but also indicate that bottleneck claims should be supported by station performance, queue behavior, and scenario sensitivity rather than utilization alone.

3.2 Bottleneck analysis and buffer sizing

Bottlenecks are stations or constraints that limit system throughput. In simulation studies, bottlenecks may be indicated by high utilization, long active periods, queue growth upstream, downstream starvation, or high sensitivity of line throughput to changes at that station (Goldratt & Cox, 2004; Roser et al., 2001). Buffer sizing is related to bottleneck behavior because buffers can decouple stations and absorb variability, but additional buffer capacity does not necessarily improve throughput if the true constraint is station processing rate or failure behavior (Liberopoulos, 2019). Therefore, the present study treats utilization-based identification as a first-level bottleneck indication and uses sensitivity experiments to support the interpretation.

3.3 Overall Equipment Effectiveness and production KPIs

Overall Equipment Effectiveness (OEE) combines availability, performance, and quality into a single productivity indicator (Nakajima, 1988; Muchiri & Pintelon, 2008). OEE is useful for summarizing losses, but it must be interpreted carefully when its components are obtained from different sources. In this study, the OEE value is treated as an approximate hybrid estimate because availability and quality were obtained from available plant information while performance was derived from simulated throughput. WIP and lead time were also analysed using Little's Law, which relates average inventory, throughput rate, and average time in system (Little, 1961).

3.4 PLC, SCADA, and virtual commissioning

Virtual commissioning uses a simulated plant model to test control logic before physical commissioning. It can reduce debugging effort during actual commissioning if the virtual model is sufficiently detailed (Hoffmann et al., 2010). For industrial packaging lines, this approach is useful because PLC sequences, interlocks, alarms, feedback signals, manual operation, and fault response can be tested without stopping the real plant.

The automation component of the present study was guided by relevant industrial standards. ISA-88 principles support modular and state-based control structuring, although the studied line is not a pure batch process. ISA-95 provides a useful framework for separating physical process, local control, supervisory monitoring, and manufacturing operations layers. ISA-101 provides guidance for operator-centered HMI/SCADA design, including clear overview displays, alarm visibility, trends, and consistency. These standards were used as guiding principles rather than as claims of full compliance.

4. METHODOLOGY

4.1. Overall Research Procedure

The methodology was organized around four project phases supported by preliminary problem definition, literature review, and software familiarization. Phase 1 covered process design, plant data collection, TPS model development, station parameterization, validation, KPI analysis, and simulation experimentation. Phase 2 developed PLC logic and a basic HMI in Siemens TIA Portal using a finite-state-machine structure.

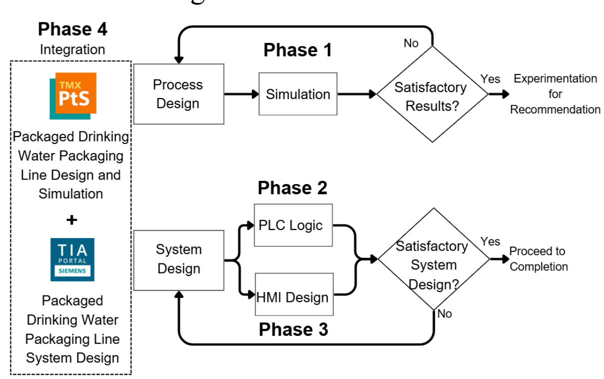

Fig. 2: *Phase-wise Methodology Flow Chart*

Phase 3 developed the PC-based HMI/SCADA-oriented screens in WinCC Runtime Advanced for process overview, alarms, trends, reporting, and logging. Phase 4 integrated the TPS model with the TIA Portal PLC program through S7-PLCSIM Advanced to demonstrate virtual commissioning. This phase-wise structure was used to prevent the simulation, control logic, SCADA, and integration activities from appearing as disconnected tasks.

4.2 Data collection and input parameters

Operational data were collected from Tashi Beverages Limited through plant observation, discussion with technical personnel, and available production information during project site visits. The collected data included station processing speeds, weekly unscheduled downtime estimates, scheduled maintenance intervals, rework assumptions, plant production goal, rated line capacity, buffer capacity, effective production time, and general layout information.

Table 1: *Machine parameters retrieved from Tashi Beverages Ltd.*

Station	Processing speed	Unscheduled downtime	Rework Assumption
Filler	1 s/bottle	1.15 h/week	0%
Sealer	1 s/bottle	0.29 h/week	0%
Labeller	0.3 s/bottle	7.00 h/week	2%
Date coder	1 s/bottle	0.37 h/week	1%
Shrink wrapper	2.5 s/group or case	7.02 h/week	2%

Table 2: *Production data retrieved from Tashi Beverages Ltd.*

Parameter	Value
Line capacity	3600 bottles/hour or 150 cases/hour
Production goal	2880 bottles/hour or 120 cases/hour
Plant operating hours	24 hours x 6 days
Scheduled maintenance	84 minutes or 1.4 hours
Effective production hours	23 hours

A later control-system observation identified the station-level controller structure and the absence of a dedicated line-level SCADA system. The data were sufficient for a case-based DES model, but they were aggregated rather than time-stamped; therefore, failure and repair distributions could not be fitted using goodness-of-fit tests such as chi-square or Kolmogorov-Smirnov.

4.3. Simulation Model Development

The simulation model was developed in Siemens Tecnomatix Plant Simulation using built-in objects such as Source, Conveyor, Buffer, Station, Drain, and Movable Units. The material flow followed the sequence: source of pre-rinsed bottles, filling, sealing/capping, date coding, labelling, buffer accumulation, shrink wrapping, and finished-case output. Customized movable units were used so that bottles could visually change state as they moved from empty/pre-rinsed to filled, capped, date-coded, labelled, and grouped products. Simplified 3D CAD representations of major stations were created in Autodesk Fusion 360 and imported into TPS to improve visual clarity for demonstration and integration.

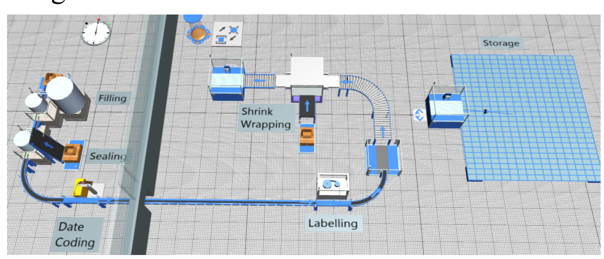

Fig. 3: *Tecnomatix Plant Simulation model overview*

Downtime and rework were implemented at the relevant stations to represent interruptions and quality losses. Station parameterization used processing time, scaled downtime, mean time to repair, availability-related failure settings, and rework percentages. Large imported CAD models were graphically optimized in TPS by reducing unnecessary nodes and polygons so that repeated validation and experimentation runs could be executed without excessive CPU/GPU load. The model recorded throughput, utilization, failure percentage, waiting percentage, blocking percentage, lead time, and WIP. Verification was performed by checking product flow, station sequence, output counting, machine states, and expected responses to downtime and control inputs.

4.4. Simulation Window and Downtime Scaling

The effective plant production window was 23 h/day. For repeated simulation and experimentation, the model was run for 7.67 h, equivalent to one-third of the effective daily production time. This reduction was used to manage computational load and enable repeated replications within the project period. Machine processing times were kept consistent with the station speeds, while downtime values were proportionally scaled to the reduced window.

This reduced-window method is a limitation. It assumes that downtime effects can be represented proportionally over the shorter window, which may not fully reproduce the actual sequence of failures during a full production day. A stronger model would use complete time-stamped failure and repair logs, fitted statistical distributions, and full-shift simulation.

$$Availability, A = \frac{Operating\ time}{Planned\ production\ time}$$

$$Downtime_{Scaled} = \frac{Original\ Downtime}{Reference\ Window} \times t_{sim}$$

$$Mean\ Output = \frac{Sum\ of\ replication\ outputs}{n}$$

$$Coefficient\ of\ Variation, CV = \frac{s}{\bar{x}} \times 100\%$$

$$Relative\ Precision, RP = \frac{CI\ halfwidth}{\bar{x}} \times 100\%$$

Where, t_{sim} is the simulation window, s is the sample standard deviation, $\bar{x}$ is the sample mean, n is the number of replications or simulation runs, and the *CI* halfwidth is calculated using the *t*-distribution for the selected confidence level.

4.5 Experiment design

Table 3: *Experimental Factors and Purpose*

Experiment	Factor levels	Purpose
Buffer capacity	1, 100, 200, 300, 400, 500 bottles	Test whether additional accumulation improves throughput
Bottleneck Stations' Speed	1.00, 0.75, 0.67, 0.50 s/bottle	Test whether reducing processing time improves throughput

Two simulation experiments were conducted after validating the baseline model. The first experiment varied buffer capacity to determine whether the line was buffer-constrained. The second experiment reduced the processing time of the governing stations identified from the station performance outputs. The analysis used throughput as the main response variable. Pairwise t-tests were used in the analysis for simple comparisons.

The statistical comparisons were treated as planned pairwise comparisons because the engineering question was not only whether any experimental level differed, but which specific parameter change produced a meaningful throughput change. Pairwise t-tests are therefore retained for direct engineering interpretation.

4.6. PLC Logic and SCADA Development

Table 4: *PLC Operating states used in the FSM*

State	Name	Function
0	Idle / stopped	System waits for start command; outputs are inactive except permitted status signals.
1	Starting	Downstream machines are started before upstream machines to prevent accumulation.
2	Running	All permitted machines operate normally while feedback and interlocks are monitored.
3	Stopping	Upstream machines are stopped first while downstream sections clear remaining products.
4	Fault	Operation is inhibited due to active fault, interlock failure, or abnormal feedback.
5	Reset / recovery	Fault reset is allowed only after fault conditions are cleared and safe restart conditions are met.

The automation component was developed using Siemens TIA Portal V16. A Siemens S7-1500 CPU 1511-1 PN was used as the supervisory PLC in the virtual implementation because S7-PLCSIM Advanced supports S7-1500 virtual PLC instances for integration with external simulation environments. The proposed industrial retrofit, however, does not require replacement of the existing station PLCs. The station controllers remain responsible for local control, while the supervisory PLC exchanges essential command and feedback signals with them. The PLC logic used a finite-state-machine (FSM) structure with defined states for idle/stopped, starting, running, stopping, fault, and fault reset. Downstream-first starting and upstream-first stopping were used to reduce product accumulation and blockage.

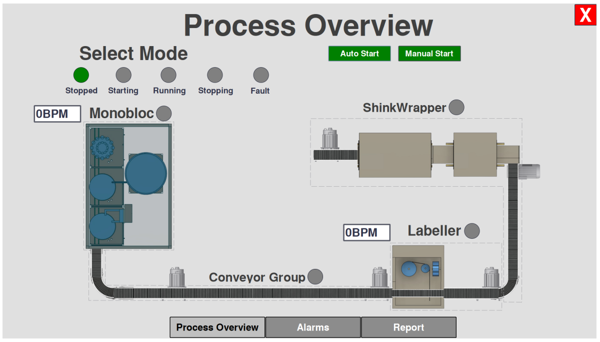

Fig. 4: SCADA Process Overview Screen

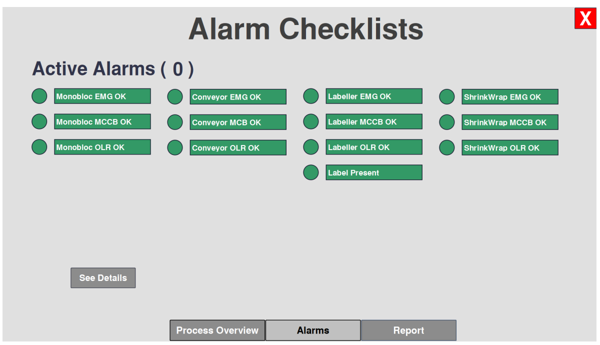

Fig. 5: SCADA Alarm Checklists Screen

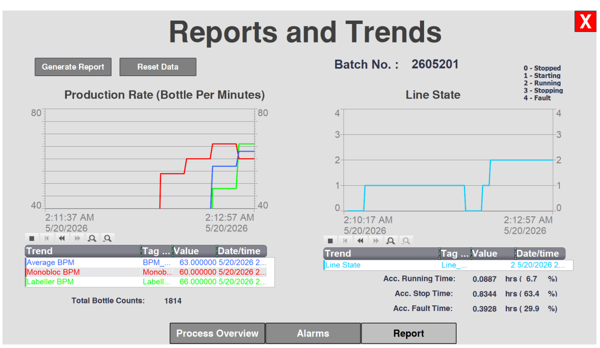

Fig. 6: SCADA Reports and Trends Screen

The SCADA screens were developed using WinCC Runtime Advanced as a PC-based HMI/SCADA-oriented supervisory interface. The screens were organised as process overview, alarm checklist, alarm-detail view, trend/report page, production count display, shift reset, and report generation functions. ISA-101 principles were considered by grouping information according to operator need, limiting decorative graphics, using consistent status indication, and separating overview, alarm, and performance information. The system also included logging of alarm events, line states, production rate, and selected time-accumulation values, so that the interface supported review of production and fault behavior rather than only real-time visualization.

4.7 Supervisory integration architecture

The observed packaging line used multiple local machine controllers rather than one unified supervisory controller. The site observation identified dedicated machine/control domains, including the monobloc section, conveyor group, labelling station, and shrink-wrapper. The observed controllers included AB Micro850, Delta DVP-S series, Siemens S7-1200 1211C, and Emerson VersaMax MicroPlus units. A dedicated packaging-line SCADA or interconnecting supervisory monitoring system had not been observed for the selected section.

The proposed architecture therefore retained the existing station controllers and added a supervisory PLC/SCADA layer above them. This approach avoids replacing local machine PLCs and reduces integration risk. Essential signals include start command, stop command, reset command, ready status, running feedback, stopped feedback, fault status, emergency-stop healthy status, and selected production-count feedback.

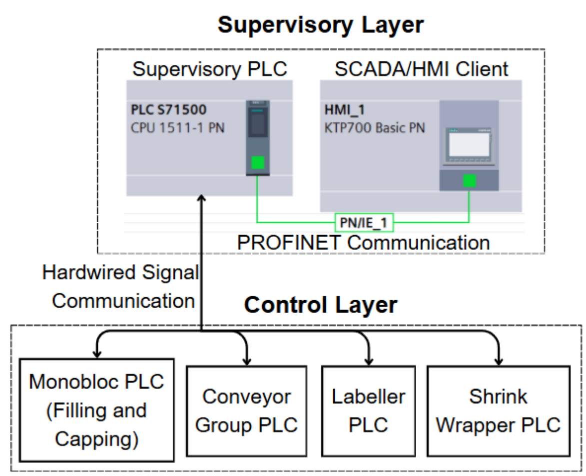

Fig. 7: Proposed supervisory control architecture for multi-vendor packaging line integration.

Hardwired signal-level integration was selected as the simplest retrofit concept for heterogeneous legacy systems. Compared with OPC UA, Modbus TCP, or other networked protocols, hardwired I/O provides less diagnostic detail but can be easier to implement when communication access, vendor software, protocol compatibility, or machine documentation is limited. A future implementation could use OPC UA or protocol gateways where it is supported by the machine controllers.

4.8 Virtual commissioning procedure

The TPS model and TIA Portal PLC logic were linked in a virtual commissioning environment using S7-PLCSIM Advanced. Before integrating the full packaging-line model, a small trial model consisting of Source, Conveyor, Workstation, and Drain objects was used to confirm that PLC output commands could be mapped to TPS inputs and that TPS feedback could be returned to the simulated PLC. After this verification, the larger packaging model was connected using mapped command and feedback tags. TPS object attributes such as station entrance locking and user-defined fault/status variables were linked to PLC tags, while SimTalk scripts and virtual control-panel objects were added where local interaction was required.

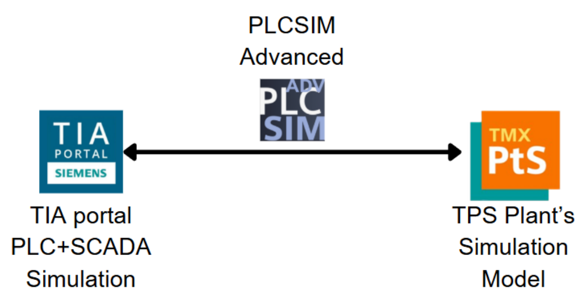

Fig. 8: *TPS and TIA Portal virtual commissioning setup*

The integrated system should be described as a virtual factory model or virtual commissioning testbed rather than a full digital twin. A complete digital twin would require continuous real-time plant data, historian integration, live synchronization, validated field signals, and model updating. The present system demonstrates command-feedback exchange, sequence verification, manual operation testing, and fault response testing in a simulated environment. This is useful for pre-deployment logic checking, but it does not replace physical commissioning, electrical verification, machine-safety validation, or plant acceptance testing.

5. RESULTS AND DISCUSSION

5.1. Baseline Validation Result

The model output was compared with the plant-derived benchmark range for the 7.67-hour simulation window. The lower benchmark was based on the production goal of 120 cases/h, equivalent to approximately 920 cases over 7.67 h. The upper benchmark was based on the rated capacity of 150 cases/h, equivalent to approximately 1150 cases over the same duration. This validation should be interpreted as benchmark-based validation rather than independent statistical field validation.

Table 5: *Simulation Throughput Results*

Run No.	Throughput
1	1074
2	1066
3	907
4	1114
5	985
6	1132
7	923
8	1088
9	990
10	1004

The mean throughput was 1028.4 cases, with a standard deviation of 77.84 cases. The 95% confidence interval was approximately 972.71 to 1084.09 cases. The coefficient of variation was 7.57%, and the relative precision was 5.41%. The mean and confidence interval lie within the benchmark range; however, Run 3 produced 907 cases, which is below the lower benchmark. This run was not removed from the analysis. It is interpreted as an unfavorable stochastic replication caused by the modeled downtime/failure behavior. Its presence shows why the result should be interpreted using replication statistics rather than a single run, and why additional replications would strengthen confidence in the validation.

The ten validation replications were also treated as a pilot replication set for checking simulation precision. Using the pilot standard deviation of 77.84 cases and the mean throughput of 1028.4 cases, the 95% confidence-interval halfwidth was approximately 55.69 cases, giving a relative precision of 5.41%. Based on the same pilot variability, approximately 12 replications would be required to reach a stricter 5% relative precision target. Therefore, the ten-run result is close to the target and acceptable for preliminary engineering analysis, but a revised publication-grade study should increase the replication count.

5.2 Interpretation of validation limitations

The validation method uses plant-derived production targets and rated capacity as benchmarks. This provides a practical engineering check but is weaker than validation against independently measured production runs. The result confirms that the model output is of the correct magnitude, but it does not prove that the model reproduces all real plant behavior. More rigorous validation would require time-stamped production output, actual failure logs, repair records, and multiple observed shifts for direct comparison with simulation replications.

5.3. Station-Wise Performance Analysis

The filler, sealer, and date coder showed high utilization of approximately 90%, suggesting that these stations governed or bottlenecked the line rate in the modeled configuration. Their blocking percentages also indicate that upstream flow and downstream interaction affected performance. The labeller and shrink wrapper showed lower utilization but high waiting percentages, indicating that they were often starved or waiting for grouped/product arrivals rather than continuously limiting output.

Table 6: *Station-wise simulation result analysis*

Station	Utilization (%)	Failure (%)	Waiting (%)	Blocking (%)
Filler	90.16	0.42	0.00	9.44
Sealer	90.12	0.30	0.44	9.17
Date coder	89.91	1.25	0.43	8.44
Labeller	26.92	7.00	62.81	3.27
Shrink wrapper	9.33	4.45	84.51	1.71

This interpretation is based on TPS station statistics, blocking/waiting behavior, and throughput sensitivity experiments. It should therefore be described as a utilization- and sensitivity-based bottleneck indication, not as a formal active-period or shifting-bottleneck analysis. A future study should apply a formal method such as Theory of Constraints, active-period analysis, or the Roser bottleneck detection method using time-series station-state data.

5.4. OEE-related analysis

The OEE-related estimate was calculated using availability, performance, and quality components. Availability was estimated as 90.4%, performance as 89.4%, and quality as 95.1%, giving an OEE value of approximately 76.8%.

$$OEE = Availability \times Performance \times Quality$$

$$OEE = 0.904 \times 0.894 \times 0.951 = 0.768 \; or \; 76.8\%$$

This value should be interpreted carefully. It is a hybrid estimate because availability and quality were obtained from available plant data, while performance was calculated from simulated throughput. Therefore, the value is not a certified measured OEE of the actual plant and not a purely simulated OEE. It is useful as an engineering indicator for comparing productivity losses within the available data constraints, but a formal plant OEE would require actual operating time, downtime, speed loss, and good-count data collected directly over multiple production shifts.

5.5. Lead Time and Work-In-Progress

The average lead time obtained from the model was 147.5 s. Using the simulated average production rate and Little's Law, WIP was estimated at approximately 130 bottles.

$$L = Arrival\ Rate\ of\ Items\ (\lambda) \times Lead\ Time(W)$$

where L is average WIP, λ is the production rate, and W is the average lead time. The value of 130 bottles means that, on average, about 130 bottles were present within the modeled packaging section during operation. This indicates moderate internal accumulation and supports the finding that increasing buffer capacity alone is unlikely to produce large throughput improvement under the modeled conditions.

5.6. Buffer Conveyor Experimentation

Increasing buffer capacity from 1 to 500 bottles increased throughput from 1022.2 to 1037.2 cases, equivalent to approximately 1.5%. The reported pairwise t-test p-values for the buffer scenarios were all greater than 0.05, indicating that the throughput changes were not statistically significant at the 5% confidence level.

***Table 7:** Buffer-capacity experiment results*

Buffer capacity (bottles)	Mean throughput (cases)	Standard deviation (cases)
1	1022.2	80.05
100	1025.5	78.68
200	1028.4	77.85
300	1031.3	77.18
400	1034.2	76.75
500	1037.2	76.69

The standard deviation decreased slightly from 80.05 to 76.69 cases as buffer capacity increased, suggesting a small stability improvement, but not enough throughput gain to justify buffer expansion as the main improvement action. This supports the interpretation that the line is not primarily buffer-constrained under the modeled conditions.

The wide range from 1 to 500 bottles was useful for observing the full sensitivity trend. However, from an industrial perspective, a narrower experimental range around the actual 200-bottle capacity, such as 100-300 bottles, would be more realistic for future plant-focused decision-making. The present conclusion is therefore limited to the modelled trend that additional buffer capacity provides negligible throughput benefit compared with changing the rate-limiting stations.

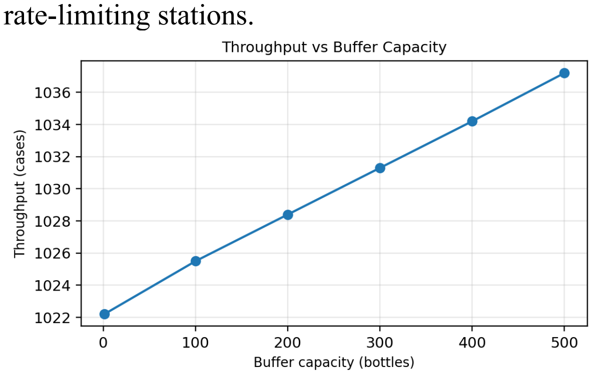

***Fig. 9:** Production Throughput vs Buffer Capacity*

5.7. Bottleneck Station Experimentation

Reducing the processing time of the filler, sealer, and date coder increased throughput more substantially than buffer expansion. Throughput increased from 1037.2 cases at 1.00 s/bottle to 1365.8 cases at 0.75 s/bottle, 1433.2 cases at 0.67 s/bottle, and 1437.8 cases at 0.50 s/bottle.

The pairwise comparisons showed significant improvement from 1.00 s/bottle to faster settings (for example, p = 0.0010 for 1.00 to 0.75 s/bottle and p = 0.0008 for 1.00 to 0.67 s/bottle), while the change from 0.67 to 0.50 s/bottle was not significant (p = 0.9223). The result should therefore be described as a practical threshold region between 0.75 and 0.67 s/bottle, not as a mathematically proven optimum.

***Table 8:** Bottleneck Station speed experiment results*

Processing time of bottleneck stations	Mean throughput (cases)	Standard deviation (cases)
1.00 s/bottle	1037.2	76.69
0.75 s/bottle	1365.8	108.22
0.67 s/bottle	1433.2	104.30
0.50 s/bottle	1437.8	103.01

A deployment recommendation should therefore be cautious: the plant should not simply increase machine speed to the lowest simulated processing time. Any real speed increase must be checked against filling accuracy, capping quality, label placement, shrink-wrap quality, drive capacity, machine warranty, energy demand, maintenance frequency, and safety requirements.

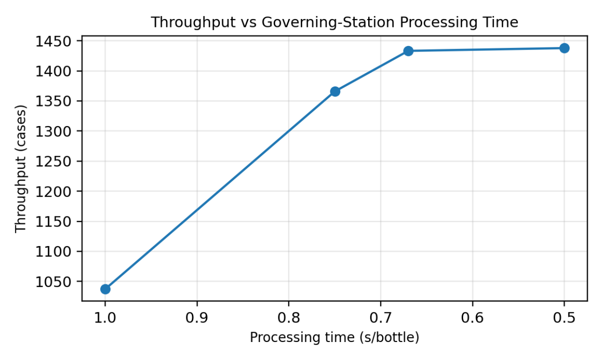

***Fig. 10:** Production Throughput vs Machine Speed*

5.8 PLC, SCADA, and virtual commissioning results

The PLC logic successfully represented the intended operating states of the packaging line. Automatic mode followed a downstream-first start sequence and an upstream-first stop sequence to reduce product accumulation. Manual mode allowed individual station control under interlock conditions. Fault logic moved the system into a fault state and required reset after fault clearance.

The SCADA system provided an operator interface for process overview, alarm checklist, detailed fault information, production trend, line state, total bottle count, report generation, and reset functions. Alarm logging was implemented in CSV format with alarm name, occurrence/clearance time strings, and alarm class information. The report screen allowed shift-based production statistics, fault time, stop time, and run-time values to be generated for later review. These functions make the system more accurately a PC-based HMI/SCADA-oriented supervisory prototype rather than a fully deployed plant SCADA system.

The integration was limited to virtual testing. It did not include physical wiring to the actual plant, final safety validation, on-site I/O testing, vendor controller access, or plant acceptance testing. Therefore, the integration result should be interpreted as a functional proof-of-concept for virtual commissioning rather than a completed industrial deployment.

5.9 Deployment implication and cost boundary

The finalized project report also evaluated a conceptual deployment expenditure for the supervisory PLC/SCADA retrofit. For physical deployment, the virtual S7-1500 used for PLCSIM Advanced integration does not have to be retained; a lower-cost Siemens S7-1200 1214C DC/DC/DC class controller with suitable DI/DO expansion can be sufficient for basic signal-level supervisory integration if the final I/O count, scan-time, and communication requirements are verified.

A conceptual build-up including PLC and I/O, SMPS/UPS and protection, control-panel enclosure, relay interfacing, industrial switch and wiring, Step 7/WinCC licensing, and contingency was estimated at about Nu. 308,000. This estimate is not a final procurement BOQ; it is a planning-level expenditure boundary. A real deployment would also require electrical drawings, interposing relays or isolation, verified machine permissive signals, safety review, commissioning labour, operator training, and coordination with the original machine vendors.

5.10 Summarized Recommendations

- Maintain the existing buffer capacity unless future plant data show frequent blocking or accumulation-related stoppages. The modeled increase from 1 to 500 bottles produced only about 1.5% throughput improvement.
- Prioritize investigation of the governing station speeds and their actual mechanical/electrical limits, because reducing processing time from 1.00 s/bottle produced the strongest throughput improvement in simulation. Before real implementation, verify filling accuracy, capping quality, date-code readability, label placement, shrink-wrap quality, drive capacity, energy use, wear, maintenance impact, and vendor capability.
- Treat 0.75-0.67 s/bottle as a practical evaluation range rather than a mathematically proven optimum.
- Use the supervisory PLC/SCADA architecture as a retrofit concept only after detailed I/O mapping, safety review, panel design, signal isolation, interposing relay selection, machine-permission verification, electrical drawings, and commissioning planning. The hardwired approach is suitable for essential command-feedback integration but provides less diagnostic depth than OPC UA, Modbus TCP, or native Ethernet-based integration.
- Improve future simulation accuracy by collecting time-stamped production, failure, repair, and quality data from the plant.

6. LIMITATIONS

The study has several limitations that affect the strength of the conclusions. First, the input data were obtained from one company and one packaging section, so the numerical results are case-specific. Second, downtime data were aggregated and not available as time-stamped failure and repair records; therefore, formal input distribution fitting could not be performed. Third, the 23-hour effective production window was reduced to 7.67 h, so downtime was represented proportionally rather than through a full-shift production history.

Fourth, the ten baseline replications were close to but slightly below the stricter 5% relative precision target, so additional runs would improve confidence. Fifth, the validation used plant-derived production targets and rated capacity, which is useful for engineering benchmarking but weaker than validation against independently measured production runs. Sixth, OEE was calculated as a hybrid estimate using plant-derived availability/quality and simulated performance.

Seventh, bottleneck interpretation was based on utilization, waiting/blocking indicators, and sensitivity experiments rather than formal active-period bottleneck analysis. Eighth, the PLC/SCADA and TPS-TIA integration were virtually tested only and were not physically connected to the plant. Finally, the system is a virtual commissioning prototype and digital-twin-oriented foundation, not a complete digital twin with live plant data, historian synchronization, and continuous model updating.

7. CONCLUSION

This study developed a case-based discrete-event simulation model of the 500 mL packaged drinking water packaging section at Tashi Beverages Limited and connected it with PLC/SCADA-oriented development for virtual commissioning. The model represented the main packaging stations, processing parameters, downtime assumptions, rework rates, buffer behavior, and product flow using Siemens Tecnomatix Plant Simulation. The baseline model produced a mean throughput of 1028.4 cases in a 7.67 h window, which lies within the plant-derived benchmark range of 920 to 1150 cases. Because one replication fell below the lower benchmark and because validation used plant-derived targets rather than independently measured production runs, the validation should be interpreted as benchmark-based and preliminary rather than definitive.

The experimental results showed that buffer capacity had little effect on throughput, with only about 1.5% improvement from 1 to 500 bottles. In contrast, reducing the processing time of the governing stations had a stronger effect, increasing throughput from 1037.2 cases at 1.00 s/bottle to 1437.8 cases at 0.50 s/bottle. However, the recommended speed-improvement point should be treated as a practical threshold range around 0.75-0.67 s/bottle rather than a formal optimum. The OEE-related estimate of 76.8%, lead time of 147.5 s, and WIP of approximately 130 bottles provided additional insight into line performance but should be interpreted within the assumptions of the model.

From a statistical standpoint, the pairwise comparison approach was retained because it answers the practical engineering question of which specific parameter changes matter. Nevertheless, the analysis should be strengthened in future work by adding more replications, controlling multiple comparisons, and rechecking the results using ANOVA with post-hoc tests if complete replicated datasets are exported from TPS.

The PLC and SCADA component demonstrated how state-based control, manual operation, alarms, trends, production reporting, and data logging can be tested using a virtual plant model. The integration through S7-PLCSIM Advanced showed command-feedback exchange between TPS and TIA Portal and therefore provided a virtual commissioning workflow for checking sequence behavior before physical deployment. However, practical deployment would require verified field I/O, electrical drawings, safety interlocks, signal isolation, commissioning tests, and plant approval. Future work should collect time-stamped production and downtime data, fit failure/repair distributions, increase replications, apply corrected statistical comparisons or supplementary ANOVA, perform formal active-period bottleneck analysis, include cost-benefit analysis, and connect the supervisory layer to real plant signals and historian-based data logging.

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