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Simulation analysis of a new semi-continuous chemical facility with automated production lines: an industrial case study

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Abstract

This work focuses on a simulation modelling and analysis of a semi-continuous chemical facility with automated production lines. The study aims to find a way to represent the behavior of a whole new chemical facility in order to analyze the feasibility of a given production plan. According to the project needs, a simulation model was created in Simio® by specific ad-hoc objects developed using standard and flow libraries. A final scenario analysis was done in order to determine the feasibility and applicability of a given production plan for different changes in the production capabilities at the new facility.

Keywords: modeling and analysis; discrete-event simulation; semi-continuous facility; viability study

1. Introduction

The objective of this study was to evaluate the design of a new facility with automated production lines. The new facility consisted in three production lines with two shared discrete areas placed at the beginning and at the end of the lines, and several automated continuous production processes disposed along the lines. Discrete processes, regarding charging and discharging operations, were performed manually by dedicated operators. While, continuous processes were done automatically according to the production plan. The new facility design had more than 50 tanks, 150 pipes and 300 valves per production line with specific features. All these elements should be coordinated to achieve a given production target.

At this point, Altran Industrial Consulting group, specialized in operations transformation supported by technological solutions, was contacted to study the operational behavior of the facility and provide an analysis of the process's operations. As a result, a discrete-event simulation model (Banks et al. 2004; Seppanen et al. 2005; Law 2007) was proposed in Simio® (Pegden & Sturrock 2013; Kelton et al. 2014) to emulate the production processes in order to study the productivity of the new facility and also evaluate its production capability.

As far as we know, no many industrial case studies that consider the viability analysis of the production plan design of a new chemical plant by using solely discrete-event simulation have been published in the recent years. Kou et al. (2001) provides a model for logistic operations of continuous material flows by using discrete-event simulation. Sharda & Bury (2010) presents a bottleneck study of semi-continuous chemical plant by using discrete-event simulation. Same authors in 2011, reports several practical applications based on reliability and improvement analysis of continuous operations in the process industry by using discrete-event simulation. Then, Spieckermann & Stobbe (2012) discuss combined discrete-continuous simulation approaches at real application in chemical industries.

The rest of the paper is focused on providing a real case study based on a viability analysis of a new chemical production plant by using modeling and simulation with the flow elements and capabilities implemented in Simio®. We will center the attention on how to represent the continuous operations of a chemical plant by using discrete events, how to control the complex operation of valves, tank capacities and sequential charging and discharging activities in order to fulfill a given production plan without suffering any blockage.

2. Problem statement

The main challenge of this project was to replicate the behavior of a new facility in order to test the viability of a given production plan. Thus, all production processes from raw material and ingredients addition to the final packaging have been represented in detail.

The raw material and ingredients addition process was modeled as set of batches that feed the process according to the production plan. The feeding process was represented by batch's inter-arrival times (time between arrivals) and batch quantities. Operators, forklift and conveyor were modeled in detail for unloading raw material bags from the trucks and put it in intermediate storage (warehouse) to be used later. Once inside the facility, raw material and ingredients were loaded by the operators in a hopper which was represented by *"Item-to-flow converter"*. All the raw materials, ingredients and product information and recipe were given in an input Excel® file. The resulting material flow of this process was used as an input for the continuous process.

All the following processes were represented as continuous production processes corresponding to flow operations. In addition, all these flows were transferred by pipes. These continuous processes were from simple holding reservoir or basic equipment, where a specific amount of products would remain there for a determined time in order to simulate physical processes, (shaking, settling, heating, cooling, etc.) to more complex chemical equipment (reactors, concentrators, separation columns, etc.), where flows were mixed or blended (homogeneous/heterogeneous) according to the production recipe. A conceptual diagram of the discrete and continuous processes represented in the simulator is shown in Figure A.1 Appendix A.

Due to confidentiality restriction, the information on the conceptual diagram of the process operations only represents a single production line in a schematic way. The scheme only shows the main processes without giving details about the number of parallel equipment and connections, personnel required at each discrete operation, materials and material-handling devices, working shifts, production targets and KPI's. Interesting works that address similar physical processes for the quality by design (QbD) of a pharmaceutical plant can be found in Zhang et al. (2013) and Gong et al. (2014).

Each of these continuous processes was performed by several equipment with the following elements:

- Inlet valves (flow regulator): flow rate, quantity of predecessor raw material/ingredient or intermediate product flow
- Equipment (tank): maximum capacity, holding time, cleanup time, I/O performance
- Outlet valves (flow regulator): flow rate, quantity of intermediate product, recycle and waste flows

Each equipment has a given sequence of operations of charging, holding, discharging, purging and cleaning which are repeated cyclically. According to the production recipe, the equipment charge specific quantities of product (raw material, ingredients or intermediate product) flows from different inlets to then process and discharge by different outlet flows. The result of the process in general provides specific quantities of intermediate product that is flown to the next step in the process sequence and recycle products that are flown to recycle processes and tanks to be reused.

The coordination of the main flow (intermediate products) and recycle flows represents one of the most challenging problems to be modelled due to specific operational constraints. Thus, flow rates and tank capacities were changed, in between specific ranges, in order to fulfill with the restrictions imposed without blocking the entire production line.

After several continuous processes, the intermediate products for each line are sent to a final step where the flows are converging in a mixer to then be discharged and packed in plastic bags. The mixing and packaging processes were also modeled as an ad-hoc object. The mixing machine produces batches with a specific batch-size with a given processing time. This has been modelled as a discrete process as a *"flow-to-item converter"* that converts flow into specific batches. Then, batches will be discharged in plastic bags by operators. At the end of the process, the plastic bags were stored in cardboard barrels to then be transferred to the final storage (warehouse) by using a manual forklift. The packaging operations were represented as packaging objects (filling machine and palletizer) consuming packaging material (bags and barrels). Finally, the outputs of the simulation (global resource utilization, daily material and packaging consumptions and production throughput) were exported in an output Excel® file for analysis.

3. Methodology

In order to ensure a faithful representation of the process operations, a primary phase of understanding the process logic in detail and its behavior was needed. The simulation model was developed after considering all the internal logic of discrete and continuous processes defined in Figure A.1 Appendix A, by creating ad-hoc objects of different equipment. Thus, the principal inlet/outlet flows of raw material from/to main production tanks by using valves, charging and discharging operations and batching/splitting activities have been modeled in detail (see Simulation model section). Afterward, the model was fully animated to provide a close-to-reality view of the main equipment and workers involved in each production process. All manual operations of raw material addition and packaging processes have been animated (see Animation model section). Once the model was ready, an exhaustive verification and validation analysis have been made to ensure the correctness of the internal logic and the validity of the results provided (see Model validation section). Finally, different scenarios of production were proposed for analysis by changing specific control variables of the process subject to strict *"Good Manufacturing Practices"* policies. For that, a design of experiments was performed and corresponding sensitivity analysis was applied in order to identify critical factors that may improve the final throughput of the entire plant (see Scenario analysis section).

4. Simulation model

The simulation model was created based on the idea of integrating discrete and continuous processes. For the operations taking place at continuous processes, a new object was developed. An edited *"Tank"* object from the standard "*Flow Library*" in Simio®, was created in order to handle multiple inlet and outlet flows with specific flow rates and with the capacity of process different operations. Due to system features, each ad-hoc tank was developed with three input and output valves that flows the product In/Out of the tank at predefined production flow rates (see Figure 1).

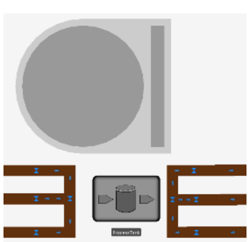

Figure 1. External view of the ad-hoc Tank object

4.1. Continuous processes

The operations taking place in the tanks have been set in an Excel® file directly binding with the simulation model. In order to preserve customer's data a modified version of continuous operations are shown in Table A.1 Appendix A.

As an example, let's start explaining the operations performed at *"Process 1"*. Thus, for *"Oper#1"*, the ad-hoc tank takes initially an input flow of 5.0 [m3] by switching on valve 1, with an input flow rate of 10 [m3/h]. Once the charging operation was finished, the input valve 1 is closed and the tank starts discharging 5.0 [m3] via output valve 2 at 5 [m3/h], by switching on this valve. Notice that there is no additional charging, holding (processing) or discharging time associated with this operation. After that, *"Oper#2"* is started by charging 5.0 [m3] of raw material products from switch valve 2 at 10 [m3/h]. After reaching the 5.0 [m3], input valve 2 is closed and a charging time of 0.5 [h] is added to this operation due to additional activities. The raw material inside the tank is processed for around 3 hours to then be discharged via output valve 1. Only 3.0 [m3] are discharged at 5 [m3/h] while the rest remains in the tank for further addition operations. *"Oper#3"* behaves similar to *"Oper#2"*, charging 3.0 [m3] of raw material and discharging 3.5 [m3]. Once *"Oper#3"* has finished, the fourth operation *"Oper#4"* of *"Process 1"* starts by charging 2.5 [m3] from input valve 3 with an input flow rate of 10 [m3/h]. Additional charging time of 0.5 [h] is needed when the material is fully charged on the tank. Then, it waits for 1.0 [h] to then be discharged via output valve 1 with a discharging time of 0.5 [h]. From the total amount in the tank only 2.0 [m3] are discharged at 5 [m3/h] via output valve 2 while 1.0 [m3] is discharged via output valve 2 as it is described in *"Oper#5"*. The rest of the material in the tank is purged to perform cleaning operations. Despite that each process is different from the other, most of the continuous processes performed in the facility were modelled following a similar sequence of operations.

4.2. Internal logic for continuous processes

In order to implement this logic, a specific process was created inside the ad-hoc tank object **MyTank** (see Figure A.2 and Figure A.3 Appendix A).

The charging logic starts by searching from the production operation table the process to be performed by the *"ProcessName"*. If it matches, then the first row in the table is assigned corresponding to the first operation to be performed. It is important to remark that each equipment is assigned to a given process and this process is performed cyclically throughout time. For this, the process should be executed at the beginning of the simulation in the "Run Initialized" add-on Process Triggers of **MyTank** object.

Once a specific row is reached, it looks into the *"SwitchIn"* column in order to determine which valve should be opened. If the number is greater than zero, then the charging process is executed. Otherwise, it jumps directly to the end and continue with the processing time delay (see Figure A.2).

If the charging is performed, then a source valve is assigned to the **MyTank.SwitchTankIn** parameter which is used for switching the inlet flow. According to this value, the corresponding valve is opened by **MyTank.Input.FlowRegulator.Enabled** while the others remain closed to avoid any mixing. Here, *"InletFlowRate"* value is dynamically updated by the following reserved state variable **FlowRegulator.CurrentMaximumFlowRate** for the **MyTank.Output** object. Once opened a threshold value is assigned by updating the following state variables **MyTank.VolumeLevelRisingAboveMidMark.CurrentThresholdValue** with the value of the current content **Tank.FlowContainer.Contents.Volume** plus the value of the *"InputFlow"* defined for this row in Table A.1.

The monitor associated with this state is enabled by **MyTank.VolumeLevelRisingAboveMidMark.Enabled** and a "wait for event" is placed until the volume of the tank reach this threshold value, firing the following event **MyTank.VolumeLevelRisingAboveMidMark.Event**.

The logic of the charging has finished by updating the total volume flow-in and closing all the input valves. Then, a "Charging time" and a "Processing time" are applied.

After processing, a discharging operation is performed as it is shown in Figure A.3. Discharging logic have similar behavior than charging. First, the logic looks into the *"SwitchOut"* column to determine if this row has a discharging operation or not. If this value is greater than zero, then **MyTank.SwitchTankOut** parameter will take the value from the column *"SwitchOut"* forcing to activate only a single outlet flow.

Then, **FlowRegulator.CurrentMaximumFlowRate** state variable for the **MyTank.Output** object takes the value of the *"OutletFlowRate"* while **MyTank.VolumeLevelFallingBelowMidMark.CurrentThresholdValue** is updated by the current content **Tank.FlowContainer.Contents.Volume** minus the amount in the *"OutputFlow"* from Table A.1. The tank starts discharging till a **MyTank.VolumeLevelFallingBelowMidMark.Event** is reached. When this event is fired, the total output flow is updated and the *"Discharging time"* is executed. As well as for the charging operation, the monitor associated with the discharging operation has to be enabled by **MyTank.VolumeLevelFallingBelowMidMark.Enabled**. Finally, the row number is increased by one. In case of the last operation, a purge of the current content with a subsequent cleanup time is performed before the process returns to the first operation.

In order to consider different shifts for continuous operations a particular logic was created. This logic is based in two principal events **OnShift** and **OffShift** defined at the beginning and at the end of each shift change. When the **OffShift** event takes place, the flow for each tank defined in the model is suspended, the previous status is saved and the current status is changed to "Cleaning" until the **OnShift** event occurs. When the process is resumed, the status is recovered to the previous status and the tank continues with the normal operation.

4.3. Discrete processes

Discrete processes were performed at the beginning and at the end of the line by the initial feeding bags of raw material and the final packaging respectively. An important thing is that, all discrete operations were performed by workers. Just like the continuous processes, the discrete processes have to consider specific shift patterns for their workers that were modelled in the tool and can be easily changed according to the production plan.

4.4. Internal logic for discrete processes

The creation of raw material bags and trays were represented by the logic shown in Figure 2.

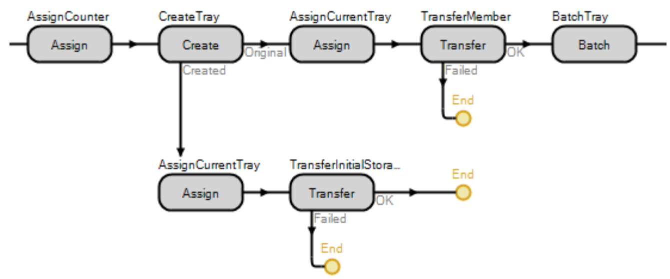

Figure 2. Creation of raw materials and batch trays

Created bags are loaded into a member station in a specific tray. When the *"BagsPerTray"* value is reached, the loaded tray is transferred to the initial storage. From here, a worker with a forklift feed the initial automated tunnel with trays. Bags from the tray are discharged by the worker which then are converted into a specific amount of flow that flown to the raw material tanks at the beginning of the continuous process.

At the end of the continuous processes, the flow is converted into powder and it is packed into plastic bags by a filler object. Then, several plastic bags are put in a secondary plastic bag forming a "batch" and finally in a cardboard barrel to be stored in a final warehouse. Once in the final storage, a specific logic is programmed to count the batch processed and then fire an event to start packaging a new batch after one batch is produced (see Figure 3).

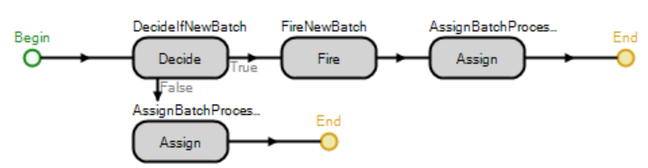

Figure 3. Final counting and fire new batches

All packaging operations at the end of the process line are performed by workers and modelled by considering specific behaviors. After a quality inspection time the barrels are moved by a worker from the warehouse to the final dispatching zone using a manual forklift.

5. Animation model

The model was animated in order to show the behavior of the discrete and continuous processes. Most of the animations were done by considering standard 3D objects from 3DWarehouse (©Trimble Inc.) webpage available from Simio®. As it can be seen in Figure 4 the stacked bar of the container was placed inside the 3D Tanks objects in order to display the behavior of the charging and discharging operations. For this, product flows were modelled with different colors to illustrate the separation phases on the tanks and pipe flows. More than 50 tanks, 150 pipes and 300 valves per line were represented in a multi-level floor facility with a given layout.

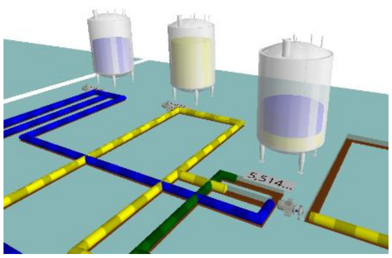

Figure 4. Tanks animation of continuous processes

Also, raw materials, workers, transporters and packaging elements were modelled and animated in detail to represent all discrete operations.

6. Model validation

A simulation baseline model of the whole facility was run for a year considering standard working shifts for discrete and continuous processes with a warm-up period of two weeks, which is the time required to reach the steady state in the whole plant. The main results of the key processes were validated taking into account the expected solution of the production facility. For the validation purposes, the main throughput at different points of the production line were measured and analyzed. These points were located at the end of critical processes represented by specific colors in Figure A.1. For each critical process, the simulation result was compared with the planned value (target value) in order to find possible gaps. Five critical processes were defined to be checked during the validation. The main results of each critical process for the baseline scenario (Scenario 1) were in between 9.2% of given targets and the final throughput was less than 1.1% of the expected value (see Figure 5 – Scenario 1). With a predefined margin of 10% the model was considered validated for the following scenario analysis process.

7. Scenario analysis

With the baseline scenario (Scenario 1) validated, it was possible to start analyzing the behavior of the processes for alternative work shift configurations. Thus, different scenarios were proposed by changing the working shift configuration of the original baseline model. The original working shift for the baseline was extended 30% for the *"ExtendedShift"* scenario (Scenario 2) and 70% for the *"FullShift"* scenario (Scenario 3). The results of the *"what-if"* analysis demonstrated that 30-70% more working hours for the continuous processes only generated an increase of 13-25% of the total throughput, which brought to the light possible limitations on the production capabilities.

Due to these limitations, additional scenarios were proposed by changing specific parameters for some of the critical processes (production rates, processing times, etc.) between specific limits defined by the engineering department. After a sensitivity analysis, it was discovered that, changing the designed production rate for the first critical process (critical process 1), the final throughput of the entire production plant was increased by 32-69% considering *"ExtendedShift"* and *"FullShift"* scenarios (Scenarios 4 and 5) respectively. This increase in the production throughput meant an important improvement for the original design, allowing reaching the expected target accordingly with the largest working shifts (Figure 5). Figure 5 shows the relative gap between the simulation results and given targets for each critical process at different proposed scenarios.

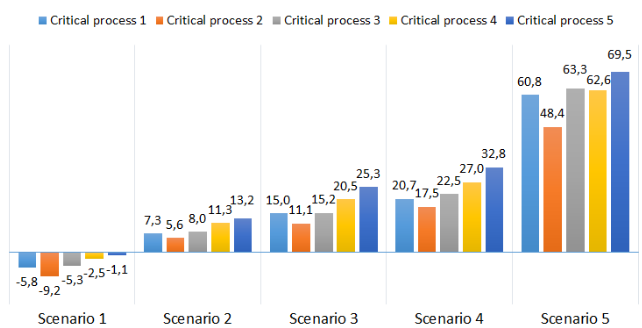

Figure 5. Scenario analysis for critical processes

8. Concluding remarks

This paper demonstrates the applicability of discrete-event simulation to represent discrete and continuous processes of a new chemical plant. This work may help practitioners and researchers on how to implement a given production plan and control it by a simple flow logic in Simio®. With this simulation-animation model, and the ulterior "what-if" analysis, it was possible to identify critical processes that affect the production capabilities and to evaluate the process productivity for the new production plan, validating throughput targets by adjusting working hours. Also, the animation made easier to visualize the whole facility showing the behavior of the discrete and continuous processes over time. All of these, and the operational suggestion of improvements for the new facility, were the main benefits provided to the customer.

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Appendix A.

Table A.1. Production operations for a given process

Oper #	Process Name	Switch In	Input Flow	Inlet FlowRate	Charging Time	Processing time	Output Flow	Outlet FlowRate	Discharging Time	Switch Out
1	Process1	1	5.0	10	0.0	0.0	5.0	5	0.0	2
2	Process1	2	5.0	10	0.5	3.0	3.0	5	0.0	1
3	Process1	2	3.0	10	0.5	3.0	3.5	5	0.0	1
4	Process1	3	2.5	10	0.5	1.0	2.0	5	0.5	1
5	Process1	0	0.0	0	0.0	0.0	1.0	5	0.0	1

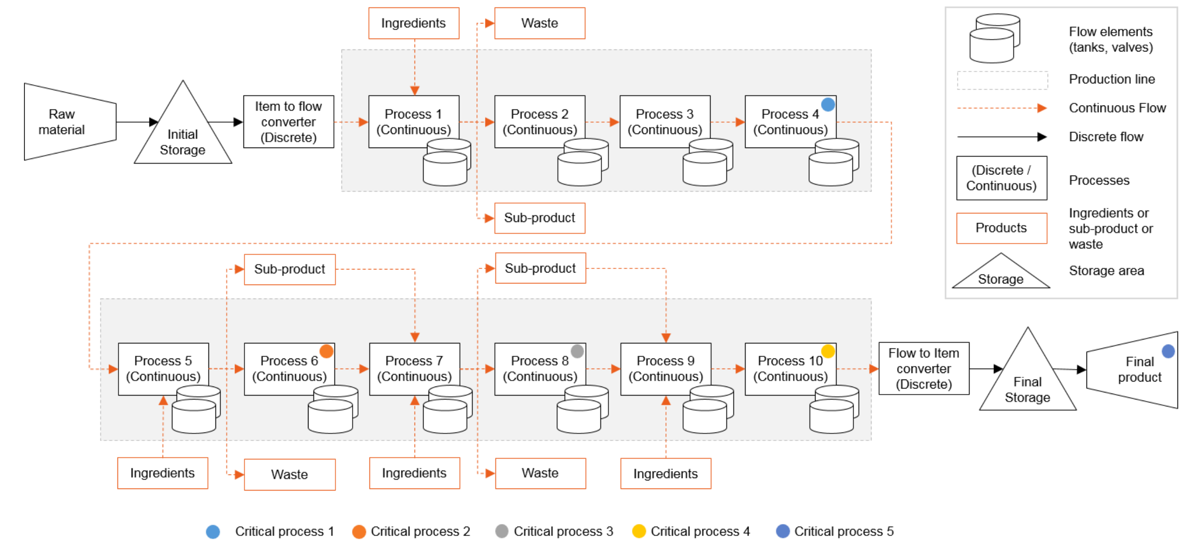

Figure A.1. Conceptual diagram of the discrete and continuous processes developed in Simio®

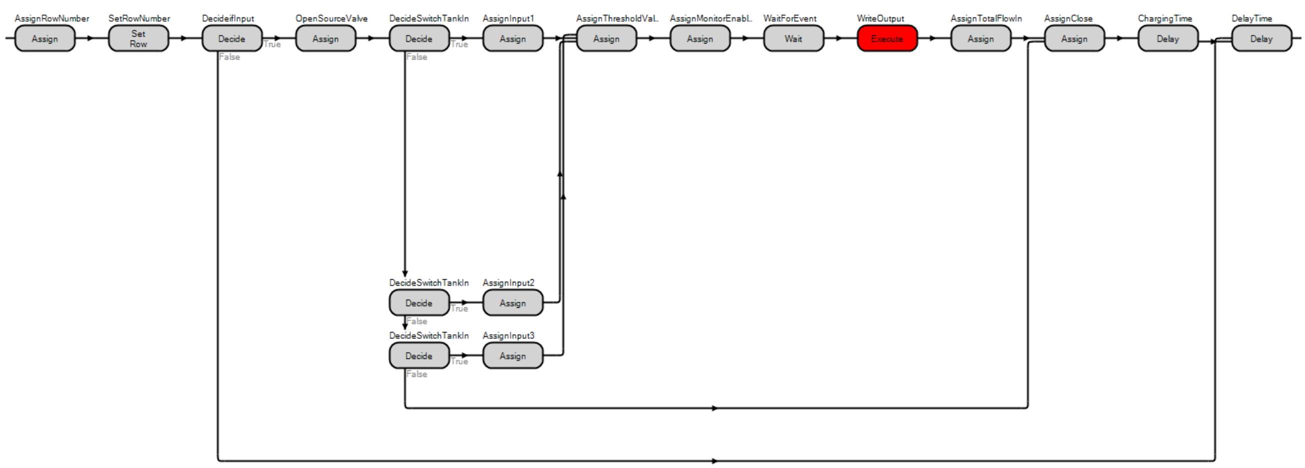

Figure A.2. Internal logic for charging and processing operations developed in Simio®

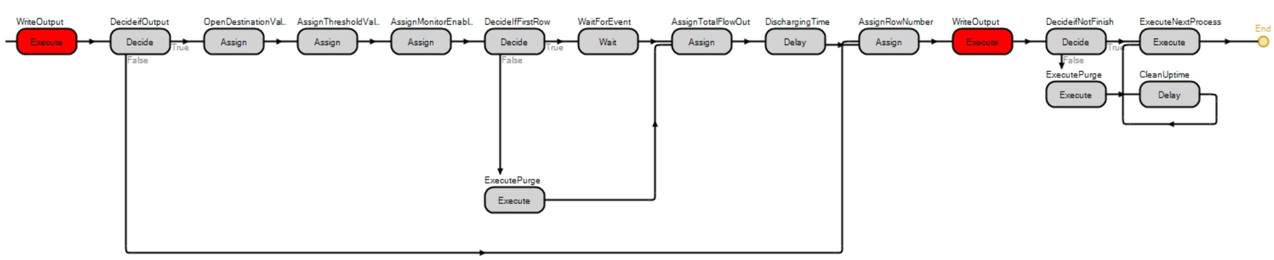

Figure A.3. Internal logic for processing and discharging operations developed in Simio®