Simulation-Aided Production and Operations Scheduling for Food and Beverage Plants

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Abstract

Establishing an optimal production schedule for a food or beverage plant is a challenging task. The best lot sequencing and sizing must be developed considering the multitude of products, packaging formats and filling lines capacities and cleaning constraints. This paper demonstrates how a discrete events simulation model of a dairy plant has been developed to represent milk pasteurizing, holding and filling processes. The model was designed with and validated by dairy technology experts, process engineers and production coordinators. The goal was to create a tool to support: selection, sizing and validation of new equipment, de-bottlenecking of ongoing operations, optimization of total operating time, and elimination of undesired waiting times. The strength of this model is to capture most of the multidisciplinary planning team know-how; a person could generate a quasi-optimal schedule in a short amount of time. The model helped in reduction of waiting and changeover times, estimation of additional volumes that could be accommodated and also supported an important plant expansion study. Capitalizing on the fact that the simulation and its results were consensual, the project team used it as a risk assessment tool.

Keywords
Plant capacity model; schedule optimization; discrete events simulation; performance optimization

1. Introduction

This paper presents the challenges that reside in food and beverage production plants with a particular emphasis in scheduling multiple products, packaging formats and filling lines. The high number of possible lot permutations and all constraints to be considered rapidly exceed human brain capacity, even for the most experienced planner. To confront this endeavor, simulation has been introduced to support scheduling. Various modeling approaches (continuous, dynamic, Monte-Carlo and equation-based simulation) with different scopes and objectives have been used (Havlik et al., Higgins, Huda and Chung, Marin et al., Schleiminger and Deselaers, Siprelle and Phelps, and Tomasula et al.).

In addition to the simulation approach, other analytic tools such as multi-objective optimization (MOO) and multi-criteria decision making (MCDM) have been utilized in the food industry (Mobin et al., Dupuy et al., Rong et al.). Considering the fact that no model was available in the application context, the MOO and MCDM approaches have been reserved for future developments when a mathematical representation of operations is available. Emphasis of the current research works was put on developing a reliable simulation model of actual operations.

Using a simulation model to support scheduling activities can serve different intentions or objectives such as: selection, sizing and validation of new equipment, de-bottlenecking of current ongoing operations, optimization of total operating time, elimination of undesired waiting times, support to continuous improvement initiatives, and increase plant Overall Equipment Effectiveness (OEE) The strength of a simulation based approach is that one model captures most of the multidisciplinary planning team (production coordination, sales, engineering, maintenance, etc.). Computers calculate faster than human with minimal risk of error.

Presented is the simulation approach based on Discrete Event Simulation (DES). Its capability to represent food and beverage plants has already been demonstrated (Higgins, Huda and Chung, and Schleiminger and Deselaers). DES is suited for batch processes, schedule-based production, and modeling of task-oriented and constrained systems that are common in agrifood. A suite of tools has been designed and developed to address the inter-related optimal scheduling and equipment selection problems.

This paper will detail the general complexity of production planning, with an emphasis on a dairy plant. A dairy plant is used but the approach can easily duplicate any industry. It will be followed by a description of the simulation model that was developed to capture this complexity and to automate the planning process. Finally, the application of the tools on three typical scheduling-centered tasks will be used to illustrate the usefulness of simulation-aided scheduling to support equipment selection and sizing for a dairy plant expansion study.

2. Production planning and its complexities

The difficulty of establishing an optimal schedule for a food or beverage plant arises from the combination and interaction of products, equipment, cleaning, regulatory and site specific constraints. For the dairy industries, planning production requires consideration of:

- Products: allergens, color, flavor, acidity, viscosity and suspended solids characteristics, flow rates;
- Fillers: allowed product families, packaging formats, daily operation shifts, cleaning and changeovers;
- Orders: interactions between cold storage space limitations, lot sizes, production days, shelf life;
- Shipping: impact of truck arrivals and loading times variability, pallets staging, traffic on site.

The items above are only the tip of the iceberg. To make sure fillers will not wait for product availability, holding tanks must be carefully managed. This means they have to be cleaned, selected and filled on time. Food preparation may involve reception, inspection, preparation, maturation, fermentation, and pasteurization; these processes have to be planned to avoid creating delays downstream at the filling lines.

Equipment availability is also affected by: cleaning cycles and queuing for CIP (cleaning-in-place), valve cluster configurations, preservation of aseptic conditions, empty cases feeding lines, palletizers, etc. Moreover, it is common that plants be constructed in several phases; the tie-in between all processes and building expansions can also add constraints and limitations.

The days when farmers simply pasteurized cow milk and packaged it in single format glass bottles before horse-drawn carts are long time gone. Having computerized tools to facilitate and accelerate the production scheduling process is crucial for modern food and beverage business as cows' milk production does not shut down on holidays and/or maintenance shut downs.

3. Modeling plant capacity

The base component of a production schedule optimization strategy is a plant capacity simulation. Such simulation usually implements mass balance calculations, execution of schedules, and impacts of all significant production constraints. The simulation results can rapidly provide information on the feasibility of scenarios, a scenario being a modification to equipment or a tentative schedule. This section presents the model that was developed for the dairy plant expansion study.

3.1. Simulation approach

The Discrete Rate Simulation (DRS) approach to represent the dairy plant process is used in this example. DRS is an extension to traditional Discrete Events Simulation (DES). With DES, simulation evolves from one event to the next one. An event typically represents process cycle time starts and ends, items in motion, vehicles/operators arrival, travel and departure, machine failures and scheduled activities.

With DRS, bulk materials and liquid flows are considered. Between two events, flow rates are assumed constant. At an event, a mass balance is performed; transferred quantities are calculated. Flow system events can be: tank reaching empty, target or full marks, batch process cycle steps, valves opening or closing, etc., in addition to all events related to traditional DES. The DRS technique has been described extensively in previous works (Béchard and Côté, Damiron and Nastasi).

3.2. Model inputs

The scope of the plant capacity model covered critical systems related to pasteurizing, milk holding in tanks and filling/packaging. Equipment cleaning and product/package changeover procedures were modeled since they have a significant impact on productivity. Preparation of ingredients, handling of cream and wastes, and handling of pallets were not considered in the model as these systems are generally not the bottleneck in the plant when compared to pasteurizing and filling systems.

Modeling tools were developed such that users can put into an Excel file all parameters describing: product characteristics: (milk formulations, packaging formats, product routing in equipment), equipment specifications (pasteurizers, tanks, fillers, clusters and CIP capacities, efficiencies, flow rates, cleaning times and rules, daily shift schedules), and weekly demand (expected daily volumes for each product).

Input file was enriched with Excel VBA macros to ease generation of production orders for fillers and pasteurizers. These macros acted as production planners; they established a weekly schedule based on rules and constraints inspired from personnel's knowledge of the plant. The result was a set of production sequences (day, product, volumes) for all fillers and all pasteurizers. These sequences are likely sub-optimal but can be used as a valuable and informed initial guess.

3.3. Model content

The model implemented in Flexsim (Flexsim) all the logic required to parse input parameters from Excel, translate production sequences into simulation tasks, calculate production times and produce results. For representation only, a screenshot from the model window is presented in Figure 1. Visual aids in Figure 1 that help examining and understanding the evolution of weekly production: vertical red bars beside equipment illustrate current content or remaining lot quantity; green boxes denote cleaning states and yellow boxes denote changeover states; tanks are grouped by category (pasteurized, aseptic, fine filter, etc.) with size indicating real life dimensions. Green and yellow lines show active flows between equipment.

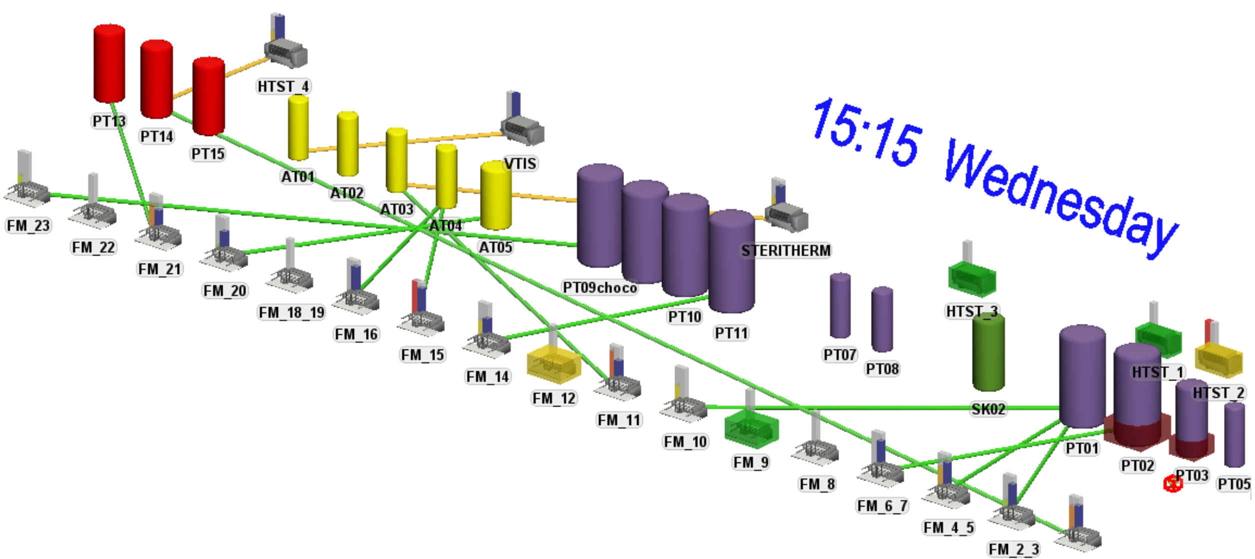

Figure 1. Screenshot from model window

Common pasteurizing modes have been implemented with the possibility to sort, split and switch between production lots in order to maintain adequate levels in tanks. A complex decisional process with predictive features carried out the task of dynamically selecting the most desirable holding tank (considering immediate and upcoming orders). The model also implemented automatic determination of cleaning and changeover times based on dynamic conditions and product versus previous product dependencies. Management of CIP queuing and cleaning of valve clusters constitutes other important features.

3.4. Model outputs

From the simulator, it was possible to export the result table. They included information such as: percentage of scheduled orders completed on time, equipment daily utilization time (Figure 2, total operating time per day for all equipment on a 24 hours basis with color legend based on percentage of total time: red if >85%, yellow if >60%, green otherwise), weekly utilization rates with breakdown, volumetric cream balance, empty cases consumption and loaded pallet releasing rates (Figure 3, number of full pallets released every 1 hour of operation), and trend chart on number of batchers in use.

Day:	1	2	3	4	5	6	7
HTST_1	8.4	9.9	8.2	9.4	7.9	10.5	9.9
HTST_2	5.1	13.7	11.6	13.9	16.0	15.0	12.1
HTST_3	4.4	9.6	12.4	13.5	12.8	10.1	7.3
HTST_4	6.9	12.9	3.9	12.3	10.9	9.0	10.1
STERITHERM	17.2	13.6	18.8	18.0	16.3	18.0	8.5
VTIS	6.5	16.0	5.7	15.9	13.5	14.7	9.1
FM_0_1	0.0	15.9	7.8	17.2	12.6	14.5	15.6
FM_2_3	0.0	15.9	16.0	17.5	19.0	17.7	19.8
FM_4_5	0.0	13.2	14.6	17.0	19.3	17.7	20.0
FM_6_7	0.0	12.7	7.0	12.9	12.4	15.3	19.5
FM_9	0.0	11.5	8.9	10.2	14.5	8.6	14.7
FM_10	0.0	19.2	0.0	15.3	11.2	13.4	15.4
FM_11	22.4	14.7	8.2	22.1	18.7	16.4	24.0
FM_12	0.0	16.3	5.8	13.9	14.0	11.0	12.5
FM_14	0.0	18.0	14.2	20.6	16.4	17.3	19.0
FM_15	0.0	6.8	0.0	6.2	6.5	5.7	0.0
FM_16	0.0	11.5	0.0	11.6	10.4	11.3	0.0
FM_20	16.6	20.6	15.5	22.6	19.8	18.8	23.7
FM_21	9.7	14.8	13.6	21.7	16.7	18.0	13.5
FM_22	0.0	7.5	0.0	6.5	6.5	8.4	4.1
FM_23	20.4	20.4	22.7	21.1	23.8	22.9	19.3

Figure 2. Daily operating time report in Excel

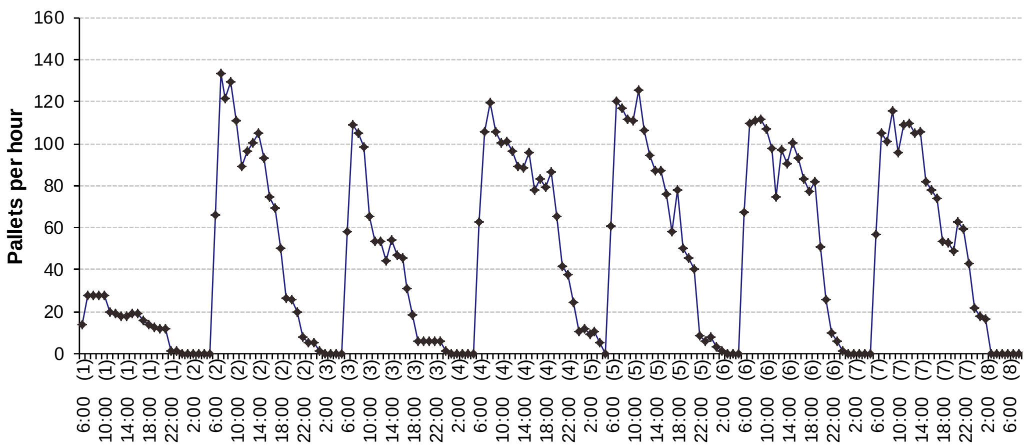

Figure 3. Released pallets trend chart

Additionally, results included the effective operating schedule, a Gantt-style chart illustrating each machine's mode during the entire week at 15 minutes intervals; Figure 4 gives a sample. The effective schedule differs from the one in the input files since it includes waiting and idle time as experienced by equipment during simulation. This was the most relevant simulation output: process experts used it to identify production bottlenecks and revise schedules to alleviate them.

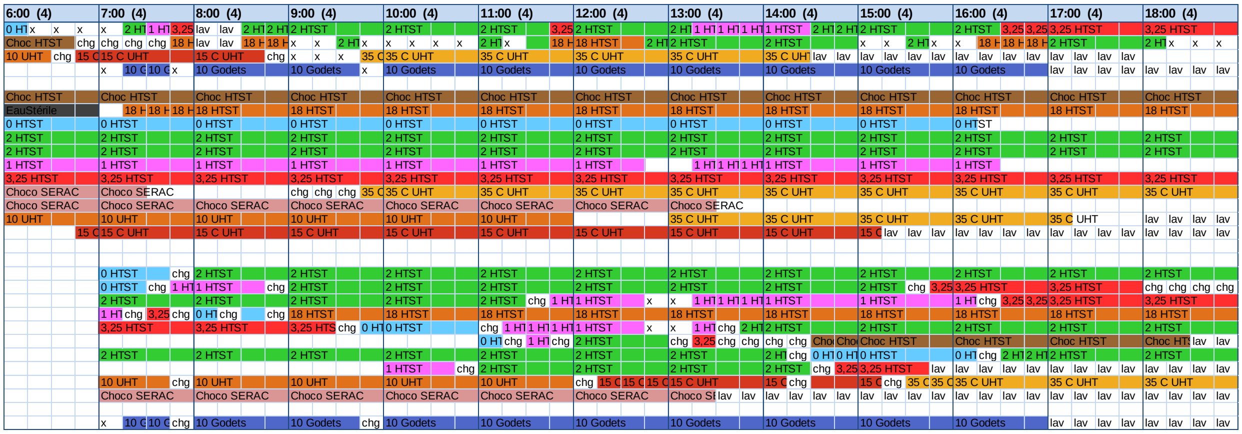

Figure 4. Effective schedule obtained by simulation
(See Appendix for a full page version)

3.5. Verification and validation

This model has been developed with the help of dairy technology experts, process engineers and production coordinators. Data and operating logic have been obtained during floor surveys and extracted from planners' logbooks. The development team verified and approved all input parameter values and model behavior in the simulator. Outputs have been analyzed for calculation accuracy soundness. Real past production weeks have been simulated and compared to historical performance. Since model results were close to real values, the model was considered to be a valid representation of the dairy plant capacity.

4. Designing and scheduling with simulation

The overall objective of production planning is to ensure that all customer orders are fulfilled on time with optimal utilization of available equipment capacity. There are three inter-related questions to be addressed simultaneously:

- What is the required equipment (and capacity)?
- What is the maximum volume that can be accommodated?
- What is the optimal production schedule?

The following sub-sections illustrate how plan capacity simulation can be used to provide answers.

4.1. Schedule optimization strategy

This is the fundamental exercise for which all developed tools were designed. The assumption is that equipment specifications, product characteristics and weekly demand (products volumes of all products for each due day) are known. Then, the scheduling task consists of establishing the sequence in which all orders have to be fulfilled. The decisional algorithm established to combine process expertise and computerized tools in order to optimize production schedules is presented in Figure 5.

With the dairy plant example, the first iteration consisted in generating a baseline feasible schedule. Simulation results indicated that the weekly machine-hour (sum of operating hours for all fillers and all days) was 1,078 hours. By progressively rectifying filling and pasteurizing sequences as explained on Figure 5, the required weekly machine-hour decreased to 840 hours. Equipment specifications, cleaning procedures and cycle times were kept unchanged. Only by reorganizing production sequences, waiting and changeover times were reduced by 28%. The whole scheduling exercise required 3 hours by one person for a gain of 28% more efficiency.

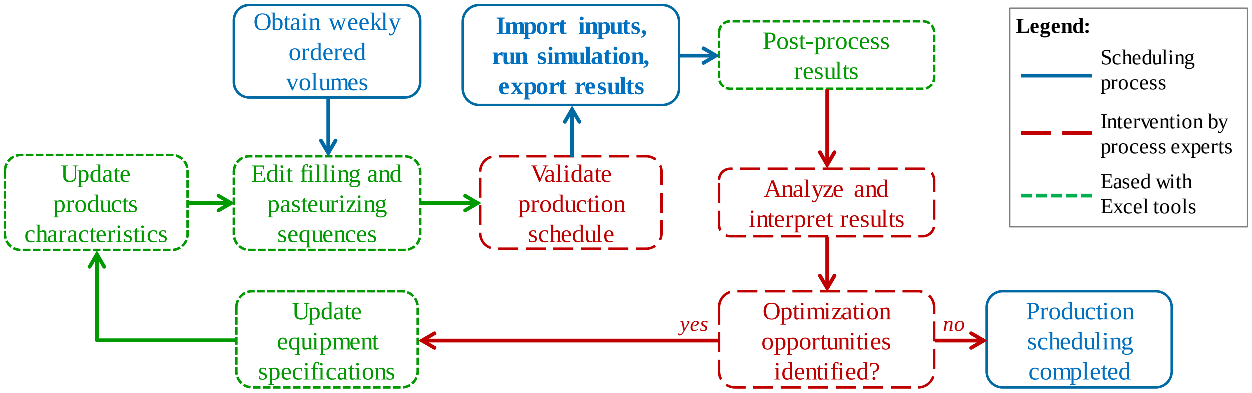

Figure 5. Simulation-aided optimal scheduling workflow

4.2. Increase or re-schedule volumes for given equipment set

This situation is typically met when marketing wants to sell promotional volumes to grocers, when a customer suddenly asks for larger quantities, or when a disturbance prevents some or all fillers from working. As a consequence, the usual scheduling pattern has to be revised quickly, sometimes during the week when scheduling team members are not available. The strategy in Figure 5 greatly helps managing these situations.

With the dairy plant example, a frequent situation is when grocers announce chocolate milk rebates. Then, marketing has to determine how many liters can be accommodated by the plant. In the scenario of concern, marketing was expecting the plant to produce 100,000 L and was looking to outsource an extra 50,000 L. Working for approximately 1 hour with the simulation tools during a meeting, the person responsible for scheduling discovered that at least 180,000 liters could be accommodated by the plant during the target week.

4.3. Add or modify equipment and volumes simultaneously

This is the typical challenge of plant modernization or expansion engineering studies. The equipment selection and sizing issues must be addressed simultaneously with the question “What is the new plant capacity”? In these situations, there is usually no reference point or comparable situation from which schedules can be adapted.

The simulation-aided technique presented in this paper can greatly reduce the time required to answer these inter-related questions. Modification to assumptions and sensitivity analysis are easily estimated using the model and contribute to risk attenuation initiatives. Simulation results provide valuable justifications to support expensive capital expenditures.

With the dairy plant example, a major plant expansion was being studied; the result would be to increase capacity by 85%. The “easy” tasks were to select the new fillers and the number of pasteurizers: additional volumes and packaging formats were known. The challenging tasks were to determine the required pasteurizer flow rates, and number and capacity of additional holding tanks. All alternatives were required to have a feasible and realistic schedule to ensure operations feasibility.

The simulation-aided scheduling strategy streamlined project team efforts, allowed examining 3 times more scenarios than planned by project managers, and provided consensual results that helped estimating accurately capital and operational expenditures.

5. Conclusions and future works

To address the production planning complex challenges, a simulation model was developed to represent and analyze operations. The strength of a simulation based approach is that one model captures most of the multidisciplinary planning team. The model was built to support these activities: selection, sizing and validation of new equipment, de-bottlenecking of ongoing operations, optimization of total operating time, elimination of undesired waiting times, and support to continuous improvement initiatives.

This simulation-aided scheduling approach demonstrated its capability to assist planners. It helped identifying important reduction in waiting and changeover times, estimating additional volumes that could be accommodated, and supported an important plant expansion study. Capitalizing on the fact that the simulation and its results were consensual, the project team used it as a risk assessment tool.

Potential extensions to this model could be to include finish product pallets handling system, cold storage constraints and shipping truck loading. Another avenue to explore should be the application of black box optimization approaches such as popular genetic algorithms or simulated annealing to optimize further schedules by reducing the involvement of process experts. Integration to Daily Management System (DMS) technologies is another potential development that would benefit to operations.

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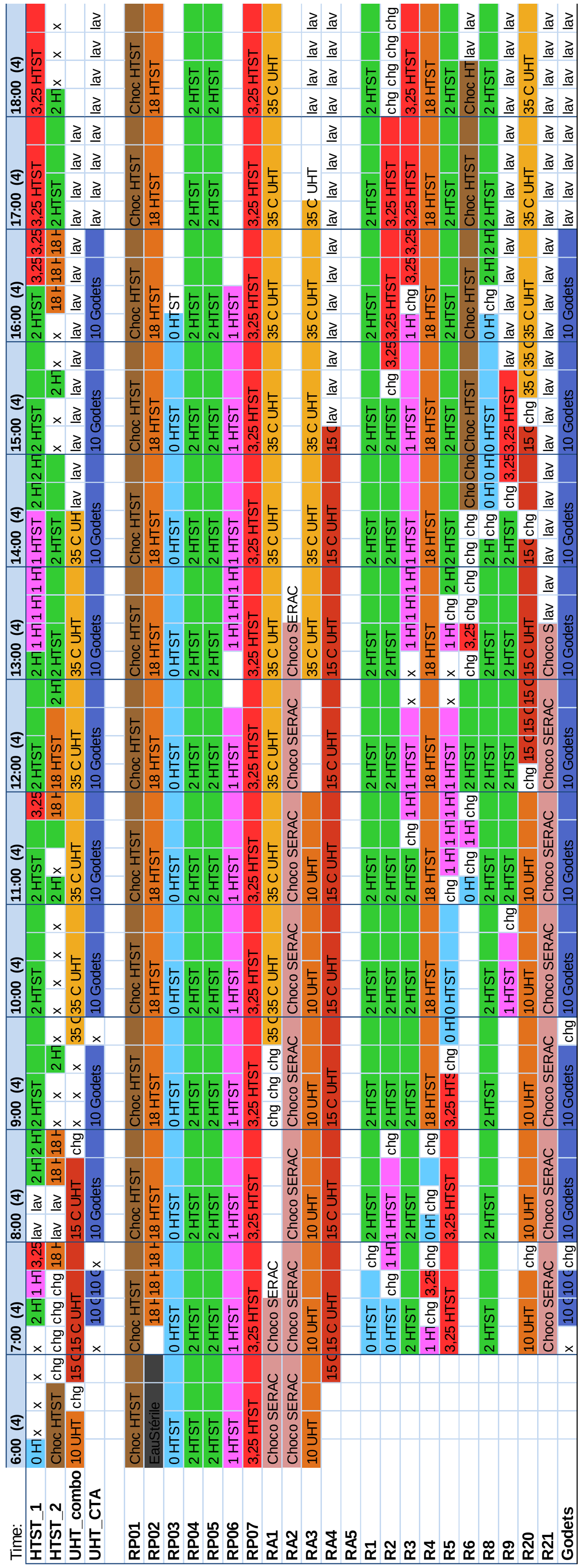
Appendix

Full page version of Figure 4.



Biography

Vincent Béchard, P.Eng., MASc., has more than 12 years of experience in modeling, simulation and optimization of industrial operations. His skills and competencies in applied mathematics include statistical data analysis, design of advanced scientific applications, discrete event simulation, black-box optimization and Lean Six Sigma in various contexts. He is familiar with parts and material handling, operations and traffic, reliability and maintenance, logistics and production scheduling. His diversified experience made him explore aluminum, iron, copper, gold and nickel ore, as well as potash and phosphate, manufacturing of food and beverages, baggage handling, pharmaceutical and pulp & paper industries. Mr. Béchard holds a Bachelor's degree in Chemical Engineering and a Master's degree in Applied Mathematics from École Polytechnique de Montréal (Canada).

André Saidah, P.Eng., has over 20 years of experience as a senior project manager for a Tier-1 global Engineering and Construction firm, and his work experience has had particular emphasis in Agrifood, Pharma and Biotech industries. His knowledge and expertise ranges from concept development to operations. Over the years, he has continuously applied his know-how to plant optimization, plant designs—from greenfield projects to start-up in all engineering disciplines—equipment layouts, lean manufacturing, and production throughput optimization. André holds a Bachelor's degree in Mechanical Engineering with a specialization in Automation and Robotics from McGill University (Montreal, Canada).