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Executive Summary of the Thesis

Optimal Design of Multiple-Effect Evaporation for Tomato Paste: A Techno-Economic Approach Supported by Digital Twin Simulation

Laurea Magistrale in Food Engineering

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1. Introduction

This thesis focuses on the production of tomato paste, a concentrated tomato product used worldwide in sauces, soups, and other foods. Tomato paste production typically includes a pretreatment stage: grading, washing, sorting, and mechanical breaking (cold- or hot-break), followed by concentration through evaporation. Hot-break processing (82–93 °C) helps preserve pectins, improving the viscosity and stability of the paste [1]. The extracted juice is concentrated in vacuum evaporators, increasing soluble solids to 24–38% while removing about 50% of water. For final packaging, the paste is hot-filled at a minimum of 90°C into cans [1]. Beyond their culinary value, tomatoes contain bioactive compounds that strongly influence product quality:

- **Lycopene**, a red carotenoid with antioxidant properties. It remains relatively stable during hot-break processing but can decrease by 20% during multi-stage evaporation and sterilization, highlighting the importance of oxygen control and optimized conditions.
- **Pectin**, which affects viscosity and texture. It degrades under prolonged heating; rapid processing helps preserve it for a thicker, more stable paste.
- **Ascorbic acid (vitamin C)** enhances freshness and oxidative stability but is highly sensitive to heat and oxygen, with losses up to 44%; vacuum evaporation and short residence times reduce degradation.

High product quality depends on processing conditions, affecting viscosity, flavor, nutritional value, and lycopene bioavailability [5]. Evaporation is typically conducted under vacuum to minimize thermal degradation, using steam as the heating medium. To improve energy efficiency, **multiple-effect evaporators** are used, where vapor from one effect heats the next, reducing steam consumption. This study focuses on a **forward-feed (equicurrent)** configuration, in which both product and steam flow in the same direction, starting from the first effect operating at the highest temperature and pressure. This thesis includes a cost analysis of the multistage evaporation process, considering both **Capital Expenditures (CapEx)**, which cover long-term investments such as machinery and infrastructure, and **Operating Expenditures (OpEx)**, which include ongoing costs like energy, materials, maintenance, and labor. Balancing CapEx and OpEx is crucial:

for tomato paste production, adding more evaporation effects reduces steam consumption, lowering OpEx, but also raises CapEx due to additional equipment. The total lifetime cost, combining CapEx and cumulative OpEx, provides a key metric for evaluating the economic feasibility of different configurations.
The food processing industry is complex and diverse, facing challenges such as evolving consumer expectations, product customization, and sustainability concerns. Advanced technologies and digital solutions are increasingly shaping this landscape. In particular, the **Digital Twin (DT)**, a concept linked to Industry 4.0, offers a dynamic virtual representation of a physical system [3]. Continuously updated with real-time data, a DT enables monitoring, prediction of future behaviors, and informed decision making, going beyond static models to support process optimization on multiple time scales. This thesis contributes to this field by exploring the application of DT technology in smarter food manufacturing, with a specific focus on the multi-effect evaporation process for tomato concentrate production. By developing and validating a DT model in AVEVA Dynamic Simulation software, this work investigates not only steady-state and economic performance, but also the dynamic behavior of the process during start-up and shut-down operations. The results aim to demonstrate how such models can support process understanding, control, and optimization in a modern, data-driven industrial environment.

2. Materials and Methods

The methodology begins with the definition of the feed composition, as it directly influences the thermodynamic and physical properties relevant to the process. The multistage evaporation system is then modeled through mass and energy balances for a range of one to five evaporation units with the objective of determining the optimal number of effects by means of an economic analysis. Once identified, the ideal configuration is simulated in AVEVA Dynamic Simulation software, focusing on start-up and shut-down procedures.

2.1. Feed Composition

Tomato juice is mainly composed of water, with small amounts of carbohydrates, proteins, and bioactive compounds such as lycopene, pectin, and vitamin C. These compounds affect nutritional value, sensory attributes, viscosity, and susceptibility to thermal degradation, making precise control of processing conditions essential [5].
Since several constituents (e.g., fat, pectin, lycopene, vitamins A, B1, B2, B3, and folate) are not available in the AVEVA component library, they are introduced as **pseudocomponents**. Each component is characterized by key physical properties such as molecular weight, density, and normal boiling point, enabling a realistic yet consistent representation of the tomato concentration process.

2.2. Data and Problem Setting

The multi-effect evaporation system processes a feed stream L_0 of 50,000 kg/h at $T_{l0} = 90\,°\mathrm{C}$, reflecting hot-break pretreatment that preserves pectin and viscosity. Heating steam enters the first effect at $T_{v0} = 129\,°\mathrm{C}$ and $P_{v0} = 260$ kPa [2]. To simplify the analysis, some assumptions are made: all effects have equal heat transfer area of 209 m^2 [2], the tomato juice/paste in the evaporator is assumed to be completely mixed, tomato juice specific heat is constant ($c_p = 1.17$ kcal/kg/K), steam flow is treated as a manipulated variable, and no heat losses are considered. A schematic representation of the process is provided in Figure 1, offering a visual overview of the system layout.

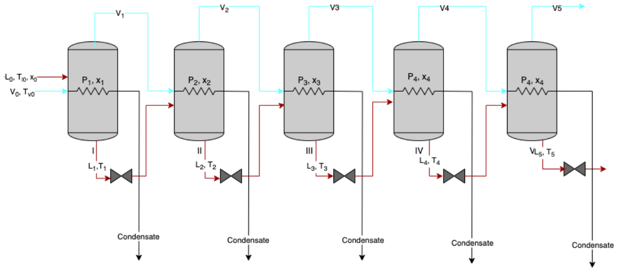

Figure 1: Schematic of the multi-stage evaporation process.

2.2.1 Design Methodology

The design is performed sequentially for each effect, applying heat transfer relations, boiling temperature calculations, and mass and energy balances. Solute concentration is tracked step by step, while boiling point elevation and vapor pressure are estimated using empirical correlations. The procedure is iterated until overall mass balance convergence is achieved:

$$F_{\text{obj}} = V_{\text{tot,spec}} - V_{\text{tot,calc}} \to 0 \qquad (1)$$

ensuring that the calculated vapor flow ($V_{tot,calc} = \sum_{i=1}^{5} V_i$) matches the specified requirement $V_{tot,spec}$ of 40955.76 kg/h.

2.3. Cost Analysis

Cost estimation is fundamental to evaluate both technical feasibility and economic viability of the evaporator system. In this work, only the major contributions are considered: capital expenditures (CapEx) for the equipment and operating expenditures (OpEx) for the steam consumption, while construction, maintenance, and contingencies are neglected.

CapEx is calculated from empirical correlations that relate equipment size to cost, corrected with the bare module and pressure factors [4]. To reflect current economic conditions, values are updated from 2001 to 2024 using the Chemical Engineering Plant Cost Index (CEPCI), increasing the accuracy of the investment estimate. The total capital cost is then obtained by scaling with the number of evaporator effects. OpEx focuses on the steam demand, which represents the dominant running cost in evaporation systems. It is estimated from the annual operating time (around 1,680 h/year, corresponding to the tomato processing season), the plant lifetime (15 years [2]), and a unit steam price of 0.03 $/kg [4]. Finally, the total cost of each configuration is obtained as the sum of CapEx and OpEx, providing a straightforward indicator for identifying the most cost-effective number of effects.

2.4. Packaging Heat Exchanger

In addition to the evaporator system, a heat exchanger is required to raise the product temperature from 50 to 90 °C for hot filling. The vapor stream V_0 leaving the first effect is used as heating medium, ensuring energy recovery within the process. This step illustrate a possible energy recovery for the downstream filling operation and is not implemented in AVEVA Dynamic Simulation. The heating duty is obtained from the product flow rate, specific heat, and target temperature rise; while the heat exchange area is determined from the duty, the assumed overall heat transfer coefficient, and the log mean temperature difference. Based on these considerations, a double-pipe heat exchanger is selected. For cost estimation, the same methodology adopted for the evaporators is applied, using empirical constants specific to double-pipe exchangers [4].

2.5. The Digital Twin

Following the identification of the most cost-effective setup, a Digital Twin of the evaporation system was implemented in AVEVA Dynamic Simulation. The model reproduces the physical and thermodynamic behavior of the plant, enabling steady-state and dynamic analyses to support process control and operability studies. The simulation environment includes sources (tomato feed, steam, nitrogen for initialization) and sinks (concentrate, solvent vapor, condensates). Each effect is represented by a heat exchanger and a flash drum, dimensioned using a residence time criterion to balance heat transfer efficiency and product quality. Valves regulate feed, steam, liquid, and vapor flows, while PID controllers maintain flow, temperature, liquid levels, and pressures across the effects. This framework ensures stable operation, allows testing of start-up and shut-down procedures, and provides a safe platform for control tuning and "what-if" scenarios.

2.6. Dynamic Scenarios: Start-Up and Shut-Down Procedures

Two dynamic scenarios were implemented in DynSim to evaluate transient operations: start-up and shut-down. In the **start-up**, the system is pre-heated with steam before admitting feed, avoiding thermal shocks and ensuring stable boiling. The steam valve is partially opened for initial warming, then progressively adjusted together with the gradual feed introduction. Once the first effect reaches the target temperature, controllers switch to automatic mode and the process stabilizes within minutes. In the **shut-down**, the feed and steam inlets are closed, controllers switched to manual mode, and the outlet valves opened to drain the drums. The procedure is completed once liquid levels fall below a predefined threshold, ensuring safe emptying and readiness for maintenance or restart.

3. Results

This section first examines economic data to determine the optimal number of effects in the multi-stage evaporation process by balancing capital and operating costs. A sensitivity analysis then assesses the impact of key input variations, ensuring the robustness of the selected configuration. Finally, system dynamics are examined through simulation on AVEVA Dynamic Simulation software, focusing on temperature, pressure, and liquid level changes during transient conditions, with particular attention to start-up and shut-down phases to evaluate stability, control requirements, and operational performance.

3.1. Cost Analysis Results and Optimal Number of effects

A key design decision in multi-effect evaporator systems is selecting the optimal number of effects, which influences both capital and operating costs. While adding effects reduces steam consumption and operating expenses, it requires higher investment. To evaluate this trade-off, five configurations (one to five effects) are analyzed, with the cost results summarized in Table 1.

Table 1: Economic Evaluation of Multi-Effect Evaporator Configurations

Effects	CAPEX [M USD]	OPEX [M USD]	Total Cost [M USD]
1	2.46	25.69	28.16
2	4.93	12.97	17.90
3	7.39	8.72	16.11
4	9.86	6.61	16.47
5	12.32	5.36	17.69

The total cost reaches a minimum at three effects, indicating that the **three-effect evaporator** is the most cost-effective option.

Table 2 summarizes the key parameters of the three-effect configuration, including outlet liquid, vapor flow, temperature, pressure, and solid content. As expected, the boiling point elevation increases along the process due to the rising solute concentration. Since the system operates under vacuum, the pressure decreases from the first to the third effect, accompanied by a corresponding temperature drop that helps preserve product quality.

Table 2: Summary of key operational parameters for the three-effect evaporator

Parameter	1st Effect	2nd Effect	3rd Effect
Feed / Outlet L [kg/h]	50,000 / 37,987	37,987 / 24,099	24,099 / 9,044
Vapor V [kg/h]	12,013	13,888	15,054
Temp T [°C]	95.6	71.5	49.0
Solids x [kg/kg]	0.066	0.104	0.276
Pressure [atm]	0.855	0.328	0.116

A sensitivity analysis is carried out to assess the robustness of the three-effect configuration. Varying feed flow rate and evaporation targets shows that three effects remain optimal in most scenarios. Only extreme conditions (-60% or $+40\%$ feed variation, or very high evaporation targets) shift the optimum to two or four effects. Overall, the three-effect design proves robust under typical operating conditions, with sensitivity only to substantial deviations.

3.2. Start-up and Shut-down Scenarios Results

This section summarizes the dynamic behavior of the three-effect evaporator during both start-up and shutdown. During start-up, the system progressively reaches stable operating conditions. Temperature, pressure, and liquid levels stabilize within 30 minutes, while the fresh steam supply requires about nine hours to settle at its steady-state flow of 11,500 kg/h, reflecting thermal inertia and gradual control response. Figure 2 shows the sequential thermal activation of the three effects, with steady-state temperatures (96 °C, 72 °C, 49 °C respectively) achieved within 15 minutes. Figure 3 illustrates the progressive pressurization under vacuum, where pressures decrease and stabilize after initial fluctuations, ensuring efficient evaporation and product quality preservation. Figure 4 highlights the evolution of liquid levels: initially zero during pre-heating, then rising sequentially with feed introduction, and finally stabilizing at 3 m in all effects after approximately 30 minutes, confirming steady operation. During shutdown, starting from steady-state operation, the controlled drain-down procedure safely isolates the steam and tomato feed by closing the inlet valves, while fully opening the bottom outlet ones to sequentially empty each evaporator. Figure 5 shows the temperature evolution: the first effect cools gradually, then more sharply, briefly rising due to residual steam before stabilizing. The second and third effects remain near steady-state temperatures until drained, after which both cool progressively to 47 °C. Figure 6 illustrates pressure trends: closing steam and feed valves while opening drains causes pressures to drop, with all effects stabilizing at low levels, confirming safe and complete depressurization. Figure 7 depicts liquid levels: the first effect drains rapidly, the second shows a brief increase due to residual inflow before gradually emptying, and the third drains more slowly at first, then more quickly as preceding stages empty. Complete drainage is achieved within 12–16 minutes without oscillations or hydraulic transients, confirming that the system transitions safely to a fully deactivated state suitable for maintenance or subsequent restart.

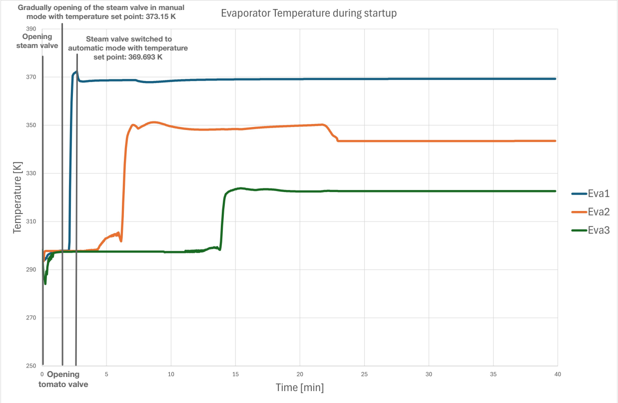

Figure 2: Dynamic temperature evolution in the three evaporators during start-up.

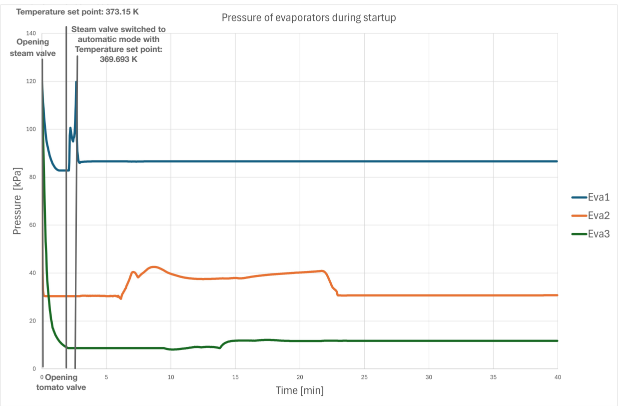

Figure 3: Dynamic pressure evolution in the three evaporators during start-up.

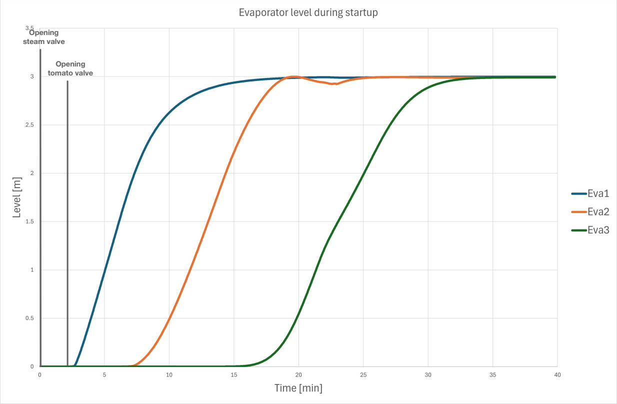

Figure 4: Dynamic evolution of liquid levels in the three evaporators during start-up.

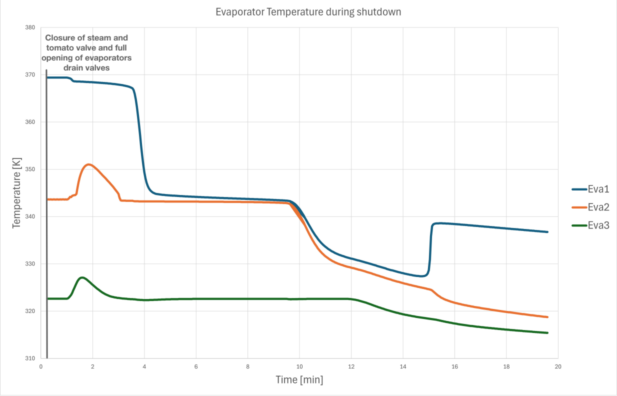

Figure 5: Dynamic temperature evolution in the three evaporators during shutdown.

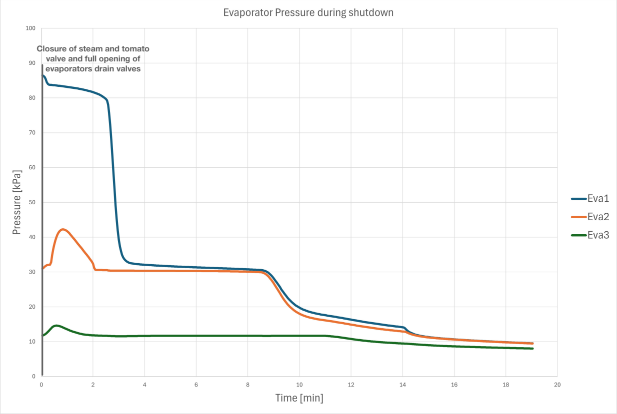

Figure 6: Dynamic pressure evolution in the three evaporators during shutdown.

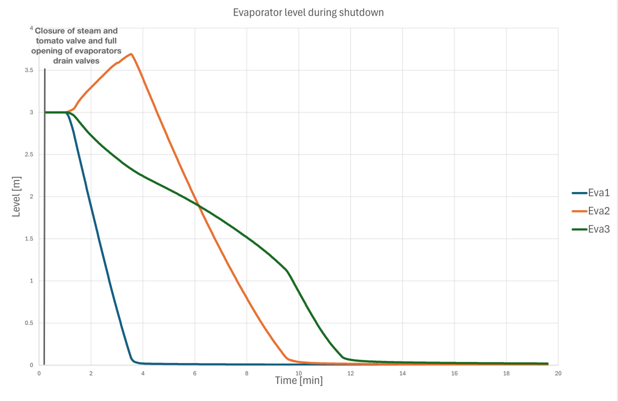

Figure 7: Dynamic evolution of liquid levels in the three evaporators during shutdown.

4. Conclusions and Further Development

This study designs and optimizes a forward-feed multiple-effect evaporator for tomato paste production and develops a Digital Twin of the process. Among the one-to-five effect configurations tested, the three-effect system minimizes total costs, requiring a fresh steam demand of about 11,500 kg/h, evaporating nearly 41,000 kg/h of water and reaching a final product concentration close to 28% solids. The Digital Twin implemented in AVEVA Dynamic Simulation software reproduces thermodynamic behavior and control strategy during start-up and shut-down, demonstrating stable convergence of temperatures, pressures and levels. As an engineering tool, it helps reduce trial-and-error, supports controller tuning, and enables operator training and "what-if" analysis without interrupting production.

Further work should focus on reducing steam stabilization time during start-up, extending the model to upstream and downstream sections for integrated plant-wide simulation, and validating the system with industrial data. Once validated, the Digital Twin could guide optimization of energy recovery and operational setpoints. Finally, future integration with Artificial Intelligence and Machine Learning could offer advanced functionalities: physics-informed soft sensors, predictive maintenance, energy-aware supervisory optimization, and transfer learning across product lines. These steps would turn the Digital Twin into a comprehensive decision-support tool for efficiency, operability, and quality assurance in tomato processing.

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