

Design and Optimization of Supply Chain for Citrus Biorefineries: A Regional Approach for Waste Valorization in Brazil

Marília G. L. Cavenaghi^{a*}, Larissa T. Bruschi^a, and Moises T. dos Santos^a

^a University of São Paulo, Department of Chemical Engineering São Paulo, Brazil

* Corresponding Author: marilia.cavenaghi@usp.br.

ABSTRACT

Brazil is the world's largest producer of orange juice, generating significant peel residues that are currently underutilized. This study proposes a mixed-integer linear programming (MILP) framework for optimal supply chain design, utilizing Special Ordered Sets of type 2 (SOS2) to accurately represent non-linear investment costs. The model maximizes Net Present Value (NPV) by integrating production costs with multi-echelon logistics, including inland transport, port handling, and international maritime freight. Applied to a case study in São Paulo, the framework evaluates pathways for the co-production of D-limonene, pectin, and bioenergy. Results indicate a positive NPV of BRL 1.27 billion, with pectin contributing over 65% of total revenue. The optimization favors centralized configurations in Araraquara or Matão to exploit economies of scale while minimizing the transport of high-volume, wet biomass. Notably, total transportation costs represent only 1.13% of expenditures, as the high value-density of the bioproducts effectively absorbs global distribution costs. This work demonstrates that in regions with high biomass abundance, strategic success is primarily governed by process efficiency and industrial scale rather than logistical constraints, providing a robust tool for decision-making in the citrus bioeconomy.

Keywords: Supply chain optimization, biorefinery, orange peel waste, mathematical programming

INTRODUCTION

The industrial processing of oranges in São Paulo generates massive volumes of peel residues, which are typically diverted to low-value uses despite their high concentration of pectin and D-limonene. These residues support the evaluation of biorefinery concepts to improve economic performance through high-value product diversification. At a regional scale, the deployment of such systems is governed by complex trade-offs between biomass availability, conversion technologies, and market demand, requiring mathematical programming for integrated assessment.

Mixed-integer linear programming allows the explicit representation of discrete decisions, such as facility siting and technology selection, alongside continuous material flows and economic performance metrics. Such models enable the systematic evaluation of alternative network configurations and support the identification of

coordinated and economically consistent solutions for the regional deployment of citrus biorefineries [1, 2].

Recent literature has extensively explored the optimization of biorefinery supply chains within the Brazilian context, primarily focusing on the sugarcane and energy sectors. Bruschi *et al.* (2026) [3] provided a comprehensive review of MILP architectures for biomass supply chains, establishing robust modeling foundations for regional networks. Abo *et al.* (2022) [4] proposed a multi-period MILP model to manage the integrated supply chain of fossil fuels and biofuels, addressing seasonality and demand fluctuations for corn and sugarcane ethanol. Similarly, [5] developed a bi-objective MILP framework to evaluate the trade-offs between financial profit and environmental impact, identifying optimal technology configurations for the transition from sugar-only to mixed-product plants. More recently, [6] utilized robust MILP optimization to assess low-carbon ammonia and hydrogen production from ethanol and biomethane,

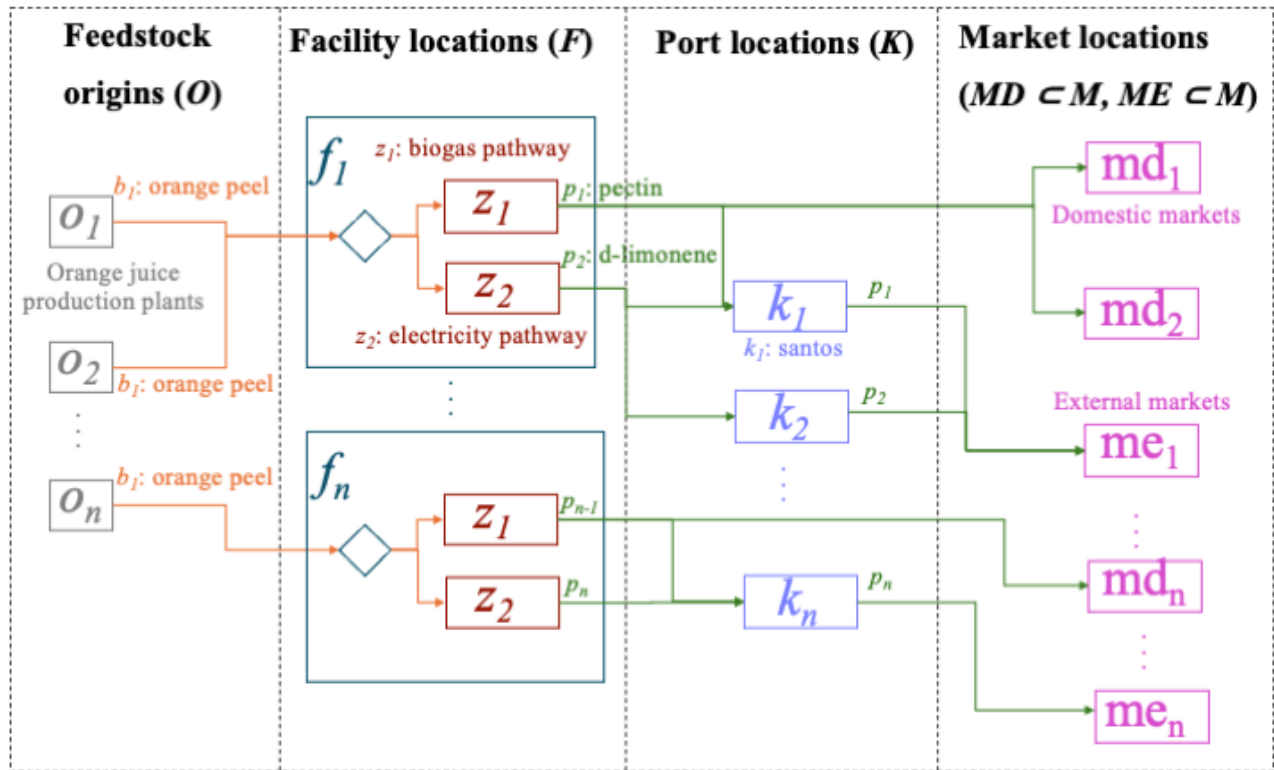


Figure 1. Schematic representation of the citrus biorefinery supply chain and associated modeling sets. Orange juice processing plants $o \in O$ generate orange peel residues $b \in B$, which are supplied to candidate biorefinery facility locations $f \in F$ for conversion through technologies $z \in Z$. Marketable products $p \in P$ are distributed to domestic market ($MD \subset M$) and external ($ME \subset M$) markets, with the latter routed via port nodes $k \in K$. Optimization variables determine facility siting, technology selection, and material flows across the network layers.

highlighting the potential for advanced transition products within existing industrial infrastructures. Although these models provide sophisticated insights into regional energy and fuel distribution, they typically prioritize domestic markets and focus on energy products or traditional sugarcane derivatives.

The proposed optimization framework integrates high-value biochemical production with residual energy valorization under a global logistics perspective. By expanding the scope beyond regional energy self-sufficiency, this model incorporates maritime freight indices and port-specific costs to evaluate citrus biorefineries as export-oriented hubs. The use of Special Ordered Sets of type 2 (SOS2) for non-linear investment costs allows the framework to assess how regional biomass density in São Paulo facilitates a strategic shift from market-oriented to feedstock-oriented configurations. This approach seeks to provide a more detailed understanding of the industrial valorization of citrus processing residues by capturing the economic trade-offs between process scale and global distribution requirements.

METHODOLOGY AND MODEL FORMULATION

A generic supply-chain-level optimization framework is adopted to analyze alternative configurations for the valorization of residues from the orange juice industry. The problem is formulated as a mixed-integer linear programming (MILP) model, designed to support strategic and operational decisions within integrated biorefinery supply chains. The formulation adopts a modular, set-based structure comprising biomass types (set B), biomass origins (set O), candidate facility locations (set F), conversion technologies (set Z), products (set P), potential domestic and external markets (set M), logistic port nodes (set K), wastes generated in conversion (set W), process inputs (set I), consumed utilities (set U), and time periods (set T). **Figure 1.** presents a schematic overview of the main components and modeling sets considered in the proposed framework.

The supply chain is represented as a multi-echelon network composed of biomass supply origins O , candidate

processing locations F , domestic markets $MD \subset M$, external markets $ME \subset M$, and port nodes K , which act as export gateways. Processing facilities and conversion technologies may be installed in selected municipalities through binary decision variables, while material flows are represented by continuous variables linking the different network layers.

Transportation costs are differentiated by the nature of the origin–destination pair and the specific logistics echelon. For biomass sourcing and domestic market ($MD \subset M$) product distribution, costs are calculated as a linear function of the distance between nodes and the transported mass, using a standardized cost-per-ton-kilometer parameter. Products destined for external markets ($ME \subset M$) are first routed from processing facilities F to port nodes K via road transport. This inland segment follows the same distance-based cost logic as domestic flows, but is supplemented by an export-specific cost layer that incorporates port handling fees and maritime freight to final international destinations. This multi-echelon formulation explicitly distinguishes between domestic and export-oriented logistics, ensuring that the model captures the economic trade-offs associated with different market allocation strategies.

Market allocation is governed by demand limits defined according to the geographic nature of the consumer nodes. For domestic markets ($MD \subset M$), demand is specified at the municipal level, reflecting local consumption. For the export segment ($ME \subset M$), demand is aggregated at representative port nodes for each destination continent. It is assumed that all products are sold within the same period, with no storage of biomass or products. This structure allows the model to capture the trade-offs between fragmented domestic supply and high-volume, port-centric export logistics

Processing capacity is modeled as a continuous decision variable and is directly associated with capital investment. Investment costs are represented using a non-linear cost function with a scaling exponent, following standard capital cost scaling principles [7]. To ensuring the representation of economies of scale within a tractable MILP framework, this non-linear investment function is approximated using a piecewise linear formulation. The approximation is implemented using Special Ordered Sets of type 2 (SOS2) [8], relying on a convex combination of discretized points. The capacity domain is discretized using log-spaced breakpoints, allowing a more accurate representation of the non-linear cost function over a wide range of capacities. Fixed operational costs are assumed to be proportional to the investment cost and are incurred over the planning horizon.

The objective function of the model is defined as the maximization of the net present value (NPV) over the planning horizon and is expressed as follows:

$$\max \text{NPV} = - \sum_{t \in T} \frac{C_t^{\text{inv}}}{(1+r)^t} + \sum_{t \in T} \frac{(R_t - C_t^{\text{op}} - C_t^{\text{tr}})}{(1+r)^t} \quad (1)$$

Where $t \in T$ denotes the time periods of the planning horizon and r is the discount rate. C_t^{inv} represents the investment cost incurred in period t , associated with the installation and capacity of processing facilities. R_t denotes the revenue obtained from product sales in period t . C_t^{op} corresponds to operating costs, including fixed and variable components, while C_t^{tr} represents transportation costs associated with biomass supply and product distribution. All cash flows are discounted to their present value using the discount rate r .

Case study: regional citrus waste valorization in São Paulo

The optimization model was applied to a regional case study focused on the valorization of orange peel generated by the orange juice industry in the state of São Paulo, Brazil. This region concentrates the largest installed orange juice processing capacity in the country and exhibits a well-defined spatial structure for biomass generation, logistics, and market access, which made it suitable for a supply-chain-level assessment of alternative biorefinery configurations.

Wet orange peel residue was assumed to be acquired directly from orange processing plants and supplied to conversion facilities without intermediate storage. The alternative valorization routes evaluated in the case study were based on the process configurations developed by [9], describe an integrated biorefinery scheme for citrus processing residues. In this scheme, orange peel is initially processed for the recovery of D-limonene and pectin. After the hydrolysis stage, a solid-liquid separation step is applied to remove residual solids from the hydrolysate prior to pectin precipitation. The resulting solid fraction, hereafter referred to as filter cake, constitutes the residual biomass directed to energy valorization.

In [9], authors propose two alternative energy valorization pathways for the filter cake generated after pectin recovery. In the first pathway, the solid residue is directed to anaerobic digestion for biogas production. In the second pathway, the same residue is routed to a gasification process followed by electricity generation. Accordingly, biogas route integrates the extraction of D-limonene and pectin with biogas production, while electricity route integrates the extraction of D-limonene and pectin with gasification-based electricity generation.

Technological parameters required to represent these routes within the optimization model, including biomass characterization, material conversion factors,

product yields, residue generation rates, and electricity consumption associated with individual process units, were obtained from the study of [9]. Data related to utility consumption, specifically cooling water and steam requirements, were obtained from [10].

Spatially explicit data on biomass availability were obtained from sectoral information reported by CitrusBR [11], including the location of juice processing plants, installed processing capacity, and processed orange volumes.

Market nodes and demand limits were defined to reflect both regional and global consumption patterns. For domestic markets (*MD*), the analysis focused on municipalities in the Southeast region and Goiás, where food, pharmaceutical, and cosmetic industries are concentrated. The domestic pectin and D-limonene markets were estimated using trade data and industrial profiles, resulting in municipal-level demand limits.

To rigorously assess export-oriented configurations (*ME*) the port of Santos was selected as the primary gateway for international flows. External demand was disaggregated into representative port nodes for each destination continent: Houston (North America), Rotterdam (Europe), and Shanghai (Asia). For these destinations, external demand was estimated based on the average historical export volumes of pectin and orange essential oils to each respective continent.

Based on these demand estimations, a base case scenario was defined by satisfying 30% of the modeled domestic demand (Southeast region and Goiás) and 30% of the external demand for each continent (North America, Europe, and Asia).

Logistics costs for the export segment were explicitly modeled to include both inland and maritime stages. The maritime transportation cost factor (BRL/mt.nm) was derived from Drewry's World Container Index [12] and associated maritime route distances. Additionally, port handling costs per product tonne were incorporated based on official reports from the National Agency for Waterway Transportation [13]. This approach ensures a more realistic economic evaluation compared to simplified models, capturing the impact of port-centric logistics on the overall Net Present Value (NPV).

For energy products, it was assumed that all generated output was fully commercialized. Candidate locations for processing facilities were restricted to municipalities with access to natural gas infrastructure or power grid connection, allowing for the direct injection of biogas or the full dispatch of electricity. Under these assumptions, transportation costs for both energy carriers were neglected, as demand was effectively localized at the point of generation. Based on these infrastructure requirements, candidate locations were selected among municipalities either close to biomass sources or major consumption centers, enabling the assessment of trade-

offs between feedstock proximity and market access.

Prices for pectin and D-limonene were primarily derived from international trade data. The price of biogas was assumed equivalent to the natural gas price with an additional premium for its renewable origin. Electricity prices were based on representative average values reported by the [14].

To avoid trivial solutions with no installed capacity while preserving the ability of the model to return economically unfavorable configurations, a sufficiently small minimum demand constraint was imposed, allowing scenarios with negative net present values (NPV) to be obtained when economic conditions were not favorable.

Model implementation

The optimization model was implemented in Python using the Pyomo modeling framework, with input data provided through structured Excel files. The model was solved using Gurobi (version 12.0.3) under an academic license, with a relative optimality gap tolerance of 5.0×10^{-3} . Computations were performed on a machine equipped with an Intel® Core™ i7-8559U CPU (4 cores, 8 threads) and 16 GB of RAM. The resulting MILP comprises approximately 15,946 constraints and 60,800 variables, including 30 binary variables and SOS2 constraints for piecewise linear cost approximation. The base case was solved within the specified tolerance in approximately 274 s of computation time.

RESULTS AND DISCUSSION

The base case scenario considers the supply of 30% of domestic demand and 30% of external demand and serves as a reference for evaluating the economic performance and structural configuration of the citrus biorefinery. The optimal processing capacity is 87,676.06 mt/year of wet orange peel, resulting in the production of around 3,621.93 mt/year of pectin, 2,576.43 mt/year of limonene, and 11,485.56 MW of biogas. Under these conditions, model results indicate a positive net present value (NPV) of approximately BRL 1.27 billion, demonstrating high economic potential of orange residue valorization within the current market framework.

An analysis of the economic structure presented in **Figure 2** reveals that total revenues reach approximately BRL 4.6 billion, with pectin accounting for the largest share (65.23%), followed by limonene (34.70%), while energy products contribute negligibly to total revenue (0.08%). This distribution highlights the strong dependence of system profitability on high-value chemical products, particularly pectin.

Regarding operating expenditures costs at present value, represent the dominant component, totaling approximately BRL 1.88 billion. Within this category, production costs are the primary driver, representing

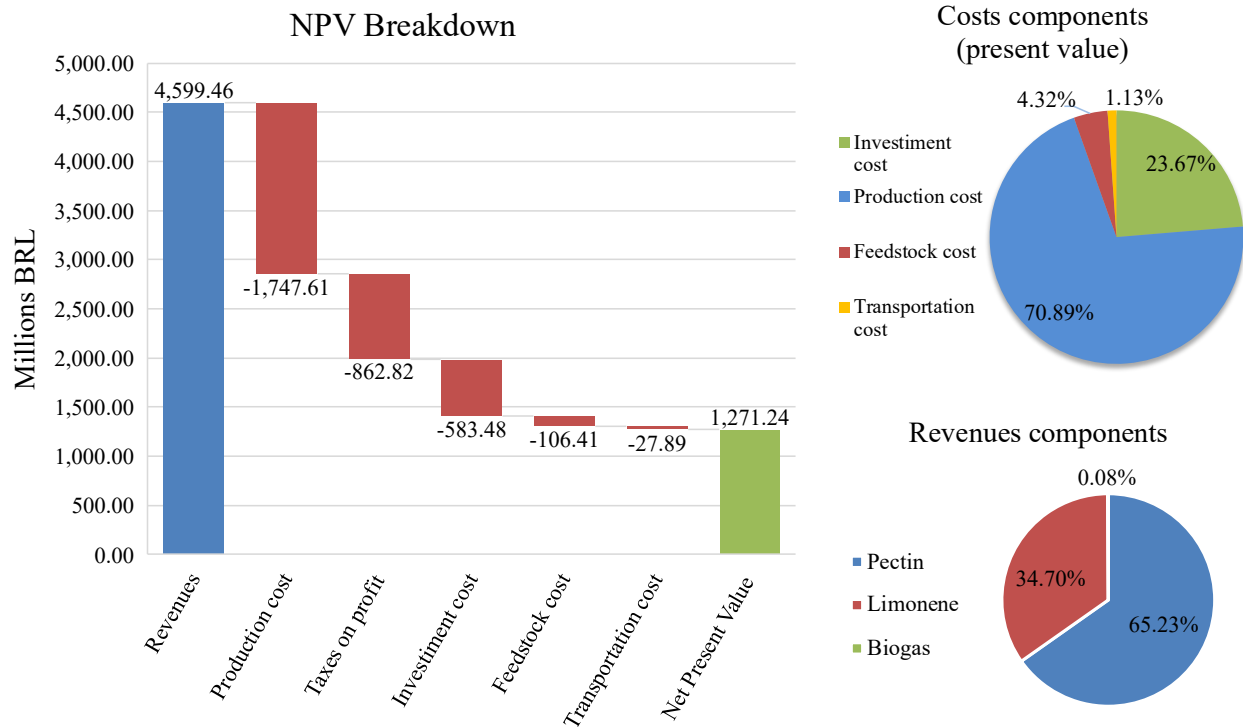


Figure 2. Base case NPV breakdown, costs composition at present value, and revenues composition.

70.89% of the total, followed by capital-related expenditures (23.67%) and feedstock acquisition (4.32%). This cost composition indicates that the economic performance of the system is dictated by the high utility requirements and energy intensity of the extraction and solvent recovery stages, rather than by biomass supply costs or logistics. Capital investment (CAPEX) for base case is BRL 5.83 billion and represents a relatively small share of total costs compared to operating expenditures, suggesting that economies of scale are effectively captured in the optimal solution.

The optimal network configuration selects a single processing facility located in Araraquara, utilizing the biogas-based conversion route. This centralized configuration reflects the combined effect of economies of scale and the spatial distribution of biomass availability, which is sufficient to sustain a large-scale facility without requiring decentralization.

The selection of the biogas route is not driven by direct revenues from energy products, which are marginal, but rather by its lower capital investment and utility consumption compared to the gasification-based electricity pathway.

Overall, the base case results highlight that the chain profitability is strongly dependent on high-value product markets, particularly pectin, and production costs, which represent the most significant financial burden. While logistics and feedstock costs play a

secondary role in the overall economic outcome, these findings provide a clear baseline for interpreting the sensitivity of the system to key economic parameters explored in the following sections.

Sensitivity analysis

The sensitivity analysis was performed to evaluate how variations in key economic and operational parameters affect both the profitability and structural configuration of the system, using the base case as reference. **Figure 3** summarizes the impact of each parameter on the net present value (NPV), relative to base case.

The results indicate an asymmetry in the economic drivers of the system, with market-related parameters exerting a stronger influence on performance than cost-related variables. Among these, pectin price has the largest impact on profitability. A 30% reduction in pectin price decreases the NPV from BRL 1.27 billion to BRL 5.14 million, while a 30% increase raises the NPV to about BRL 2.28 billion. These variations occur without changes in system configuration, indicating that price fluctuations primarily affect revenue levels rather than structural decisions. This behavior is consistent with the base case results, in which pectin accounts for the largest share of total revenues.

Market demand affects both economic performance and network configuration. A 75% reduction in demand leads to a decrease in NPV to approximately BRL 59.13

NPV Sensitivity Analysis

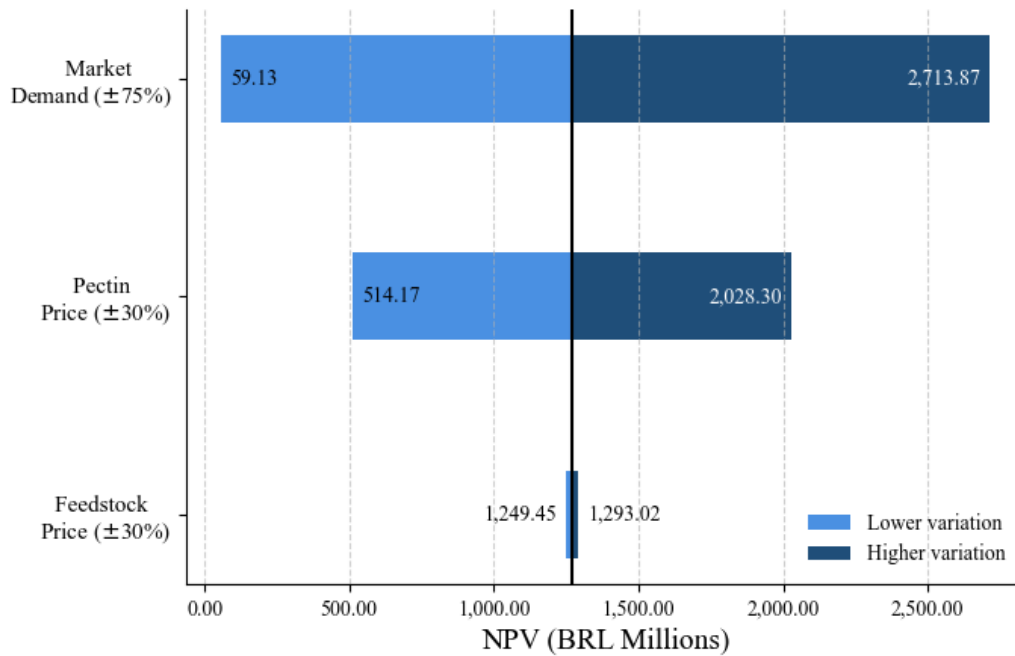


Figure 3. Tornado chart illustrating the sensitivity of the Net Present Value (NPV) to variations in market demand ($\pm 75\%$), pectin price ($\pm 30\%$), and raw material price ($\pm 30\%$).

million and a reduction in processing capacity from about 87,676.06 mt/year to 21,919.01 mt/year, with the optimal location shifting to Rio Claro. Conversely, a 75% increase in demand raises the NPV to approximately BRL 2.71 billion and increases processing capacity to about 153,433.10 mt/year, with the model selecting Matão as the optimal location. In the base case, the selected location is Araraquara, with an intermediate capacity level. These findings show that demand influences both production scale and spatial configuration.

This behavior can be explained by the interaction between economies of scale and the spatial distribution of biomass resources. As demand increases, the model favors larger processing capacities, reducing specific investment costs and improving the dilution of fixed operating costs. Although transportation costs represent a small share of total operating costs, they influence spatial decisions due to differences in unit transportation costs. Due to its density, the cost of transporting orange peel residue (BRL 0.83 per mt.km) is higher than that of processed products such as pectin (BRL 0.22 per mt.km) and limonene (BRL 0.21 per mt.km). As a result, the model prioritizes locations with sufficient local biomass availability to supply the plant, reducing the need for long-distance feedstock transport.

At higher demand levels, the impact of economies of scale significantly favors centralized network

configurations. The model tends to select a single, large-capacity facility positioned as close as possible to the port of Santos, provided that local biomass availability is sufficient to sustain the required throughput. This siting strategy reflects a fundamental trade-off of the system, where the framework prioritizes the exploitation of scale-related cost reductions while minimizing the transportation of low-density feedstock. In the context of São Paulo, the high regional concentration of residues allows the facility to achieve these economies of scale without triggering the need for a decentralized or market-oriented shift.

In contrast, feedstock-related parameters have a smaller impact on system performance. A $\pm 30\%$ variation in biomass purchase cost leads to changes in NPV between approximately BRL 1.25 billion and BRL 1.29 billion, without affecting plant location, technology selection, or processing capacity. This is consistent with the cost structure observed in the base case, where feedstock costs represent a relatively small share compared to production costs.

Alternative scenarios

In addition to the sensitivity analysis, a set of alternative scenarios was evaluated to further investigate the structural behavior of the system under specific operational and modeling constraints. These scenarios aim to

assess (i) the robustness of the network under reductions in biomass availability, and (ii) the conditions under which decentralized configurations may emerge due to capacity limitations.

To evaluate the robustness of the system under feedstock scarcity, scenarios with reductions of 30% and 50% in biomass availability were considered under base case demand conditions. The results show negligible changes in economic performance, with NPV remaining approximately constant at around BRL 1.27 billion in both cases. However, a shift in plant location is observed, from Araraquara in the base case to Matão under reduced availability conditions.

These results indicate that biomass availability, while not limiting overall system feasibility, can still influence spatial decisions when local supply becomes relatively more constrained. Under such conditions, the model exhibits patterns similar to those observed in high-demand scenarios, shifting facility locations toward regions with a higher concentration of biomass resources to ensure sufficient feedstock for the required processing capacity. Accordingly, biomass availability does not act as a binding constraint, but can still drive localized adjustments in the optimal network configuration.

To investigate scenarios in which decentralized configurations may emerge, a constraint was imposed on the maximum processing capacity of individual plants, limiting it to 75,000.00 mt/year of biomass. Under base case demand conditions, the model continues to select a centralized configuration with a single facility in Araraquara, operating at the imposed capacity limit. In this case, total system capacity is reduced from approximately 87,676.06 mt/year to 75,000.00 mt/year, leading to a decrease in NPV from BRL 1.27 billion to approximately BRL 1.01 billion. Although the capacity constraint becomes binding, the model still favors a single-facility configuration, even at the expense of reduced throughput and economic performance. Under these demand conditions, the loss of economies of scale associated with splitting capacity across multiple plants outweighs the potential gains from increased product supply.

To further assess decentralization effects, a second scenario was evaluated under higher demand conditions (50% of domestic and 50% of external demand), maintaining the same capacity constraint. In this case, the required processing capacity exceeds the maximum allowable capacity of a single plant, leading to the installation of two facilities, located in Araraquara and Matão. The total installed capacity reaches approximately 146,126.76 mt/year, with an NPV of approximately BRL 1.94 billion. Despite enabling full demand satisfaction, this decentralized configuration presents lower economic performance compared to the corresponding centralized configuration without capacity constraints. This reduction is primarily associated with the loss of economies of scale and the

increase in total capital investment resulting from capacity splitting across multiple plants.

Comprehensively, decentralized configurations emerge only when capacity constraints become binding at higher demand levels.

General considerations on network configuration

The results obtained across the evaluated scenarios identify consistent structural patterns governing the optimal configuration of the supply chain. Rather than being driven by isolated parameters, facility siting and capacity decisions emerge from a complex interaction between market scale, regional biomass availability, and economies of scale.

Market demand plays a central role in determining both the scale and spatial orientation of the system. At lower demand levels, the model favors locations that balance proximity to major consumption centers with sufficient biomass supply. In this context, Rio Claro emerges as the preferred location, as it represents the most suitable area with significant biomass availability near key demand centers such as Araras, Campinas, Jundiaí, São Paulo, and Santos (external market), which together account for approximately 87% of total demand across all evaluated scenarios.

As demand increases, the system transitions toward plant locations capable of supporting larger processing capacities while remaining reasonably close to the primary consumption hubs. Under these conditions, Araraquara becomes the preferred location, as it represents the nearest region to the main demand centers with sufficient biomass availability to sustain higher throughput levels. This shift reflects the model's behavior of securing feedstock at scale as demand rises. Importantly, this tendency to source the full feedstock requirement from a single location is an emergent behavior of the system under the specific regional context rather than a pre-defined model constraint. In this study, such transitions are possible because biomass is highly abundant and spatially concentrated, allowing several candidate locations to independently supply the full feedstock requirement over a broad range of demand levels. Consequently, minimizing wet biomass transportation remains an important driver of location decisions, as it avoids the significantly higher transport efforts associated with feedstock compared to final products.

Under more restrictive or higher-demand conditions, alternative locations may also emerge. Matão, for example, is selected in specific scenarios due to its substantial biomass supply, stemming from its position as a major national hub for orange processing. This vast local availability allows the facility to sustain the large-scale operations required by high-demand levels without the need for decentralization. Although Matão is less

favorably located in relation to the primary consumption centers compared to Araraquara or Rio Claro, it becomes economically attractive when demand increases significantly, such as in scenarios exceeding the base case by 50% (representing approximately 60% of total combined demand). In these instances, the benefit of concentrated biomass availability at a single node offsets the logistical disadvantage of being further from the market hubs.

Furthermore, the optimization results exhibit a consistent structural preference for centralized configurations as long as individual plant capacity constraints remain non-binding. This behavior is a direct manifestation of the economies of scale embedded in both capital investment and process operations, which prioritize higher throughput levels to maximize the Net Present Value (\$NPV\$). Decentralized networks emerge only as a necessary alternative when capacity saturation prevents a single facility from meeting the aggregate demand. In such instances, the forced splitting of capacity across multiple sites leads to a measurable degradation of economic performance, as the system loses the significant cost-dilution benefits inherent to large-scale, centralized hubs.

Ultimately, the supply chain architecture is governed by a clear hierarchy of strategic drivers: market demand dictates the required industrial scale, regional biomass density defines the feasible spatial anchors, and economies of scale drive the system toward centralization. The dynamic interplay between these factors provides a robust explanation for the spatial transitions observed between Rio Claro, Araraquara, and Matão across the evaluated scenarios. These findings underscore that for high-value bioproducts like pectin, the citrus-producing region of São Paulo offers a resilient landscape where process-scale advantages outweigh logistical complexities, provided the network design remains aligned with these primary economic drivers.

CONCLUSIONS

A MILP-based optimization framework was developed and applied to assess the supply chain configuration of citrus residue biorefineries in the state of São Paulo, incorporating a multi-echelon logistics structure that captures both domestic and global market dynamics. The results demonstrate that the proposed biorefinery is highly profitable under the evaluated conditions, achieving a Net Present Value (NPV) of BRL 1.27 billion in the base case. This economic performance is fundamentally anchored by the high-value biochemical market, specifically pectin, which accounts for over 65% of total revenue.

Sensitivity and scenario analyses reveal that market scale and product pricing serve as the fundamental pillars of the supply chain architecture. As demand rises,

the network exhibits a distinct preference for facilities sited at locations capable of satisfying the entire feedstock requirement locally, rather than prioritizing proximity to high-demand consumer centers. This structural pattern is intrinsically tied to the regional context of São Paulo, where the exceptional spatial concentration of residues allows the system to minimize the significant logistical effort of high-volume, wet biomass while maximizing economies of scale through centralized configurations. Furthermore, the comprehensive inclusion of multi-echelon logistics including inland transport, port handling, and international maritime freight reveals that total transportation costs represent a mere 1.13% of total expenditures. This marginal share is particularly striking when contrasted with production costs, which constitute the primary economic bottleneck of the system. Given the high utility and energy intensity of the extraction and recovery stages, the relative impact of product distribution is significantly diluted within the overall cost structure. Ultimately, the high value-density of products like pectin effectively absorbs global logistics costs, reinforcing that in regions with high biomass density, strategic success is governed by process efficiency and industrial scale rather than logistical constraints.

Building on these economic interdependencies, this research provides a robust baseline for strategic planning in the citrus bioeconomy. The findings indicate that the most resilient configurations are those that maximize throughput in centralized hubs to exploit non-linear investment scaling. While the system is logistically robust to biomass scarcity due to regional abundance, its long-term viability is strictly contingent upon process efficiency, especially regarding the management of production costs and utility consumption, as well as favorable market positioning for high-value bioproducts. This framework offers a comprehensive tool for sustainable waste valorization in major agro-industrial clusters, supporting the transition toward a circular bioeconomy.

ACKNOWLEDGEMENTS

This study was financed, in part, by the São Paulo Research Foundation (FAPESP), Brazil. Process Number #2024/17847-0.

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