Cost optimization in the production process of the company Cueros JCG through linear programming: an economic and environmental approach*

Optimización de costos en el proceso productivo de la empresa Cueros JCG mediante programación lineal: un enfoque económico y ambiental

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Abstract

This article describes the design, implementation, and validation of a linear programming (LP) model to optimize production costs at the Cueros JCG tannery, located in the San Benito neighborhood of Bogotá. The main objective was to minimize total input costs while meeting projected demand and complying with technical, capacity, and environmental constraints. The model integrates real data on prices, technical consumption, input availability, and pollutant load limits. The optimal solution achieved a significant cost reduction compared to the traditional method, reaching a unit cost of 1200 COP in the base scenario, with 100 % compliance with the permitted environmental limits. Simulations were conducted by varying demand, critical input prices, and environmental capacity, demonstrating that the model is flexible, adaptable, and replicable in other companies within the sector. This work contributes to the pursuit of cleaner and more sustainable production in the tanning industry.

Keywords:

linear programming, cost optimization, tanneries, sustainable production, scenario simulation.

Resumen

El presente artículo describe el diseño, implementación y validación de un modelo de programación lineal (PL) para optimizar los costos de producción en la curtiembre Cueros JCG, ubicada en el barrio San Benito en Bogotá. El objetivo principal fue minimizar el costo total de insumos cumpliendo con la demanda proyectada y respetando las restricciones técnicas, de capacidad y ambientales. El modelo integra datos reales de precios, consumos técnicos, disponibilidad de insumos y límites de carga contaminante. La solución óptima obtenida redujo significativamente los costos respecto al método tradicional, alcanzando un costo unitario de 1200 COP en el escenario base, con cumplimiento del 100 % del límite ambiental permitido. Se realizaron simulaciones variando la demanda, los precios de insumos críticos y la capacidad ambiental, demostrando que el modelo es flexible, adaptable y replicable en otras empresas del sector. Este trabajo se enmarca en la búsqueda de una producción más limpia y sostenible en la industria curtidora.

Palabras clave:

programación lineal, optimización de costos, curtiembres, producción sostenible, simulación de escenarios.

Introducción

Tanning is one of the oldest industrial activities in Bogotá (Colombia), with a long production tradition in the San Benito neighborhood of Tunjuelito. Since the mid-20th century, this sector has formed a productive cluster that brings together small and medium-sized enterprises, many of which originate from families with a long tradition in leather tanning. According to data from the Observatorio de Desarrollo Económico de Bogotá (2019), the tanning sector contributes approximately 1.2 % to the district's manufacturing gross domestic product (GDP) and generates more than 3500 direct jobs, making it a key driver of economic and social development in the city, with San Benito being the epicenter of this activity. At a national level, the leather and footwear sector contributes approximately 0.6 % to the national manufacturing GDP and generates more than 55 000 direct jobs in the country (Departamento Administrativo Nacional de Estadística, 2022). This cluster has been recognized as one of the main leather processing centers in Colombia, supplying both the domestic market and related industries such as footwear, leather goods, and upholstery.

Despite its social and economic relevance, the tanning industry faces multiple challenges. First, the high cost of inputs (salts, tanning agents, dyes, lime, sodium sulfide, among others) puts pressure on profit margins, especially in smaller companies that lack bargaining power with suppliers. Second, environmental req uirements have increased significantly in recent decades, forcing the industry to invest in wastewater treatment systems, emissions reduction, and the safe disposal of hazardous solid waste, such as chromium-containing residues. Finally, international competition with low-cost countries (such as Bangladesh, India, and Pakistan) increases pressure to reduce operating costs and improve efficiency (United Nations Industrial Development Organization [Unido], 2019). In addition, the volatility of international leather prices adds further uncertainty, as Colombia mainly exports to Mexico, Italy, and China, where quality and competitiveness requirements are high (ProColombia, 2021).

In this scenario, there is a need to incorporate quantitative management and optimization tools that enable local tanneries to make more informed and sustainable decisions. Linear programming, widely used in logistics, transportation, and production planning, is an appropriate methodology for addressing the problem of input allocation and cost minimization within a framework of technical and environmental constraints (Hillier & Lieberman, 2021; Taha, 2017).

In the leather production process, one of the critical aspects from an environmental perspective is wastewater management. This wastewater contains a high load of organic matter and chemical compounds derived from processes such as dehairing, liming, tanning, and retanning. Therefore, it is essential to monitor indicators such as biochemical oxygen demand (BOD) and chemical oxygen demand (COD), which are widely used to characterize the level of contamination in these effluents.

BOD represents the amount of oxygen that microorganisms require to degrade the biodegradable organic matter present in the water over a period of five days at 20 °C. It is a key parameter for estimating the impact that a discharge may have on a natural water body and is primarily associated with organic compounds of biological origin (López & Martínez, 2021). COD, on the other hand, measures the total amount of oxygen required to oxidize both biodegradable and non-biodegradable organic matter using a strong chemical oxidizing agent, such as potassium dichromate. For this reason, its values are always equal to or higher than those of BOD. COD is especially useful for identifying recalcitrant pollutants that may be present in tanning, dyeing, or greasing baths (Ministerio de Ambiente y Desarrollo Sostenible, 2015).

The combined monitoring of these two parameters enables the design of more efficient treatment systems and the evaluation of compliance with the maximum permissible limits established by current environmental regulations for industrial liquid discharges. The tanning sector is considered one of the most environmentally impactful due to the discharge of wastewater with high levels of BOD, COD, and hexavalent chromium, which has led to the implementation of strict regulations. Among these are:

Este renglón tiene una sangría manual de 1 centímetro.

- Decree 3930 of 2010, issued by the Ministry of Environment and Sustainable Development, which establishes the regulatory framework for discharges into water bodies (República de Colombia, 2010).
- Resolution 0631 of 2015, which sets maximum permissible limits for pollutants in specific discharges from sectors such as tanning (Ministerio de Ambiente y Desarrollo Sostenible, 2015).
- Ministerio de Ambiente, Vivienda y Desarrollo Territorial (2010). Política Nacional de Producción y Consumo Sostenible (Ministerio de Ambiente, Vivienda y Desarrollo Territorial, 2010), which promotes the reduction of environmental impacts in productive sectors.
- Consejo Nacional de Politica Económica y Social Consejo Nacional de Política Económica y Social (2018), which establishes circular economy guidelines applicable to the leather and leather goods sector.

The combination of high operating costs and increasing environmental requirements creates the need to implement new production management tools. In this context, linear programming is proposed as an effective strategy for optimizing input use, reducing costs, and ensuring regulatory compliance, thereby contributing to the sustainability of small-scale companies such as Cueros JCG.

The Colombian tanning industry faces two opposing forces: on the one hand, pressure to compete in markets that demand quality and environmental traceability; on the other, production structures that have historically been intensive in water, chemicals, and energy. In the last decade, the regulatory framework has become more stringent—with regulations on water use and discharges República de Colombia (2015) (República de

Colombia, 2015) and maximum permissible limits for specific discharges (Ministerio de Ambiente y Desarrollo Sostenible, 2015)—prompting companies to measure, treat, and reduce their pollutant loads and consumption, under the risk of sanctions and partial or total closures.

At the same time, the external context reveals a volatile dynamic. According to the National Administrative Department of Statistics (DANE), between January and September 2024, footwear exports reached 26.9 million USD (Semana, 2024). Later, in the first quarter of 2025, these exports amounted to 8.3 million USD (La Nota Económica, 2025), while foreign sales of leather goods rose to 11.8 million USD during the same period (La Nota Económica, 2025). These trends, within the framework of tariff chapters 41 and 42 for leather and related products, underscore that the sector's competitiveness depends on both operational efficiency and environmental compliance.

Against this backdrop, linear programming is justified as a tool for allocating inputs (salt, lime, sulfur, tanning agents, dyes) at the lowest possible cost without violating technical and environmental restrictions. The added value of this study lies in applying this optimization approach to the microenterprise context of Cueros JCG, using parameters and limits in line with Colombian regulations.

Research problem

In the context of tanneries, managing production costs represents a critical challenge. The tanning, retanning, dyeing, and finishing processes involve inputs with both high economic impact (such as salts, tanning agents, and dyes) and significant environmental impact (due to discharges with high BOD, COD, and chromium loads). Inefficient use of these materials increases costs and, at the same time, raises the risk of environmental non-compliance. Given this situation, the central research question arises: how can the allocation of inputs in small-scale tannery production be optimized in order to minimize costs without exceeding environmental limits or compromising the quality of the final product?

General objective

To optimize the use of inputs in the Cueros JCG production process using a linear programming model that minimizes total cost while considering technical, capacity, and environmental constraints.

Specific objectives

- To formulate and solve a linear programming model that determines the optimal combination of inputs to minimize production costs, subject to technical and environmental constraints.
- To analyze the optimal distribution of inputs derived from the model, evaluating its impact on unit costs and environmental indicators such as BOD and COD.
- To simulate alternative scenarios involving variations in demand, input prices, and regulatory limits in order to assess the robustness and applicability of the model in real-world contexts.

Research background

At the national level, research on the tanning sector has traditionally focused on environmental impacts and cleaner production (Centro Nacional de Producción Más Limpia, 2018; Secretaría Distrital de Ambiente, 2018). However, studies adopting a quantitative optimization approach remain scarce. Delgado Hidalgo & Toro Díaz (2010) applied linear programming to a manufacturing system, demonstrating how efficient resource allocation improves productivity. In the field of cost analysis, Díaz (2007) examined the application of optimization models in small Colombian industries and highlighted their usefulness for business decision-making.

In Latin America, Reyes Vasquez & Molina Velis (2014) presented a case study in Ecuador, where linear programming applied to aggregate planning in tanneries enabled reductions of up to 12 % in input costs, confirming its relevance for this sector. In Peru, research conducted by the Ministry of Production (Ministerio de la Producción, 2016) has emphasized the need to adopt quantitative management models for small polluting industries, including tanneries in Arequipa and Trujillo.

At the international level, Sharma & Gupta (2018) applied linear programming models in the Indian textile industry, achieving an 18 % reduction in raw material costs. In Italy, a country with a strong tanning tradition, several studies have documented the use of mathematical optimization to balance costs and emissions in leather tanning (Baldassarre et al., 2017). Meanwhile, research in the United States highlights the application of linear programming in agribusiness and leather manufacturing to integrate sustainability criteria (Rao & Miller, 2013).

In summary, the evidence shows that, although linear programming has yielded favorable results in different industries, the systematic application of this type of model in Colombian tanneries remains a research gap. This gap creates an opportunity to contribute applied knowledge, validated with real data, aimed at improving the economic and environmental efficiency of companies such as Cueros JCG in Bogotá.

The use of quantitative tools in industrial management is not new; however, their application in Colombian tanneries has been limited. In this country, literature has focused mainly on the environmental aspects of the sector. The District Secretary of Environment (Secretaría Distrital de Ambiente, 2018) has documented the need to reduce pollutant loads in the tanneries in San Benito, while studies by the Centro Nacional de Producción más limpia Centro Nacional de Producción Más Limpia (2018) have promoted the implementation of cleaner technologies in the leather industry.

Theoretical framework

Efficient resource management in production processes has been a central theme in the literature on management, industrial engineering, and operations economics. In traditional industries such as tanning, characterized by intensive use of chemical inputs, water, energy, and labor, cost optimization becomes essential to ensure sustainability and competitiveness in increasingly demanding markets.

One of the most effective methods for addressing efficiency problems is linear programming (LP), an operational research tool that allows the determination of the best possible combination of variables under a set of technical and economic constraints. Its main utility lies in identifying optimal solutions to problems involving scarce resource allocation, cost minimization, or profit maximization in contexts where relationships are linear (Winston, 2004).

In simple terms, linear programming translates a real-world problem into a mathematical model composed of three fundamental elements: an objective function, a set of constraints, and non-negativity conditions. This structure enables the simulation of scenarios, supports informed decision-making, and facilitates the identification of solutions that may not be evident in empirical contexts (Taha, 2017). Its applicability has been widely documented in sectors such as transportation, manufacturing, and agriculture, and more recently in industries with high environmental impact, such as tanning.

In these types of processes, the inputs used not only represent a significant proportion of operating costs but are also subject to environmental regulations that require responsible management. Products such as formic acid, ammonium sulfate, tanning salts, and other chemical compounds must be carefully dosed not only to ensure leather quality but also to avoid exceeding permissible limits for indicators such as biochemical oxygen demand (BOD) and chemical oxygen demand (COD), which are commonly used to assess the pollutant load of wastewater (López & Martínez, 2021).

From this perspective, cost optimization is not limited to reducing expenses but involves designing more efficient production systems that make better use of resources, minimize waste, and comply with quality and sustainability standards. Linear programming, by enabling these systems to be modeled using quantitative criteria, represents a strategic tool for decision-making in small and medium-sized enterprises within the tanning sector.

In this context, the present study builds on the fundamentals of LP to develop an optimization model applied to the case of the company Cueros JCG, aiming to demonstrate how the integration of quantitative methods into operational management can lead to significant cost savings without compromising product quality or required production volumes.

Methodology

The methodology used in this research is based on the approach developed by Lozano Rodríguez et al. (2023), who propose a circular economy strategy for the tanning sector based on the identification of critical processes and the assessment of economic and environmental impacts.

The production process at Cueros JCG consists of a series of technical stages organized sequentially, aimed at transforming raw hides into finished leather while complying with quality standards, operational efficiency, and environmental requirements. These phases, described below, are common in most industrial tanneries and have been adapted at Cueros JCG in accordance with its production conditions and the available materials and supplies (Centro Nacional de Producción Más Limpia, 2018; Gómez, 2018; United Nations Industrial Development Organization, 2019).

- Receipt and classification of hides: Raw hides are visually inspected, weighed, and classified according to type, size, and level of deterioration.
- Soaking and washing: Hides are hydrated to restore their original elasticity, and residues such as blood, dirt, salt, and organic matter accumulated during storage are removed.
- Descaling and dehairing: Chemical agents such as sulfides and acids are used to remove hair, subcutaneous fat, and lime residues, conditioning the hide for the tanning process.
- Tanning: This phase transforms the hide into leather through the application of tanning salts (commonly chromium or other vegetable or synthetic agents) that stabilize the collagen structure, preventing putrefaction and improving the material's resistance.
- Retanning, dyeing, and greasing: Additives, dyes, oils, and fats are reintroduced to impart desired properties to leather, such as flexibility, color, texture, and durability.
- Drying and softening: Drying equipment (such as hot air or vacuum tunnels) and softening machinery are used to reduce residual moisture and improve leather's workability.
- Finishing: Pigments, lacquers, waxes, or surface treatments are applied to enhance leather's appearance and protect it from external agents.
- Final sorting and packaging: The finished product is inspected again, classified according to batch or quality grade, and packaged for domestic or international distribution.

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Figure 1

Diagram of operations in the retanning and greasing process

CURTIEMBRES JCG						
DIAGRAMA DE OPERACIONES		OPERACIONES	15			
		TRANSPORTE	1	ACTUAL	X	
PROCESO	RECURTIDO TEÑIDO Y ENGRASE	INSPECCIONES	4	PROPUESTO	ELABORADO POR:	WILSON RODRIGUEZ
		DEMORAS	2		REVISADO POR:	CARLOS LOZANO
		ALMACENAMIENTO	0			CARLOS ANDRES RUBIO

Recurso Humano	Distancia en Mts.	Tiempo en Min.	Operación	Transporte	Inspeccion	Demora	Almacenamiento	DESCRIPCION DE LA ACTIVIDAD	ITEM	MAQUINARIA UTILIZADA
1	1	20						RECEPCION DEL CUERO	Recibir la mp de provedor de acuerdo a condiciones pactadas de compra	Estibas, gato hidraulico
1	4	15						LLEGADA DE MAQUINA REBAJADORA	Esto se hace tercerizado	N/A
2	2	30 - 40						DESORILLAR	Colocar lo que llega de la maquina rebajadora en caballetes para quitar lo que no sirve para los otros procesos	Cuchillo para corte
1	3	50-60						PESAR	Colocar en la bascula el cuero ya rebajado y desaorillado para iniciar el proceso de curtido y engrase	Bascula
1	5	15						CARGAR AL FULON O BIOMBO	Introducir el cuero ya rebajado y desaorillado al fulon para iniciar el proceso de curtido y engrase	N/A
1	1	15-20						AGREGAR AGUA REQUERIDA	Llenar el fulon de agua para iniciar el lavado del cuero se saca de la fomula de 1 un kg por litro de agua al 200%	Agua
1	0	30						LAVAR	Poner en funcionamiento el fulon para empezar la limpieza del cuero	N/A
1	0	15						ESCURRIR	Dejar salir el agua del fulon por los ductos del desague	N/A
1	0	15-20						AGREGAR AGUA	Llenar el fulon de agua para iniciar el lavado del cuero se saca de la fomula de 1 un kg por litro de agua al 150%	Agua
1	0	45 - 90						NEUTRALIZAR	Es la actividad de cambiar el ph a 3,6 para que el cuero reciba los quimcos para su proceso de fabricacion	basificantes a base de bicarbonato, son divrsos para el tipo de cuero que se va a producir, acido formico, cromo
1	2	5						INSPECCION DE ATRAVESADO	Se realiza un control de calidad si el neutralizado es el apropiado. Adicionalmnete se le agrega quimicos para elevar nuevamentamente el ph para darle contextura al cuero	bicarbonato,acido formico, sales basicas, acido oxalico
1	1	20						LAVAR CON LA TAPA SELLADA	Poner en funcionamiento el fulon para empezar la limpieza del cuero	N/A
1	0	10						ESCURRIR	Dejar salir el agua del fulon por los ductos del desague	N/A
1	2	15-20						AGREGAR AGUA	Llenar el fulon de agua para iniciar el lavado del cuero se saca de la fomula de 1 un kg por litro de agua al 100%	Agua
1	3	20-25						PESAR LOS ADITIVOS SEGÚN ESPECIFICACION DEL CUERO	Se realiza la actividad de pesar los quimicos de acuerdo al cuero que se requiere	Cromo, bicarbonato, acido formico, acrilicos, grasa sinteticas, proteinas, anilina,oxolico
1	3	10						AGREGAR ADITIVOS	Aplicar los quimicos pesados al cuero por los ductos del fulon para tal fin	N/A
1	2	10						INSPECCIONAR AGUA	Se realiza la verificacion del ph del agua como control de calidad del producto	bicarbonato,acido formico, sales basicas, acido oxalico
1	0	10						LAVAR	Poner en funcionamiento el fulon para empezar la limpieza del cuero	N/A
1	1	45-60						DESCARGAR	Dejar salir el agua del fulon por los ductos del desague	N/A
1	0	45-60						DEJAR REPOSAR	Se deja el cuero en el fulon un tiempo mas para que se pueda evacuar la mayor cantidad de agua	N/A
1	10	45-60						COLGAR	Sacar el cuero del fulon y colocarlo en caballetes para dejar secar el cuero	N/A
1	0	5 a 10 dias						SECAR AL AIRE	Dejar el cuero a temperatura ambiente para que se seque por si solo en los caballetes	N/A

NEUTRALIZAR: VOLVER A SUBIR EL PH

el proceso se demora total 8- a 10 horas DESPUES DE DESORILLAR(QUITAR LO QUE NO SIRVE)

Source: own elaboration.

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This process is structured as a value chain that is intensive in the use of chemical inputs and water, making it necessary to implement cleaner production practices as well as technical and environmental optimization models.

Building on this conceptual framework, this study delves into the quantitative analysis of these processes by integrating optimization techniques, particularly linear programming, to achieve efficient input management. In this context, the research was structured into four methodological phases aimed at identifying opportunities for optimizing input use within the production process at Cueros JCG. Each of the implemented phases is described below:

Information gathering

In this first phase, a database provided by the company was consolidated, consisting of spreadsheets with detailed information on inputs, unit prices, consumption per production stage, and production projections. Analysis focused primarily on records related to raw leather, retanned leather, and ranch nappa leather products. This information made it possible to identify the most representative cost components of the process, as well as the units of measurement used in each operation (kilograms, liters, units).

Costs and consumption were calculated for a production of 100 units of split leather, 50 units of reprocessed split leather, and 200 units of ranch nappa leather, corresponding to a total demand of 350 units per year.

Cost analysis

Based on this information, inputs were classified according to their role in the production process and their economic weight. Total unit cost per input was determined as the product of estimated unit consumption and the purchase price per unit. This analysis made it possible to identify inputs with the greatest impact on total production costs and, therefore, those that should be prioritized in the optimization model. In addition, the current average cost of the production process was estimated at 5909.17 COP per reference unit, which served as the baseline for comparison. This value was calculated by adding the actual unit costs of all inputs, based on consumption data reported by Cueros JCG. The total unit cost of the production process was estimated based on the consumption and prices of inputs used; results are presented in table 1.

Tabla 1

Total unit cost calculation

Inputs	Unit of measurement	Cost per unit purchased (COP)	Total consumption (COP)
Water	Liter per kilogram	$ 6.19	$ 1374.02
Formic acid (PROCUR)	Kilogram	$ 5200.00	$ 4209.67
Actan ALF	Kilogram	$ 10 115.00	$ 0.09
Actan TV	Kilogram	$ 10 257.00	$ 0.09
Adatan PF Org	Kilogram	$ 5950.00	$ 0.13
Atralin	Kilogram	$ 6.19	$ 136.62
Bisulfite (Nation)	Kilogram	$ 3873.00	$ 0.15
Bruno G	Kilogram	$ 3272.00	$ 0.02
Calentana bait	Unit	$ 63 367.00	$ 41.67
Celesal DLA	Kilogram	$ 18 000.00	$ 46.00
Colorfix JL	Kilogram	$ 5000.00	$ 0.01
Chromium	Kilogram	$ 16 184.00	$ 0.06
Descaler D86	Kilogram	$ 4495.00	$ 0.37
NP Grease	Kilogram	$ 5100.00	$ 0.14
Engrasan CON	Kilogram	$ 3700.00	$ 0.05
Baked	Kilogram	$ 6771.00	$ 0.05
Humectol AS 21	Kilogram	$ 2873.00	$ 0.10
Oxalic acid	Kilogram	$ 2000.00	$ 13.80
Plenatal HBE	Kilogram	$ 2000.00	$ 36.80
Procryl R4	Kilogram	$ 2000.00	$ 9.20
Proctan D	Kilogram	$ 2000.00	$ 9.20
Progran DP	Kilogram	$ 8092.00	$ 0.01
Prolin KAT	Kilogram	$ 5835.00	$ 0.05
RA 115	Kilogram	$ 4416.00	$ 0.09
Discounted bait x 3	Unit	$ 4598.00	$ 0.04
Discounted cowhide	Unit	$ 1700.00	$ 9.20
Retanal RC 200	Kilogram	$ 8092.00	$ 0.07
Salt	50-kilogram bag	$ 1500.00	$ 36.80
Santantan TD	Kilogram	$ 3000.00	$ 13.80
Aluminum sulfate T-A	Kilogram	$ 6900.00	$ 0.14
Ammonium sulfate	Kilogram	$ 16 000.00	$ 0.43
Total unit cost			**$ 5938.86**

Source: own elaboration.

This value represents the average cost per unit produced under current process conditions, based on consumption data (in pesos) recorded in the Excel file.

After applying the linear programming model, the optimized unit cost of the production process was obtained. This result is presented in detail in table 2, highlighting the adjustments in input consumption and their impact on reducing total costs.

Optimized model cost

After applying the linear programming model, solved using Excel's Solver tool, the main results of the optimal solution were obtained, showing an efficient combination of inputs that meets the established minimum production levels.

Only a subset of inputs is used in the optimal solution. The resulting quantities correspond to a combination that satisfies the minimum production requirements. The total projected cost of this combination was:

Result	**Value (COP)**
Optimized total cost	\$1238.26
Absolute reduction	\$5909.17 – \$1238.26 = \$4670.91
Percentage reduction	~79.04 %

Source: own elaboration.

This result demonstrates that the mathematical model allows for a considerable reduction in cost without violating production constraints.

Mathematical model formulation

Based on the principles of linear programming, a mathematical model was designed aimed at minimizing the total input cost required to meet a minimum projected demand by type of leather. Decision variables correspond to the quantities of each input to be used (xi), while constraints were defined to ensure compliance with the minimum technical requirements of the process, capacity limitations, and environmental restrictions, as well as the non-negativity condition for all variables. The complete formulation of the linear programming model is presented in the mathematical application of the model.

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Tabla 2

Optimized unit cost calculation

Inputs	Purchase unit	Price per purchase unit (COP)	Total consumption (COP)
Transportation of bait	Unit	$ 80.00	$ 36.80
Formic acid (PROCUR)	Kilogram	$ 5200.00	$ 4209.67
Actan ALF	Kilogram	$ 10 115.00	$ 0.09
Actan TV	Kilogram	$ 10 257.00	$ 0.09
Adatan PF Org	Kilogram	$ 5950.00	$ 0.13
Atralin	Kilogram	$ 6.19	$ 136.62
Bisulfite (Nation)	Kilogram	$ 3873.00	$ 0.15
Bruno G	Kilogram	$ 3272.00	$ 0.02
Calentana bait	Unit	$ 63 367.00	$ 41.67
Celesal DLA	Kilogram	$ 18 000.00	$ 46.00
Colorfix JL	Kilogram	$ 5000.00	$ 0.01
Chrome	Kilogram	$ 16 184.00	$ 0.06
Descaler D86	Kilogram	$ 4495.00	$ 0.37
NP Grease	Kilogram	$ 5100.00	$ 0.14
Engrasan CON	Kilogram	$ 3700.00	$ 0.05
Baked	Kilogram	$ 6771.00	$ 0.05
Humectol AS 21	Kilogram	$ 2873.00	$ 0.10
Oxalic acid	Kilogram	$ 2000.00	$ 13.80
Permit for tanning hides	Unit	$ 600.00	$ 46.00
Permit for re-tanning and dyeing	Unit	$ 200.00	$ 23.00
Permit for retanning and dyeing	Unit	$ 5712.00	$ 0.04
Prenatal HBE	Kilogram	$ 2000.00	$ 36.80
Procryl R4	Kilogram	$ 2000.00	$ 9.20
Proctan D	Kilogram	$ 2000.00	$ 9.20
Progran DP	Kilogram	$ 8092.00	$ 0.01
Prolin KAT	Kilogram	$ 5835.00	$ 0.05
Polished suede bait x 2	Unit	$ 5885.00	$ 0.09
RA 115	Kilogram	$ 4416.00	$ 0.09
Discounted bait X 3	Unit	$ 4598.00	$ 0.04
Discounted cowhide	Unit	$ 1700.00	$ 9.20
Retanal RC 200	Kilogram	$ 8092.00	$ 0.07
Salt	50-kilogram bag	$ 1500.00	$ 36.80
Santantan TD	Kilogram	$ 3000.00	$ 13.80
Aluminum sulfate T-A	Kilogram	$ 6900.00	$ 0.14
Ammonium sulfate	Kilogram	$ 16 000.00	$ 0.43
Togly bait x 1	Unit	$ 10 971.00	$ 0.14
Totals			**$ 4670.91**

Source: own elaboration.

Expected results

Once the linear programming model is formulated and solved using a tool such as Excel Solver, it is expected to provide key information to support decision-making at Cueros JCG. The expected results are detailed below.

Optimal input quantity

The model determines the optimal input quantity required to meet the minimum production levels established for the different types of leather (clothing leather, retanned leather, and ranch nappa leather). Examples of active inputs and their corresponding total unit cost within the process are also identified.

Details of the optimized unit cost calculation, resulting from the application of the linear programming model, are presented in table 4, which shows the adjustments in input quantities and their impact on reducing the total cost of the production process.

Tabla 4
Optimized unit cost calculation by input

Input	Total unit cost (COP)
Transportation of bait	$ 12.40
Formic acid (PROCUR)	$ 1.01
Adatan PF Org	$ 3.23
Atralin	$ 0.52
Bruno G	$ 0.25
Celesal DLA	$ 2790.70
Descaler D86	$ 6.10
NP Grease	$ 2.97
Permit for tanning meat	$ 93.02

Note: Values correspond to the total estimated unit cost based on declared consumption and the purchase price per input.
Source: own elaboration.

These values are not assigned arbitrarily but follow a mathematical logic that considers:

- The unit price of each input,
- Its role in the production processes, and
- Constraints related to production demand and resource availability.

As a result, the company can determine the exact quantities of each chemical, material, or service required to operate efficiently, avoiding unnecessary resource use.

Calculation of total costs per input

Table 5 presents the consolidated total costs for each input, comparing current with optimized costs.

Tabla 5
Current and optimized costs

Inputs	Unit of measurement	Total cost (COP)	Optimized costs (COP)
Water	Liter per kilogram	$ 12 034 494.87	$ 8505.18
Formic acid (PROCUR)	Kilogram	$ 21 890 268.40	$ 21 890 268.40
Actan ALF	Kilogram	$ 930.58	$ 930.58
Actan TV	Kilogram	$ 943.64	$ 943.64
Adatan PF Org	Kilogram	$ 766.36	$ 766.36
Atralin	Kilogram	$ 845.68	$ 845.68
Bisulfite (Nation)	Kilogram	$ 570.11	$ 570.11
Bruno G	Kilogram	$ 60.20	$ 60.20
Calentana bait	Unit	$ 2 640 300.12	$ 2 640 300.12
Celesal DLA	Kilogram	$ 828 000.00	$ 828 000.00
Colorfix JL	Kilogram	$ 64.40	$ 64.40
Chrome	Kilogram	$ 1042.25	$ 1042.25
Descaler D86	Kilogram	$ 1654.16	$ 1654.16
NP Grease	Kilogram	$ 703.80	$ 703.80
Engrasan CON	Kilogram	$ 170.20	$ 170.20
Baked	Kilogram	$ 311.47	$ 311.47
Humectol AS 21	Kilogram	$ 290.75	$ 290.75
Oxalic	Kilogram	$ 27 600.00	$ 27 600.00
Plenatal HBE	Kilogram	$ 73 600.00	$ 73 600.00
Procryl R4	Kilogram	$ 18 400.00	$ 18 400.00
Proctan D	Kilogram	$ 18 400.00	$ 18 400.00
Progran DP	Kilogram	$ 111.67	$ 111.67
Prolin KAT	Kilogram	$ 268.41	$ 268.41
RA 115	Kilogram	$ 406.27	$ 406.27
Discounted bait X 3	Unit	$ 169.21	$ 169.21
Discounted cowhide	Unit	$ 15 640.00	$ 15 640.00
Retanal RC 200	Kilogram	$ 595.57	$ 595.57
Salt	50-kilogram bag	$ 55 200.00	$ 55 200.00
Santantan TD	Kilogram	$ 41 400.00	$ 41 400.00
Aluminum sulfate T-A	Kilogram	$ 952.20	$ 952.20
Ammonium sulfate	Kilogram	$ 6918.40	$ 6918.40
Totals		**$ 37 661 078.71**	**$ 25 635 089.02**

Source: own elaboration.

Cost difference

Cost difference was calculated as: Difference = Current cost − optimized cost

This allows to identify the potential savings per input:

Scenario	Cost (COP)
Traditional model	$ 37 661 079
Optimized model	$ 25 635 090
Savings	**$ 12 025 989**

In many cases, optimized consumption is equal to total consumption; therefore, the cost remains unchanged. However, when there is an opportunity to reduce consumption without affecting the process, the model adjusts the corresponding values.

One of the most relevant findings of the optimization model was the significant reduction in water consumption, an input that, in the current process, represents a considerable share in both volume and environmental impact. In the baseline scenario, water was one of the most heavily used resources; however, its consumption was not guided by technical rationalization criteria, leading to high waste levels.

The simulation carried out using linear programming made it possible to optimize water use, contributing not only to the reduction of operating costs but also to a decrease in pollutant loads in liquid discharges. This improvement is consistent with the requirements of Decree 3930 of 2010 (República de Colombia, 2010), which regulates water resource use in Colombia, and Resolution 0631 of 2015 (República de Colombia, 2015), which establishes the maximum permissible limits for point discharges into surface water bodies. In this way, the proposed optimization strategy not only addresses economic objectives but also strengthens regulatory compliance and supports the transition toward more sustainable and responsible water resource management.

Application of the linear programming model to optimized cost

The linear programming model is formulated based on consumption data presented in table 6, corresponding to a total demand of 350 units across the three products.

Tabla 6

Consumption per input by unit of measurement

Variables	Inputs	Unit of measurement	Utilization percentage			Cost per purchase unit (COP)	Unit consumption	Total consumption
			Tanned meat	Retanned hides	Rancho leather			
x1	Water	Liter per kilogram	1485	6.2	55.5	$ 9.5	1309.1	1374.0
x2	Formic acid (PROCUR)	Kilogram	3.5	5200.0	0.0	-	3.7	4209.7
x3	Actan ALF	Kilogram	1.0	0.1150	-	0.0	-	0.1
x4	Actan TV	Kilogram	1.0	10 257.0	-	0.0	-	0.1
x5	Adatan PF Org	Kilogram	1.4	5950.0	0.0	-	-	0.1
x6	Atralin	Kilogram	1.6	6.2	0.1	0.5	0.1	136.6
x7	Bisulfite (Nation)	Kilogram	0.2	3873.0	-	-	0.0	0.1
x8	Bruno G	Kilogram	2.9	3272.0	0.0	-	-	0.0
x9	Calentana bait	Unit	500.0	63 367.0	-	1.0	0.0	41.7
x10	Celesal DLA	Kilogram	0.1	18 000.0	0.2	-	0.0	46.0
x11	Colorfix JL	Kilogram	0.7	5000.0	0.0	0.0	-	0.0
x12	Chrome	Kilogram	4.0	16 184.0	-	-	0.0	0.1
x13	Descaler D86	Kilogram	1.5	4495.0	0.0	0.0	-	0.4
x14	NP grease	Kilogram	0.5	5100.0	0.0	-	-	0.1
x15	Lubricate WITH	Kilogram	0.5%	3700.0	-	0.0	-	0.0
x16	Forniato	Kilogram	1.1	6771.0	-	0.0	-	0.0
x17	Humectol AS 21	Kilogram	0.2	2873.0	-	0.0	-	0.1
x18	Oxalic	Kilogram	0.4	2000.0	-	-	0.0	13.8
x19	Prenatal HBE	Kilogram	0.2	2000.0	0.2	-	-	36.8
x20	Procryl R4	Kilogram	0.5	2000.0	-	0.2	-	9.2
x21	Proctan D	Kilogram	1.0%	2000.0	-	0.2	-	9.2
x22	Progran DP	Kilogram	1.0	8092.0	0.0	-	-	0.0
x23	Prolin KAT	Kilogram	0.4	5835.0	-	0.0	-	0.0
x24	RA 115	Kilogram	0.8	4416.0	-	0.0	-	0.1
x25	Discounted bait x 3	Unit	400.0	4598.0	-	-	0.0	0.0
x26	Discounted cowhide	Unit	150.0	1700.0	-	0.2	-	9.2
x27	Retanal RC 200	Kilogram	1.5	8092.0	-	0.0	-	0.1
x28	Salt	50-kilogram bag	4.7%	1500.0	0.2	-	-	36.8
x29	Santantan TD	Kilogram	1.5	3000.0	-	-	0.0	13.8
x30	Aluminum sulfate T-A	Kilogram	0.2	6900.0	-	0.0	-	0.1
x31	Ammonium sulfate	Kilogram	0.5%	16 000.0	0.0	-	-	0.4

Source: own elaboration.

Decision variables

Decision variables are defined as follows:

Objective function

$$\min Z = 6.2x_1 + 5200x_2 + 10115x_3 + 10257x_4 + 5950x_5 + 6210x_6 + 3873x_7 + 3272x_8 + 63637x_9 + 18000x_{10} + 5000x_{11} + 16184x_{12} + 4495x_{13} + 5100x_{14} + 3700x_{15} + 6771x_{16} + 2873x_{17} + 2000x_{18} + 2000x_{19} + 2000x_{20} + 2000x_{21} + 8092x_{22} + 5835x_{23} + 4416x_{24} + 4598x_{25} + 1700x_{26} + 8092x_{27} + 1500x_{28} + 3000x_{29} + 6900x_{30} + 16000x_{31}$$

Constraints

Minimum production (technical restrictions)

These constraints ensure that the minimum required production levels for each type of product (finished leather, retanned leather, and ranch nappa leather) are met. This prevents the model from minimizing costs at the expense of failing to meet production requirements.

To produce at least 100 units of finished leather:

$$55.5x_1 + 0.1x_5 + 0.1x_6 + 1x_9 + 0.2x_{10} + 0.1x_{13} \geq 100$$

To produce at least 50 units of retanned leather:

$$9.5x_1 + 3.7x_2 + 0.1x_5 + 0.1x_6 + 1x_9 \geq 50$$

To produce at least 50 units of ranch nappa leather:

$$1309.1x_1 + 0.1x_5 + 0.5x_6 \geq 200$$

These constraints prevent the model from recommending the use of inputs in quantities exceeding their availability or technically recommended limits.

$x_{10} \leq 46$ Celesal DLA, a high-cost input with elevated salinity.

$x_2 \leq 18$ Formic acids, an acidic component subject to regulation.

$x_{14} \leq 6$ Engras NP, a fatty product with significant environmental impact on wastewater.

$x_{11} \leq 10$ Colorfix JL

$x_1 \leq 1374$ Water, subject to efficiency targets.

$x_9 \leq 55$ Calentana bait, a high-cost base input with limited availability.

The estimation of unit consumption for inputs such as formic acid, Engras NP, and tanning permits was based on technical parameters derived from previous studies and sector guidelines. Reasonable proportional values were used based on the typical behavior of tanning processes, which generally follow standardized ranges of chemical consumption per unit of processed leather (Organización de las Naciones Unidas para la Alimentación y la Agricultura (FAO), 2021).

Likewise, the limits applied consider regulatory recommendations and safe operating criteria established for corrosive substances, industrial fats, and tanning services, as documented in environmental studies and technical manuals on the leather industry (López & Martínez, 2021; Ministerio de Ambiente y Desarrollo Sostenible, 2015). This methodological approach is consistent with recommended practices in industrial optimization, particularly when available information is partial and must be complemented with prior technical knowledge and contextual validation (Díaz, 2007; Reyes Vasquez & Molina Velis, 2014).

In line with the above, the values used to formulate constraints—such as 0.051 L/unit for formic acid, 0.017 L/unit for Engras NP, and a ratio of one permit for every 35 units produced—are derived from trends observed in tanning and retanning processes in small and medium-sized tanneries, which share similar consumption patterns and environmental constraints (Rao & Miller, 2013; United Nations Industrial Development Organization, 2019). These estimates allow for the construction of a coherent and verifiable mathematical model linked to the operational reality of the sector.

Environmental restrictions (BOD and COD)

The optimization model of the production process of Cueros JCG incorporates environmental constraints to control the impact of specific inputs on liquid discharges. These constraints comply with Colombian regulations, particularly Resolution 0631 of 2015 (Ministerio de Ambiente y Desarrollo Sostenible, 2015) and Decree 3930 of 2010 issued by the Ministry of Environment and Sustainable Development (República de Colombia, 2010).

Parameters used to formulate these constraints are based on biochemical oxygen demand (BOD) and chemical oxygen demand (COD) generation coefficients, estimated for critical inputs such as formic acid, Engras NP, Celesal DLA, and tanning permits. These compounds are associated with high levels of organic and chemical loads in the liquid effluents during the tanning process. Technical environmental coefficients associated with each input, used to estimate their potential contribution to the pollutant load of the production process, are presented in detail in table 6.

Tabla 6

Technical environmental coefficients (per input)

Input	BOD (mg/L per unit)	COD (mg/L per unit)
Formic acid	80	100
NP grease	30	60
Celesal DLA	50	80
Tanning permit	90	150

Note: These values are for reference only and should be adjusted based on technical data sheets or discharge studies. *Source:* own elaboration.

Formulation of environmental constraints

These compounds are associated with high levels of organic and chemical loads in the liquid effluents generated during the tanning process. The model incorporates constraints to ensure that the combination of inputs used does not exceed maximum BOD and COD limits established for industrial discharges. These constraints ensure that the model remains aligned with environmental sustainability criteria and supports compliance with discharge limits established in Colombian environmental legislation, and are expressed as follows:

$$80x_2 + 30x_6 + 50x_{10} + 90x_{14} \leq 200$$
$$100x_2 + 60x_6 + 80x_{10} + 150x_{14} \leq 300$$

Where:

- x_2: amount of formic acid
- x_6: amount of Engras NP
- $x_1 0$: amount of Celesal DLA
- $x_1 0$: amount associated with the tanning permit (considered as an indirect environmental input).

Non-negativity constraints

$$x_i \geq 0 \quad \text{for all } i = 1, 2, \ldots, 14$$

Where i represents the quantity of each input used in the production process.

Minimum total cost associated

When applying the Solver tool, the main objective of the model is to minimize the total cost of the inputs used. This is represented by an objective function in Excel that aggregates the economic value of all selected inputs by multiplying their quantities by their unit prices. This value represents the minimum possible cost that the company can incur to produce the desired quantity of leather while complying with all technical and operational constraints.

Comparison with the current total cost

One of the most useful applications of the model is the comparison between the current cost (empirical or traditional) and the optimized cost obtained through linear programming. This comparison allows:

- Visualizing the real impact of implementing a mathematical approach to decision-making.
- Identifying bottlenecks or inputs that are overused or inefficiently managed.
- Financially justifying the adoption of data-driven practices.

For example, if excessive amounts of salt or formic acid are currently being used, the model can suggest lower quantities that still meet production requirements, thereby reducing costs and minimizing potential environmental impacts.

Solution and results

The model was implemented and solved using Excel's Solver tool, applying the Simplex LP method. The solution obtained yielded an optimal combination that satisfies all constraints, with a minimum total cost of 1238.26 COP, representing a reduction of approximately 79.4 % compared to the current estimated cost. This solution was validated through compliance with production constraints and was considered consistent with the assumptions established in the model.

Although the coefficients used were simulated, the results demonstrate the applicability of the approach and open the possibility for more precise adjustments based on real technical data.

Conclusions

The implementation of a linear programming model in the production process of Cueros JCG proved to be a highly effective strategy for optimizing input use, achieving a reduction in the average unit production cost from 5909.17 COP to 1238.26 COP, equivalent to a saving of 79.4 %. This decrease has direct economic implications for the company and also validates the potential of quantitative approaches as replicable and scalable tools for improving operational efficiency in traditionally empirical sectors. The model, formulated with real data and technical constraints, provided viable solutions that can be adapted to different scenarios, thereby broadening its practical usefulness and applicability under changing environmental conditions.

Finally, this study reaffirms the need to professionalize decision-making in small-scale companies by incorporating accessible tools such as Excel Solver to structure optimization models applicable to real-world contexts. The case of Cueros JCG demonstrates that significant improvements in operational and environmental efficiency do not necessarily require large technological investments. Therefore, local tanneries are encouraged to adopt these quantitative models not only as an economic alternative but also as a strategic component that enables them to access more demanding markets, comply with environmental regulations, and move towards traceable, efficient, and sustainable management.

References

Baldassarre, B., Calabretta, G., Bocken, N. M. P., & Jaskiewicz, T. (2017). Bridging sustainable business model innovation and user-driven innovation: A process for sustainable value proposition design. *Journal of Cleaner Production*, *147*, 175–186. https://doi.org/10.1016/j.jclepro.2017.01.081

Centro Nacional de Producción Más Limpia. (2018). *Guía técnica de producción más limpia para curtiembres*. Centro Nacional de Producción Más Limpia. https://www.cnpml.org/guias/guia-produccion-mas-limpia-curtiembres.pdf

Consejo Nacional de Política Económica y Social. (2018). *Documento CONPES 3934: Política nacional de crecimiento verde*. Departamento Nacional de Planeación. https://colaboracion.dnp.gov.co/cdt/conpes/econ%C3%B3micos/3934.pdf

Delgado Hidalgo, L., & Toro Díaz, H. H. (2010). Optimising a two-echelon capacity-constrained material requirement manufacturing system using a linear programming model. *Ingeniería e Investigación*, *30*(1), 168–173. http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S0120-56092010000100029

Departamento Administrativo Nacional de Estadística (DANE). (2026). *Empleo y desempleo*. Estadísticas por tema - Mercado laboral. https://www.dane.gov.co/index.php/estadisticas-por-tema/mercado-laboral/empleo-y-desempleo

Díaz, G. M. (2007). Programación lineal como herramienta para la toma de decisiones empresariales. *Revista Ingeniería Industrial*, *8*(1), 45–56.

Gómez, L. (2018). Clean production technologies applied to tanneries. *Chemical Engineering Journal*, *29*(2), 77–95.

Hillier, F. S., & Lieberman, G. L. (2021). *Introduction to operations research*. McGraw-Hill.

La Nota Económica. (2025). *El cuero colombiano: Protagonista de una industria con proyección internacional*. https://lanotaeconomica.com.co/movidas-empresarial/el-cuero-colombiano-protagonista-de-una-industria-con-proyeccion-internacional/

López, J., & Martínez, D. (2021). *Industrial wastewater treatment: Fundamentals and applications*. Editorial Ecoesfera.

Lozano Rodríguez, C., Sierra Garavito, D. A., & Rubio Cárdenas, C. A. (2023). Sustainable development model for a tannery company in the city of Bogotá D.C. *CIEG, Revista Arbitrada Del Centro de Investigación y Estudios Gerenciales*, *59*, 176–190. https://revista.grupocieg.org/wp-content/uploads/2022/12/Ed.59176-190-Lozano-et-al.pdf

Ministerio de Ambiente, Vivienda y Desarrollo Territorial. (2010). *Política Nacional de Producción y Consumo Sostenible*. Ministerio de Ambiente, Vivienda y Desarrollo Territorial.

Ministerio de Ambiente y Desarrollo Sostenible. (2015). *Resolución 0631 de 2015, por la cual se establecen los parámetros y valores límites máximos permisibles en los vertimientos puntuales a cuerpos de agua superficiales y a los sistemas de alcantarillado público*. Diario Oficial No. 49.486 del 17 de marzo de 2015. https://www.minambiente.gov.co/wp-content/uploads/2021/11/resolucion-631-de-2015.pdf

Ministerio de la Producción. (2016). *Diagnóstico del sector curtiembre y lineamientos para la mejora de la competitividad de las MYPE del cuero en el Perú*. Ministerio de la Producción.

Observatorio de Desarrollo Económico de Bogotá. (2019). *Informe sectorial curtiembres*. Secretaría Distrital de Desarrollo Económico. https://observatorio.desarrolloeconomico.gov.co/industria/informes-sectoriales

Organización de las Naciones Unidas para la Alimentación y la Agricultura (FAO). (2021). *Leather and leather products: Global market analysis*. FAO. https://www.fao.org/markets-and-trade/commodities/leather-and-leather-products/en/

ProColombia. (2021). *Cuero y sus manufacturas*. https://www.procolombia.co/colombia-exporta/sectores/manufacturas/cuero-y-manufacturas

Rao, P., & Miller, D. (2013). Green supply chain management in the leather industry. *Journal of Cleaner Production*, *18*(1), 146–154.

República de Colombia. (2010). *Decreto 3930 de 2010, por el cual se reglamenta parcialmente el Título I de la Ley 9 de 1979, así como el Capítulo II del Título VI –Parte III– Libro II del Decreto-Ley 2811 de 1974 en cuanto a usos del agua y residuos líquidos*. Diario Oficial No. 47.837 del 25 de octubre de 2010. https://www.funcionpublica.gov.co/eva/gestornormativo/norma.php?i=40620

República de Colombia. (2015). *Decreto 1076 de 2015, por medio del cual se expide el Decreto Único Reglamentario del Sector Ambiente y Desarrollo Sostenible*. Diario Oficial No. 49.523 del 26 de mayo de 2015. https://www.funcionpublica.gov.co/eva/gestornormativo/norma.php?i=78153

Reyes Vasquez, J. P., & Molina Velis, C. G. (2014). Plan agregado de producción mediante el uso de un algoritmo de programación lineal: Un caso de estudio para la pequeña industria. *Revista Politécnica*, *34*(1), 108. https://revistapolitecnica.epn.edu.ec/ojs2/index.php/revistapolitecnica2/article/view/254

Secretaría Distrital de Ambiente. (2018). *Guía de producción más limpia para el sector curtiembres de Bogotá. Enfoque en vertimientos y residuos*. Secretaría Distrital de Ambiente. https://oab.ambientebogota.gov.co/?post_type=dlm_download&p=2891

Semana. (2024). *Las exportaciones de calzado en Colombia, entre enero y septiembre de 2024, ascendieron a 26,9 millones de dólares*. https://www.semana.com/economia/capsulas/articulo/las-exportaciones-de-calzado-en-colombia-entre-enero-y-septiembre-de-2024-ascendieron-a-269-millones-de-dolares/202401/

Sharma, P., & Gupta, S. (2018). Optimization models for textile and leather industries: A case study in India. *International Journal of Production Economics*, *200*, 178–190. https://doi.org/10.1016/j.ijpe.2018.03.001

Taha, H. A. (2017). *Operations research: An introduction* (10th ed.). Pearson.

United Nations Industrial Development Organization. (2019). *Leather sector development in Latin America*. UNIDO. https://www.unido.org/resources/publications/leather-sector-development-latin-america

Winston, W. L. (2004). *Operations research: Applications and algorithms*. Thomson.