

Integrating the sugar agro-industry value chain into knowledge management through mathematical models

Integración cadena de valor de la agroindustria azucarera a gestión del conocimiento: mediante modelos matemáticos

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ABSTRACT: The integration of the sugar agroindustry value chain into knowledge management seeks to enhance efficiency, innovation, and sustainability in this sector. This approach involves connecting the different links of the value chain, from the field to commercialization, through strategies that enable the capture, analysis, transfer, and effective use of knowledge. This research was framed within the development of the project 'Methodology for the Integrated Management of Sugarcane and Derivatives Value Chains in Sugar Agroindustrial Enterprises', which is associated with a National Program. Its objective was to determine the existence of a relationship and dependency among key variables through mathematical models within the sugar agroindustry value chain. The analysis, based on data from the AZCUBA Group, allowed the identification of five dependent and five independent variables, from which five linear models were generated. The results show that none of the models reached an optimal level of statistical significance; however, three of them (CT - ACI, I - MMA, and FL - CP) present weak relationships that, although insufficient in their current state, constitute initial approximations with potential for improvement through variable transformations or the incorporation of new predictors. Despite the weak relationships found, the study provides a methodological foundation that can guide future work toward more robust and useful models for the integrated management of the sugar value chain.

Keywords: sugar agroindustry, value chain, integrated management, regression models.

RESUMEN: La integración de la cadena de valor de la agroindustria azucarera a la gestión del conocimiento busca potenciar la eficiencia, la innovación y la sostenibilidad en este sector. Este enfoque implica conectar los diferentes eslabones de la cadena de valor desde el campo hasta la comercialización, con estrategias que permitan la captura, análisis, transferencia y el uso efectivo del conocimiento. Esta investigación se enmarcó en el desarrollo del proyecto "Metodología para la gestión integrada de las cadenas de valor del azúcar de la caña y derivados en Empresas Agroindustriales azucareras" que está asociado a un Programa Nacional, con el objetivo de determinar la existencia de una relación y dependencia entre las variables claves mediante modelos matemáticos en la cadena de valor de la agroindustria azucarera. El análisis basado en datos del Grupo AZCUBA, permitió identificar cinco variables dependientes y cinco independientes, de las cuales se generaron cinco modelos lineales. Los resultados muestran que ninguno de los modelos alcanza un nivel óptimo de significancia estadística; sin embargo, tres de ellos (CT - ACI, I - MMA y FL - CP) presentan relaciones débiles que, aunque insuficientes en su estado actual, constituyen aproximaciones iniciales con potencial de mejora mediante transformaciones de las variables o la incorporación de nuevos predictores. Aunque las relaciones encontradas son débiles, el estudio aporta una base metodológica que puede orientar futuros trabajos hacia modelos más robustos y útiles para la gestión integrada de la cadena de valor azucarera.

Palabras clave: agroindustria azucarera, cadena de valor, gestión integrada, modelos de regresión.

INTRODUCTION

The conditions of today's business environment, characterized by high complexity and strong competition, have made knowledge management a key element of vital importance for ensuring the long-term sustainability of

businesses and companies (Vitale *et al.*, 2020). In this context, the sugar agro-industry is directly linked to the fulfillment of several of the Sustainable Development Goals (SDGs), approved in the United Nations' 2030 Agenda and unanimously supported by political, economic, scientific, and social actors globally.

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In Cuba, it is essential to identify and manage the value chain of primary production, since it determines the aspects that influence productive growth and the profitability of institutions. The current state of the economy and the infrastructure of state-owned enterprises suggests increasing efforts to minimize deficiencies in production and service processes, in order to promote the economic improvement of the country and the entities involved. The value chain in knowledge management applied to the sugar agro-industry is a relevant topic, as it addresses how companies can optimize their processes and improve their competitiveness through the effective management of knowledge. The Cuban government's political will to achieve the development indicators is expressed in the Socialist Economic and Social Development Model and in the Foundations of the Development Plan to 2030 [Partido Comunista de Cuba \(2021\)](#), conceived from the guidelines of the Economic and Social Policy of the Party and the Revolution.

Achieving high levels of productivity and quality in the processes and products of the raw sugar value chain is a requirement of domestic and international markets, which demand increasingly higher standards. However, a low level of competitiveness is recognized, stemming from the poor production results of recent years, without specific measurements for the national sugar sector ([Caballero & Michelena, 2023](#)). Within this framework, the present research is part of the project *"Methodology for the Integrated Management of Sugarcane and Sugar Derivative Value Chains in Sugar Agro-industrial Companies,"* associated with a National Program. The main objective was to determine the existence of relationships and dependencies between key variables in the value chain through the application of mathematical models, specifically linear regression models, recognized as fundamental tools for describing and analyzing relationships between variables in various fields of science and engineering ([Montemayor et al., 2017](#); [Fernández et al., 2019](#)).

Linear regression models constitute an essential methodological tool for analyzing relationships in complex systems such as the sugar agro-industry value chain. Their application allows for the identification of patterns, the estimation of dependencies, and the projection of scenarios that facilitate strategic decision-making in integrated knowledge management. In this sense, linear regression provides statistical rigor and becomes a key support for optimizing processes, improving competitiveness and guiding sustainability policies in the agro-industrial sector ([García & López, 2023](#)).

MATERIALS AND METHODS

This research was descriptive-correlational and employed a mixed-methods approach. It is based on the combination of qualitative and quantitative tools to analyze the value chain of the sugar agro-industry from a knowledge management perspective. The theoretical framework used was based on [Sabato & Botana \(1970\)](#), which allows for understanding the interaction between the State, the

productive sector, and the scientific-technological system in the development of innovation, and [Porter \(1985\)](#), used to disaggregate and visualize the value chain processes into specific links. These approaches provided the conceptual basis for integrating knowledge management into the analysis of the sector's competitiveness.

Porter's Value Chain Design

The conceptualization of the raw sugar value chain in Cuba, adopted in 2020 ([Figure 1](#)), allowed for the identification of the processes and actors involved, as well as the risks that have the greatest impact on the quality and safety of the product. [Ruiz & Soto \(2022\)](#) identified the direct actors (those involved in the transformation or marketing of the product) and the indirect actors, those who supply inputs and services, as well as regulatory and certifying entities.

Sabato's Triangle Model

The triangle model ([Figure 2](#)) by [Sabato & Botana \(1970\)](#), was used as a framework to analyze the interaction between production factors, business management, and the institutional environment. This approach allowed for visualizing the interdependencies and establishing a conceptual framework for integrating knowledge management into the sugar value chain.

Comparison of ISO Standards

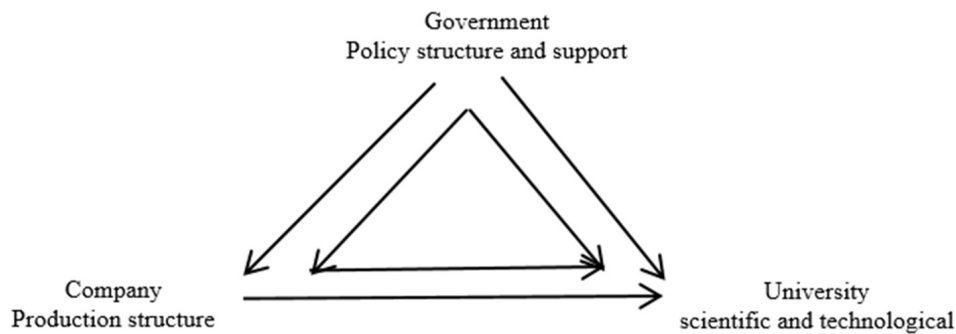
A comparative analysis was conducted of ISO standards related to value chain management and quality in agro-industrial processes. The lack of effective implementation of management systems based on ISO 9000 standards in the sugar sector over the last twenty years was found to be a factor affecting competitiveness. Except in rum production, where the introduction of risk management in these plants found widespread application and contributed to maintaining these products in the international market and increasing the product range, experts assessed that the use of these models is not visible in cooperatives, sugar factories, and other service entities.

A comparative table ([Table 1](#)) was prepared with the ISO standards related to quality management, food safety, and sustainability in agro-industrial processes. This comparison allowed for the identification of the requirements established by international standards and their contrast with current practices in the Cuban sugar agro-industry. The analysis was aimed at detecting compliance gaps, areas for improvement and opportunities for alignment with global standards, which constitutes a methodological input to strengthen the competitiveness and sustainability of the value chain.

Knowledge of the NC-ISO standard families that impact sustainability and competitiveness, and in particular the new NC-ISO 56002:2019 standard, will decisively contribute to the paradigm shift in the Cuban sugar sector. ([Caballero & Michelena, 2023](#)).



Figure 1. Raw sugar value chain in Cuba. Source: Ruiz & Soto (2022)



Statistical modeling using linear regression

The modeling was carried out using five pairs of key variables selected by experts from the AZCUBA Group, who validated their strategic relevance to the value chain. Simple linear models were fitted for each pair of variables, evaluating statistical significance using the p-value and explanatory power using the coefficient of determination (R^2). Different functional forms (linear, reciprocal, double reciprocal) were compared to select the best-fitting model. The procedure included:

- Definition of dependent and independent variables.
- Parameter estimation using ordinary least squares.
- Evaluation of model assumptions (normality of residuals, absence of autocorrelation).
- Selection of the model with the highest R^2 and analysis of its significance.

Regression Analysis - Linear model: $Y = a + bX$

- $Y \rightarrow$ the dependent or response variable.
- $X \rightarrow$ the independent or explanatory variable.
- $a \rightarrow$ the intercept or constant. Represents the value of Y when $X = 0$.
- $b \rightarrow$ the slope of the line. Indicates how much Y changes for each unit increase in X .

This process allowed the identification of weak relationships between the variables, constituting initial approximations with potential for improvement through transformations or the incorporation of new predictors (Montemayor *et al.*, 2017; Fernández *et al.*, 2019; García & López, 2023).

The selection and validation of the variables were carried out using expert criteria from the AZCUBA Group, who contributed specialized knowledge on the production and administrative processes of the sugar agro-industry. This process ensured the appropriateness of the variables used in the models and their relevance to the integrated management of the value chain.

Table 1. Comparison of ISO Standards related to the value chain

ISO Standards	Objective	Description
9001/2015 (Quality Management Systems)	To increase organizational awareness of tasks and commitment to meeting the needs and expectations of customers and stakeholders, achieving satisfaction through the quality of products and services.	- It proposes a well-defined Quality Management System. It is based on a framework that integrates established fundamental concepts, principles, processes, and resources related to quality. It helps companies achieve their objectives. Applicable to all organizations.
56002/2019 (Innovation Management)	To help organizations use the correct terminology for Innovation Management and communicate consistently about their processes, achievements, and learning paths.	-Applicable to all types of organizations -Innovations: product, service, process, model, and method, from incremental to radical -Approaches: internal and open innovation activities, driven by the user, the market, technology, and design
22301/2019 (Business Continuity Management)	To enable organizations to mitigate disruptions and ensure business continuity in the event of an incident.	-Based on a framework that integrates established fundamental concepts, principles, processes, and resources related to quality.
31000/2018 (Risk Management)	To manage the risks that organizations face.	-Used by any type of organization, regardless of the sector it belongs to -Offers decision-making, operational, and process strategies for risk management and adapts to any scenario.
28001/2021 (Supply Chain Security Management)	To improve security management in the supply chain by establishing standards to identify and control risks.	- Facilitates the company's integration into the market, boosting international trade and the movement of goods. - Ensures more efficient management and strengthens the company's image and credibility with customers. - Optimizes processes - Improves the monitoring of the flow of raw materials, goods, and merchandise.
14001/2015 (Environmental Management Systems)	To establish controls to address aspects that may be harmful to the environment, providing the legal framework to be followed in environmental matters.	-It helps organizations of all sizes in all sectors to make their daily operations more sustainable
22000/2018 (Food Safety Management Systems)	To ensure food safety from the beginning to consumption.	Applicable to any organization related to the food chain, from primary production to packaging manufacturing or distribution.
27001/2023 (Information Security Management Systems)	To ensure good practices to prevent risks and improve information processes.	-It requires a strategy aligned with the business and its objectives, resources and a set of activities directed and coordinated by a security organization that extends throughout the entire organization, from senior management to end users.

Source: Author's own elaboration

Cause-and-effect diagram

The analysis of the situation in the Cuban sugar sector, carried out by a Temporary Working Group made up of academics, specialists, and sector managers, proposed an action plan for its recovery. One of the actions is to design a new management model for this value chain. (AZCUBA, 2021).

According to Caballero & Michelena (2023), strategic foresight exercises were conducted in all sugar companies in the country, identifying internal strengths and weaknesses, as well as the threats and opportunities

presented by the environment. These were weighed, and possible scenarios for the recovery and development of each entity were conceived, along with their corresponding specific action plans.

The analysis revealed low competitiveness as the central problem, associated with deficiencies in management, the workforce, supply, machinery, the market, and the environment. This instrument complemented the statistical modeling by offering a qualitative perspective on the structural factors that condition the performance of the value chain.



Figure 3. Cause and effect of competitiveness in the sugar agro-industrial sector. Source: Caballero & Michelena (2023)

Selection of experts and key variables

The research used as methodological input the 10 key variables [1. Sugarcane Production (SC), 2. Working Capital (WC), 3. Management Model (MM), 4. Workforce (WM), 5. Profitability (P), 6. Innovation (I), 7. Utilization of Industrial Capacity (UIC), 8. Maintenance of Agricultural Machinery (MMA), 9. Resource Management (RM), and 10. Staff Training (ST)] previously defined by experts from the AZCUBA Group, who have extensive experience in the management of production and administrative processes in the sugar agro-industry. These variables, already validated in internal studies by the institution, were classified as dependent and independent and used directly in the statistical modeling.

The decision to work with these variables ensured the relevance of the analysis and its coherence with the sector's strategic objectives. These variables were integrated into five pairs of relationships, on which simple linear regression models were fitted. The analysis focused on evaluating the statistical significance of the parameters and the explanatory power of each model, in order to determine the existence of relationships and dependencies within the sugar agro-industry value chain.

RESULTS AND DISCUSSION

Measuring these variables not only provides a comprehensive view of the value chain performance in the sugar agro-industry, but also allows for the identification of key areas for improvement through knowledge management. The effective integration of these variables can contribute to greater competitiveness and sustainability in the sector. This approach was key to prioritizing continuous improvement interventions, based on statistical evidence.

Statistical modeling was carried out using the Statgraphics statistical software on 10 key variables previously defined by experts from the AZCUBA Group, organized into two groups:

- Independent variables: Innovation (I), Working Capital (TC), Workforce (W), Management Model (MM), and Profitability (P).
- Dependent variables: Industrial Capacity Utilization (ICA), Agricultural Machinery Maintenance (AMM), Staff Training (ST), Resource Management (RM), and Sugarcane Production (SMP).

Based on these variables, five simple linear regression models were designed, the results of which are presented below:

Relational analysis of key variables

The results show the fit of a linear model to describe the relationship between R and PC. The equation of the fitted model is $R = 10.5333 - 0.13333 * PC$. The p-value ≥ 0.10 indicates that there is no statistically significant relationship between R and PC at a 90% (or higher) confidence level.

Since the p-value is greater than 0.05, there is no evidence of serial autocorrelation in the residuals.

Of the fitted models, the linear model has the highest R-squared value, at 0.784314%. This is the currently selected model.

The relationship between R and PC was practically nil, with minimal explanatory power. This finding suggests that the raw material price is not a suitable predictor of performance under current industry conditions.

The results show the fit of a linear model to describe the relationship between investment (I) and the maximum average cost (MMA). The fitted model equation is $I = 7,37097 + 0,177419 * MMA$

Table 2. R and PC regression analysis

Dependent variable: R					
Independent variable: PC					
Standard T					
	Parameter	Estimate	Error	Statistic	P-Value
	Intercept	10.5333	4.73266	2.22567	0.0531
	Slope	-0.133333	0.499877	-0.266733	0.7957
Analysis of Variance					
Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	0.0484848	1	0.0484848	0.07	0.7957
Residual	6.13333	9	0.681481		
Total (Corr.)	6.18182	10			

Source: Statgraphic statistical program (Plus Version 5 Online)

Table 3. Regression Analysis I and MMA

Dependent variable: I					
Independent variable: MMA					
Standard T					
	Parameter	Estimate	Error	Statistic	P-Value
	Intercept	7.37097	3.12019	2.36234	0.0424
	Slope	0.177419	0.338795	0.523678	0.6132
Analysis of Variance					
Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	0.177419	1	0.177419	0.27	0.6132
Residual	5.82258	9	0.646953		
Total (Corr.)	6.0	10			

Source: Statgraphic statistical program (Plus Version 5 Online)

Table 4. CT and ACI regression analysis

Dependent variable: CT					
Independent variable: ACI					
Standard T					
	Parameter	Estimate	Error	Statistic	P-Value
	Intercept	15.5357	4.13894	3.75355	0.0045
	Slope	-0.678571	0.44144	-1.53718	0.1586
Analysis of Variance					
Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	1.17208	1	1.17208	2.36	0.1586
Residual	4.46429	9	0.496032		
Total (Corr.)	5.63636	10			

Source: Statgraphic statistical program (Plus Version 5 Online).

The $p\text{-value} \geq 0.10$ indicates that there is no statistically significant relationship between I and MMA at a 90% (or higher) confidence level.

Of the fitted models, the two-reciprocal model has the highest R-squared value, at 5.24431%. This is 2.28732% higher than that of the selected linear model.

The relationship between I and MMA showed a slight dependence. The low level of statistical significance

indicates that the model requires transformations of the variables to better capture the dynamics between investment and technological modernization.

The results show the fit of a linear model to describe the relationship between CT and ACI. The equation of the fitted model is $CT = 15,5357 - 0,678571 * ACI$

A $p\text{-value} \geq 0.10$ indicates no statistically significant relationship between CT and ACI at the 90% confidence level (or higher).

Table 5. FL and CP regression analysis

Dependent variable: FL					
Independent variable: CP					
Standard T					
	Parameter	Estimate	Error	Statistic	P-Value
	Intercept	7.0	2.58452	2.70843	0.0241
	Slope	0.264706	0.277816	0.952809	0.3656
Analysis of Variance					
Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	0.433155	1	0.433155	0.91	0.3656
Residual	4.29412	9	0.477124		
Total (Corr.)	4.72727	10			

Source: Statgraphic statistical program (Plus Version 5 Online)

Table 6. MG and AR regression analysis

Dependent variable: MG					
Independent variable: AR					
Standard T					
	Parameter	Estimate	Error	Statistic	P-Value
	Intercept	9.56522	3.22891	2.96237	0.0159
	Slope	-0.0217391	0.347448	-0.0625679	0.9515
Analysis of Variance					
Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	0.00197628	1	0.00197628	0.00	0.9515
Residual	4.54348	9	0.504831		
Total (Corr.)	4.54545	10			

Source: Statgraphic statistical program (Plus Version 5 Online)

Of the fitted models, the two-reciprocal model has the highest R-squared value, at 23.7509%. This is 2.95595% higher than that of the selected linear model.

The model relating CT to ACI showed a weak relationship, with a low coefficient of determination (R^2). Although insufficient in its current state, it constitutes an initial approximation that suggests the need to incorporate new predictors to improve its explanatory power.

The results show the fit of a linear model to describe the relationship between FL and CP. The equation of the fitted model is $FL = 7,0 + 0,264706 * CP$

A p-value ≥ 0.10 indicates no statistically significant relationship between FL and CP at the 90% confidence level (or higher).

Of the fitted models, the linear model has the highest R-squared value, at 9.1629%. This is the currently selected model.

The model linking FL to CP showed a weak relationship, although with some potential for improvement. The low competitiveness identified in the cause-and-effect diagram is reflected in this result, showing that the workforce, in its current state, does not significantly impact product competitiveness.

The results show the fit of a linear model to describe the relationship between MG and AR. The equation of the fitted model is $G = 9,56522 - 0,0217391 * AR$

With a p-value ≥ 0.10 , there is no statistically significant relationship between MG and AR at a 90% (or higher) confidence level.

Of the fitted models, the reciprocal Y model has the highest R-squared value, at 0.336606%. This is 0.293128% higher than the selected linear model.

The model relating MG and AR also showed a very low level of significance, making it inadequate to describe the relationship between these variables. This result coincides with the administrative deficiencies identified in the cause-and-effect diagram.

Of the five models evaluated, only three show a weak relationship between the variables, indicating potential for improvement, although they do not reach statistical significance. In particular, the double reciprocal model for CT-ACI shows the highest level of fit ($R^2 = 23.75\%$), constituting the most promising approach. Similarly, the double reciprocal model for I-MMA ($R^2 = 5.24\%$) and the linear model for FL-CP ($R^2 = 9.16\%$) show incipient relationships that could be strengthened through transformations of the variables or the incorporation of additional predictors. On the other hand, the R-PC and MG-AR models present extremely low R^2 values (0.78% and 0.33%, respectively), reflecting a lack of explanatory power and making them inadequate in their current form.

More suitable (though not optimal) models:

- CT-ACI (double reciprocal, $R^2 = 23.75\%$) → best overall fit.
- I - MMA (double reciprocal, $R^2 = 5.24\%$) → slight improvement compared to the linear model.
- FL - CP (linear, $R^2 = 9.16\%$) → weak relationship, but somewhat more consistent.
- Less suitable models:
- R - PC (linear, $R^2 = 0.78\%$) → almost no explanatory power.
- MG - AR (reciprocal, $R^2 = 0.33\%$) → practically no fit.

The coefficients obtained in these models indicate how the dependent variable changes in response to changes in the independent variables, allowing us to identify which factors have the greatest influence on product quality and customer satisfaction, as well as to evaluate the environmental impact associated with the implemented practices.

The results show that the relationships between the key variables are weak and do not reach optimal levels of statistical significance. However, three of the models (CT-ACI, I-MMA, and FL-CP) are initial approximations with potential for improvement through variable transformations or the incorporation of new predictors.

Comparison with ISO standards revealed gaps in the application of international standards, limiting the sector's efficiency and sustainability. These gaps partially explain the models' weakness, as the lack of alignment with globally recognized quality and management practices affects data consistency and the models' ability to capture significant relationships.

The cause-and-effect diagram complemented the statistical analysis by highlighting low competitiveness as a central problem, associated with deficiencies in administration, the workforce, supply, machinery, the market, and the environment. These structural factors condition the models' effectiveness and underscore the need for integrated management that combines innovation, operational efficiency, and compliance with international standards.

CONCLUSIONS

The findings suggest that integrating knowledge management into the sugar agro-industry is fundamental to boosting innovation, efficiency, and sustainability in the sector, which in turn could improve the quality and explanatory power of the models. Comparison with ISO standards related to value chain management identified gaps in the application of international standards, limiting the sector's efficiency and sustainability. Furthermore, the cause-and-effect diagram revealed low competitiveness as a central problem, associated with structural deficiencies in resource management, innovation, production and machinery utilization, low added value to products, and poor supply chain integration. These structural factors limit the effectiveness of the models and highlight the need for integrated management. The analysis showed

that the five adjusted mathematical models did not reach optimal levels of statistical significance; however, three of them (CT-ACI, I-MMA, and FL-CP) exhibit weak relationships that constitute initial approximations with potential for improvement through variable transformations and the incorporation of new predictors. In contrast, the R-PC and MG-AR models exhibit minimal explanatory power, rendering them inadequate in their current state. These results highlight the need to strengthen mathematical modeling to achieve a more robust representation of the interdependencies in the sugar value chain.

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