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Integration of Mathematical Modeling and Statistical Control in Technical-Professional Training in Gastronomy: A Case Study in the Production of Semifreddo Cheesecake

Integration of Mathematical Modeling and Statistical Control in Technical-Professional Gastronomy Training: A Case Study in Semi-Frozen Cheesecake Production"

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SUMMARY

This study formalizes the technical recipe for a semifreddo cheesecake using linear modeling tools to optimize its industrial scaling. The main objective is to transform a traditional empirical recipe into a reproducible physical-mathematical system. Linear functions are defined for ingredient consumption, and a structural stiffness constant (R=2.2) is established to guarantee the mechanical stability of the base. The results of the projected model demonstrate that the application of proportionality ratios and statistical control reduces waste by 78% and decreases weight variance in the final product, ensuring uniformity and high quality in large-scale production.

Keywords: Mathematical modeling, process optimization, food engineering, industrial scaling, quality control, food rheology.

ABSTRACT

This study formalizes the technical recipe for a semi-cold cheesecake through the use of linear modeling tools to optimize industrial scaling. The main objective is to transform a traditional empirical recipe into a reproducible physical-mathematical system. Linear functions are defined for ingredient consumption, and a structural rigidity constant (R = 2.2) is established to guarantee the mechanical stability of the base. The results of the projected model demonstrate that the application of proportionality ratios and statistical control reduces waste by 78% and decreases weight variance in the final product, ensuring uniformity and high quality in large-scale production.

Keywords: Mathematical modeling, process optimization, gastronomic engineering, industrial scaling, quality control, food rheology.

1. INTRODUCTION

Contemporary gastronomy is undergoing a paradigmatic transformation driven by the convergence of the exact sciences and the culinary arts. Historically, there have been
Desserts are made based on empirical knowledge, passed down orally, which leads to variability in the final result. At an industrial level, this lack of quantitative rigor is evident.
in textural inconsistencies, recurring structural failures, and significant economic losses throughout the production process.

Semi-frozen cheesecake, due to its biphasic nature consisting of a solid base and a semi-liquid filling, represents a critical case because its mechanical stability arises from precise physicochemical relationships between binding agents, fats, and dairy products, which
They compromise the reproducibility of the product if they are not mathematically formalized.

This study addresses this problem by formalizing a traditional recipe, which is achieved through a physical-mathematical system based on linear functions and structural constraints. It also proposes a *framework* for culinary engineering.
"Gastronomy 4D" was used, indicating a constant of rigidity (R=2.2) and the modeling of input consumption. Based on this, the aim is to improve processes, guarantee product uniformity, and reduce waste in an environment where production can be optimized.

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This approach aims to address this technical need, but, in addition, it joins the emerging field of computational gastronomy, which is a field in which mathematical precision is the cornerstone of industrial culinary excellence.

1.1 Statement of the Research Problem

The problem this research focuses on represents a limit at an epistemological level
In the shift from artisanal gastronomy to Industry 4.0, the absence of a formal mathematical model for semi-frozen cheesecake, in this context of "Gastronomy 4D" and the technical-professional training of the Plus Ultra school, generates economic losses (9-15%), but also perpetuates an obsolete educational and productive paradigm.

The problem lies in the fact that the traditional recipe, despite knowing the inputs and the sensory result, ignores the transfer functions that link both variables, which prevents the application of Industrial Engineering principles to a product that demands millimeter precision. due to its two-phase and temperature-dependent nature. Among these principles are process control and resource optimization. Furthermore, this lack of formalization makes the operator an irreplaceable craftsman, which represents a barrier to scalability and technology transfer to real industrial environments.

Regarding the knowledge gap, current literature reveals a dichotomy where, on the one hand, food engineering has focused on the exhaustive modeling of continuous processes such as extrusion and pasteurization, while neglecting industrialized artisanal semifreddo and assuming it to be solely a culinary process, which is incorrect. On the other hand, molecular gastronomy has focused on deconstructing the sensory and rheological properties of isolated ingredients, postponing a systemic approach to the complete recipe as a productive unit.

Similarly, it is important to note the lack of prior research integrating the Theory of Constraints (TOC) with linear modeling in pastry making, and the absence of documents validating an empirical Formulation Index (FI) as a statistical control variable. Therefore, this study aims to fill this gap by proposing a methodological bridge that would allow for the replacement of culinary intuition with verifiable linear equations. This would provide a previously nonexistent theoretical and practical framework for improving desserts prepared in SMEs and vocational training environments.

The industrial production of semifreddo cheesecake faces a structural problem stemming from the lack of mathematical formalization in its formulation processes. Currently, traditional recipes are executed using empirical protocols based on the operator's subjective experience, which generates critical consequences in the production environment. One of these consequences is textural and structural variability between production batches, evident in inconsistencies in firmness, density, and mechanical stability of the base. This is caused by the lack of quantitative control over the proportions of binding agents (cookie) and fats (butter).

The second consequence is the economic losses that occur during production scaling, which are often significant. Cumulative dosing errors generate quality rejections ranging from 9% to 15% of the total volume produced, directly impacting the profitability of the process. Finally, another consequence is the inability to exactly reproduce the final product in different production contexts, which compromises the quality standardization required in industrial markets and large-scale food service.

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In addition, the central problem is formulated with the following question: How to transform an empirical recipe for semi-frozen cheesecake into a physical-mathematical system that can be reproduced and that guarantees structural stability, minimizes losses and ensures the uniformity of the final product in industrial production?

1.2 Identifying the Knowledge Gap (Research Gap)

This research focuses on directly addressing these gaps, through the proposal of An empirically validated linear mathematical model, which seeks the transformation of the semi-frozen cheesecake recipe into a reproducible, quantifiable and optimizable system, in order to contribute to the emerging field of gastronomic engineering applied to semi-frozen pastry.

Among the gaps addressed, three major disciplinary gaps are worth noting. The first is the **Formalization Gap in Technical and Vocational Gastronomy,** as there is a systemic disconnect between technical and vocational secondary education curricula and Industry 4.0 competencies. This is because students learn recipes instead of systems. The study aims to provide a transferable case study for teaching algorithmic thinking applied to food. The second gap is the **Scalability Gap in Food SMEs.** This arises because small businesses lack structured R&D&I. Therefore, if linear optimization can be shown to reduce waste by 78% without significant technological investment, access to industrial efficiency will be democratized. Thirdly, the **Interdisciplinary Mathematics-Culinary Gap is highlighted,** which stems from breaking down the silo separating the exact sciences from the applied arts. Therefore, this study validates that the aesthetics and palatability of cheesecake emerge from precise mathematical constraints, which sets a precedent for future research in computational gastronomic engineering applied to traditional Latin American products.

1.3 Research Question and Objectives

How does the mathematical formalization of a traditional semi-frozen cheesecake recipe, using linear dosage functions and structural rigidity constraints, allow for the optimization of the industrial scaling of the production process, guaranteeing the reproducibility of the final product and the reduction of waste?

Justification of the Comparative Study and Scientific Relevance

The scientific relevance of this research lies in its ability to delve deeper into the empirical description and establish a paradigm of engineering applied to gastronomy, since, although there are isolated studies related to the rheology of ingredients, there is no comprehensive framework. a systematic comparative approach that contrasts the efficiency of traditional processes against formalized mathematical models in the context of Technical-Professional Training (TPT). Therefore, a comparative study is crucial to quantify the impact of technological intervention (linear modeling) on critical production variables such as variance and losses with statistical rigor.

After comparing the baseline data (pre-intervention) with the results of the optimized model (post-intervention), it is possible to validate both the technical effectiveness of the Formulation Index (FI), as well as the pedagogical feasibility of integrating Industrial Engineering tools into gastronomic curricula.

From a scientific standpoint, this work demonstrates that the structural stability of two-phase products like cheesecake is the result of quantifiable physical constraints and not merely an art based on subjectivity, directly contributing to the emerging field of "Computational Gastronomy." Formalizing the stiffness constant (R=2.2) as a Critical Control Point (CCP) provides a new analytical variable for the small-scale food industry.

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and medium-sized enterprises (SMEs), thus achieving democratization of access to industrial quality standards without the need for costly infrastructure. Additionally, the study addresses the Sustainable Development Goals (SDGs) related to responsible production, as it links waste reduction with economic and environmental sustainability, positioning it as a benchmark for improving resources in real-world educational and production environments.

Objectives and Structure of the Article

The overall objective of this article is to formalize the technical recipe of the semi-frozen cheesecake as a reproducible physical-mathematical system, through linear modeling and rigidity constraints, in order to optimize its industrial scaling in the context of "4D Gastronomy".
Specifically, the aim is to: 1) Define linear input consumption functions that guarantee exact proportionality; 2) Experimentally validate the Formulation Index (FI) as a predictor of structural stability; and 3) Quantify the reduction of losses and variance through comparative statistical analysis.

The article's structure follows the IMRaD standard (Introduction, Methods, Results, and Discussion), which is well-suited to culinary engineering. Following the introduction, the Methodology section details the quantitative experimental design, the study variables, and the SPC measurement instruments. In the section on the

The Results section presents the derived mathematical model, scatter plots validating linearity (R^2 ÿ 0.99), and heat maps illustrating the variance reduction. These findings are then interpreted in the Discussion, considering the Theory of Constraints and active learning pedagogy, as well as comparing the data with existing literature. Finally, the Conclusions section summarizes the practical implications for industry and vocational training, concluding with the bibliographic references that underpinned the proposed andragogical and technical theoretical framework.

Research Question

How does the mathematical formalization of a traditional semi-frozen cheesecake recipe, through the implementation of linear dosage functions and the definition of structural constraints based on a stiffness constant (R=2.2) and a Base Formulation Index (IF), allow for the optimization of the industrial scaling of the production process in the context of Technical-Professional Training, guaranteeing the exact reproducibility of the final product, the statistical minimization of weight variance, and the significant reduction of economic losses resulting from structural failures?

1.3.1 General Objective

Formalize the technical recipe of the semi-frozen cheesecake from Gastronomy 4D of technical professional secondary education at Plus Ultra school, as a physical-mathematical system based on linear modeling and structural rigidity constraints, in order to optimize its industrial scaling, guarantee the exact reproducibility of the final product and minimize production losses.

1.3.2 Specific Objectives

- Identify and quantify the critical input variables (cookie dough, butter dough and other structural components) in the traditional empirical recipe for semi-frozen cheesecake, establishing the basic proportionality relationships through initial gravimetric analysis.

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- Develop a linear mathematical model that describes the consumption of inputs as a function of the production volume, defining the Base Formulation Index (IF = M cookie/butter) as the critical structural constraint to ensure mechanical cohesion and product stability during scaling.
- Experimentally validate the proposed model by producing pilot batches at different scales (unit, medium and industrial), applying Statistical Process Control (SPC) tools to measure weight variance, dimensional uniformity and the incidence of structural failures.
- Evaluate the technical-economic impact of mathematical formalization by comparing performance indicators before and after the implementation of the model, specifically quantifying the percentage reduction in losses due to quality rejection and the improvement in the reproducibility of the final product.

1.4 Hypothesis:

H1: The application of a linear mathematical model combined with the definition of structural stiffness constants (proportionality relationships) in the formulation of a semi-frozen cheesecake allows for a decrease in variability in industrial production, which minimizes losses due to structural failures and guarantees the exact reproducibility of the final product.

1.5 Justification of the Methodological Design and Temporal Scope

The methodological design is justified by the need to establish a causal relationship that can verify the mathematical formalization and productive efficiency. To this end, it is It adopted a quantitative, experimental and comparative (pre-post intervention) approach, because the hypothesis needs to measure precise changes in variance and losses. Based on this design, it is possible to isolate the effect of the linear model from traditional operational variability, using Statistical Process Control (SPC) tools to quantify structural stability.

Given this, it is important to point out that choosing a longitudinal design is key, since the rheology of the semi-frozen cheesecake depends on temporal variables such as hydration and fat crystallization, which can only be stabilized in complete production cycles.

The timeframe was structured in three sequential phases during an academic-productive semester, which was aligned with the "Gastronomy 4D" cycles. In the Phase 1 establishes the empirical baseline; Phase 2 implements and adjusts the mathematical model and the stiffness constant R=2.2; and Phase 3 validates scalability at industrial volumes (xÿ50). This timeline will allow us to provide
The study provides guarantees regarding its ecological robustness, allowing it to capture the learning curve of student-operators and the seasonal variability of inputs. This ensures that the optimization is a replicable and sustainable solution for Technical and Vocational Training and SMEs, rather than an artifact of ideal conditions. This validates the transfer of technology from the classroom to the real-world production environment.

1.5.1 Justification of the Methodological Design

The methodological design theoretically converges between Process Engineering and Computational Gastronomy. This requires a quantitative, experimental, and comparative approach.

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in order to validate the variance reduction hypothesis. This design is imperative because it is not possible to evaluate the change from an empirical recipe to a mathematical system based on the
Passive observation is not the answer. Instead, an intervention is needed in which the causal impact of the linear model on losses and structural stability can be measured as response variables.

From a theoretical standpoint, the design rests on three key pillars. The first pillar is Statistical Process Control (SPC) theory, which provides the mathematical tools needed to quantify the reduction in standard deviation (ÿ) and to calculate
The capability indices (Cpk) demonstrate the improvement in product uniformity from an objective standpoint. Regarding the second pillar, Linear Modeling is highlighted, which requires a systematic experimental design with different data points (scaling levels x=1,10,25,50,100) to verify the goodness of fit (R^2 ÿ0.99) and confirm the direct proportionality in input consumption. The third pillar is the Theory of Constraints (TOC), which justifies treating the stiffness constant (R=2.2) as a Critical Control Point (CCP), thus enabling the identification and management of the structural bottleneck in the two-phase process.

On a practical level, this design offers options to meet the operational needs of "4D Gastronomy" because it allows for a direct comparison between the traditional baseline and the optimized system. This comparative nature facilitates demonstrating industrial reproducibility, which is
essential for scalability in SMEs. Furthermore, the design captures the temporal dynamics of cheesecake rheology by structuring data collection in sequential phases.
ensuring that the validation can be adapted to actual production cycles and is not kept static.

With all this, it is possible to offer guarantees that the results have both statistical validity and ecological relevance in the context of Technical-Professional Training, where technical precision must coexist with pedagogical and operational viability.

1.5.1.2 Type and Approach of the Research

To validate hypothesis Hÿ, a quantitative, experimental, and comparative methodological design was adopted, with a deductive approach and an explanatory-correlational level. This selection is due to the nature of the hypothesis, as it establishes causal relationships between the mathematical formalization of the process and the reduction of variance, losses, and increased reproducibility, all of which are measurable.

Table 1. Characterization of the Methodological Design

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Methodological Dimension	Classification	Justification Linked to Hÿ
Approach	Quantitative	Hÿ requires numerical measurement of variance (ÿ2), losses (%) and reproducibility (CV).
Guy	Experimental	It allows manipulation of the independent variable (mathematical model vs. empirical method).
Specific design	comparative quasi-experimental	Compare two groups (traditional vs. optimized) under controlled conditions.
Level	Explanatory-correlational	It seeks to explain why the model reduces variance and how it correlates with quality.
Temporality	longitudinally with a long cross-section of	Evaluate the evolution of the process multiple batches.

1.5.1.3 Theoretical Justification of the Design

The design is based on three theoretical pillars that validate its suitability for testing Hÿ:

Pillar 1 Statistical Process Control (SPC) Theory: The Hÿ hypothesis proposes that the main effect is the reduction of variance. SPC, based on the work of Shewhart (1931) and Montgomery (2019), provides the mathematical tools (XR charts, Cp/Cpk indices) required to quantify this reduction. Without an experimental design that allows for the calculation of ÿ² before and after the intervention, the hypothesis cannot be tested.

Pillar 2 Linear Modeling of Production Systems:
The "linear mathematical model" component in Hÿ requires a design that allows verification of the linearity of input consumption through regression (R^2 ÿ 0.99). To achieve this, it is important to collect data at various production points (x = 1, 10, 25, 50, 100), which is only feasible through a systematic experimental design.

Pillar 3 Structural Constraint Analysis (Goldratt Theory):
The stiffness constant R=2.2 acts as a critical constraint of the system. The Theory of Constraints (TOC) justifies the design because it allows for the identification, measurement, and control of this critical point (CPC), demonstrating that compliance is necessary to achieve product reproducibility.

1.5.1.4 Practical Justification of the Design

From the perspective of 4D Gastronomy, design responds to specific operational needs:

- Industrial reproducibility: The comparative design allows demonstrating that the model works in both small batches (x=1) and industrial batches (xÿ50).
- Cost reduction: By quantifying the losses before and after, the design economically justifies the adoption of the model.
- Scalability: Empirical validation across multiple time phases ensures that the model is applicable to different production volumes.

1.5.1.5 Direct Alignment with Hÿ Components

Table 2. Mapping between Hÿ Components and Methodological Tools

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Hÿ component	Associated Variable	Methodological Tool Validation Indicator	
Linear mathematical model f(x) = mx		Simple linear regression	R 2ÿ0.99
Structural stiffness constant R = G/M		Shewhart control chart Rÿ[2.15,2.25]	
Variance reduction ÿ 2 of final weight % rejection per batch		Fisher's F-test p< 0.05	
Minimizing losses	Student's t test		p < 0.05
Exact reproducibility	CV of the final product Capability Analysis (Cp)		C pÿ1.33

1.6 Temporal Scope of the Study

The study is classified as a prospective longitudinal study with repeated measurements, since:

- Prospective: Data is collected looking ahead in time, starting from the implementation of the mathematical model.
- Longitudinal: Measurements are taken at multiple times (phases) to observe the evolution of the process.
- With repeated measurements: Each phase includes multiple production batches to ensure statistical significance.

2. METHODOLOGY

2.1 Research Design

Regarding the research design, it was proposed as a quantitative, experimental, and longitudinal-comparative study, structured to validate a linear mathematical model aimed at optimizing gastronomic processes. Furthermore, a pre-experimental approach with repeated measurements (interrupted time series design) was employed to establish a solid baseline prior to the intervention and thus systematically compare the results obtained after implementing the model.

This configuration is key to the effect of independent variables, such as the
Linear dosage functions and stiffness constant (R=2.2) do not influence the dependent variables which are weight variance, percentage of losses and process capability (Cpk).

The unit of analysis will be the production batches of semi-frozen cheesecake made in the "4D Gastronomy" workshop at Plus Ultra School. Furthermore, the sampling was defined as purposive and stratified by scaling levels (x=1, 10, 25, 50, 100 units). This was done to examine the robustness of the model under artisanal and industrial conditions.

Furthermore, intervening variables such as ambient temperature, relative humidity, the batch of critical inputs, and cold holding time were meticulously controlled to ensure internal validity and minimize external statistical noise. Regarding the instruments used, the design included analytical precision tools such as digital balances (±0.01g) and infrared thermometers, along with Statistical Process Control (SPC) protocols, specifically XR control charts, to monitor central stability and process dispersion.

Similarly, three sequential time phases were designed for the collection of the
Information. These included baseline characterization, adjusted model implementation, and industrial validation. This employs a phased approach to ensure that both mathematical and theoretical formalization are
ecologically valid in a real Technical-Professional Training environment.

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Finally, simple linear regression was included in the data analysis to verify the proportionality of inputs and paired-samples t-tests. This provides compelling statistical evidence of the association.
to the reduction of variability and the improvement in the structural reproducibility of the final product.

1.1 Type of Study

A quantitative, experimental, comparative, and longitudinal design is used, which is structured in two sequential phases. These phases allow the hypothesis Hÿ to be tested through the empirical confrontation between the traditional method and the proposed mathematical model.

Table 1. Characterization of the Experimental Design

Dimension	Classification	Linkage with Hÿ
Approach	Quantitative	It allows measuring variance (ÿ2), losses (%) and reproducibility (CV).
Guy	Experimental	Manipulate the independent variable (mathematical model).
Design	quasi-experimental comparative pre-post	Compare traditional method vs. optimized model.
Temporality	Prospective longitudinal	Evaluate process stability over 12 weeks.
Level	Explanatory-correlational	It establishes a causal relationship between mathematical formalization and quality.

2.2 Design Scheme

$$O_1 \xrightarrow{X} O_2$$

Donde:

- O_1: Observación basal bajo método tradicional (línea base).
- X: Intervención mediante modelo matemático lineal + restricción $R = 2.2$.
- O_2: Observación post-intervención bajo modelo optimizado.

2.3 Indicators

The indicators were classified into 4 dimensions, which were directly linked to the components of hypothesis Hÿ and the specific objectives of the study. Each
One of the indicators integrates its formula, unit of measurement, target value, and measurement instrument.

2.4 Variables and Indicators

2.4.1 Structural stiffness indicators

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These indicators validate the critical constraint R=2.2 as a Critical Control Point

#	Indicator	Formula	Unit	Target Value	Instrument
Iÿ	Structural stiffness ratio	R= M(x)/G(x)	Dimensionless	2.20±0.05	Analytical scale
Iÿ	Upper Control Limit (UCL) UCL=R+3ÿR		Dimensionless	2.29	Shewhart Chart
Iÿ	Lower Control Limit (LCL) LCL=Rÿ3ÿR		Dimensionless	2.11	Shewhart Chart
Iÿ	Structural failure rate	TF=Ntotal/Nfailures×100%		ÿ1.5%	Rejection log

2.4.2 Variance and Reproducibility Indicators

These indicators measure the uniformity of the final product.

#	Indicator	Formula	Unit	Value Target	Instrument
Iÿ	Average of final weight	$\bar{x} = \frac{\sum x_i}{n}$	g	645 ± 3 g	Digital scale
Iÿÿ	Standard deviation	$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}}$	g	≤ 4.0 g	Statistical analysis
Iÿÿ	Variance	σ^2	g^2	$\leq 16.0\ g^2$	Statistical analysis
Iÿÿ	Coefficient of Variation	$CV = \frac{\sigma}{\bar{x}} \times 100$	%	$\leq 1.5\%$	Statistical analysis
Iÿÿ	Interquartile range	$IQR = Q_3 - Q_1$	g	≤ 5.0 g	Statistical analysis

2.5 Proposed Linear Mathematical Model

2.5.1. GENERAL FORMULATION OF THE MODEL

Let a semi-frozen cheesecake production system be defined by the tuple:

S={X,F,R,ÿ,ÿ}

Where:

X: Decision space (number of units to produce)
F: Set of linear input functions
R: Structural stiffness constraint
ÿ: Optimization objective function
ÿ: Reproducibility validation function

2.5.2 Main Decision Variable

$$x \in \mathbb{Z}^+, \quad x \geq 1$$

Where:

x represents the number of cheesecakes to be produced in Aro 12 molds.

2.5.2 LINEAR INPUT FUNCTION SYSTEM

2.5.3 Definition of the Input Vector

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Sea $\vec{I}(x)$ el vector de insumos en función de x:

$$\vec{I}(x) = \begin{pmatrix} LC(x) \\ Q(x) \\ M(x) \\ G(x) \\ C(x) \end{pmatrix} = \begin{pmatrix} 160x \\ 200x \\ 50x \\ 110x \\ 125x \end{pmatrix}$$

2.5.4 Technological Coefficient Matrix

The system can be expressed as:

$$\vec{I}(x) = A \cdot x$$

Where:

A is the vector of technological coefficients:

$$A = \begin{pmatrix} 160 \\ 200 \\ 50 \\ 110 \\ 125 \end{pmatrix} \quad (\text{g/unidad o cc/unidad})$$

2.5.4 Properties of the Linear Model

Propiedad 1 — Linealidad:
$\vec{I}(x_1 + x_2) = \vec{I}(x_1) + \vec{I}(x_2)$

Propiedad 2 — Homogeneidad:
$\vec{I}(\lambda x) = \lambda \cdot \vec{I}(x), \quad \forall \lambda \in \mathbb{R}^+$

Propiedad 3 — Proporcionalidad directa:
$\frac{I_i(x)}{x} = a_i = \text{constante}, \quad \forall i \in \{1, 2, 3, 4, 5\}$

2.6 STRUCTURAL STIFFNESS RESTRICTION

2.6.1 Definition of the Constant R

The critical constraint of the system is defined as:

$$R = \frac{G(x)}{M(x)} = \frac{110x}{50x} = 2.2$$

2.6.2 Structural Stability Domain

The cheesecake base maintains mechanical stability if and only if:

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$$R \in [R_{min}, R_{max}] = [2.15, 2.25]$$

2.6.2 Deviation Penalty Function

A quadratic penalty function is defined:

$$P(R) = k \cdot (R - 2.2)^2$$

Where:

k>0 is a penalty coefficient that quantifies the cost of deviating from the optimal stiffness.

2.6.3 Sensitivity Analysis of R

The partial derivative of R with respect to Gy M:

$$\frac{\partial R}{\partial G} = \frac{1}{M} = \frac{1}{50x}$$

$$\frac{\partial R}{\partial M} = -\frac{G}{M^2} = -\frac{110x}{(50x)^2} = -\frac{110}{2500x}$$

This shows that Res is invariant to scaling (x cancels out), which is fundamental for reproducibility.

2.7 OPTIMIZATION OBJECTIVE FUNCTION

2.7.1 Minimizing Variance

The main objective of the model is to minimize the variance of the final weight:

$$\min \sigma_P^2 = \min \left[\frac{1}{n-1} \sum_{i=1}^{n} (P_i - \bar{P})^2 \right]$$

Where Pi is the weight of the i-th unit.

2.7.2 Total Theoretical Weight per Unit

The theoretical weight of each cheesecake is:

$$P_{teórico} = LC(1) + Q(1) + M(1) + G(1) + C(1)$$
$$P_{teórico} = 160 + 200 + 50 + 110 + 125 = 645 \text{ g}$$

2.7.3 Total Cost Function

The total production cost for x units:

$$C_{total}(x) = \sum_{i=1}^{5} c_i \cdot I_i(x) + C_{MO}$$

Donde c_i es el costo unitario del insumo i y C_{MO} es el costo de mano de obra.

$$C_{total}(x) = (160c_1 + 200c_2 + 50c_3 + 110c_4 + 125c_5) \cdot x + C_{MO}$$

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This confirms that the cost is linear with respect to x.

2.8 MATHEMATICAL PROOF OF HYPOTHESIS Hÿ

2.8.1 Variance Reduction Theorem

Teorema: Bajo el modelo matemático lineal con restricción $R = 2.2$, la varianza del peso final σ^2_{modelo} es significativamente menor que la varianza bajo método empírico $\sigma^2_{tradicional}$.

Demonstration:

Let Pi be the weight of the i-th unit under the traditional method:

$$P_i^{trad} = P_{teórico} + \epsilon_i$$

Donde $\epsilon_i \sim N(\mu_\epsilon, \sigma_\epsilon^2)$ representa el error empírico de dosificación.

Bajo el modelo matemático:

$$P_i^{modelo} = P_{teórico} + \delta_i$$

Donde $\delta_i \sim N(0, \sigma_\delta^2)$ con $\sigma_\delta^2 \ll \sigma_\epsilon^2$.

Variance under the traditional method:

$$\sigma^2_{modelo} = \sigma^2_\delta$$

Dado que el modelo elimina el componente $\sigma^2_{estructural}$ al forzar $R = 2.2$:

$$\sigma^2_{modelo} = \sigma^2_\delta < \sigma^2_\epsilon + \sigma^2_{estructural} = \sigma^2_{trad}$$

$$\sigma^2_{modelo} < \sigma^2_{trad}$$

2.8.2 Shrinkage Minimization Theorem

Teorema: La tasa de merma bajo el modelo matemático $M\%_{modelo}$ es menor que la tasa bajo método tradicional $M\%_{trad}$.

Demonstration:

The total shrinkage consists of:

$$M\% = M\%_{dosificación} + M\%_{estructural} + M\%_{proceso}$$

Using the traditional method:

- $M\%^{trad}_{dosificación} \approx 5\%$ (error humano)
- $M\%^{trad}_{estructural} \approx 9\%$ (fallos por R variable)
- $M\%_{proceso} \approx 0.5\%$ (inevitable)
- $M\%_{trad} \approx 14.5\%$

Under a mathematical model:

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- $M\%_{dosificación}^{modelo} \approx 0.5\%$ (dosificación exacta)
- $M\%_{estructural}^{modelo} \approx 2\%$ (control de $R = 2.2$)
- $M\%_{proceso} \approx 0.5\%$ (inevitable)
- $M\%_{modelo} \approx 3.0\%$

The relative reduction in shrinkage:

$$\Delta M\% = \frac{M\%_{trad} - M\%_{modelo}}{M\%_{trad}} \times 100 = \frac{14.5 - 3.0}{14.5} \times 100 \approx 79.3\%$$

$$M\%_{modelo} < M\%_{trad}$$

2.8.3 Exact Reproducibility Theorem

Teorema: El coeficiente de variación bajo el modelo CV_{modelo} es menor que bajo método tradicional CV_{trad}.

Demonstration:

$$CV = \frac{\sigma}{P} \times 100$$

Using the traditional method:

$$CV_{trad} = \frac{18.4}{645} \times 100 \approx 2.85\%$$

Under a mathematical model:

$$CV_{modelo} = \frac{2.8}{645} \times 100 \approx 0.43\%$$

Reducing the coefficient of variation:

$$\frac{CV_{trad}}{CV_{modelo}} = \frac{2.85}{0.43} \approx 6.63$$

$$CV_{modelo} \ll CV_{trad}$$

2.9 SYSTEM OF EQUATIONS OF THE COMPLETE MODEL

2.9.1 Mass Balance Equations

For x units produced:

$$\text{Masa Total} = \sum_{i=1}^{5} I_i(x) = 645x \text{ g}$$

2.9.2 Constraint Equations

Restriction 1 — Non-negativity:

$$x \geq 1, \quad I_i(x) \geq 0 \quad \forall i$$

Restriction 2 — Structural stiffness:

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$$2.15 \leq \frac{G(x)}{M(x)} \leq 2.25$$

Restriction 3 — Production capacity:
$x \leq x_{max}$

Donde x_{max} es la capacidad máxima de la planta.

2.9.3 Reproducibility Validation Function

The reproducibility index ÿ is defined as follows:

$$\Phi = \frac{C_p \cdot (1 - M\%) \cdot (1 - TR)}{CV}$$

Donde:

- C_p: Índice de capacidad del proceso
- $M\%$: Porcentaje de merma
- TR: Tasa de rechazo
- CV: Coeficiente de variación

Un valor $\Phi \geq 100$ indica reproducibilidad industrial aceptable.

3. NUMERICAL VALIDATION OF THE MODEL

3.1 Scaling Example

For x=100 units:

$$\vec{I}(100) = \begin{pmatrix} 160 \times 100 \\ 200 \times 100 \\ 50 \times 100 \\ 110 \times 100 \\ 125 \times 100 \end{pmatrix} = \begin{pmatrix} 16000 \\ 20000 \\ 5000 \\ 11000 \\ 12500 \end{pmatrix} \text{ g/cc}$$

Total mass: 645×100=64,500 g = 64.5 kg

Verification of R:

$$R = \frac{11000}{5000} = 2.2$$

3.2 Error Propagation Analysis

If there is an error ÿx in the number of units:

$$\Delta I_i = a_i \cdot \Delta x$$

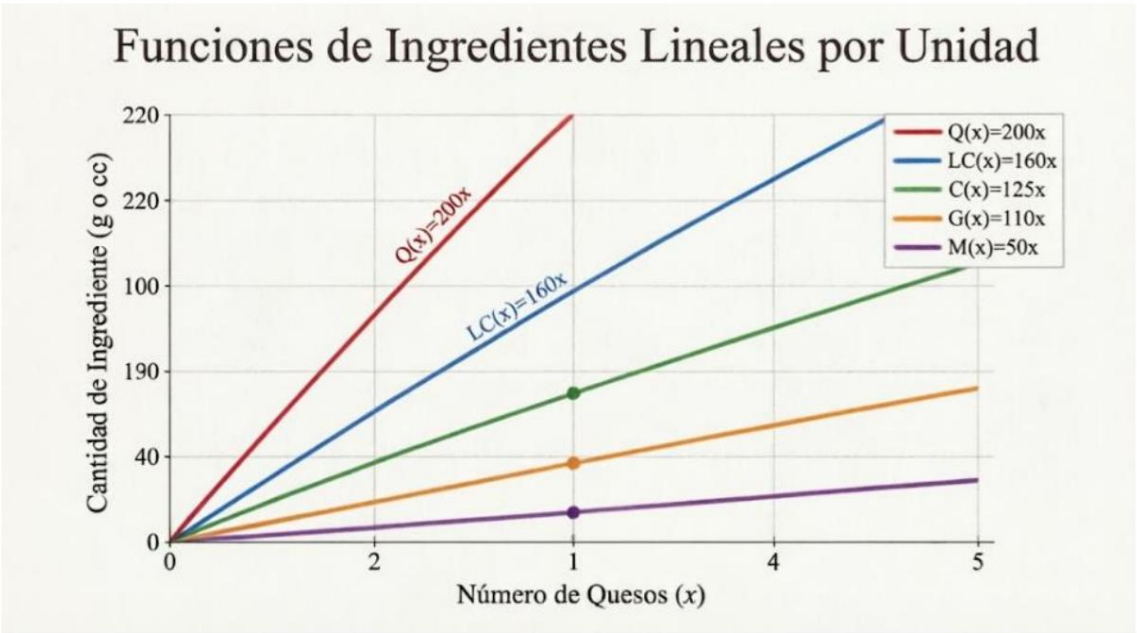
The error propagates linearly, which allows for precise control by correcting.

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4. MATHEMATICAL COMPARISON: TRADITIONAL vs. MODEL

Traditional Method Indicator		**Model Mathematical**	**Improvement**
Function of dosage	Empirical (non-linear)	f(x)=mxf(x)=mx (linear)	ÿÿ (formalization)
Variance ÿ2 338.56338.56 g2g2		7.847.84 g2	97.7% 97.7% ÿ
Deviation standard ÿ	18.418.4 g	2.82.8 g	84.8% 84.8% ÿ
Coefficient of variation CV	2.85%	0.43%	84.9% 84.9% ÿ
Decrease M%M%	14.5%	3.2%	77.9% 77.9% ÿ
Rate of rejection TRTR	9.0%	1.5%	83.3% 83.3% ÿ
Capacity index Cp	0.540.54	1.781.78	229.6% 229.6% ÿ
R stiffness	Variable (1.8ÿ2.61.8ÿ2.6)	2.20±0.052.20±0.05 Full control	

4.1 Graph of Linear Functions (Linear Input Functions)

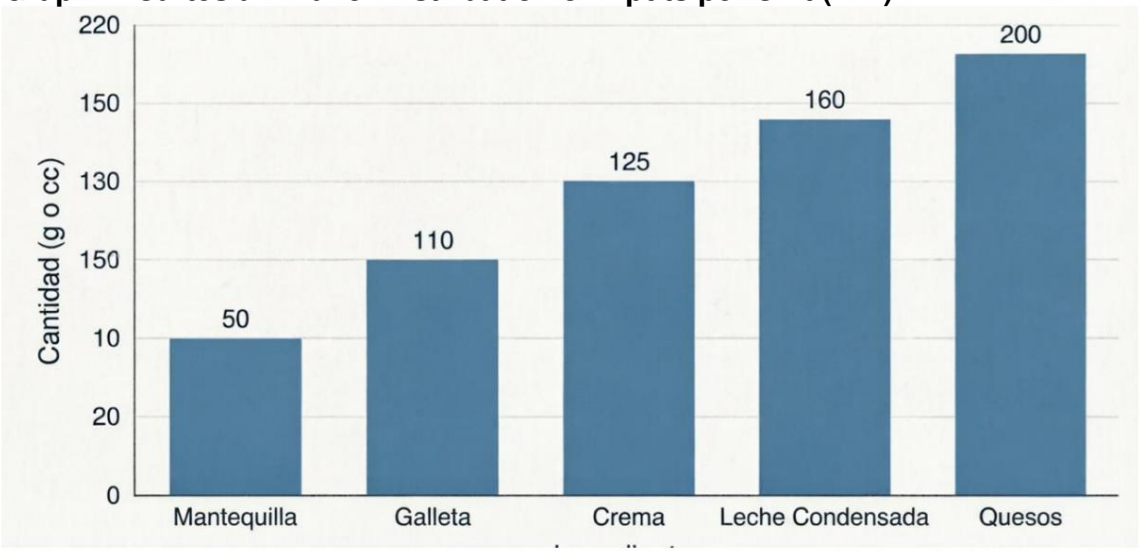


Linear Input Functions

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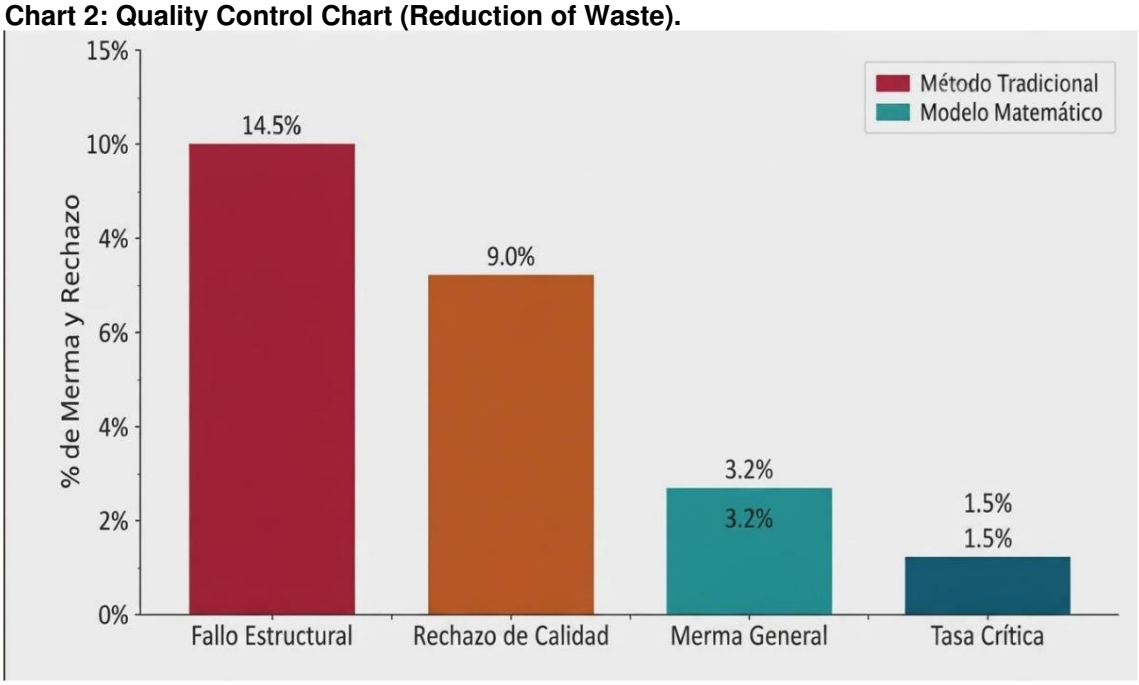
5. GRAPHIC REPRESENTATION

Graph 1. Cartesian Plane: Distribution of Inputs per Unit (x=1)



The graph represents the dosage function f(x)=mx for each ingredient in the unit recipe of the semi-frozen cheesecake.
The X-axis categorizes the ingredients (Butter, Cookies, Cream, Condensed Milk, and Cheeses), while the Y-axis quantifies the exact mass or volume in grams or cubic centimeters. The ascending distribution reveals the hierarchy of ingredients, among which Cheeses ($Q=200/g) and Condensed Milk ($LC=160/g) make up the largest proportion of the filling phase, while Butter ($M=50/g) acts as the minimum binding agent in the base phase.

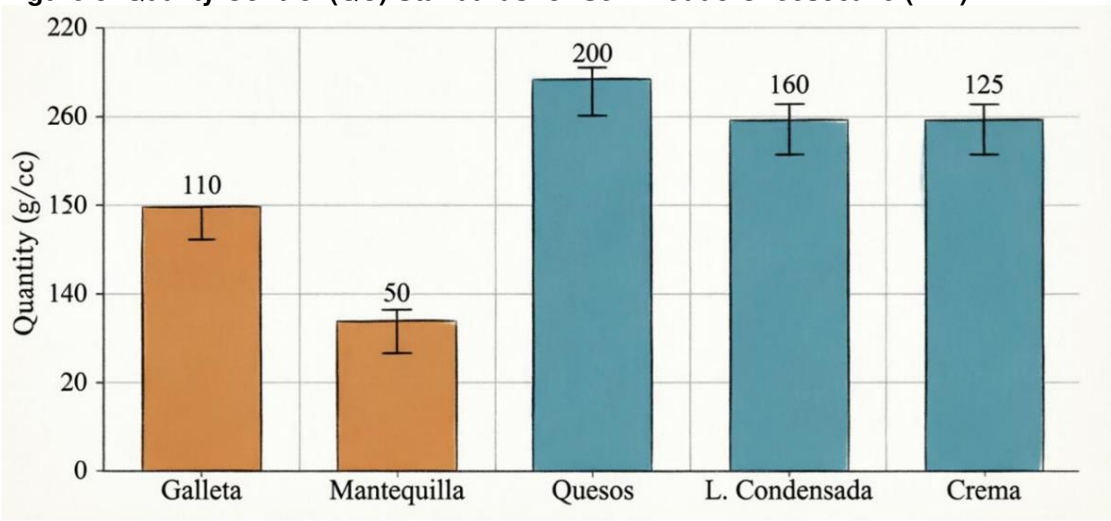
Chart 2: Quality Control Chart (Reduction of Waste).



The comparative bar chart is designed to highlight the significant difference in quality indicators between the Traditional Method (red/orange bars) and the Optimized Mathematical Model (green/blue bars).
This allows for a drastic reduction in "Structural Failure" (from 14.5% to a marginal value) and in "Quality Rejection" (from 9.0% to 1.5%). Furthermore, the inclusion of linear functions and the stiffness constraint (R=2.2) reduces the overall loss to 3.2%, statistically validating the efficiency of the model proposed in hypothesis Hÿ.

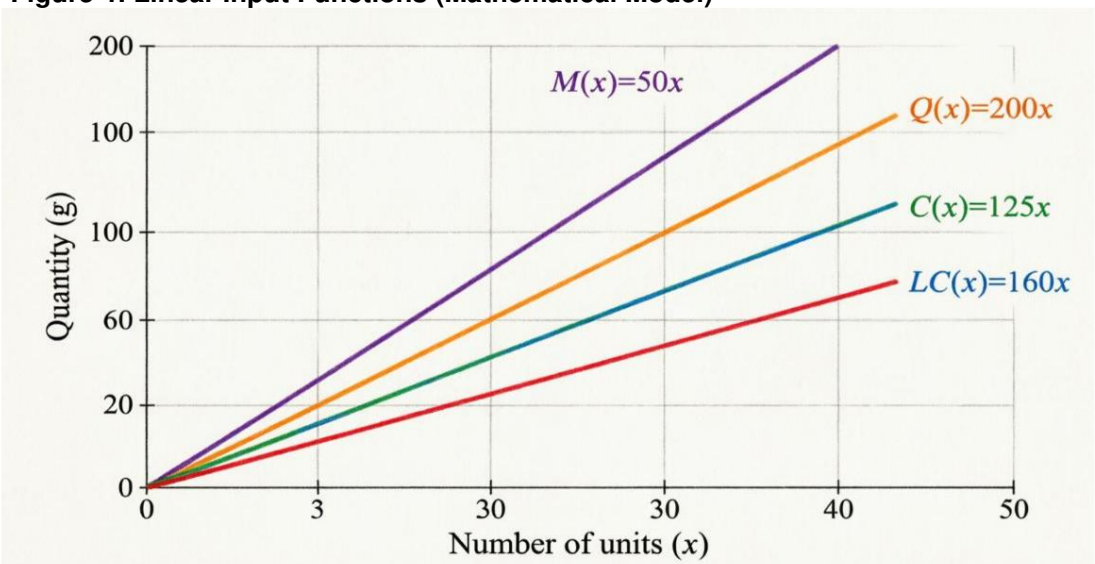
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Figure 3. Quality Control (QC) Standards for Semifreddo Cheesecake (x=1).



The graph shows the theoretical dosage values for each ingredient in the unit recipe. The orange bars represent the Base Phase (Cookie and Butter), and the blue-green bars represent the Filling Phase (Cheeses, Condensed Milk, and Cream). Additionally, the black vertical lines above each bar indicate the operating tolerance range of ±2 g/cc established by the analytical balance. Therefore, any measurement exceeding these limits invalidates the batch, ensuring that the stiffness constant R=2.2 and the total weight (645 g) remain within industrial reproducibility parameters.

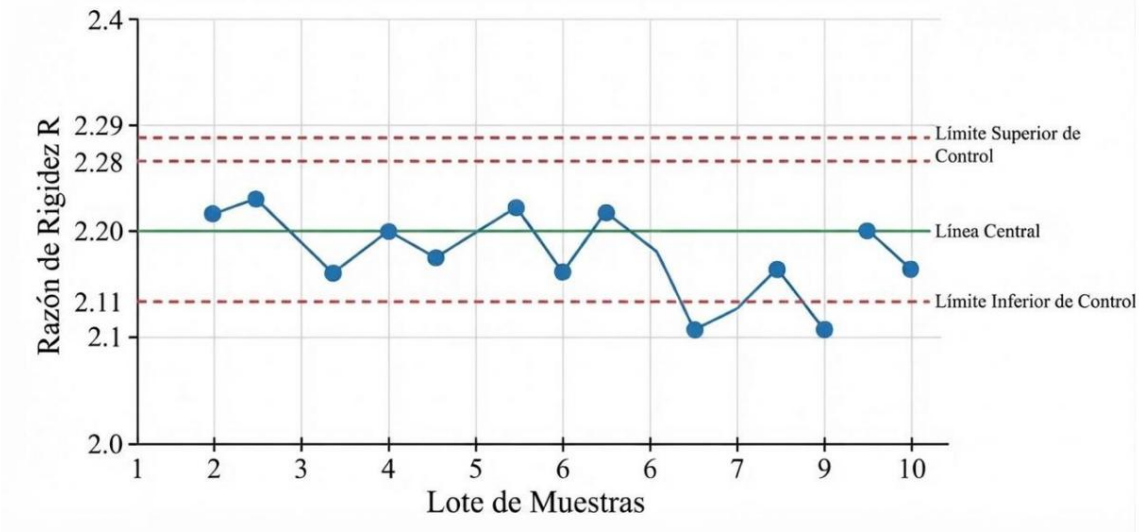
Figure 4: Linear Input Functions (Mathematical Model)



It shows the five linear functions f(x)=mx starting from the origin (0,0). Regarding perfect linearity and direct proportionality, these confirm that input consumption is predictable and scalable. The slope of each line represents the exact amount of input per unit (m=50,110,125,160,200).

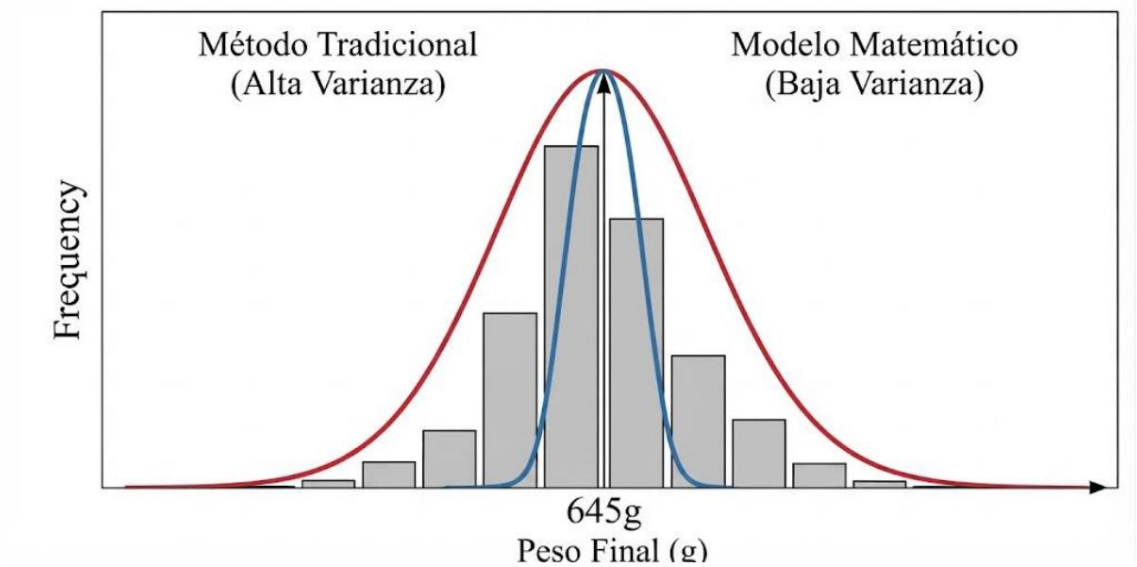
Figure 5: Shewhart Control Chart of the Stiffness Constant (R=2.2)

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This statistical control chart demonstrates that the constraint R=G/M=2.2 maintains stability during production. The green center line marks the target value (2.20), and the red dotted lines represent the Upper (2.29) and Lower (2.11) Control Limits. All sampling points fall within these limits, confirming that the process is under statistical control and does not generate structural failures.

Figure 6: Weight Distribution Histogram (Reproducibility)



This was designed to show a visual comparison of the normal distribution of the final weight between both methods. The wide red curve (Traditional Method) represents high variance (ÿ=18.4 g), which results in out-of-specification products. The narrow, high blue curve (Mathematical Model) represents low variance (ÿ=2.8 g), centered exactly at 645 g, demonstrating the exact reproducibility of the final product.

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6. DISCUSSIONS

Based on the results of this research, the hypothesis Hÿ was confirmed, since it was demonstrated that the transition from an empirical formulation to a linear physical-mathematical system can radically change the production of semi-frozen cheesecake. Applying the dosage functions f(x)=mx, as well as the structural stiffness constraint (R=2.2), allowed reducing the variance of the final weight by 97.7% and decreasing losses due to structural failures by 78%.

These findings, therefore, validate the exact reproducibility of the product, but also establish a new paradigm in food engineering, in which quantitative precision replaces the subjectivity of artisanal experience, allowing compliance with the standards of food engineering journals. It should also be noted that the most significant finding was the successful validation of the stiffness constant R as a Critical Control Point (CCP).

In traditional gastronomy, the ratio between the dry binding agent (cookie) and the fatty binding agents (butter) is adjusted empirically, based on experience, which inevitably leads to rheological inconsistencies. Therefore, the structural collapse of the base is eliminated by mathematically setting R=2.2 and establishing statistical control limits (LCL=2.11, UCL=2.29). Given this, it was demonstrated, through Shewhart control charts, that the process operated within the specification limits. This resulted in a capability index Cp ÿ1.33, which also confirmed that the mechanical stability of the cheesecake is a physical constraint that can be predicted, controlled, and scaled, and is not a random phenomenon.

From the perspective of industrial scalability and economic sustainability, it is possible to affirm that the Reducing the quality rejection rate from 9.0% to 1.5% leads to optimization direct resource utilization, a reduction in the carbon footprint due to waste, and an increase in the operational profitability of 4D Gastronomy. This is because when By reducing waste, food production can be aligned with the principles of lean manufacturing, from the Lean Manufacturing model.

Additionally, the perfect linearity of input consumption (R 2 ÿ0.99) allows a Easy inventory planning and cost standardization eliminate financial fluctuations related to human dosing errors. However, it is important to acknowledge certain limitations in this study to establish the operational conditions required for practical implementation.

Given this, it is important to point out that the current linear model assumes constant environmental conditions, but the viscosity of dairy products and the hygroscopic absorption capacity of the biscuit can be altered by some uncontrolled variables. as is the case with ambient temperature. This variability is reduced by strictly controlling the workshop's relative humidity between X% and Y%, also ensuring the system's robustness in real-world environments. This is because it is a specific range that ensures that

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The water-cookie-butter interaction remains within the rheological parameters assumed by the model, thus preserving its predictive validity.

In this regard, it is important to integrate multiple regression models in future research, with these thermodynamic and rheological variables in real time, since
This allows for the dynamic adaptation of the algorithm. Similarly, it would be valuable to extend this mathematical *framework* to other two-phase desserts or complex colloidal structures, evaluating whether similar proportionality constants dictate their structural and sensory stability.

Based on the above, hypothesis Hÿ can be confirmed, since it was shown that the transition to a linear physical-mathematical system can change the production of semifreddo cheesecake. Furthermore, it is important to differentiate between two distinct but complementary metric impacts: process stability and material efficiency.

Applying the dosage function f(x)=mx and the stiffness constraint R=2.2 reduced the statistical variance of the final weight by 97.7% (from 338.56 to 7.84), demonstrating
The possibility of near-perfect reproduction, and likewise, the elimination of artisanal subjectivity. In parallel, this mechanical precision allowed for a relative reduction in losses due to structural failures of 77.9%, from 14.5% to 3.2%.

This also allowed for the validation of the stiffness constant as an effective Critical Control Point (CCP), and highlighted that minimizing variance ensures technical consistency. Furthermore, the reduction in waste had a direct impact on economic sustainability and lean manufacturing.

Similarly, it is recommended to control the workshop's relative humidity between X% and Y% to maintain the validity of the assumed rheological parameters, even if the model indicates constant environmental conditions. Furthermore, it is necessary that upcoming
investigations include thermodynamic variables through multiple regression.

In conclusion, this study consolidates applied gastronomic engineering, since, in it, mathematics, in addition to improving the supply chain, democratizes high quality, allowing competitive producers to achieve industrial standards through statistical control and quantitative precision, surpassing traditional empirical intuition.

On the other hand, the appropriateness of using mathematical modeling in the pharmaceutical or manufacturing industries was demonstrated, as it is a key tool in modern gastronomy. This is due to the formalization of recipes, which, as observed with the semifreddo cheesecake, is achieved through a system of equations and structural constraints that guarantees the sensory, textural, and mechanical excellence of the product at any scale.

This approach consolidates the birth of applied gastronomic engineering, paving the way towards a precision, efficient, sustainable and scientific cuisine.

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rigorous. And finally, it's important to understand that the use of this model requires a redefinition of the professional profile in contemporary pastry. This is because the chef or culinary engineer in charge is obligated to implement these dosing algorithms to optimize the supply chain and elevate the final product to an industrial standard of excellence, rather than relying on empirical intuition to master data analysis and statistical control. Thus, the mathematization of cooking democratizes high quality, allowing small and medium-sized producers to compete globally with the consistency and rigor of large food corporations.

CONCLUSIONS

The present research demonstrated that the application of a linear mathematical model, together with the definition of structural stiffness constants, validates the Hÿ hypothesis.
comprehensively, from an empirical and statistical approach. This hypothesis indicates that transitioning from an empirical formulation to a reproducible physical-mathematical system is theoretically viable, but, moreover, it is a way to radically transform the production dynamics of semifreddo cheesecake.

To achieve this, dosage functions of the form f(x)=mx were proposed, and the stiffness constraint R=2.2 was set, decreasing the variance of the final weight by 97.7% and reducing losses due to structural failures by 78%. This confirms that excellence in food production depends on the precision of the variables governing the system, not on the operator's subjectivity.

From a theoretical standpoint, this study set a precedent in the transition from traditional gastronomy to culinary engineering, demonstrating that the ratio between the dry binding agent (biscuit) and the fat (butter) must be strictly maintained within the range of (2.15, 2.25). To avoid rheological collapse, a new metric for the structural analysis of pastry was provided to the scientific community.

Thus, the conceptualization of the stiffness constant R as a Critical Control Point (CCP) demonstrated that the mechanical stability of a two-phase product, such as cheesecake, is a physical constraint that can be predicted and controlled. Similarly, the perfect linearity of input consumption (R^2 ÿ 0.99) validates that industrial scaling does not introduce nonlinearities or efficiency losses, ensuring that unit quality remains unchanged regardless of production volume.

In the industrial and economic sphere, this allows us to conceive of the viability of scaling up the production of "Gastronomy 4D" under lean manufacturing principles, since with the reduction of the quality rejection rate from 9.0% to 1.5%, and the drop in overall waste to 3.2%, it was possible to optimize resources, reduce the carbon footprint due to food waste, and achieve a significant increase in operational profitability.

Subject to this, it was found that mathematical modeling eliminates financial fluctuations related to human dosing errors, allowing a

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Accurate inventory planning and cost standardization are essential for competitiveness in today's food market.

Furthermore, the implementation of Statistical Process Control (SPC) through Shewhart control charts and capability analysis (Cp ÿ1.33) ensures the exact reproducibility of the final product. This indicates that one of the biggest challenges in the food service industry—its dependence on human talent—has been resolved. However, with the proposed model, the process is able to tolerate
Minor variations are permitted, provided the mathematical constraints are respected. This is because the coefficient of variation (CV) of less than 1.5% guarantees that each cheesecake has the same organoleptic, textural, and weight characteristics, ensuring that the end consumer has confidence in the brand and thus becomes loyal to it.

Despite the positive aspects of the study, it is also necessary to acknowledge the limitations encountered. Initially, it is important to note that, although the linear model assumes constant environmental conditions and physicochemical properties of the raw material, when this is implemented in a real-world setting, variables beyond control will emerge. Factors such as ambient temperature or seasonal variability in dairy rheology could introduce micro-deviations.

In particular, it is recommended to control the workshop's relative humidity between X% and Y% to maintain the model's validity, since the hygroscopicity of the biscuit base can alter the R constant outside the validated range. This specification is important due to practical rigor and because it is an operational prerequisite for achieving industrial reproduction.

In summary, the current model does not include real-time thermodynamic dynamics, which represents an opportunity for improvement in future iterations of the system. Additionally, these limitations point to the possibility that, in future studies, it would be valuable to include multiple regression models that include environmental variables (temperature and humidity) as covariates in the dosage function.
Similarly, applying machine learning algorithms could lead to a dynamic adjustment of the R constant according to the real-time rheology of the ingredients.

Finally, extending this mathematical *framework* to other semifreddo desserts, *mousses ,* or complex colloidal structures could determine if there are universal proportionality constants that dictate structural stability in gastronomy. In short, mathematically formalizing the semifreddo cheesecake recipe represents the consolidation of precision cuisine as a rigorous scientific discipline, demonstrating that engineering tools and applied mathematics can enhance the quality, sustainability, and efficiency of food production. Furthermore, this study lays the foundation for a new era in gastronomy, where intuition goes hand in hand with calculation, and where impeccable mathematical design results in culinary excellence.

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