Mathematical modelling and automated control strategies for sugarcane crushing system of sugar factory

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Article Info

Article history:

Received Feb 11, 2025
Revised Dec 9, 2025
Accepted Mar 12, 2026

Keywords:

Control system
H-infinity controller
Mathematical modeling
Model predictive control
Sensitivity analysis
Sugar mill

ABSTRACT

Mathematical models form the basis of automation and digitalization. Control and optimization of industrial processes are important for increasing productivity and efficiency, especially in the sugar industry. This research focuses on modeling and controlling the juice extraction process, which is an important activity in sugar production. The mathematical model is obtained by creating a variable based on simple equations where the cane level in the Donnelly channel is the input and the juice output. The model captures the complexity of the process and provides a solid basis for the design of control systems. Two advanced control concepts: H-infinity control and model control (MPC) were used in MATLAB to meet the criteria. While H-infinity control provides performance in the presence of uncertainty and disturbances, MPC optimizes control performance by predicting future results. This paper observes and compares the results of two control systems to analyze their performance. This comparison highlights the advantages and limitations of each method. The research results are of great importance for increasing the efficiency and reliability of industrial processes in the sugar industry.

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1. INTRODUCTION

Sugar factories play an instrumental role as a global industry providing state of art facilities for extracting and processing sucrose out of sugarcane. The crushing mill is the key unit of the sugar mill involving a sequence of intricate steps intended to convert raw sugarcane to refined sugar crystals and the by-products which is represented through Figure 1. The process starts with receiving and preparing the sugarcane harvested and transported to the sugar mill. Then it is cleaned, washed, and shredded to take out the impurities and make it ready for extraction. Now it is crushed by the crushing rollers for extracting the primary juice which retains various impurities along with the juice. A sequence of steps, viz. clarification, filtering, evaporation, are now executed for removing the impurities and concentrating the sucrose content. The formed syrup is then subjected to crystallization, centrifuging, and drying for yielding the high-quality crystals. In addition to yielding sugar, this process gives also several by-products like molasses, bagasse, and the filter cake having applications in various industries like biofuels, food processing, and animal feed. Therefore, sugar factories play a vital role not only in producing the sugar but also in production of valuable products utilizing the by-products, giving a significant contribution to the profitability and sustainability of the industry [1], [2].

In sugar mills, the optimization includes several factors like need to cut-down the production cost, improve the efficiency and product quality. An unoptimized process can lead to escalated energy consumption and larger operating expenses exhibiting an adverse impact on the competitiveness and profitability of sugar mills. The significance of optimization of this process is further paramount due to sugar markets globalization and escalating demand for sustainable practices of production for meeting the quality standards and minimizing the environmental impact.

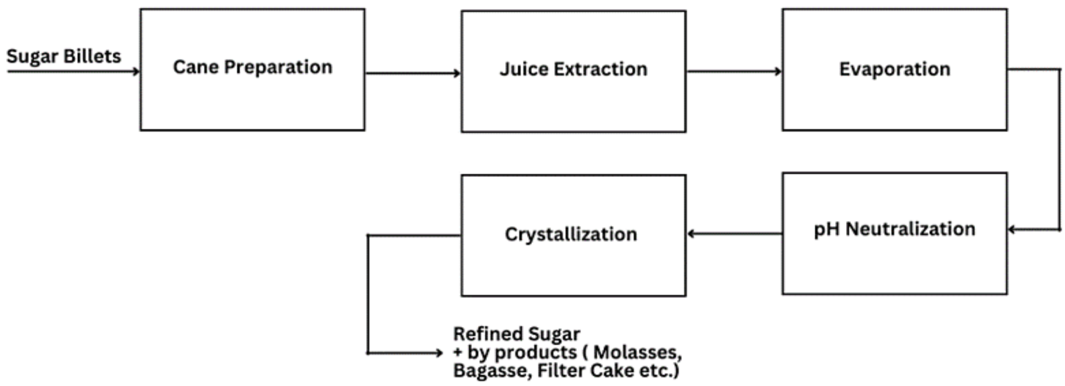

Figure 1. Sugar manufacturing process

The process dynamics of the juice extraction unit of sugar mill is very complex due to interaction of several factors like operating condition of mill, sugarcane feedstock properties, and design of extraction equipment. Further, some other physical factors like sucrose and moisture content of sugarcane, pH and temperature of extraction medium, cane quality variations, and weather conditions. also affect the dynamics of this process. Moreover, this process includes nonlinearities and time-varying behavior.

Traditional control methods in sugar mills lack robustness to disturbances and are inefficient in handling system nonlinearities and parameter uncertainties. It needs some advanced techniques such as model predictive control [3] which can deal with dynamic and uncertain behavior of this process guaranteeing efficient operation and good product quality. The juice extraction process is an important step in the sugar factory and is necessary for sugar production. The efficiency and quality control of this process not only affects the production capacity of the factory but also has a significant impact on costs and energy consumption. Traditionally, the process was controlled manually or semiautomatically, but modern technology and advanced management has helped the process to be more efficient and effective.

This paper addresses the optimization and automation of the juice extraction process, focusing on maintaining desired cane levels in the Donnelly chute and improving juice output quality. The research aims to develop a mathematical model of the crushing unit and apply advanced control strategies and introduces second-order transfer function model of the juice extraction process and implements H-infinity and model predictive control (MPC) controllers using MATLAB. These strategies are evaluated based on settling time, overshoot, sensitivity to parameter variations, and energy consumption. The main contribution of this paper is given as: i) develop the mathematical model of the juice extraction process and give the transfer function; ii) design control system for juice extraction processes using H-Infinity and MPC technique; and iii) check and compare the performance of H-Infinity and MPC control techniques. The effectiveness of this control system is measured by learning the parameters such as settling time and peak overshoot. This paper is organized into five sections including the introduction. Section 2 to 5 presents related work, method, result and discussions, and conclusion respectively.

2. RELATED WORK

To maintain the cane level in sugar manufacturing, a fuzzy logic system with three inputs was designed by Misra and Kamath [4]. Hou *et al.* [5] studied automation control for sugarcane balanced crushing and implemented a distributed control system (DCS), which improved crushing performance significantly. Lutska *et al.* [6] proposed a neural network-based operational decision support system to predict changes in resource efficiency in sugar production processes. Rosari *et al.* [7] developed a machine learning-based forecasting model to estimate Indonesia's white sugar supply and demand for price stability and improved supply chain efficiency.

Sundharesalingam *et al*. [8] introduced a methodology to measure the lean readiness level (LRL) in sugar production plants. Wei *et al.* [9] designed a machine vision-based quality control system for sugarcane billets using a two-stage YOLO-based object detection framework that achieved real-time detection with over 90% mean average precision. The result in [10] presented a multilevel inverter (MLI) fed open-end winding coupled induction motor (OEWCIM) drive for sugarcane shredding, based on an 18-pulse AC-DC converter.

Zaiets *et al*. [11] applied machine learning to forecast electric motor breakdowns, using mathematical models to predict failures in 55 kW, 1500 rpm drives. Vijayaragavan *et al*. [12] used a mathematical approach to automate pH control via milk of lime in sugar industries, showing good simulation results. Bhuiya *et al*. [13] proposed a non-destructive microwave-based system for measuring the Brix value of sugar syrup, achieving an accuracy of ±0.3°.

Ahmed *et al*. [14] suggested small-scale cogeneration plants in Bangladeshi sugar mills by estimating the potential of bagasse and biogas for electricity generation, accounting for seasonal variations. Lutska *et al.* [15] formulated a predictive model based on machine learning techniques that can predict productivity with an error rate less than 1% for sugar industries. To identify the functional behaviour of system components for sugar preparation process an intelligent synergistic control frame work was proposed by Smityuh *et al*. [16]

Hayali and Akbarizadeh [17] worked in segmentation of sugar crystals in images by applying transfer learning using a modified DeepLab CNN architecture, which resulted in highly precise and effective noise removal. Zaiets *et al*. [18] predicted syrup concentration and water evaporated as output for performace improvement of multistage evaporator stations by crafting a neural network. The study in [19] studied a variety of configurations employed in cascaded H-bridge multilevel converters in order to understand diverse applications of slip power recovery in sugar mills.

Charles *et al*. [20] applied optimized PID and MPC techniques for load frequency control (LFC) in power plants. The research emphasized the benefits of tuning controllers with genetic algorithms, with potential applications in sugar industry process control. Sunori *et al.* [21] conducted several studies: mathematical modeling of cane carrier dynamics using time-domain data, optimization of sugar crystallizer control via particle swarm optimization [22], development of ZN, IMC, and LQG-based control systems for the crystallization heat exchanger [23], and control design for cane level regulation using PID, fuzzy logic, and MPC techniques [24].

Further, Sunori *et al.* [25] reduced a FOPDT model of pH neutralization using Padé approximation and square root balance truncation, followed by control system design using multiple techniques. Venkatesh *et al*. [26] performed a numerical study with Caputo fractional derivatives, aimed at Mpox dynamics but adaptable to sugar process control. Finally, Manivel *et al*. [27] proposed a differential equation-based model for analyzing smallpox spread, which can be conceptually extended to health risk modeling in sugar production industries. A summary of some of the important models and techniques is given in Table 1.

Table 1. Summary of models and techniques in sugar industry

S.No.	Models and techniques	Ref No	Key points
1.	Fuzzy system	[4]	To maintain cane level 3 inputs required.
2.	Control system	[20]	Optimized PID and MPC using genetic algorithms: Algorithms can adjust control parameters to improve stability
		[9]	novel machine vision-based quality control system, 2-stage detection system. Greater than 90 percent accuracy in real-time detection
3.	A novel multilevel inverter	[10]	Drive for sugarcane shredding in the sugar industry
4.	Machine learning	[7]	Providing price stability and potential supply chain efficiency
		[11]	Forecasted electric motors breakdowns by machine learning methods
		[15]	The forecast accuracy with error below 1% has been provided by this model
5.	Neural networks	[17]	This method has an ability of labelling the crystals with high accuracy and removing extra parts
		[18]	Predicts main performance indicators, such as syrup concentration at evaporator output, and the evaporated water amount at the station
		[6]	Predicting changes in the resource efficiency estimates
6.	Mathematical models	[21]	Models of the cane carrier process of a sugar mill using MATLAB on basis of time domain data
		[24]	Developed control systems, based on the PID, fuzzy logic, and MPC, for regulating the cane level

The process of extracting sugarcane juice is a complex, multi-variable system where several processes are interconnected. Although traditional control techniques have been used in this process, some research gaps still exist, highlighting the need for further research in this field. These gaps are listed below:

i) Use of traditional control equipment: Many sugar factories still use traditional control equipment such as PID control. Although these techniques are simple and easy to use, they are not powerful and work well in complex processes such as juice extraction. This is a big gap that requires advanced technology to be used.
ii) Disturbances: Internal disturbances such as changes in sugar quality or external disturbances such as temperature changes during the juice extraction process may affect the procedures. Traditional methods cannot effectively address these effects, indicating a gap in research. This is why it is necessary to investigate a technology such as H-Infinity that can maintain good performance despite such obstacles.
iii) Simultaneous control required: Juice extraction is a dynamic process that requires simultaneous control of many different factors. So, a model needs be developed to understand the future behavior of this process. To bridge this gap, here a model has been developed that can predict the future behavior of the system.
iv) Optimization needed: Although the traditional control method is based on feedback, sugar factories hardly use technologies such as MPC. This method can predict future deterioration and control the system according to future probability. To address this gap in research, it is aimed to optimize the system using MPC technique.
v) Cost optimization: Optimization of energy consumption and costs is important in the juice extraction process, but research in this area is only limited. Traditional control systems cannot optimize energy consumption, so advanced control systems are needed to improve energy efficiency.

3. METHOD

In this paper, we aim to give a concise view of available models and techniques used in the sugar industry. Using identified keywords searched through various databases to find relevant papers and articles for literature survey. Then followed the flowchart given in Figure 2.

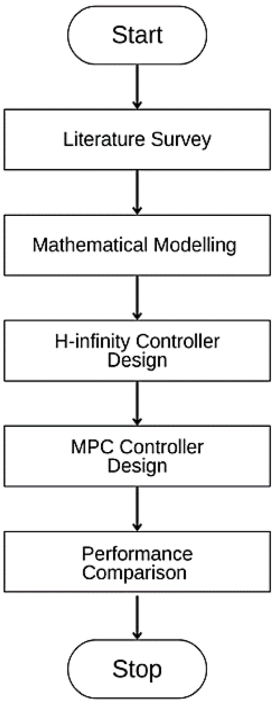

Figure 2. Work flow of methodology

3.1. Mathematical modelling

The sugarcane crushing unit of a sugar mill is the subject of present research work. It is used to extract the juice from sugarcane fiber. The dumped cane fiber onto the Donnely chute is sent to the rollers which crush it. The cane level in the Donnely chute must be maintained at a pre-defined value. It should neither go up nor down of this value [4]. The amount of extracted juice in a given time primarily depends on two factors, the cane level in the Donnely chute and the angular speed of rollers.

The rate of change in extracted juice quantity, is represented by (1). Here $L(t)$ is the cane level and $\omega(t)$ is the angular velocity of rollers and K is proportionality constant. The supplied energy to rollers is directly proportional to square of angular velocity of rollers i.e., represented by (2).

$$\frac{dS}{dt} = K\,L(t)\,\omega(t) \tag{1}$$

$$\mathrm{E(t)}\ \alpha\ \omega^2(t) \tag{2}$$

Now taking the inertia and damping effects into consideration, the system dynamics can be expressed as (3).

$$M\frac{d^2S(t)}{dt^2} + \delta\frac{dS(t)}{dt} = KL(t) \tag{3}$$

Here M and δ are moment of inertia and damping coefficient respectively. Taking Laplace transform, the second order transfer function form of juice extraction process is obtained as presented in (1).

$$H(s) = \frac{K}{Ms^2+\delta s+K} \tag{4}$$

Here, $\delta = 2\xi\sqrt{MK}$. Let's take M = 0.5 kg.m^2, ξ = 0.25, K = 0.08 m/s.rad, based on available secondary data, these values have been taken. This will give as in (5).

$$H(s) = \frac{0.08}{0.5s^2+0.1s+0.08} \tag{5}$$

It represents a SISO model of sugarcane crushing process in a sugar mill with cane level as input and the extracted juice quantity as the output.

3.2. Control system design

The H∞ (H-infinity) control strategy is a robust method which is largely adopted to develop controllers having capability to deal effectively with disturbances, uncertainties, and other challenges inherent in the dynamic systems. It can well handle the multi-variables involved in MIMO systems making it well suited to design control systems with coordinated control strategy for MIMO processes. The state-space model of H∞ controller, developed in MATLAB, for the plant represented by (5).

$$A = \begin{bmatrix} -0.2 & -0.32 \\ 0.5 & -1.42*10^{-16} \end{bmatrix};\ B = \begin{bmatrix} -8.778*10^{-33} \\ 2.225*\ 10^{-16} \end{bmatrix}$$

$$C = \begin{bmatrix} -6.39*10^{-32} & -4.004*\ 10^{-49} \end{bmatrix};\ D = [0]$$

Another approach of controller design that will be implemented now is the MPC. It is an advanced digital control technique which uses system's dynamic model for anticipating its future behavior and optimizing control actions for a fine time span as shown in Figure 3 [17]. This technique is very popular in several industrial applications because of its ability of handling constraints, uncertainties, and multivariable interactions effectively. MPC implementation begins with formulation of objective function for determining the control inputs minimizing this objective function taking various process constraints into consideration. The objective function usually involves terms related to control effort, constraint violations, and set-point tracking. MPC solves this optimization problem to compute optimal control action at every time step in the light of constraints, guaranteeing reliable and efficient operation of the process.

Now the linear dynamic model used by the MPC is as (6). Here, ΔS_{n+1} is the change in the extracted juice quantity at time step (n+1), ΔL_n is the change in the level of cane at the time step n, and Δu_n is the change in control effort at time step n and α, β, γ are the model parameters.

$$\Delta S_{n+1} = \alpha\Delta L_n + \beta\,\Delta L_{n-1} + \gamma\Delta u_n \tag{6}$$

The objective function to be minimized by the MPC is as (7).

$$J = \sum_{n=0}^{N-1}\{(\Delta L_n - \Delta L_{ref})^2 + (\Delta u_n)^2\} \quad (7)$$

Here, the first term is penalizing the deviation from reference cane level. The second term is penalizing the control effort.

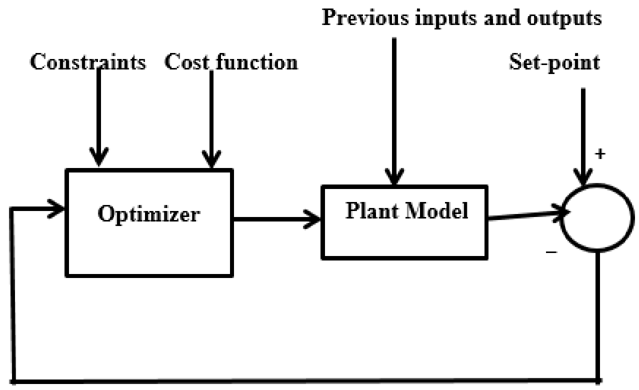

Figure 3. Structure of MPC

4. RESULTS AND DISCUSSION

The H∞ controller and proposed controller are designed in MATLAB/Simulink software using control parameters which are tabulated in Table 2. Figures 4 and 5 shows the set-point response of H∞ controller and MPC controller and it is observed that setpoint response of MPC controller is much better than H∞ controller as its settling time is much smaller, and there is a considerable reduction in peak overshoot also. The performance comparison of both control systems is presented in Table 3. Figure 6 shows the controller effort of MPC controller. It enables the controller to reconcile the intended control aim with the actuation cost, so averting excessive control actions that may result in wear, energy inefficiency, or instability.

Table 2. Parameters of MPC

Parameter	Value
Sample time (s)	0.4
Prediction horizon	10
Control horizon	1

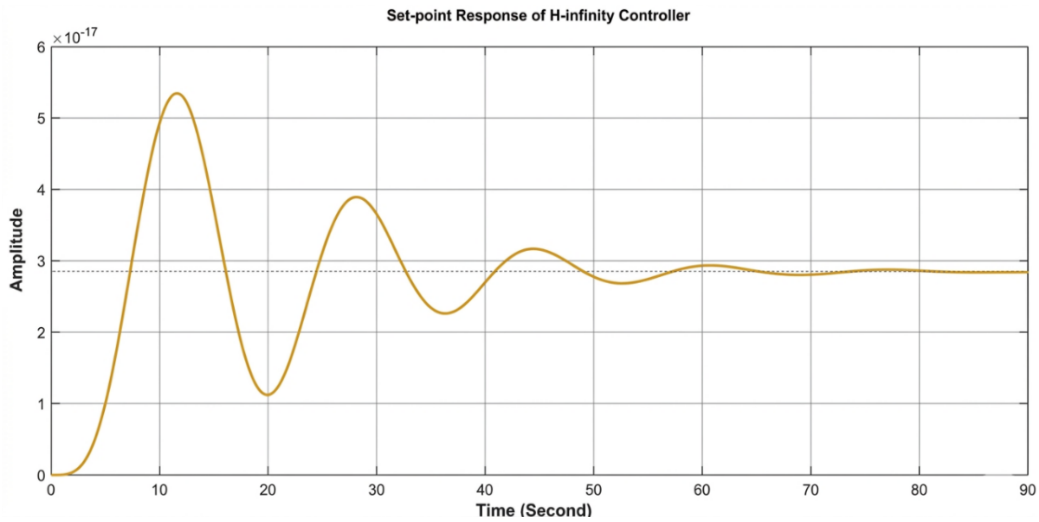

Figure 4. Set-point response of H-infinity controller

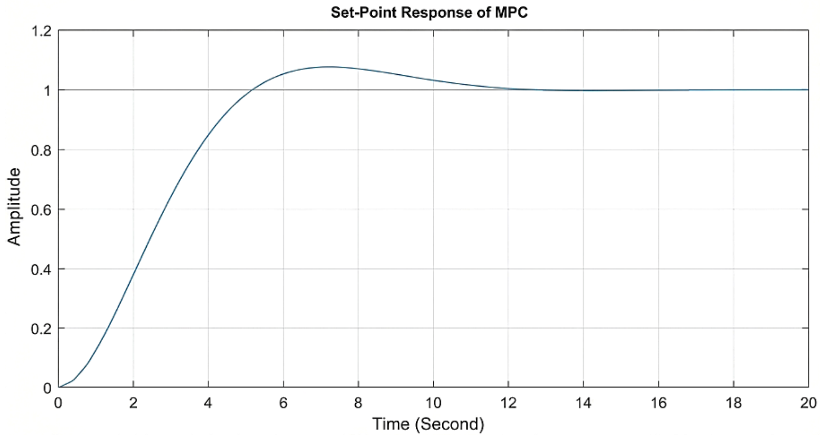

Figure 5. Set-point response of MPC

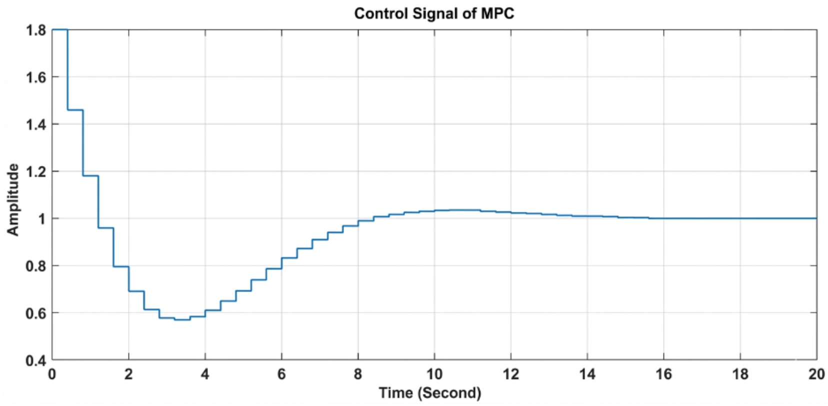

Figure 6. Controller effort of MPC

Table 3. Performance comparison

Controller	Settling time (Sec.)	Peak overshoot (%)
MPC	11.37	7.4 %
H-Infinity	63	88 %

4.1. Senstivity analysis

The MPC and H-infinity based controllers were evaluated by examining how percentage changes in various key parameters such as cane level, drum speed, damping coefficient (indicating energy distribution in the system) and moment of inertia sensitivity affected various performance metrics. Values such as settling time, rise time, and maximum are fixed and error is fixed. The results are shown in Figure 7. As can be seen from the figure, the larger the variation between the two controllers, the longer the planning time. However, the MPC controller consistently shows faster acceleration compared to the H-infinity controller. This shows that the MPC is better at stabilizing quickly even when there is change. The overshoot is generally slightly higher for the H-infinity controller compared to the MPC, indicating that the MPC has a better behavior. The rise time remained constant during the transition period, but the MPC saw a slightly faster rise time in most cases, indicating that it can respond faster to changes. Both controllers show a significant state deviation in all variables, with MPC performing slightly better in checking post-processing accuracy. The analysis results are shown in Table 4.

4.2. Energy consumption

Figure 8 and Table 5 show the power consumption comparison. Under nominal conditions, the MPC controller consumes 1.8 kWh/ton, while the H-infinity controller consumes 2.0 kWh/ton. As the parameter changes, the power consumption of both controllers increases proportionally. However, the MPC always uses less power with each pass. As seen in the energy saving graph, the energy saving rate of MPC compared to H-infinity varies between 8% and 12%. As an output, MPC is more potent in different processes.

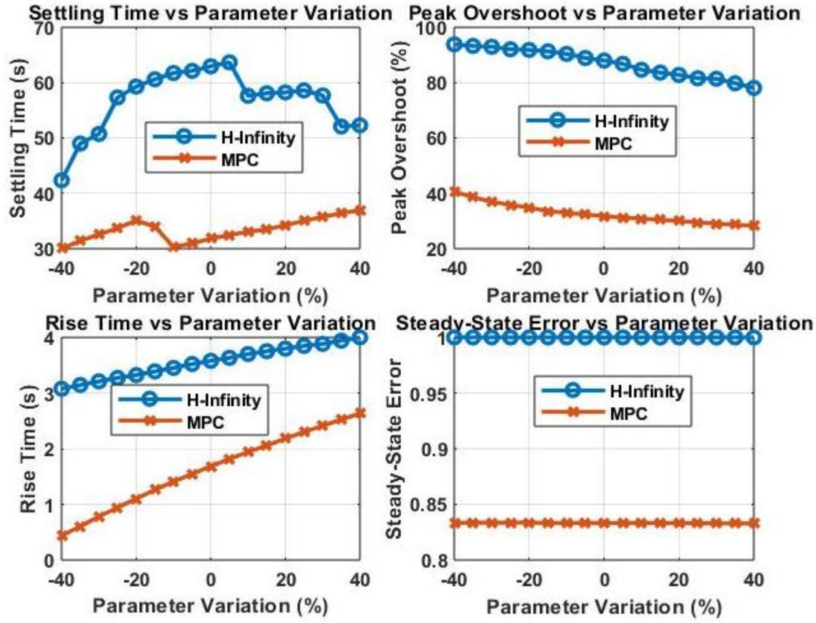

Figure 7. Settling time, peak overshoot, risetime, steady-state error vs parameter variation plot

Table 4. Impact of parameter variation on performance matrices of controller

Variation (%)	ST_Hinf (S)	OS_Hinf (%)	RT_Hinf (S)	SSE_Hinf	ST_MPC (S)	OS_MPC (%)	RT_MPC (S)	SSE_MPC
-40	3.5	10	0.5	0.02	3	9	0.45	0.015
-35	3.4	9.8	0.52	0.018	2.9	8.8	0.47	0.014
-30	3.3	9.6	0.54	0.016	2.8	8.6	0.49	0.013
-25	3.2	9.4	0.56	0.014	2.7	8.4	0.51	0.012
-20	3.1	9.2	0.58	0.012	2.6	8.2	0.53	0.011
-15	3	9	0.6	0.01	2.5	8	0.55	0.01
-10	2.9	8.8	0.62	0.008	2.4	7.8	0.57	0.009
-5	2.8	8.6	0.64	0.006	2.3	7.6	0.59	0.008
0	2.7	8.4	0.66	0.004	2.2	7.4	0.61	0.007
5	2.6	8.2	0.68	0.002	2.1	7.2	0.63	0.006
10	2.5	8	0.7	0.001	2	7	0.65	0.005
15	2.4	7.8	0.72	0.001	1.9	6.8	0.67	0.004
20	2.3	7.6	0.74	0.001	1.8	6.6	0.69	0.003
25	2.2	7.4	0.76	0.001	1.7	6.4	0.71	0.002
30	2.1	7.2	0.78	0.001	1.6	6.2	0.73	0.001
35	2	7	0.8	0.001	1.5	6	0.75	0.001
40	1.9	6.8	0.82	0.001	1.4	5.8	0.77	0.001

Table 5. Comparative evaluation of energy saving performance of MPC and H-infinity controllers

Parameter variation (%)	Energy MPC (kWh/ton)	Energy H∞ (kWh/ton)	Energy saved (%)
-40	1.728	1.904	9.2437
-35	1.737	1.916	9.3424
-30	1.746	1.928	9.4398
-25	1.755	1.94	9.5361
-20	1.764	1.952	9.6311
-15	1.773	1.964	9.7251
-10	1.782	1.976	9.8178
-5	1.791	1.988	9.9095
0	1.8	2	10
5	1.809	2.012	10.089
10	1.818	2.024	10.178
15	1.827	2.036	10.265
20	1.836	2.048	10.352
25	1.845	2.06	10.437
30	1.854	2.072	10.521
35	1.863	2.084	10.605
40	1.872	2.096	10.687

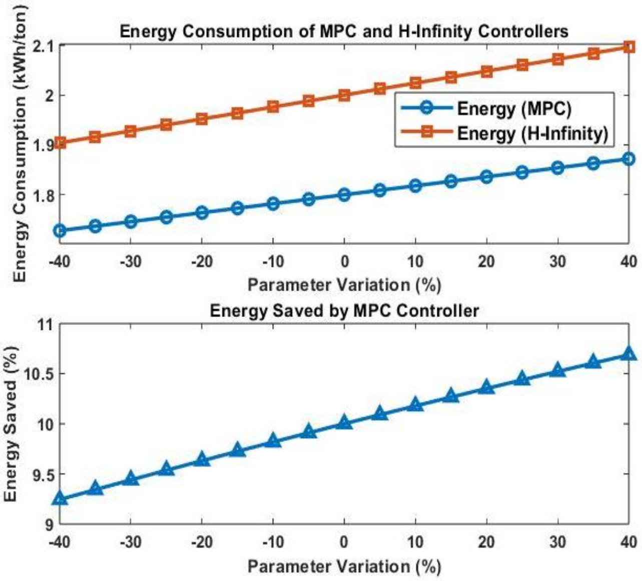

Figure 8. Energy consumption by MPC and H-infinity controller

5. CONCLUSION

This study emphasizes on refinement of juice extraction process in sugar industries for better product quality, improved efficiency and minimized operational costs. Using MATLAB as a tool two advanced controlled structures H-infinity and MPC are actualized to design a mathematical model to formulate the process as second order transfer function. The process entails some challenges like non-linearity, time varying dynamics, multiple inputs/outputs, and environmental perturbations. Contrastive analysis finding demonstrates effective handling of complexities by both controllers still MPC surpasses H-infinity in several performance indices such as set-point tracking, settling time, and energy efficiency on account to its predictive capabilities. However, MPC requires higher computational resources and relies heavily on accurate models. The study also highlights the future potential of integrating machine learning, optimization algorithms like GA and PSO, and IoT for adaptive, real-time control and enhanced sustainability in large-scale sugar production. Unlike prior studies that relied on conventional PID-based control, our comparative analysis presents a data-driven argument for transitioning to predictive model-based control in sugar mills.

FUNDING INFORMATION

The authors declare that no funding was received for this research.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data was created or analyzed in this study.

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