Predictive modeling and optimization of paper mill using hybrid machine learning techniques

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ABSTRACT

The paper has played a vital role in the life of humans from ancient times covering a vast range of applications such as writing, packaging, and printing. The present paper is presenting a comprehensive review of various optimization and control methodologies, ranging from conventional to advanced ones, pertaining to the paper mill. The final goal of these control strategies is to upgrade the mill's production and quality in presence of multiple technical challenges such as nonlinear and multivariable nature of the involved processes, various disturbance parameters, and time delays. In this work, the integration of machine learning with paper mill process is illustrated. For any manufacturing process, the final product quality is the key goal. There are various traditional techniques which have already been practiced for final produced paper quality in paper mills. This paper highlights the capability of support vector machine (SVM) algorithm to assess the produced paper quality, capturing the two crucial inputs viz. the pulp consistency and the headbox level. The basic goal of this research is twofold, firstly it presents an exhaustive literature survey exploring various strategies which are practiced currently in the domain of control and optimization of various paper mill processes. Secondly, it intends to develop and evaluate various SVM and SVM-RF hybrid models using MATLAB for assessment of quality of final product on basis of two parameters- pulp consistency and head box level. Finally, genetic algorithm has been employed in MATLAB for multivariate optimization.

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1. INTRODUCTION

A pivotal role has been played by paper mills from ancient times when its invention was done by Cai Lun in 105 A.D by pounding pulp from a mix of rags, mulberry bark, and hemp, and flattening it into thin sheets. With the passage of time, there are huge changes in paper mill's operation dynamics. Paper production has been remarkable evidence of human creativity and technology evolution in the domain of industrial manufacturing. The paper is a most ancient medium of communication which has proved to be a keystone in propagating the ideas, culture, and knowledge over generations. However, the paper production of high quality is a highly multivariable and intricate process that requires a strict monitoring and control of each step of this process. It is a complex process of interaction of chemical, mechanical, and environmental parameters during the paper production process that makes it difficult to optimize good quality production. It pleads a pressing concern to maintain positive favourable conditions of some vital parameters such as head box level and pulp consistency which directly affect the quality of end product. The variations of these parameters to the optimal values may result into defects such as low printability, non-uniform thickness, and low mechanical strength. Engineers and researchers have addressed these challenges with the help of the most recent computational practices, including artificial intelligence and machine learning.

The significance of machine learning (ML) in the exploitation of the various manufacturing processes was identified with its applications that differ in application if operational strategies or even the maintenance of equipment. To take an example, passive operational space interaction control existing in more precision in production environment of paper mills that are founded on robotics milling strategies [1]. In addition, the optimization of the power systems that used to be implemented in the traditional sense highlights the likelihood of incorporation of modern technology to achieve efficiency in the functioning of the system [2].

In the recent studies, emphasis is laid more on interval type 3 fuzzy logic systems, which depicts the new methods used to address the uncertainties in the manufacturing processes [3]. Like this method, one technique was called as fiber estimation technique was applied to improve the efficient net- based patch classification [4]. Along with it, when accompanied with technique which focuses on degradation of effluent, it not only results in stability of the environment, but also operational control of paper mill sector [5]. The paper mills have a serious operational problem, which is trim loss minimization. It takes place when jumbo reels are cut in the intermediate rolls. This has been proven by recent studies which have shown that smart optimization techniques such as reinforcement artificial bee colony algorithm can greatly minimise trim loss and related costs [6].

Other areas of study related to paper mills include safety concern. Advanced protection systems such as fiber optic sensors and arc-flash detection relays have been shown to reduce the arc-flash energy levels by up to 90 percent and make the working environment significantly safer [7]. The incorporation of computer-based control systems has been instrumental in ensuring that mills that have adopted automation not only maintained stability within their processes but also increased their production throughput with a high degree of real time data use and close control logic [8]. Over the last few years, integrated mills have turned more and more towards predictive planning procedures and discrete-event simulation in order to create production schedules which are more resistant and stable even when there are operational disturbances [9].

One of the recent developments that can be identified is the inclusion of energy and resource flexibility in the production planning processes. As an illustration, operational features of the steam power generation and its contribution to the grid services can be embedded in the scheduling frameworks to enable mills secure an additional revenue and a stable and reliable operation [10]. Another important field of research is fault detection and increasing the resilience of the system. Detailed systems that combine adaptive principal component analysis, fuzzy logic methods, and artificial neural networks have been found to be quite useful in detecting faults in large-scale chemical and pulp processes and thus enable decentralized fault-tolerant controls [11]. Wastewater and sludge management remains a key issue of concern, particularly to small paper mills where agricultural residues are used as feedstock. The electrochemical treatment methods have been demonstrated to be effective in enhancing the sludge settling and filtration as well as facilitating the beneficial reuse of the resulting by-products as alternative sources of fuel or as additives in building materials [12].

The use of model-based predictive control (MPC) has become relevant in the control of the highly dynamic nature of pulp and paper processes in which other methods such as proportional-integral-derivative (PID) control may fail. The MPC optimizes stability, conserves energy, and improves product quality by predicting reactions on the processes and making changes to operations in advance [13]. Specialized algorithms are aimed at managing certain changes in operation within paper mills. An example of such a system is model algorithmic control (MAC) which has been shown to be effective in grade transitions. MAC provides faster and more steady changes than traditional techniques by modeling grade changes using a neural network and computing an impulse response, which results in more gradual changes and high product consistency [14].

Moreover, brown stock washing, a key step in pulping, significantly affects production costs and environmental impact. Using system dynamics models, researchers have better understood stage-wise interactions and identified ways to optimize this process for multiple performance goals [15]. Finally, improving water use efficiency remains crucial for sustainable growth in the pulp and paper sector. Approaches like water-pinch analysis and treated effluent reuse help lower both water and energy demands [16].

There are several gaps which persists in the existing research pertaining to the paper mills. Understanding and addressing these gaps is pivotal to provide more efficient and cost-effective solutions to this industry. Following are few noted research gaps of this domain:

i) Many of studies till date, focus on theoretical frameworks which lag in real-time control and optimization. Papermill is a continuously running process which needs constant feedback and adjustment. But the existing models have a limited real-time application. The real-time adaptive models based on support vector machine (SVM) are hardly found in the existing research in papermills.
ii) There are several other parameters also other than headbox level and pulp consistency which affect the paper quality such as flow rate, temperature, and pressure. But several studies are focusing on only few of them. A comprehensive model considering all these parameters is hardly found.

iii) There is limited research found on the scalability and generalization of the developed models i.e. models developed for one paper mill may not work successfully for other paper mills. The raw material quality, machine configuration and environmental conditions may vary severely in different paper mills.
iv) A limited focus has been given on energy efficiency and sustainability in the research pertaining to control of papermill processes. In today's scenario, minimizing the energy consumption and environmental impact is a major concern. SVM or some similar ML technique is relatively less explored to attain an energy-efficient process control.
v) Availability of high-quality and large-scale data pertaining to papermills is limited. A large dataset is required to train a ML based model effectively. Inconsistent and noisy data result in degradation in the performance of models. Sturdy research is required to resolve this issue.
vi) Hybrid ML models are rarely found in addressing the control of papermill processes.

2. RELATED WORK

The review presented in this work is exploring various techniques pertaining to optimization and control of paper mills. With rapidly escalating demand of paper products by numerous industries, there has been a rise in the need for modern control methodologies also, to meet the production standards. The classical techniques have proven to be a foundational framework but they are not matching to the demand of futuristic approaches such as modern sensing technologies. This survey looks for such advanced approaches for bridging this gap. The objective is to study the challenges in their implementation and impact on quality and productivity.

The final implementation of any control system requires the interpretation of relationship among process dynamics, automation, and monitoring in real time. Therefore, there is an urgent need to address all the challenges which are there in real time implementation of advanced control systems for paper mill. There is also a need of forecasting future advancements in control mechanisms of paper production processes to upgrade the quality and productivity.

Carlberg [17] presented a research work on digital twins based autonomous mill of future which runs itself with a little or no intervention of humans. This research gave an overview of equipment and operations associated with pulp and paper mills, and concluded with various examples where advanced process control (APC) and MPC) based optimization of control systems can elevate the production and decrease the cost. Rajan *et al.* [18] designed and implemented an intelligent load-shedding system (ILSS) in a paper mill for ensuring power system's stability, after the steam turbine generator makes transitions from back-pressure mode of operation to the isochronous mode upon the loss of electric grid. This approach has been validated by the use of dynamic simulation.

Shahi and Dia [19] evaluated the performance of pulp and paper mills using bootstrap data envelopment analysis method. They compared the performance of 3 types of Ontario's pulp and paper mills. This study provided detailed performance analysis to the policy makers so that the reallocation of the input resources can be done for improving performance of pulp and paper mills in Ontario.

Tao *et al.* [20] carried out a research work on optimal running model of power-heat system (coal-fired) associated with paper mill. They researched on the physical structure of power plant, established the superstructure, and analyzed the boiler and turbine running model. Castillon *et al.* [21] presented research on safety lockout pertaining to AC and DC drives for the paper mills. They examined both alternating current (AC) and direct current (DC) sources. Li *et al.* [22] designed a test for exploring the correlation between milling speed and milling force coefficient in order to attain optimization of plunge process parameters.

Aziz *et al.* [23] presented a new decision model, pertaining to the paper mill, for meeting the actual customer demand. It can be used to simultaneously cut the master reels and stocked rolls. Here, the goal is to satisfy customer need with least possible number of master reels and stocked rolls. Duan *et al.* [24] carried out research with an aim to enhance treatment performance of the pulp and paper mill effluents. They proposed a combination of adsorption and coagulation treatment. McAuliffe *et al.* [25] analyzed the impact of upgrading the power distribution equipment in paper mill (by replacing the vintage air-break circuit breakers by the new vacuum circuit breakers in the existing switchgear) versus replacing it with new equipment, on total installed cost and profitability. The presented literature survey offers a complete understanding of different factors impacting the paper quality, opportunities and challenges inherent in paper mill, and the techniques adopted to deal with them. More stress is on data analytics, sensor technologies, and machine learning in handling final product quality, enhancing overall efficiency.

Having gained the primary knowledge from this literature review, various SVM based models have been explored for assessing the produced paper quality on the basis of two significant parameters viz. pulp consistency and head box level. The pulp consistency is a measure of cellulose fiber concentration in pulp suspension. The mechanical properties and printability of the final product is severely affected by this parameter. Another critical parameter deciding the uniformity and stability of produced paper is the head box level. Its regulation controls the rate of flow of pulp onto the paper machine wire. SVM models are well known for their capability of dealing with high-dimensional and nonlinear data offering a promising avenue of development of predictive models based on intricate dynamics of paper making process. In this work, four distinct variants of SVM are explored viz. linear SVM, quadratic SVM, cubic SVM, and fine Gaussian SVM.

3. METHOD

The basic aim of this research is the control and optimization of the critical processes of the paper mill, particularly accurate assessment of final product quality based on headbox level and pulp consistency. To meet this goal, SVM based predictive model has been developed for improving the paper quality. Following are the key objectives of this research: i) to develop predictive models for accurately determining headbox level and pulp consistency so that their control can be done for attaining good final product quality; ii) assessment of final product quality using various SVM models along with their confusion matrices and comparison table; and iii) to develop multivariate optimization model based on genetic algorithm (GA) considering several parameters. The aim is to parallelly control various critical aspects to optimize the overall final paper quality.

3.1. Development of predictive models for pulp consistency and headbox level

In this section, the first objective of this research is addressed i.e. to develop predictive models for two output variables, headbox level and pulp consistency, based on three input features: flow rate, pressure, and valve position as depicted in Figure 1. The challenge is to accurately model the relationship between these inputs and outputs to provide a reliable prediction tool for process optimization. This research proposes the use of SVM and random forests (RF) in a hybrid model to predict the output variables using MATLAB, followed by a comparative evaluation based on performance metrics such as root mean squared error (RMSE) and R-squared (R^2). The overall objective is to assess the accuracy of these models and to determine whether combining SVM and RF can improve predictive performance compared to individual models.

3.2. Development of paper quality assessment models

The SVM algorithm may be based on different kernel functions such as linear, quadratic, cubic, and Gaussian. The secondary data containing 100 samples with two attributes viz. pulp consistency (%) and the head box level (mm), and three classes of quality, i.e., high, medium, and low is depicted in Figure 2. Now using this data, a classification model such as shown in Figure 3 is to be developed, using support vector machine (SVM) technique in MATLAB, which can estimate the quality of produced paper based on the pulp consistency and head box level values.

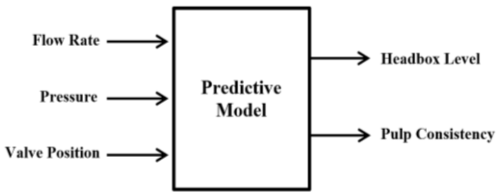

Figure 1. Conceptual representation of the desired model

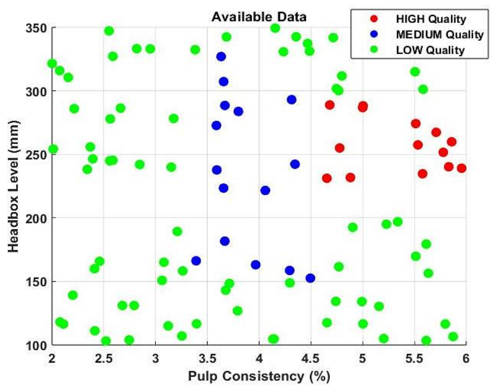

Figure 2. Paper quality data

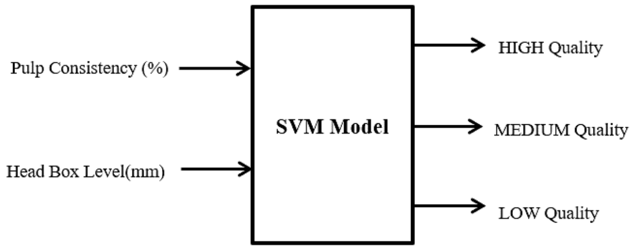

Figure 3. SVM based classification model to be established

3.3. Development of multivariate optimization model

The goal is to ensure high- quality paper production by minimizing deviations from the target values of key parameters: headbox level, pulp consistency, and temperature. The following parameters affect the properties, quality of paper, and requires precise control and optimization. The limitations and boundaries for these parameters can be determined by the machinery and process limitations intrinsic to the industry.

Mathematically, this can be framed as a restricted optimization problem. By using weighted sum of squared differences, the objective function deviates from the target values, which is minimised by making use of optimization process to ensure operational feasibility. The parameters and constraints are as follows:
- Flow rate (m^3/s): [30,100]
- Pressure (Pa): [40, 200]
- Temperature (°C): [28, 80]
- Headbox level (m): [3, 15]
- Pulp consistency (%): [4, 14]

The following are the target values for optimal quality:
- Headbox level = 8 m
- Pulp consistency = 12%
- Temperature = 65 °C

Now, genetic algorithm is applied using MATLAB to solve this optimization problem. It envelops a population of candidate solutions over multiple iterations converge towards the optimal solution.
- Population size: 30
- Number of generations: 150
- Mutation rate: 0.1
- Elitism count: 1

4. RESULTS AND DISCUSSION

All the methods have been considered and evaluated in this section and a clear analysis has been made based on the various parameters.

4.1. Predictive modeling and analysis for pulp consistency and headbox level

Using the inputs flow rate, pressure, and valve position, the outputs—headbox level and pulp consistency as shown in Figure 1—were calculated using the respective linear models. The data was split into two sections, training (80% of data) and testing (20% of data) sets to configure the guaranteed evaluation of models on unseen data. The used secondary data is shown in Figure 4.

SVM, a supervised machine learning algorithm, is widely utilized for regression tasks. In this study, the SVM model incorporates a Gaussian (radial basis function) kernel, which is well suited for capturing nonlinear relationships between input and output variables. To ensure the models performance, the data was standardized to ensure all features are on a comparable scale. SVM regression operates by identifying a hyperplane that optimally fits the training data while minimizing errors within a defined margin. The SVM models were individually trained for headbox level and pulp consistency using the training data set. For each model, hyperparameters such as kernel functions and standardization options are optimized for best performance.

Random forest, an ensemble learning method, constructs multiple decision trees during training. Each tree is built using a randomly selected subset of the data, and predictions are made by aggregating the outputs of all the individual trees. In this study, the random method employed bagging as the ensemble technique and utilized 100 learning cycles to construct the forest. The random forest proved to be a more reliable choice for this regression due to its naturally managing the space overfitting. The same training dataset were used for RF models training as SVM models for both outputs. An integrated hybrid model is designed for the outputs from SVM and random forest models, in order to enhance the predictive accuracy. This hybrid model makes predictions by combining the outputs obtained from these models by assigning weights to predictions obtained from SVM and random forest, respectively.

Figure 5 shows the comparative difference between the true and predictive values for paper consistency. This comparison highlights the difference in the performance between SVM-RF model. Following are the key observations:

- These two models equally apprehend the comprehensive trend of the true values, signifying their capability to model the system dynamics.
- Greater precision is observed using hybrid model in region with sharp variability, highlighting its capability in reducing outfitting and better handling of non- linear relationships.
- Larger prediction error is observed in case of SVM model with extreme paper consistency values, which is successfully addressed by the hybrid model. This reinforces the robustness of using hybrid approach. A better performance of hybrid model is noticeable through reduced prediction deviations as highlighted in case of lower RMSE and higher R2 values.

Figure 6 showcases the benefits of hybrid model in predicting headbox level:

- A better performance than standalone SVM model is observed in case of using hybrid model, wherein the hybrid model has a consistent alignment which is close to the true values across all tested samples.
- Fluctuation in prediction accuracy in comparatively reduced in case of hybrid model in the presence of outliers or edge cases. This simply signifies the harmonious strengths of using random forest's ensemble-based generalization and SVM's kernel-based approximation.
- By using random forest's workability in modifying to local variations and SVM's ability to capture smooth trends, the hybrid model becomes capable to provide a comprehensive analysis of input output relationship. These findings validate the hybrid model as a reliable and precise solution for applications requiring high accuracy and robustness.

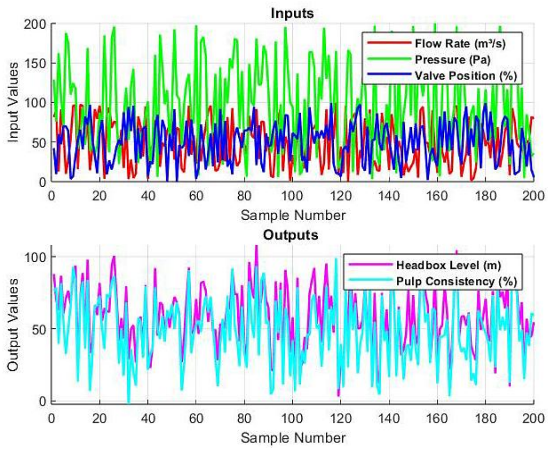

Figure 4. Available secondary data

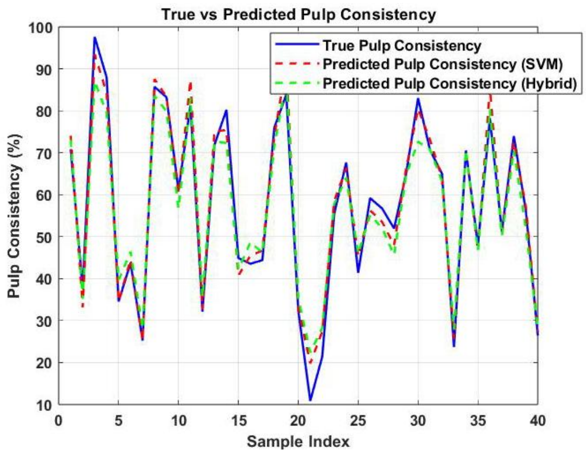

Figure 5. Comparison of test results for pulp consistency

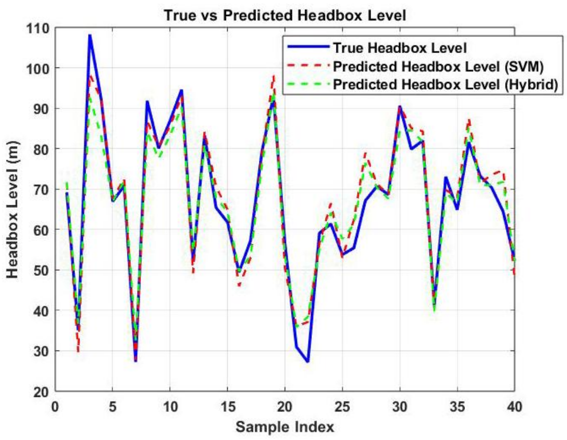

Figure 6. Comparison of test results for pulp consistency

The quantitative demonstration of superiority of the hybrid model is presented by the comparison of the RMSE and R^2 metrics, shown in Figure 7 and Table 1:

i) Root mean squared error (RMSE):
- In case of the headbox level, the hybrid model has a significant drop in RMSE model (3.45) than the SVM model (4.70), which is an improvement in 26.6% of the model.
- In the case of pulp consistency, the hybrid model decreases the RMSE by 5 % i.e. to 4.71 from 4.96.

ii) R^2 metrics:
- The hybrid model has greater values of R2 of both outputs with a value of 0.97 of headbox level and 0.95 of pulp consistency as compared to 0.94 and 0.93 of pulp consistency and headbox level, respectively in the SVM model. This means that there is a closer correlation between the predicted and true values, and the model that includes a hybrid model is better able to account for a larger percentage of the variance in the output.
- The success of the hybrid model is explained by the fact that it can trade-off local and global errors. SVM component offers local trend fitting accuracy and the random forest component offers robust outliers and variability resistance.

The findings conclusively establish the hybrid SVM-RF model as a superior alternative to standalone SVM for predicting critical parameters in industrial processes. By achieving lower RMSE and higher R^2 values, the hybrid model delivers improve precision and robustness. Additionally, its adaptability and scalability make it well- suited for deployment in critical, data-driven decision- making scenarios.

4.2. Assessment of final product quality using SVM

The confusion matrices of four different SVM models developed in MATLAB are presented in Figures 8-11. Each figure illustrates the performance of a specific SVM model in terms of classification results, providing a clear representation of prediction accuracy and error distribution. Furthermore, the comparison of the respective accuracies of these models is summarized in Table 2.

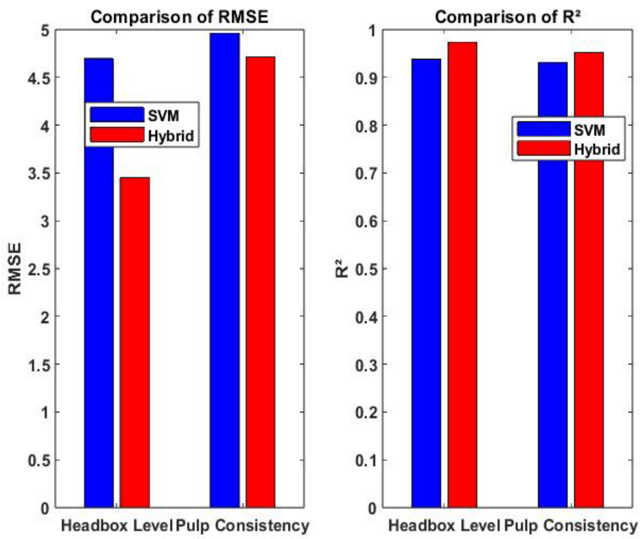

Figure 7. Comparison of performance matrices

Table 1. Performance comparison

Technique	R.M.S.E.		R^2	
	Headbox level (m)	Pulp consistency (%)	Headbox level (m)	Pulp consistency (%)
SVM	4.70	4.96	0.94	0.93
SVM-RF hybrid	3.45	4.71	0.97	0.95

Table 2. Performance comparison of various SVM models

S.L.	Technique	Accuracy (%)
1	Linear SVM	73.3%
2	Quadratic SVM	80%
3	Cubic SVM	90%
4	Fine gaussian AVM	83.33

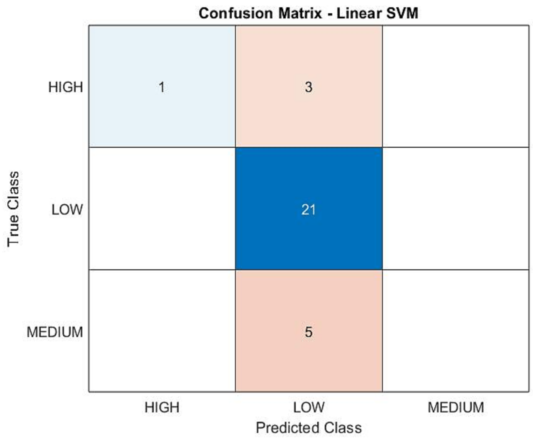

Figure 8. Confusion matrix of linear SVM model

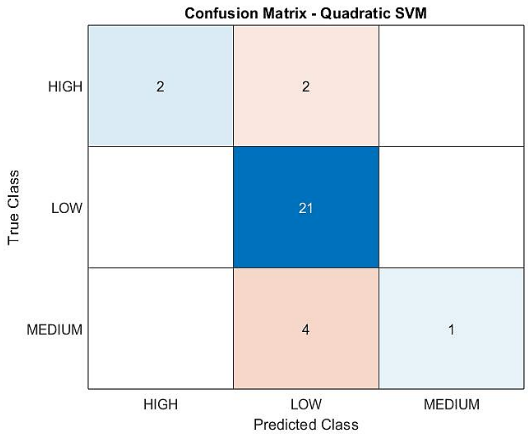

Figure 9. Confusion matrix of quadratic SVM model

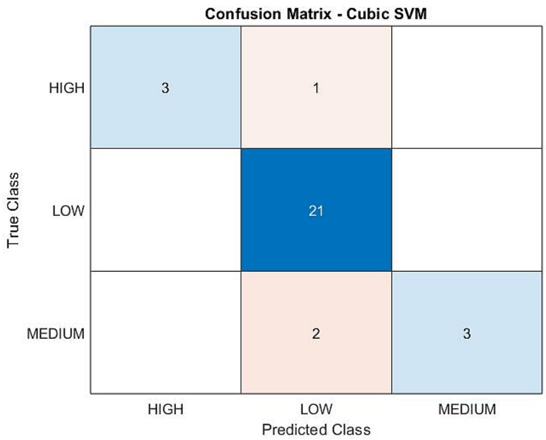

Figure 10. Confusion matrix of cubic SVM model

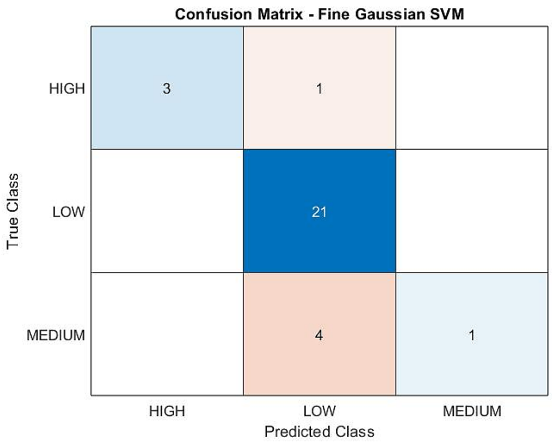

Figure 11. Confusion matrix of fine Gaussian SVM model

4.3. Multivariate optimization using GA for quality enhancement

Figure 12 illustrates the convergence behaviour of the fitness function over 150 generations. The rapid decline in the fitness value during the initial generations indicates the effectiveness of the genetic algorithm in narrowing the solution space. The values of fitness stabilize after the 50th generation indicating that the algorithm has reached a near optimal solution at the beginning. The last objective value of 0.02 indicates that the deviation is minimal to the ideal target, which is a strength of the chosen weights in the objective function.

Figure 13 shows the bar chart that gives the clear picture of the obtained parameter values. The fact that these values are close to their target justifies the accuracy of the genetic algorithm in optimization of a number of objectives at the same time. The implications are followed by:

- Flow rate: At 90.39 m^3/s, the system achieves an efficient throughput without compromising other quality parameters.
- Pressure: The low pressure of 40.08 Pa ensures minimal energy usage while maintaining structural integrity during processing.
- Temperature: The value of 65.03 °C aligns with the target, crucial for ensuring uniform pulp distribution and bonding quality.
- Headbox level: The optimized level of 8.04 m facilitates smooth sheet formation, preventing inconsistencies in thickness.
- Pulp consistency: Achieving 12.08% ensures optimal fiber distribution, contributing to improved paper strength and surface properties.

The optimization process successfully determined the best set of parameters that minimize the deviation from the target quality metrics for paper production. The final optimized parameters are summarized in Table 3.

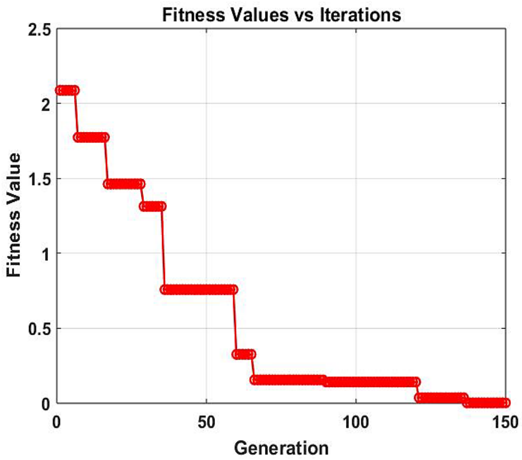

Figure 12. Fitness values

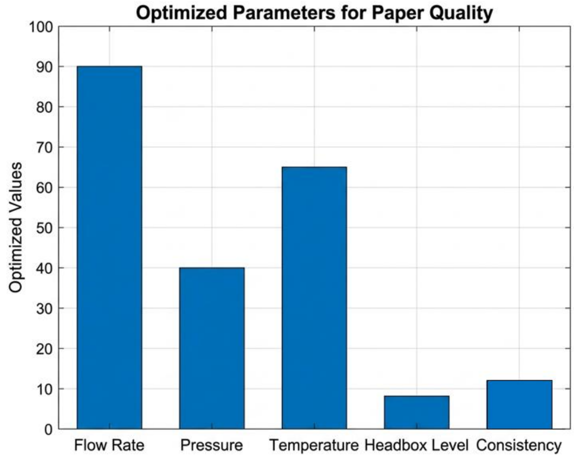

Figure 13. Attained optimized values

Table 3. Attained optimized values

S.L.	Parameter	Optimized value
1.	Flowrate (m^3/s)	90.39
2.	Pressure (Pa)	40.08
3.	Temperature (ºC)	65.03
4.	Headbox level (m)	8.04
5.	Pulp consistency (%)	12.08

5. CONCLUSION

This study examines how to incorporate an advanced machine learning and optimization in enhancing the working of industries, specifically in the method of monitoring and optimization of important measures like the headbox level and pulp consistency. This study offers an account of an extensive literature review and employs the predictive capacity of different SVM models using MATLAB and helps in illuminating some of the issues that are intrinsic to paper manufacturing, and new directions that can be taken in the quest of enhancing sustainability in paper printing. A very comprehensive analysis of the current literature on optimization and control of different systems which make up a paper mill has been discussed. Various methods of SVM have also been created to identify paper quality in classification models in MATLAB. The fine Gaussian SVM model has been observed to show the best accuracy of all the SVM models developed. This paper employs a hybrid approach with SVM and random forest to demonstrate that hybrid models are effective in predicting results compared to when the individual standalone method is applied. The hybrid method has superior performance in terms of less errors (small RMSE) and higher reliability (increased R^2 values). The last one is to streamline industrial environment such as headbox level, pulp consistency, and temperature by utilizing genetic algorithm (GA) in MATLAB. The best sets of these parameters are indicated using this method as the goals are balanced to achieve quality standards and adhering to certain limits to make the results viable and realistic.

This study describes the advantages of hybrid modelling and optimization in solving non-linear and complicated industrial systems. Another issue that is brought to the fore in this study is the need to integrate prediction and optimization to enhance the efficiency and quality of products of complex industrial systems. Also, it employs visual comparisons to assist in making superior judgments as well. The study forms a strong foundation on additional innovations in the area of monitoring, control, and optimization strategy in the paper industry with prospects of enhanced quality and efficiency guarantees.

Future work could include real-time data from futuristic sensors, and other optimization methods like particle swarm optimization (PSO) or differential evolution (DE). Furthermore, combining cost and energy saving processes for optimization. Overall, this study shows how artificial intelligence (AI) techniques can improve industrial processes and make it a smarter and more efficient manufacturing system.

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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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Pradeep Juneja	✓		✓	✓	✓		✓			✓	✓		✓	✓

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

This work is based on available data which belongs to the paper mill- Century Pulp and Paper Mill, Lalkuan, Uttarakhand.

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