Factory Energy Management by Steam Energy Cluster Modeling in Paper-Making

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Abstract— **This paper presents a steam energy modeling for paper-making, focusing on factory energy management in the paper drying process and analysis of the response characteristics of the process. A heuristic methodology is developed to model steam energy consumption by efficiently and robustly solving correlations among significant factors. Using paper production and operation data, independent variables were selected to identify the relationships among influencing factors. Data on paper breakage and branching were extracted from facility operation data and analyzed using Spearman correlation. Results of this study showed that the type of paper-making, the cylinder of the drying process, and the pressure and temperature of the steam energy supply were identified as the main influencing factors. Feature factors were extracted, classified into support vector machine (SVM) models, and analyzed using t-distributed stochastic neighbor embedding (T-SNE) dimensionality reduction. The proposed clustering modeling methodology can solve specific problems by extracting additional generalized factors and improving energy efficiency. Based on the analysis of actual process operation data, it is found that controlling steam pressure applied to the cylinder is a significant variable that can reduce steam energy consumption while maintaining appropriate quality. Overall, this study provides valuable insights into the energy management of the paper drying process and offers a methodology for modeling steam energy consumption in paper-making that can be applied to other industrial processes.**

Keywords— Factory Energy Management, Steam Energy Cluster Modeling, Paper-Making, Optimization

I. INTRODUCTION

The industrial revolution and the acceleration of capitalism have significantly impacted the environment, leading to climate change through the destruction of natural ecosystems and global warming [1]. To address this crisis, the global community is promoting carbon neutrality, which reduces greenhouse gas emissions to zero. The pulp and paper industry (PPI) is among the top five energy-consuming industries, and its energy use has been increasing at an average annual rate of 0.3% between 2018 and 2000. The PPI accounts for 6% of global industrial energy consumption and 2% of direct industrial CO2 emissions [2, 3]. However, despite these significant contributions to carbon emissions, production in the PPI is expected to continue to increase. As a result, significant efforts will be required to achieve the '2050 carbon neutral scenario' where global net carbon emissions are zero by 2050 [4]. The PPI needs to play a significant role in these efforts by implementing measures to reduce energy consumption, increase energy efficiency, and shift towards renewable energy sources. The industry must also explore new technologies and innovative solutions to address the climate crisis and promote sustainability.

The paper manufacturing process involves using pulp made from wood and other plants through a mechanical/chemical process [5]. Typically, the paper-making process is divided into four stages: the adjusting process, the paper-making process, the coating process, and the last stage process. The paper-making process involves a significant amount of steam energy and includes the dehydration and drying of the paper stock, which goes through processes such as stratum formation, compression dehydration, and drying. By analyzing steam energy consumption and developing empirical models, the researchers aim to provide insights into the paper-making process that can be used to optimize control and improve energy efficiency. This could ultimately help the paper industry meet ESG goals and contribute to global efforts to reduce carbon emissions.

To effectively reduce carbon emissions in the paper-making process, it is essential to go beyond simply minimizing energy consumption and focuses on improving energy efficiency [6]. The fourth industrial revolution and environmental social governance (ESG) have gained global attention recently, with ESG becoming a new paradigm for sustainable corporate management. Societal demands environmental protection, the social safety net reinforcement, and transparency of corporate governance drive ESG. One way to address ESG management in the paper industry is to improve the energy efficiency of the paper manufacturing process. Steam energy is mainly used in the paper-making process, representing a significant proportion of consumed energy. In this study, we analyzed steam energy consumption in the paper-making process and developed empirical models to present strategic implications for optimal control in a complex system. The main contributions of this study are:

1) A heuristic methodology for modeling steam energy consumption in paper drying by efficiently and robustly solving correlations among significant factors is introduced. This methodology can be applied to other industrial processes to improve energy efficiency.

2) This study identified the type of paper, cylinder of the drying process, and pressure and temperature of the steam energy supply as the main influencing factors on energy consumption in the paper drying process. This information can be used to optimize energy management in paper-making and potentially other manufacturing industries.

3) Support vector machine (SVM) models and t-distributed stochastic neighbor embedding (T-SNE) dimensionality reduction were used to analyze the relationships among influencing factors and extract feature factors. This approach can be applied to other studies identifying complex relationships and optimizing energy consumption in industrial processes.

The study begins with the description of correlation analysis in Section II. Section III presents the modeling and power management. Finally, concluding remarks are presented in Section IV.

II. Correlation Analysis

Figure 1 illustrates the overall structure of the paper-making process, energy system, and control system. The paper-making process comprises several stages: headbox, wire, press, pre-dryer, post-dryer, machine calendar, and reel. The raw material is ejected from the headbox and forms paper in the wire part. The paper is then pressed and dewatered in the press part. Evaporated residual moisture in the dryer part, and finally, the thickness of the paper is adjusted in the calendar part to achieve the target paper basis weight. During the paper drying process, there is a risk of paper breakage, which can occur depending on the moisture content of the paper. Paper breakage can lead to diagnosis and maintenance time to stabilize the paper-making process, resulting in the wastage of pulp, energy, and power to replace the damaged paper. Steam pressure is reduced through the drying cylinder to prevent overheating of the cylinder during paper breakage.

Energy system is a crucial component of the paper-making process, particularly in the drying stage. Steam evaporates residual moisture from the paper and achieves the target paper basis weight. However, the pressure and temperature of the steam supply can also affect the quality and energy consumption of the paper drying process. The battery storage system can also be used in paper-making to store excess energy generated for later use. This can improve overall energy efficiency and reduce energy costs. Utility management is essential in paper-making to ensure that the energy used in the process is optimized and that the waste is minimized. Effective utility management can help in reducing costs and environmental impact.

Moreover, sensors are critical in controlling the paper-making process, particularly in monitoring moisture content and preventing paper breakage. By providing real-time data on process parameters, sensors can enable effective control and optimization of the paper-making process. Overall, effective energy management, steam supply, battery technology, utility management, and sensor monitoring are all essential for optimizing the paper-making process, minimizing waste, and improving product quality.

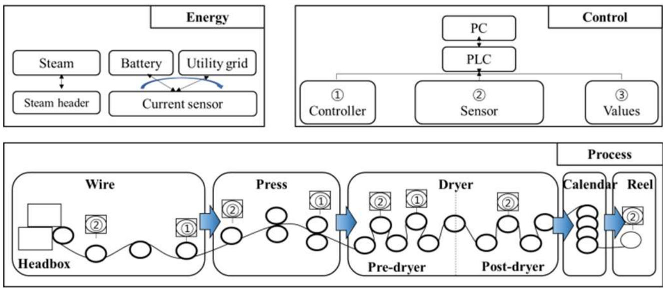


Fig.1. Structure of the paper-making process.

Control is carried out in the headbox, wire, and dryer when changing the paper stock to match the paper's basis weight, ash content, and moisture content. This helps to ensure that the paper produced meets the desired quality standards. The paper-making process is complex, and effective control is critical in minimizing paper breakage, optimizing energy consumption, and improving product quality.

When paper breakage occurs during production operation, it leads to diagnosis and maintenance time to stabilize the paper-making process, resulting in a waste of pulp, energy, and electricity. In the paper-making process, factors related to the temperature and pressure of the steam applied to the cylinder affect energy efficiency, and factors related to the moisture content and basis weight of the paper are controlled based on the type of paper being produced. Paper grade replacement, which various dependent variables can influence, may be one of the causes of paper grade failure.

In paper manufacturing, distributed control systems (DCS) and quality cleanness service (QCS) data are crucial for identifying the causes of paper breakage. The data collected at 15 minute intervals from DCS and QCS systems are analyzed using statistical techniques such as the Spearman correlation coefficient to identify the factors related to paper breakage. Factors such as paper grade, power factor of process energy, steam pressure, dry cylinder, and ash amount are examined to determine their correlation with paper breakage. The Spearman correlation coefficient is a non-parametric measure of correlation that assesses the relationship between two variables, even if they are not linearly related. By analyzing the correlation between these factors and paper breakage, manufacturers can identify the factors contributing to it and take appropriate measures to address them.

In addition to the Spearman correlation coefficient, machine learning techniques such as support vector machine (SVM) and t-distributed stochastic neighbor embedding (T-SNE) are used to analyze the data. Tags related to energy consumption are used as inputs for SVM and T-SNE techniques to identify the patterns and relationships in the data. The SVM is a machine learning algorithm used for classification and regression analysis. It can be used to identify the relationships between the tags related to energy consumption and paper breakage. The T-SNE is a dimensionality reduction technique that can be used to visualize high-dimensional data in a lower-dimensional space. By applying T-SNE to the data collected from DCS/QCS systems, manufacturers can gain insights into the patterns and relationships between the factors related to energy consumption and paper breakage.

A. Spearman's Correlation Coefficient

Spearman's Rank Correlation Coefficient is a statistical technique that assigns ranks to two variables and calculates a correlation coefficient [7]. Unlike Pearson's correlation coefficient, which only measures linear relationships, Spearman's can identify nonlinear correlations. This makes it particularly useful for analyzing correlations in highly complex paper-making processes, where relationships between variables may not be immediately apparent. Using Spearman's Rank Correlation Coefficient and other machine learning techniques, paper manufacturers can identify the factors contributing to paper breakage and take corrective measures to improve product quality and reduce production costs. This type of analysis allows manufacturers to understand better the underlying factors that affect the paper-making process and optimize the process accordingly. Ultimately, combining statistical and machine learning techniques can help manufacturers produce higher-quality paper more efficiently while minimizing waste and reducing costs.

In the paper-making process, the dryer is crucial in carrying out pre-drying and post-drying operations while maintaining moisture levels around 50% of the weight per one square meter of pressurized pressure. Half of the moisture is removed in the press during the paper drying process. The remaining moisture is directly supplied to the inside of the drying cylinder using steam energy through the drying cylinder, where the paper undergoes pre-drying and post-drying.

Due to the complex structure of the paper drying process, steam energy exhibits correlations between the basis weight and moisture content of the drying cylinder and paper. To gain insights into these correlations, researchers conducted a correlation analysis of paper basis weight, moisture content, and steam pressure in the pre-drying and post-drying sections of the dryer. The results of this analysis are presented in Fig. 2.

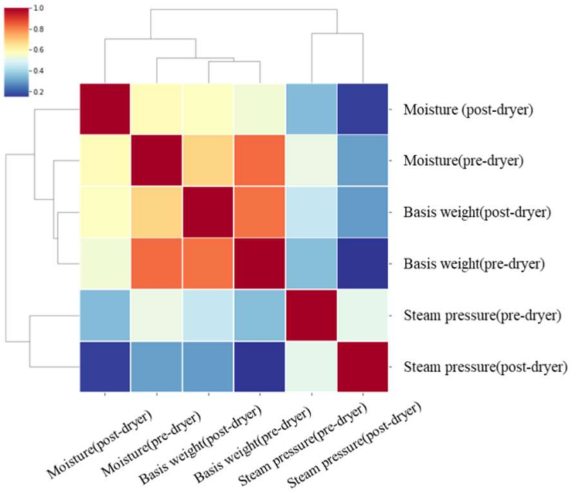


Fig.2. Correlation analysis of paper basis weight, moisture content, and steam pressure in the paper-making process.

The results of the correlation analysis revealed that paper basis weight, moisture content, and steam pressure have various correlations and characteristics that vary depending on the pre-drying and post-drying sections of the dryer. These findings suggest that controlling steam pressure is critical to optimizing paper drying and minimizing paper breakage. By better understanding the correlations between these variables, paper manufacturers can optimize the paper drying process and improve product quality while minimizing waste and reducing costs.

B. SVM classification

The SVM is a linear classification model that finds classification boundaries from several classes and determines which category the given data belongs to [8]. When the data is nonlinear, a radial basis function (RBF) kernel can be applied to solve the problem. In this study, the factors for process energy, cylinder of the drying process, steam supply pressure and temperature, and ash content are set as dependent variables. In contrast, the top 17 paper types with high production in the process are analyzed for SVM-based correlation as independent variables. The dataset consists of 3.08 million data points collected at 15-minute intervals. The accuracy score of the classification model using SVM is 0.98, indicating a high degree of accuracy. The results of the analysis are presented in Fig. 3.

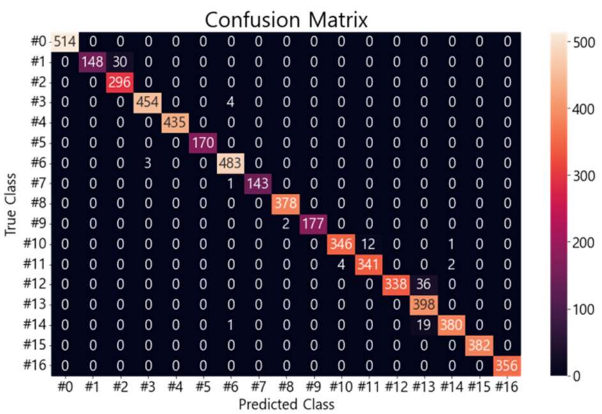


Fig.3. Confusion matrix as an evaluation index by SVM classification

The type of paper to be produced can be specified based on the factors of process energy, steam supply pressure and temperature in the cylinder of the drying process, and the amount of ash. By using SVM-based classification, paper manufacturers can accurately predict the factors that affect the quality of the paper and optimize the paper-making process accordingly. This can help to minimize waste, reduce costs, and improve product quality.

C. *T-SNE analysis*

The T-SNE is a dimensionality reduction technique that transforms high-dimensional complex data into low-dimensional data [9]. It is primarily used for visualization since its results can be challenging to interpret. In Fig. 4, the left side shows the original data, while the right side shows the results of applying T-SNE to the data that the SVM model has processed.

Using the Spearman correlation coefficient and feature factors extracted based on basis weight, we classified the top 17 paper types into three groups based on their basis weight: high basis weight (150-250), low basis weight (50-100), and medium basis weight (100-150). The results are presented in the clustered visualization on the right side of Fig. 4.

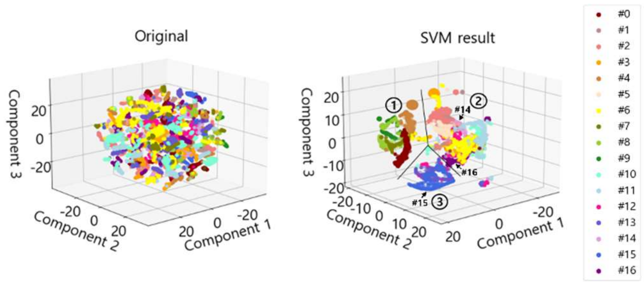


Fig.4. Original and SVM model data T-SNE visualization

It is interesting to note that some paper types that are not easily distinguishable visually are classified into different groups based on their basis weight. This indicates that basis weight is a crucial factor in the paper-making process, and accurate control can improve the quality and consistency of the paper produced.

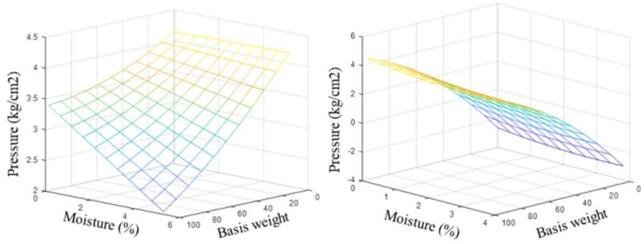
Overall, combining statistical analysis, machine learning techniques such as SVM, and dimensionality reduction using T-SNE can help paper manufacturers identify the factors contributing to paper breakage and optimize the paper-making process to improve product quality and reduce production costs.

III. MODELING AND POWER MANAGEMENT

The drying unit in the paper-making process consumes about 60% or more of the total energy used in the process, and it is challenging to recover steam energy, indicating that improving efficiency is crucial. However, it is vital to avoid the issues of over-drying or under-drying during the paper-making process while efficiently using steam energy. To achieve this, pre-drying and post-drying stages are modeled separately in the drying section to ensure efficient use of steam energy at each stage.

A. *Empirical modeling*

A three-dimensional model was developed to analyze the correlations between basis weight, moisture content, and steam pressure in the pre-drying and post-drying sections. The model revealed an inverse relationship between steam pressure and moisture content when the basis weight of the paper is the same. As shown in Fig. 5, increasing steam pressure decreases paper moisture content, reducing the energy required for drying. This highlights the importance of optimizing steam pressure to achieve maximum energy efficiency and reduce production costs in the paper-making process.



(a) (b)

Fig.5. Empirical modeling of dryer parts: (a) pre-dryer; (b) post-dryer.

B. *Power management*

The optimization of the paper process can be expressed as a constrained optimization problem, where the goal is to minimize the objective function while satisfying certain constraints. The objective function is the gross pressure modeling over a predetermined time interval, and it is a function of the temporal variations of the paper moisture, basis weight, and steam pressure. The variables that need to be optimized are the steam pressure in the pre-dryer section P_P, basis weight in the pre-dryer section B_P, steam pressure in the post-dryer section P_A, and basis weight in the post-dryer section B_A. The integral in the objective function represents the total gross pressure over the time interval, which is minimized.

$$\underset{P_P(t),B_P(t),P_A(t),B_A(t)}{Min} \int_{t_s}^{t_f} P_P(t)\big(M_P, B_P(t)\big) + P_A(t)(M_A, B_A(t))\, dt \quad (1)$$

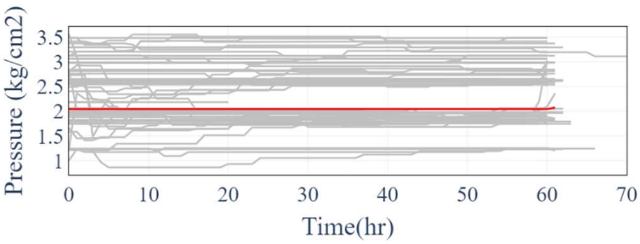
subject to

$$B_{P,\min} \le B_P(t) \le B_{P,\max} \text{ for all } t \quad (2)$$

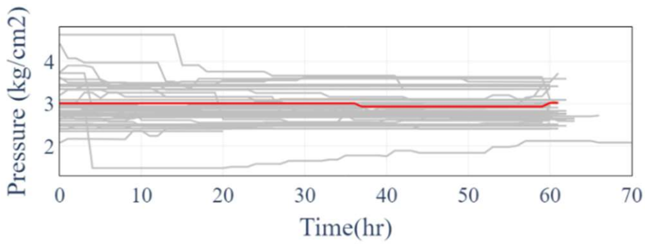
$$M_A(P_A(t), B_A(t)) \le M_{A,max} \text{ for all } t \quad (3)$$

where M_P (t) is the time-varying M_P as a function of temporal variables $P_P(t)$ and $B_P(t)$ at time t. There are two constraints. The first constraint in equation (2) limits the basis weight in the press section to be within a certain range, where $B_{P,}$ min and $B_{P,\max}$ are the minimum and maximum allowed basis weights, respectively. The second constraint in equation (3) limits the moisture within a certain range in the dryer section, where $M_{A,max}$ is the maximum allowed moisture. Solving this optimization problem aims to find the variables' values that minimize the objective function, subject to the constraints. This can be done using various optimization techniques, such as nonlinear programming. Solving this problem can optimize the paper process to achieve the desired gross pressure while ensuring that the basis weight and moisture are within acceptable ranges.

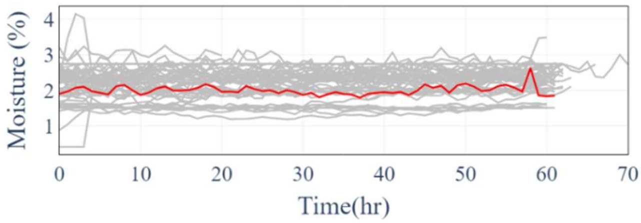
Fig. 6 illustrates the optimal moisture content achieved by adjusting the pressure of the pre-dryer and post-dryer using an optimization technique in equations (1), (2), and (3). This technique reduces the steam energy used in the paper-making process by lowering the pressure in the pre-dryer and post-dryer. The optimal moisture content achieved under these conditions is shown in Fig. 6. Effective energy management is critical in paper-making and optimization techniques can help reduce energy consumption and improve product quality. The industry can reduce costs and environmental impact by optimizing the paper-making process while improving efficiency and product quality. As shown in Fig.6(a) and Fig.6(b), steam pressure decreases from 3kg/cm2 to 2 kg/cm2 in the pre-dryer and from 3.5 kg/cm2 to 3 kg/cm2 in the post-dryer.



(a)



(b)



(c)

Fig.6. Simulation results: (a) pre-dryer pressure; (b) post-dryer pressure; (c) paper moisture.

Optimizing the paper-making process by adjusting the pressure of the pre-dryer and post-dryer using an optimization technique reduced steam energy consumption and improved the quality of paper products. The optimal moisture content achieved under these conditions is shown in Fig. 6(c), where the moisture content of the paper changed from 3% to 2%. By achieving the optimal moisture content, the efficiency of steam energy in the paper-making process is maximized, resulting in reduced energy consumption. In addition, the quality of the paper products improved due to optimizing the process variables. Effective optimization of the paper-making process can lead to significant cost savings, increased efficiency, and improved product quality.

IV. Conclusion

This paper presents a modeling approach to improve the efficiency of steam energy in the drying cylinder of the paper-making process. The approach analyzes the correlation between the pre-drying and post-drying sections using 3-dimensional modeling of steam energy, paper basis weight, and moisture content. This study utilizes process operation data to identify steam energy applied to the cylinder as a significant variable. The proposed methodology provides an optimal control point by configuring a complex system with 3D modeling. This research aims to contribute to developing a more efficient and sustainable paper-making process by improving energy efficiency and identifying additional generalized factors. The optimal moisture content was achieved by lowering steam pressure in the pre-dryer and post-dryer using an optimization technique to reduce energy consumption and improve paper quality. Specifically, steam pressure was reduced from 3kg/cm2 to 2 kg/cm2 in the pre-dryer and from 3.5 kg/cm2 to 3 kg/cm2 in the post-dryer. In addition, the moisture content of the paper changed from 3% to 2%. Optimizing the paper-making process through effective energy management and optimization techniques can reduce costs, increase efficiency, and improve product quality.

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