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Optimization of Energy Consumption During Industrial Veneer Drying – A Preliminary Assessment

Optimizacija potrošnje energije tijekom industrijskog sušenja furnira – preliminarna procjena

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ABSTRACT • *The soaring energy prices and the increasing environmental issues have challenged many energy-intensive manufacturing processes, including wood veneer drying. This study aimed to explore how data-driven approaches could help optimize the industrial veneer drying process to minimize energy consumption and maintain quality. Four optimization scenarios were defined to determine optimal dryer temperature and drying speed. The results demonstrate the feasibility of using data-driven methods in veneer drying for process improvement. This approach could be used to optimize the veneer drying schedule or evaluate the potential of using alternative energy sources.*

KEYWORDS: *data-driven approach; minimize energy cost; maximize quality turnout; veneer drying case study; process improvement*

SAŽETAK • *Rastuće cijene energije i sve veći ekološki problemi postavili su izazov mnogim energetski intenzivnim proizvodnim procesima, uključujući sušenje furnira drva. Cilj ove studije bio je istražiti mogu li se na temelju podataka optimizirati industrijski procesi sušenja furnira kako bi se smanjila potrošnja energije i održala kvaliteta. Za određivanje optimalne temperature i brzine sušenja definirana su četiri optimizacijska scenarija. Rezultati pokazuju da primjena metoda vođenih podatcima pridonosi poboljšanju procesa sušenja furnira. Taj bi se pristup mogao primjenjivati za optimizaciju rasporeda sušenja furnira ili za procjenu potencijala korištenja alternativnih izvora energije.*

KLJUČNE RIJEČI: *pristup vođen podatcima; smanjenje troškova energije; maksimizacija kvalitete; studija slučaja sušenja furnira; poboljšanje procesa*

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1 INTRODUCTION
1. UVOD

Drying wood veneers from wet to their intended moisture content (MC) is a process that consumes a great amount of thermal and electric energy. Currently, wood veneer manufactures are encouraged to improve energy efficiency due to rising energy prices, increasing carbon taxes, and ongoing social-environmental concerns about energy usage. In addition, veneer drying is also known as a complicated and little-understood process to control. Achieving a consistent and uniform final MC could be challenging due to the anisotropy nature of wood itself. Modifications on the drying temperatures and time for less energy consumption might impact the quality turnout unfavourably. Therefore, the ultimate objective of this research was to optimize the veneer drying schedule to enhance overall energy performance and quality goals. In the literature, previous research has been found on estimating energy consumption of a drying process or predicting veneer drying quality but not in the combined field. Reports on drying process of grains (Bayati *et al*., 2023) or other energy intensive industrial processes (Matsunaga *et al*., 2022) were considered. However, their approaches did not apply to the current industrial context under study. As a preliminary assessment, the research examined four different optimization scenarios combining various requirements for energy consumption and veneer quality.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The raw data used in this study was collected by various sensors and recorded during production by a veneer manufacturing company located in British Columbia, Canada. The continuous jet dryer under study is fired with natural gas and contained four decks. Its longitudinal section was divided into three zones (i.e., Zone 1, Zone 2, and Zone 3), excluding the cooling area. There were multiple burners inside each zone to maintain the drying temperature so each zone could be further separated into subzones (e.g., Zone 1a and Zone 1b for Zone 1). Theoretically, the temperature of each subzone could be set to any valid value. However, in practice, the company primarily adjusted the temperature of the first subzone – Zone 1a – and ensured the temperatures of the sequential subzones decreased according to a gradient. Therefore, it may be possible to tailor the drying conditions by adjusting the temperature of Zone 1a and the drying speed.

2.1 Data collection and prediction models
2.1. Prikupljanje podataka i modeli predviđanja

The raw data obtained for this research can be classified into five categories: (1) energy consumption, (2) dryer parameters, (3) pre-drying veneer properties, (4) post-drying veneer properties, and (5) weather variables. The first four groups were collected by sensors positioned along the drying line and queried from the industry partner's internal servers, while the last group was collected on a daily basis and extracted from the Environment and Natural Resources of Canada database (http://climate.weather.gc.ca, accessed on July 1, 2020). As these five groups of raw data were recorded at various intervals, namely, per hour, per minute, per load, per veneer sheet, and per day, respectively, data transformation and compilation were necessary to harmonize raw data into a consistent and ready-for-analysis format. Details related to data description, transformation, and compilation can be found in Qiu (2022) and Qiu and Cool (2023a, b).

To achieve the ultimate goal of decreasing the energy consumed when drying Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) veneers while maintaining or improving the drying quality turnout, an easy-to-implement strategy is to determine the optimal drying schedule that fulfils these objectives. In this study, a preliminary assessment was conducted to examine how the generalized least square (GLS) models developed by Qiu and Cool (2023b) and the logistic regression (LR) models established by Qiu and Cool (2023a) could be employed in optimizing the Zone 1a temperature and drying time (i.e., drying speed) under different objectives and restrictions. As the dryer is expected to operate in a steady-state, the following assumptions were made:

- the hourly standard deviations of Zone 1a temperature and drying speed were approximated to be zero;
- the dryer only operates within the valid speed range;
- the variables from the energy prediction models have the same values as those from the quality classification models;
- the dryer only dries 3.175 mm thick light sapwood veneers in an hour;
- the weather was assumed to correspond to a temperature of 15 °C and precipitation of 0 mm;
- the batch ID, load weight, and the ambient temperature around the infeed conveyor were assumed to be 1, 1814.4 kg and 23.9 °C, respectively.

As a result, the models developed by Qiu and Cool (2023a, b) were simplified into Eqs. 1-4.

$$\widehat{UnitGasUsage} = -0.1161 + 0.0007 Zone1aTemp + 0.0277 DryingTime \quad (1)$$

$$\widehat{UnitGasUsage} = 1.9372 - 0.003 Zone1aTemp + 1.3604 DryingTime \quad (2)$$

$$logit(Quality{=}Overdry \mid x) = -4.5106 + 0.0041 Zone1aTemp + 0.3096 DryingTime \quad (3)$$

$$logit(Quality{=}Redry \mid x) = -0.0853 - 0.0033 Zone1aTemp - 0.1234 DryingTime \quad (4)$$

Where $\widehat{UnitGasUsage}$ is the unit gas usage (GJ), $Zone1aTemp$ is the average temperature of Zone 1a (°F), $DryingTime$ is the amount of time (minute) a veneer sheet spends in the dryer and corresponds to the drying speed, $\widehat{UnitGasUsage}$ is the unit electricity usage (KWh), *logit(Quality=Overdry│x)* is the probability of a veneer sheet to be characterized as over-dry, and *logit(Quality=Redry│x)* is the probability of a veneer sheet needing to be re-dried.

2.2 Optimization scenarios
2.2. Optimizacijski scenariji

Although better managing the energy use of a veneer dryer is an essential goal, this objective is often subjected to one or multiple quality requirements. This preliminary study explored four optimization scenarios including: 1) minimizing energy use, 2) minimizing energy cost, 3) minimizing energy cost while maintaining quality turnout, and 4) minimizing energy cost and maximizing quality turnout. The first two cases take only the energy aspect into consideration, while the last two include the quality of dried veneer sheets as well. The formulation of each optimization case and their preliminary results is presented below.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Minimizing energy use
3.1. Minimiziranje potrošnje energije

The first scenario consisted in simultaneously optimizing two types of energy consumption (i.e., gas and electricity usage). At the same time, the Zone 1a temperature and the drying time were limited by the partner company's operation specifications. The bi-objective optimization model is shown below (Eqs. 5-6) and was solved using the *mco* package in R (Mersmann *et al*., 2020).

Objective 1: Minimize Unit gas usage, $\widehat{UnitGasUsage}$ (5)

Objective 2: Minimize Unit electricity usage, $\widehat{UnitGasUsage}$ (6)

Subject to: $176.7\ °C \leq Zone1aTemp \leq 210\ °C$ (7)

$3.8\ min/sheet \leq Dryingtime \leq 10\ min/sheet$ (8)

Figure 1 shows the Pareto front, on which solutions were non-dominated. According to the equations, both gas and electricity consumptions were in positive correlation with the drying time. It was therefore expected that all Pareto-optimum solutions held the same minimum drying time of 3.8 minutes per sheet. In contrast, the Zone1a temperature varied among Pareto-optimum solutions due to gas and electricity usage having opposite trends with Zone 1a temperature. Consequently, taking the prices of both energy types into consideration for the optimization of drying time, Zone 1a temperature may result in a different solution.

3.2 Minimizing energy cost
3.2. Minimiziranje troškova energije

The second scenario introduced energy prices to the optimization and reshaped the bi-objective problem into a single objective one – minimizing energy cost, with the constraints remaining the same. The electrical energy was charged at $0.07527 per kWh ($p_{elec}$) for commercial service (FortisBC, n.d.-b), and the natural gas rate (p_{gas}) was billed at $5.321 per GJ in terms of

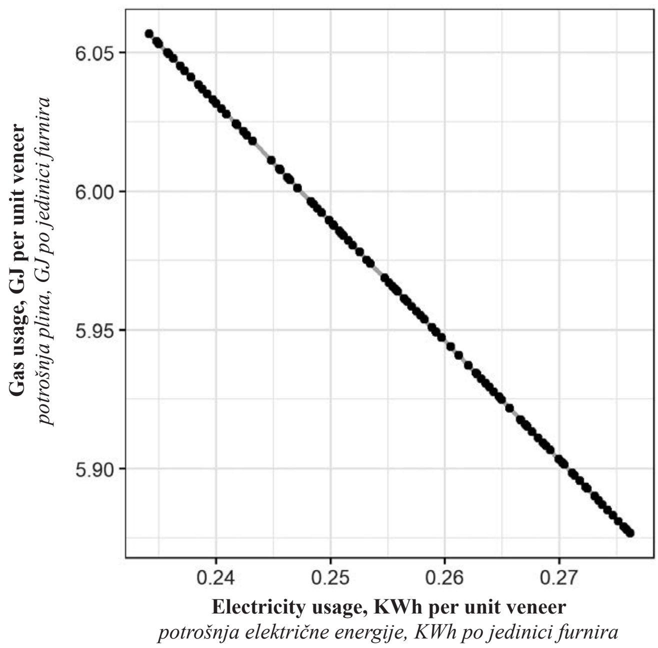

Figure 1 Pareto front of Scenario 1. The points are a set of non-dominated solutions
Slika 1. Pareto krivulja za 1. scenarij, točke su skup nedominiranih rješenja

commodity related charges for "a large-volume commercial, institutional, multi-family or other customer that uses about 5,000 GJ or more annually" (FortisBC, n.d.-a, para. 3). The model is presented below (Eq. 9).

Objective: Minimize Unit energy cost, Z_{cost}

$$Z_{cost} = p_{gas} \times Unit\widehat{GasU}sage + p_{elec} \times Unit\widehat{GasU}sage \quad (9)$$

Subject to: Eqs. 7-8

This second case was solved using a graphical method (Figure 2). When the dryer runs at a Zone 1a temperature of 350 °F (corresponding to 176.7 °C) and a drying time of 3.8 minutes per sheet, the energy cost per unit veneer could be minimized to $1.70. As explained previously, it was expected that the drying speed remained unchanged compared to that of the first scenario. However, in this second scenario, it was the cost of natural gas ($5.321 per GJ vs. $0.07527 per kWh for electricity) that was the main cause for limiting the dryer temperature. It is hypothesized that this optimization scenario would recommend a lower Zone 1a temperature as the cost of natural gas is steadily increasing (U.S. Energy Information Administration, 2022). However, this assumes the industry partner would be willing to lower their minimum Zone 1a temperature (Equation 7) and doing so would not impact the quality turnout of the veneer drying process, which will be discussed in the next two scenarios.

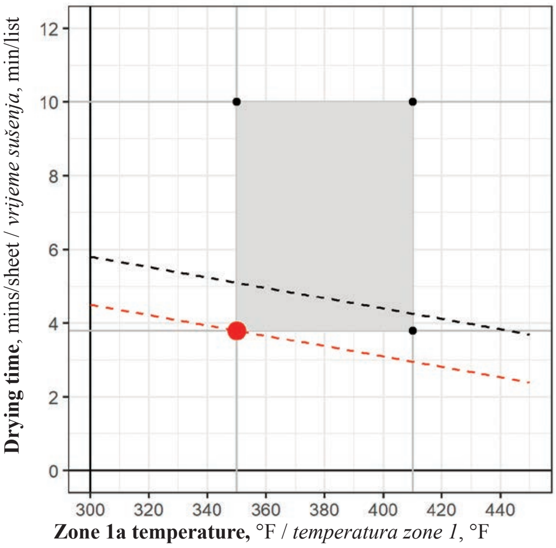

Figure 2 Graphical method to solve Scenario 2 (The grey represents the feasible solution region. The y-intercept of the black line indicates the objective function. As the goal is to minimize the objective function, the optimal solution (the red point) is achieved when the line of the objective function aligns with the left-bottom corner of the feasible region.)
Slika 2. Grafička metoda za rješavanje 2. scenarija (Sivi pravokutnik predočuje područje mogućeg rješenja. Y – odsječak crne linije označava istraživanu funkciju. Kako je cilj minimizirati istraživanu funkciju, optimalno rješenje – crvena točka, postiže se kada se linija istraživane funkcije poravna s donjim lijevim kutom područja mogućeg rješenja.)

3.3 Minimizing energy cost while maintaining quality turnout
3.3. Minimiziranje troškova energije uz održavanje kvalitete

When also considering the quality turnout, the third scenario maintained the single objective of minimizing energy cost, but upper specification limits were added to the probability of a veneer sheet being overdried ($USL_{overdry}$) or needing to be re-dried (USL_{redry}), which can be calculated by Eqs. 10-11, respectively.

$$Prob(Quality = Overdry|x) = \frac{e^{logit(Quality=Overdry|x)}}{1+e^{logit(Quality=Overdry|x)}} \quad (10)$$

$$Prob(Quality = Redry|x) = \frac{e^{logit(Quality=Redry|x)}}{1+e^{logit(Quality=Redry|x)}} \quad (11)$$

The corresponding optimization model for minimizing energy cost while maintaining quality turnout is shown below.

Objective: Minimize Unit energy cost, Z_{cost}

Subject to: Eqs. 9-10

$$Prob(Quality{=}Overdry|x) \leq USL_{overdry} \quad (12)$$

$$Prob(Quality{=}Redry|x) \leq USL_{redry} \quad (13)$$

When assuming $USLoverdry{=}USLredry{=}0.15$, the optimal drying time remained 3.8 minutes per sheet, but the optimum Zone 1a temperature changed from 350 °F (corresponding to 176.7 °C and optimum in Scenario 2 (Figure 2)) to 357.8 °F (corresponding to 181 °C) to meet the quality requirements, and the minimum energy cost increased to $1.73 per unit veneer. This indicates that results from Scenario 2 would not create a profitable production yield for the industry partner, despite a reduction in energy cost. While the $0.03 increase in energy cost per unit veneer is a significant increase, the difference in value associated with higher quality veneers ($0.08 was the smallest difference between two grades sold by the company partner) offsets this rise in production costs.

3.4 Minimizing energy cost and maximizing quality turnout
3.4. Minimiziranje troškova energije uz povećanje kvalitete

Instead of having the drying quality requirements as constraints, the last scenario included them as objective functions to reduce the probabilities of a veneer sheet being over-dried and re-dried. These objectives formulated the multi-objective optimization model listed below along with the energy goal, and was solved using the mco package in R.

Objective 1: Minimize Unit energy cost, Z_{cost}

Objective 2: Minimize Probability of a veneer sheet being over-dried, $Prob(Quality{=}Overdry|x)$

Objective 3: Minimize Probability of a veneer sheet needs to be re-dried, $Prob(Quality{=}redry|x)$

Subject to: Eqs. 7-8

Figure 3 shows the Pareto front in pairs of objective functions. According to the figure, unit energy cost and the over-dry probability changed in the same direction as decision variables varied, but the re-dry probability demonstrated an opposite trend. A subset of Pareto-optimum solutions where the probability of over-dry or re-dry was not greater than 0.15 can be found in Table 1. The minimum unit energy cost of $1.70 was again achieved when the Zone 1a temperature was maintained at 350 °F (corresponding to 176.7 °C), and the drying speed was 3.8 minutes per sheet, with the over-dry and re-dry probability equal to 0.13 and 0.15, respectively. However, the unit energy cost could climb to $1.84 when the re-dry probability was down to 0.14 (with over-dry probability still equal to 0.15). Thus, eclipsing the benefits associated with a better-quality product ($0.14 increased unit energy cost vs. $0.08 increase product value). Although the data from the start-up hours were not included in this study, the knowledge gained while analyzing the dataset and discussing with the partner company suggests that using the time when dryers warm up to re-dry veneers may be a good strategy not to increase energy consumption costs.

Based on the results obtained in the four scenarios considered in this preliminary assessment, optimizing the veneer drying schedule to reduce energy costs could be a relatively simple and valuable approach to implement. However, the benefit associated with such an approach will depend on the scenario, the energy costs and the potential increase in product value. Optimizing the drying schedule could be a short-term solution that could be implemented, while exploration on alternative (and cost-saving) energy sources to natural gas are underway.

In this preliminary assessment, single, bi- or multi-objective functions were used to effectively optimize veneer drying schedules based on a series of assumption. This type of optimization was referred to as machine parameter optimization by Matsunaga *et al*. (2022), and has the potential to optimize different sub-processes (Bayati *et al*., 2023) as well as assist in process control systems. In a future phase of this project, it would be interesting to maintain the complexity of the industrial dataset to evaluate the benefits of using cyber-physical systems and deep learning algorithms to both maintain or improve product quality and minimize energy consumption in real-time. The approach described by El Mazgualdi *et al*. (2022) could serve as a framework to develop an optimization model involving big data.

4 CONCLUSIONS
4. ZAKLJUČAK

In summary, this study explored how previously developed prediction models could be implemented in

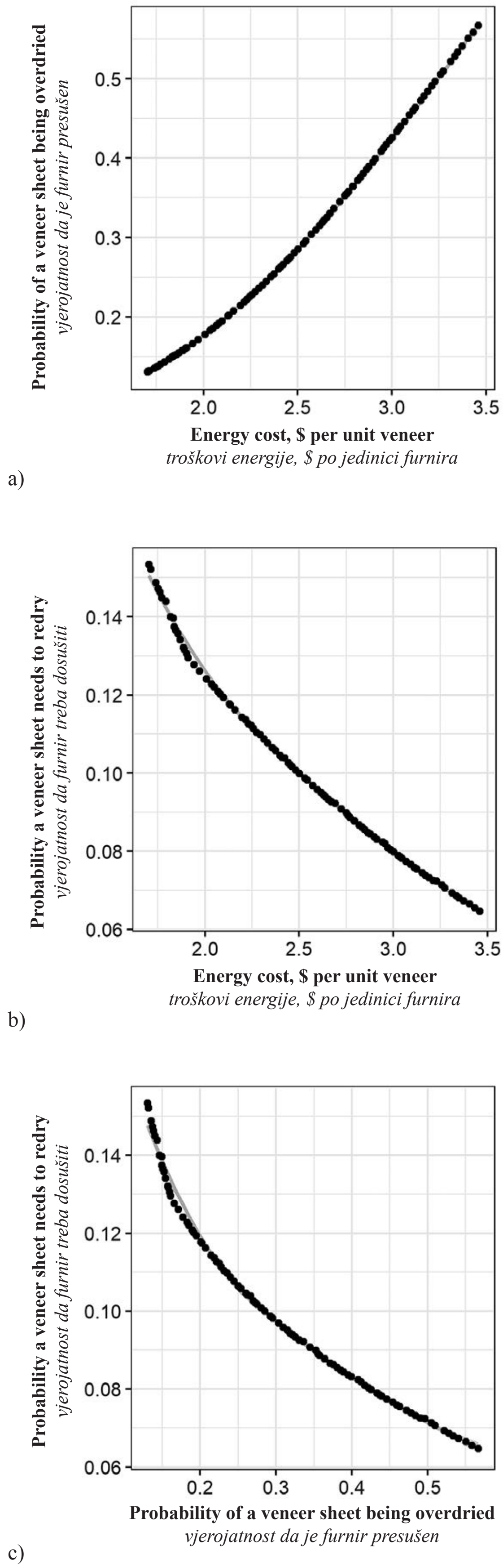

Figure 3 Pareto front of Scenario 4
Slika 3. Pareto krivulja za 4. scenarij

Table 1 A subset of the Pareto-optimum solutions obtained from the optimization model to minimize unit energy cost and maximize the quality turnout (i.e., minimizing the probabilities of a veneer sheet being over-dried or needing to be re-dried) with Zone 1a temperature and drying time being the decision variables
Tablica 1. Podskup Pareto optimalnih rješenja dobivenih iz optimizacijskog modela za minimiziranje jediničnih troškova energije i maksimiziranje kvalitete (tj. minimiziranje vjerojatnosti da će list furnira biti previše osušen ili da se treba dosušiti) u zoni 1, u kojoj su temperatura i vrijeme sušenja varijable odluke

Zone 1 temperature, °F *Temperatura u zoni 1, °F*	**Drying time, mins/sheet** *Vrijeme sušenja,* min/list	**Unit energy cost, $ per unit veneer** *Jedinični trošak energije, $ po jedinici furnira*	**Probability of a veneer sheet being over-dried** *Vjerojatnost da je furnir presušen*	**Probability of a veneer sheet needing to be re-dried** *Vjerojatnost da furnir treba dosušiti*
350.02	3.8	1.70	0.13	0.15
352.69	3.8	1.71	0.13	0.15
360.66	3.8	1.74	0.14	0.15
364.36	3.8	1.75	0.14	0.15
366.77	3.8	1.76	0.14	0.15
369.13	3.9	1.79	0.14	0.14
369.13	3.9	1.79	0.14	0.14
370.08	3.8	1.77	0.14	0.14
378.32	3.9	1.83	0.15	0.14
381.66	3.8	1.82	0.15	0.14
388.86	3.8	1.84	0.15	0.14

operation research, assisting the quality control of industrial veneer drying processes. The preliminary results obtained from four different optimization scenarios provided insights on improving the veneer drying schedule in terms of Zone 1a temperature and drying speed. While this preliminary optimization study only focused on 3.175 mm thick light sapwood veneers, it is anticipated that a similar approach could be applicable to other types of veneer products.

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