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Optimization of energy consumption and costs of wood drying with use of different drying techniques

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Abstract

The time and energy required for wood drying and therefore drying costs are among the highest in wood products manufacturing. Analysis of the drying process costs is very complex and needs to evaluate the cost of investments, energy, labour as well as defects of lumber or added value. In the present research work, we upgraded the computer aided engineering (CAE) model of wood drying processes with the economic evaluation of different drying techniques. By analyzing and comparing the costs of different drying processes, the model is able to predict the transition wood moisture content (MC_t) at which the alteration from one to another drying technique would get the best results. The model was verified on data from several air- and kiln-drying experiments on 38 mm thick beech wood (*Fagus sylvatica* L.) boards. Computer simulation predicted advantages of combined dying beech wood with air pre-drying and continued and finished with kiln drying. The MCt in the winter period was at about 40% MC and decreased to 23% in favourable climate conditions in spring and summer months. The model can be also used for optimising the combination of other drying techniques.

Ključne besede: kiln wood drying, air drying, beech wood, energy consumption, drying costs, drying simulation

Optimizacija porabe energije in stroškov sušenja lesa s kombinacijo različnih sušilnih tehnik

Abstract

Dolgotrajnost in energijska potratnost sušenja lesa povečuje tudi stroške, ki so med največjimi med lesnopredelovalnimi postopki. Analiza stroškov zahteva vsestransko obravnavo z vrednotenjem stroškov investicije, energije in dela kot tudi upoštevanje razvrednotenja zaradi napak ali dodane vrednosti kakovostnega osušenega lesa. V raziskavi smo nadgradili računalniški model sušilnega procesa z ekonomskim vrednotenjem različnih sušilnih tehnik. S primerjavo stroškov različnih sušilnih postopkov smo predpostaviti prehodno vlažnost lesa, pri kateri bi s kombinacijo več načinov sušenja dosegli najboljše ekonomske rezultate. Metoda je bila preverjena na sušenju bukovine debeline 38 mm s kombinacijo sušenja na prostem in komorskega sušenja. V zimskih mesecih je sušenje na prostem smotrno do vlažnosti 40 %, v najugodnejših klimatskih razmerah pa je optimalna vlažnost prehoda iz sušenja na prostem v komorsko sušenje 23 %. Predstavljeno metodo je mogoče uporabiti tudi za optimizacijo različnih tehničnih postopkov sušenja lesa.

Key words: *komorsko sušenje lesa, sušenje na prostem, bukev, poraba energije, stroški sušenja*

1 Uvod

1 Introduction

Technical drying of wood is, in a modern woodworking production, an obligatory technological process by which we reduce the otherwise time-consuming removal of water from timber. Unfortunately, all drying techniques are energy consuming, despite the use of modern technologies. After all, the time still remains an important issue as the wood is the limiting factor in the efficiency of water transport in the wood itself (KEEY *et al*. 2000). For choosing the optimal technical, technological and economical decision, the evaluation and detailed analyses of time, energy consumption and cost of drying process are obligatory. Even then the decision is not always simple or the same for each case, as it influences a large number of variables (wood species, timber dimensions, initial and final MC, type and size of dryers, energy availability and its price, etc.).

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Great attention is nowadays focused on energy saving. A major part of consumed energy in currently most commonly used convective kiln drying is heat, although electricity should certainly not be ignored (MÜLLER, 1989). The ratio of consumed heat and electric energy is very varied, depending on the type of wood, thickness of assortments, the initial and final moisture content of wood, and the drying schedule. In some modified drying programs (e.g. for drying "white" beech), the consumption of electric energy can exceed the consumption of heat. The total energy consumption varies greatly; according to SEEGER (1989), even from 140 kWh to 1260 kWh per m^3 of dried wood.

For the energy efficiency of various drying techniques, the specific energy consumption, defined as energy required for the removal of 1 kg of water from wood, is more appropriate to use. Above the fibre saturation point (FSP), the specific energy consumption varied between 3.4 MJ/kg and 6.23 MJ/kg of evaporating water; below FSP, it can drastically increase even to 10.5 MJ/kg (VILLIER, 1982; BRUNNER, 1987; GUZENDA *et al*., 2004).

The great energy consumption in wood drying process also requires consideration of effective technological measures for its reduction. The maintenance of all equipment is one of the basic measures to ensure minimum energy loss. The efficiency may be increased with sufficient isolation and sealing of the chamber, by using heat recovery systems, with linking the ventilation systems of more drying chambers, and by controlling the circulation of air in the chamber. A considerable saving of electric energy (up to 45%, LIPPOLD (1987)) can be achieved by the use of frequency regulators. The economic effect can be further improved by adjusting the tariff classes.

In drying practice, a combination of different techniques has been applied to take advantage from each of them. Air pre-drying has also been used to minimize the energy consumption, despite the unpleasant oscillating climate conditions (JAMROZ *et al*. 1996). We can find various reasons to dry some wood species (c.f. beech wood) with more different drying techniques (GORIŠEK *et al*. 2008). For instance, we have usually two main cutting seasons annually with concentration of great amounts of green logs and therefore fresh sawn wood as well; the drying capacity in the industry is limited; with the exploitation of natural condition, we get better energy effectiveness of drying, etc.

In order to achieve optimal economic results, the main aim of the study was to set up a computer aided (CAE) simulation of drying kinetics, energy demand and costs for different drying techniques. By analyzing and comparing the costs of different drying processes, a mathematical model was built up, enabling us to predict the transition wood moisture content (MC$_t$) when the alteration from one drying technique to another would yield the best economic results.

Verification of the model and the calculation of transition MC$_t$ were done on the example of air pre-drying and kiln drying processes of 38 mm thick beech wood.

2 Material and methods

2 Material in metode

2.1 CAE model of wood drying process

2.1 CAE-model procesa sušenja lesa

The complete model for optimization presents calculation in four steps with adequate sets of database and/or results (Tab. 1).

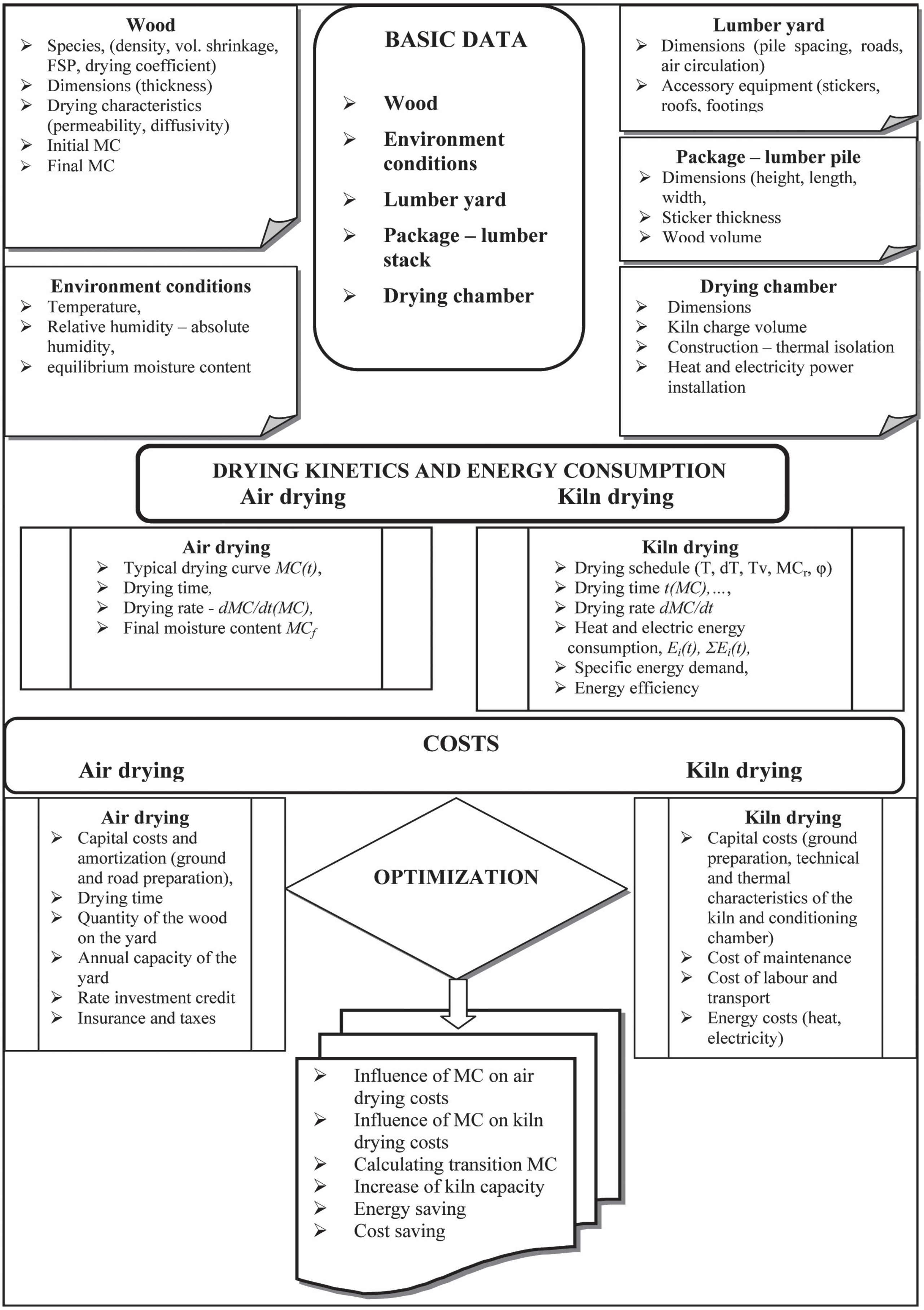
Basic information is collected in the first package and contains date about wood (species, dimensions, initial MC, final MC), environment conditions (temperature, relative humidity – absolute humidity, equilibrium moisture content), lumber pile (dimensions, sticker thickness, wood volume), drying chamber (dimensions, kiln charge volume, construction – thermal isolation, heat and electricity power installation) and lumber yard (area – dimensions, accessory equipment).

In order to determine the drying kinetics and energy consumption for air and kiln drying, the already presented improved CAE model (STRAŽE / GORIŠEK, 2007) has been used. From the model, the typical drying curve, drying time and drying rate for air and kiln drying can be predicted. Furthermore, heat and electric energy consumption, specific energy demand, energy efficiency for kiln drying can be calculated.

In the third part of the program the costs of each drying processes, based on the parameters of the process and costs, are calculated. This allows us to estimate the influence of different factors, such as capital costs and amortization (ground and road preparation), drying time, quantity of the wood in the yard, annual capacity of the yard, rate investment credit, insurances, taxes, labour and transport costs, drying schedule, drying time, drying rate, heat and electric energy consumption, specific energy demand, and energy efficiency for kiln drying.

Due to drying kinetics and total drying costs, calculated in the second and third steps, the influence of drying time and moisture content on drying cost for each selected interval either for air or for kiln drying process can be further analysed and predicted. Afterwards, it was presumed that in favourable climate conditions the air drying of fresh wood could be susceptible or even very successful with low cost. Air drying to lower moisture content takes more and more time and the cost increases over reasonable and acceptable value, so the drying process has to be continued and finished in the kiln. The optimum transition wood moisture content (MC$_t$) from air to kiln

Table 1: Four step model for calculating and optimizing wood drying process



Wood
- Species, (density, vol. shrinkage, FSP, drying coefficient)
- Dimensions (thickness)
- Drying characteristics (permeability, diffusivity)
- Initial MC
- Final MC

BASIC DATA
- Wood
- Environment conditions
- Lumber yard
- Package – lumber stack
- Drying chamber

Lumber yard
- Dimensions (pile spacing, roads, air circulation)
- Accessory equipment (stickers, roofs, footings

Package – lumber pile
- Dimensions (height, length, width,
- Sticker thickness
- Wood volume

Environment conditions
- Temperature,
- Relative humidity – absolute humidity,
- equilibrium moisture content

Drying chamber
- Dimensions
- Kiln charge volume
- Construction – thermal isolation
- Heat and electricity power installation

DRYING KINETICS AND ENERGY CONSUMPTION
Air drying **Kiln drying**

Air drying
- Typical drying curve $MC(t)$,
- Drying time,
- Drying rate - $dMC/dt(MC)$,
- Final moisture content MC_f

Kiln drying
- Drying schedule (T, dT, Tv, MC_r, φ)
- Drying time $t(MC)$, ...,
- Drying rate dMC/dt
- Heat and electric energy consumption, $E_i(t)$, $\Sigma E_i(t)$,
- Specific energy demand,
- Energy efficiency

COSTS
Air drying **Kiln drying**

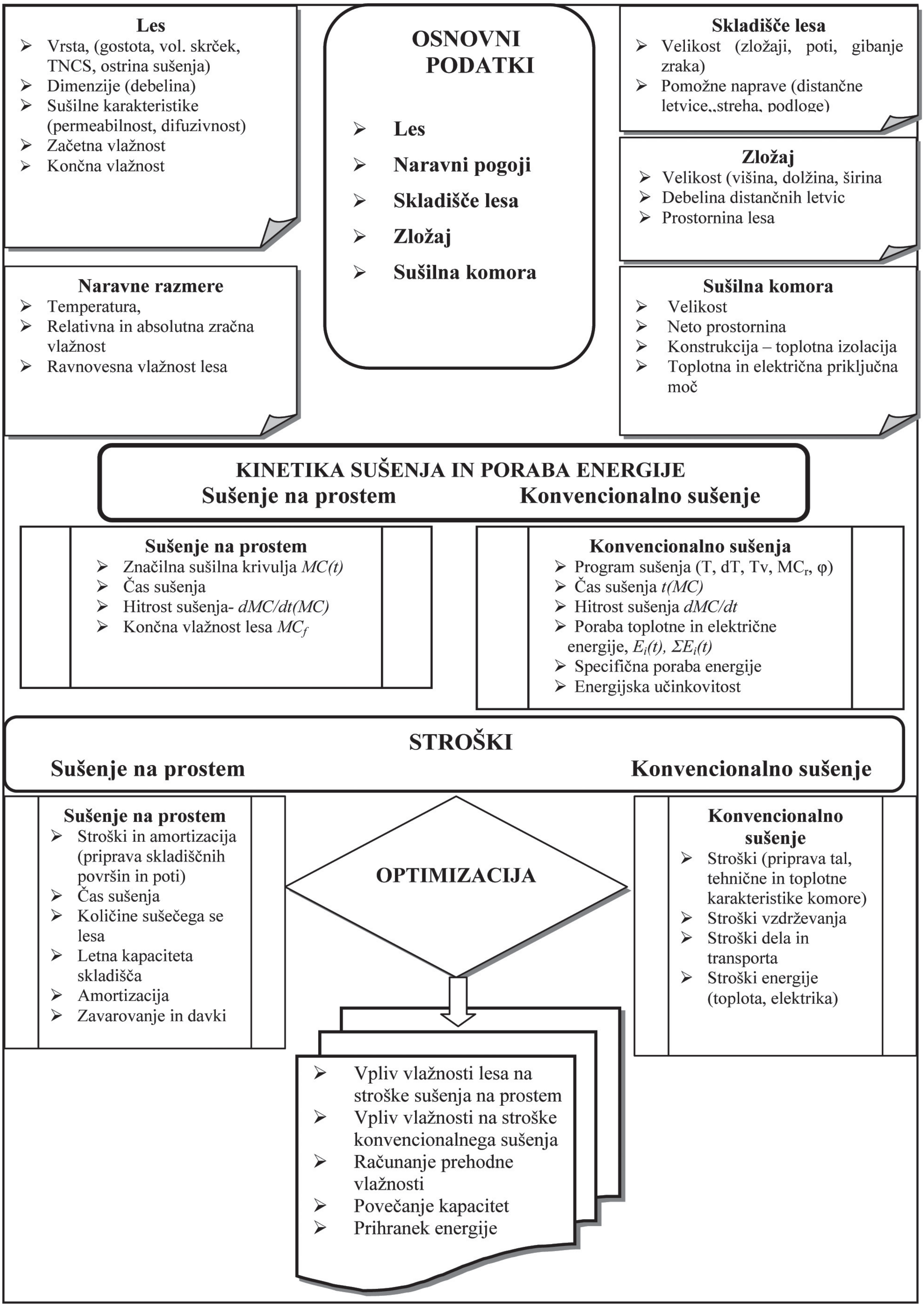
Air drying
- Capital costs and amortization (ground and road preparation),
- Drying time
- Quantity of the wood on the yard
- Annual capacity of the yard
- Rate investment credit
- Insurance and taxes

OPTIMIZATION

- Influence of MC on air drying costs
- Influence of MC on kiln drying costs
- Calculating transition MC
- Increase of kiln capacity
- Energy saving
- Cost saving

Kiln drying
- Capital costs (ground preparation, technical and thermal characteristics of the kiln and conditioning chamber)
- Cost of maintenance
- Cost of labour and transport
- Energy costs (heat, electricity)

Preglednica 1: Štiristopenjski model algoritma izračunavanja in optimiziranja sušilnega postopka



Les
- Vrsta, (gostota, vol. skrček, TNCS, ostrina sušenja)
- Dimenzije (debelina)
- Sušilne karakteristike (permeabilnost, difuzivnost)
- Začetna vlažnost
- Končna vlažnost

OSNOVNI PODATKI
- **Les**
- **Naravni pogoji**
- **Skladišče lesa**
- **Zložaj**
- **Sušilna komora**

Skladišče lesa
- Velikost (zložaji, poti, gibanje zraka)
- Pomožne naprave (distančne letvice,,streha, podloge)

Zložaj
- Velikost (višina, dolžina, širina
- Debelina distančnih letvic
- Prostornina lesa

Naravne razmere
- Temperatura,
- Relativna in absolutna zračna vlažnost
- Ravnovesna vlažnost lesa

Sušilna komora
- Velikost
- Neto prostornina
- Konstrukcija – toplotna izolacija
- Toplotna in električna priključna moč

KINETIKA SUŠENJA IN PORABA ENERGIJE

Sušenje na prostem **Konvencionalno sušenje**

Sušenje na prostem
- Značilna sušilna krivulja *MC(t)*
- Čas sušenja
- Hitrost sušenja- *dMC/dt(MC)*
- Končna vlažnost lesa MC_f

Konvencionalno sušenja
- Program sušenja (T, dT, Tv, MC_r, φ)
- Čas sušenja *t(MC)*
- Hitrost sušenja *dMC/dt*
- Poraba toplotne in električne energije, $E_i(t)$, $\Sigma E_i(t)$
- Specifična poraba energije
- Energijska učinkovitost

STROŠKI

Sušenje na prostem **Konvencionalno sušenje**

Sušenje na prostem
- Stroški in amortizacija (priprava skladiščnih površin in poti)
- Čas sušenja
- Količine sušečega se lesa
- Letna kapaciteta skladišča
- Amortizacija
- Zavarovanje in davki

OPTIMIZACIJA

Konvencionalno sušenje
- Stroški (priprava tal, tehnične in toplotne karakteristike komore)
- Stroški vzdrževanja
- Stroški dela in transporta
- Stroški energije (toplota, elektrika)

- Vpliv vlažnosti lesa na stroške sušenja na prostem
- Vpliv vlažnosti na stroške konvencionalnega sušenja
- Računanje prehodne vlažnosti
- Povečanje kapacitet
- Prihranek energije

drying was defined at the point, where the costs increase is the same in both drying processes. Mathematically, the transition MC_t is calculated with equalizing the derivation of cost curves for air and kiln drying (eq. 1).

$$\frac{dCost_{air}}{dMC} = \frac{dCost_{kil}}{dMC} \qquad (1)$$

According to the calculated transition MCt, the energy savings, rise of available kiln drying capacities as well as drying costs saving could be predicted.

2.2 Air drying

2.2 Sušenje na prostem

The air drying part of the CAE model was verified on experimental data obtained from drying 38 mm thick beech wood board. Every month from December 2007 till July 2008, eight series of ten boards from freshly sawn logs were air dried in an open lumber yard till "apparent" equilibrium moisture content with the climate condition was achieved. At the beginning of the drying process, the boards were weighted twice a week, and only once below FSP. The accurate moisture content and moisture gradient were determined by the gravimetrical method (EN 13 183-1) on small samples taken from the boards in the beginning and in the end of the process. The experimental data were correlated with the model of the exponential function of natural growth (eq. 2), where a represents the maximum drying rate, k the drying rate at the end of drying, and MC_c the moisture content of the drying rate's quickest decrease.

$$\frac{\Delta MC}{\Delta t} = \frac{a}{1 + e^{(-k(MC - MC_c))}} \qquad (2)$$

At the end of the drying process, wood quality was evaluated regarding the drying rate, time of drying, variability of moisture content, moisture content gradient, casehardening and occurrence of drying defects. During the experiment, the air temperature and relative humidity were noted, from which the equilibrium moisture content was calculated. The acquired data were entered into the computer database model.

2.3 Kiln drying

2.3 Komorsko sušenje

In the CAE model, the standard drying schedules were used. In the experiment, for comparison and verification of the model, we used 13 fresh 38 mm thick beech wood boards with 78±12% average initial moisture content. The boards were dried in the experimental kiln dryer with the capacity of 1 m^3. Drying conditions in the kiln was controlled with dry and wet bulb temperatures through the Vea regulation system. Every two hours, dry and wet bulb temperatures, mass of wood, energy consumption, as well as MC in 6 places were registered.

3 Results

3 Rezultati

During the entire experimental time, air drying of beech wood was quiet rapid, with typical impact of initial moisture content of wood and climate condition on drying rate and on drying time (Fig. 1).

During the first drying period, with apparent constant rate, the drying velocity increased from the average 2.1%/day in winter months to approx. 5.5%/day during spring or early summer months (Fig. 2). The velocity strongly depends on local drying conditions. Drying rate rapidly dropped, when the outer layer had achieved the fibre saturation point. Thereupon, the drying rate exponentially declines until an apparently steady state condition has been reached. We get quite good correlation with the model of the exponential function of natural growth (Tab. 2)

During winter months, the low constant rate period lasted for about 3 weeks and ended with a decrease of drying rate when the MC dropped below 40% ($MC_c \approx$ 40%). During spring and summer months, the constant rate period was shorter than in winter time (approx. 1 week), and the so-called diffusion barrier occurred at a higher moisture content ($MC_c \approx 53\%$). In extremely dry and especially windy weather, there is also a very great risk of casehardening.

With numerical integration of the drying rate we were able to get the drying curve for each month of our experiment (Fig. 3).

Overall drying time in the kiln drying was 330 hours (heating 10 h, drying 272 h, conditioning 48 h). At the beginning, the drying was very intensive, but the drying rate dropped very quickly and decreased exponentially to the final MC (Fig. 4).

Influence of MC on the drying cost greatly depends on drying kinetics in each drying process. While drying fresh wood in the open air, the costs were low. In favourable climate conditions, the drying was susceptible or even very successful (Fig.5). Air drying to a lower moisture content takes more and more time and the cost increases over reasonable and acceptable value. Many times, low target MC could not have been reached.

In the early drying stage, the cost of kiln drying was expectably higher than the cost of air drying. Air drying to a lower MC takes more and more time and the cost increases over reasonable and acceptable value, forcing us to continue and finish the drying process in the kiln (Fig. 6).

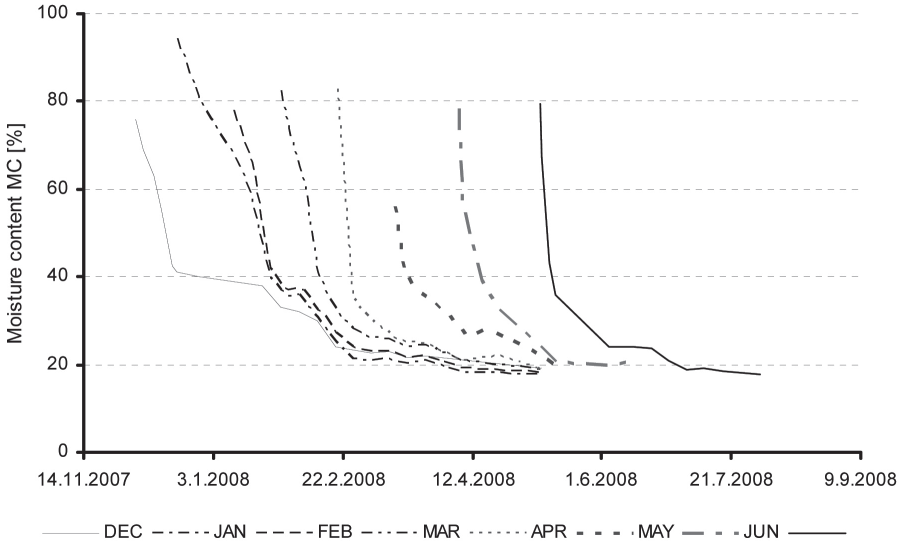


Fig. 1: Air drying curves for 38 mm thick beech wood timber

Slika 1: Krivulje naravnega sušenja za 38 mm debelo bukovino

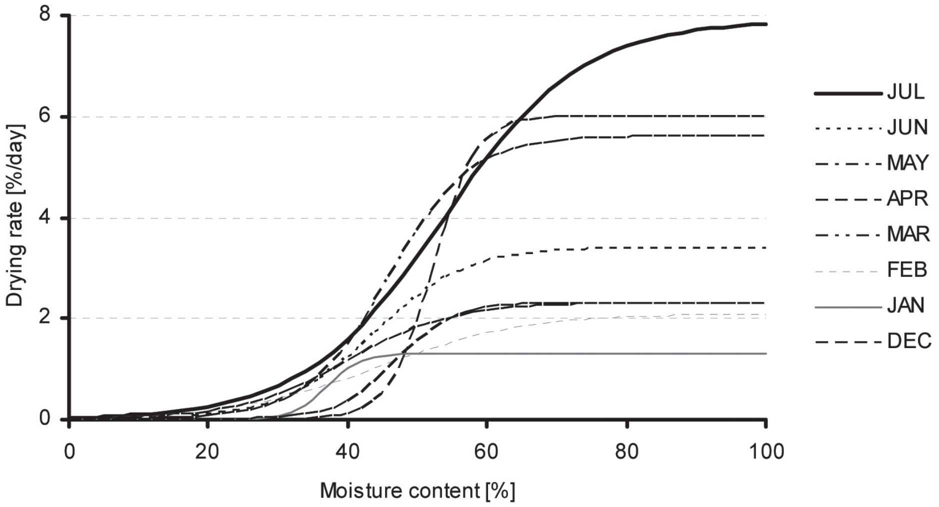


Fig. 2: Typical dependences of drying rate from wood moisture content for eight series of drying (Dec. – Jul.) for 38 mm thick beech wood timber

Slika 2: Odvisnost hitrosti sušenja od lesne vlažnosti za osem serij sušenja na prostem (od decembra do julija) za 38 mm debelo bukovino

Table 2: Drying period, initial and final moisture content, maximal drying rate and moisture content of the quickest decrease of drying rate for eight air drying processes for 38 mm thick beech wood

Preglednica 2: Sušilno obdobje, začetna in končna lesna vlažnost, največja hitrost sušenja ter lesna vlažnost najhitrejšega padanja sušilne hitrosti za osem serij sušenja na prostem 38 mm debele bukovine

Period / *Obdobje*	Initial MC (MC_i) / *Začetna vlažnost* [%]	Final MC(MC_f) / *Končna vlažnost* [%]	Max. drying rate / *Maks. hitrost sušenja* [%/day]	MC_c *Vlažnost pri največji hitrosti* [%]	R^2 eq. (2)
DEC - APR	46.4 - 91.3	17.9 - 19.9	2.3	47.1	0.72
JAN – APR	65.0 - 109.0	17.3 - 18.4	1.4	37.0	0.75
FEB - MAY	60.3 - 101.1	17.5 - 18.7	2.1	44.7	0.63
MAR – JUN	56.5 - 92.3	17.7 - 20.0	2.4	40.1	0.84
APR – JUL	69.1 - 89.8	17.3 - 19.1	6.3	52.3	0.97
MAY – JUL	43.7 - 69.1	15.9 - 21.7	5.6	45.9	0.91
JUN – AVG	52.7 - 81.8	19.1 - 21.7	3.5	43.7	0.92
JUL - SEP	71.0 - 88.5	17.4 - 18.4	6.2	53.6	0.98

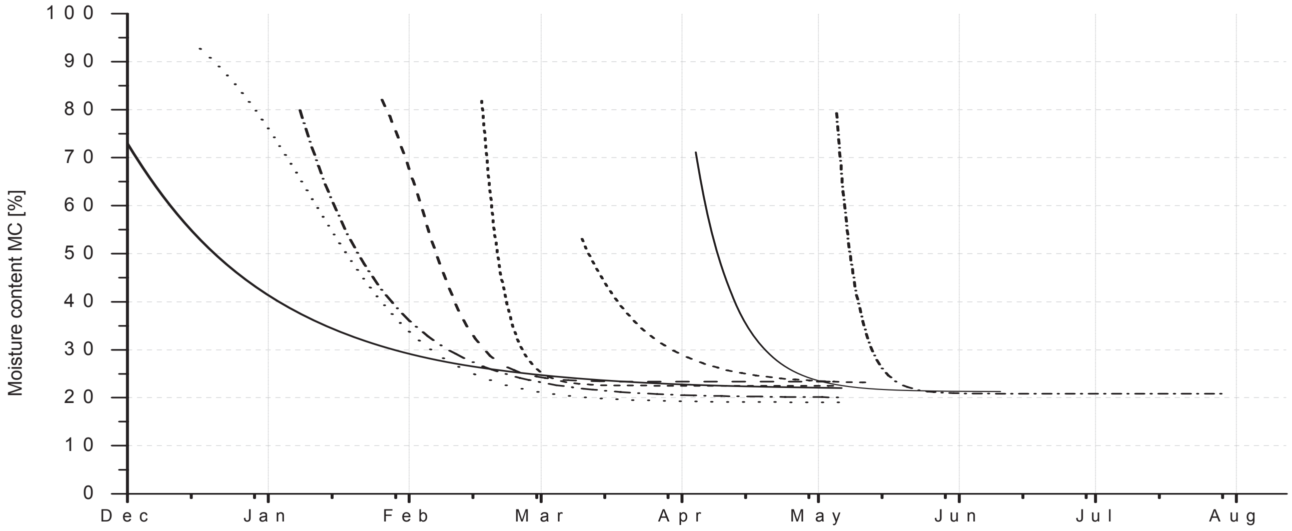


Fig. 3: Fitted eight air drying curves for 38 mm thick beech wood timber obtained during drying from December till July

Slika 3: Prilagojene sušilne krivulje na prostem za 38 mm debelo bukovino, sušeno od decembra do julija

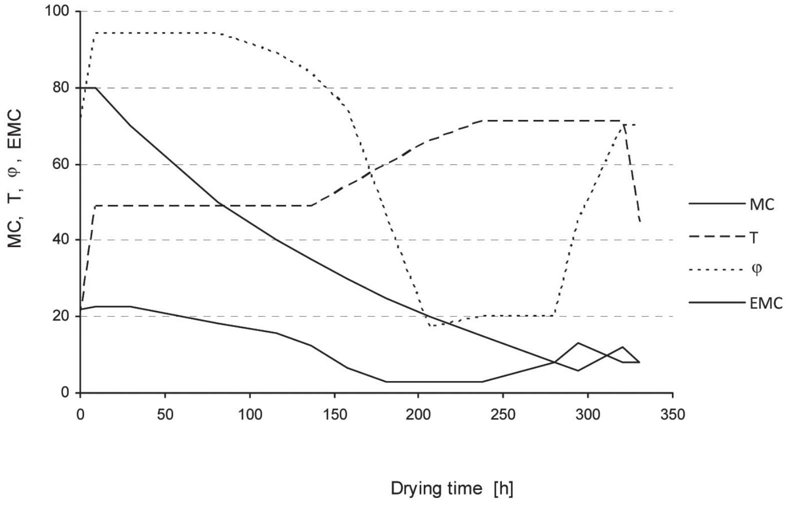


Fig. 4 Drying schedule (temperature T, relative humidity φ, equilibrium moisture content EMC) and drying curve for 38 mm thick beech wood timber

Slika 4 Sušilni program (temperatura T, relativna zračna vlažnost φ, ravnovesna vlažnost EMC) in sušilna krivulja za sušenje 38 mm debele bukovine

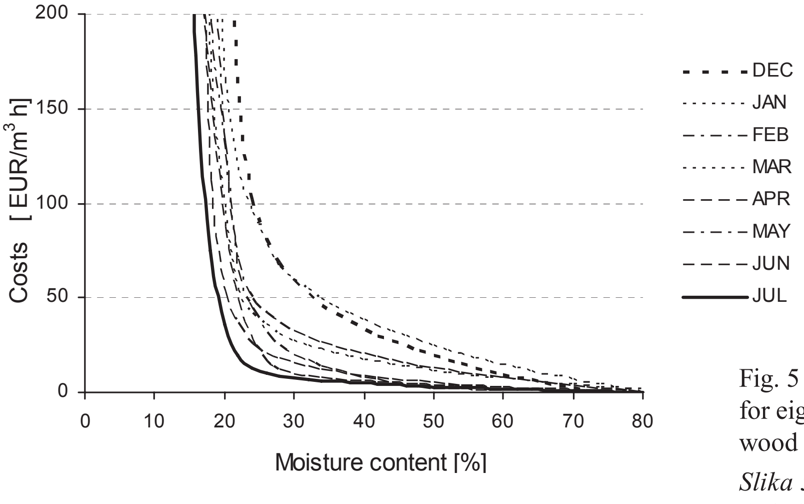


Fig. 5 Increase of drying costs during air drying for eight series (DEC – JUL) for 38 mm thick beech wood timber

Slika 5 Naraščanje stroškov sušenja za osem serij (od decembra do julija) 38 mm debele bukovine

The effect of drying kinetics on drying cost is more pronounced in air drying than in kiln drying. Therefore, the air drying has a greater influence also on the optimum transition moisture content (MC_t) from air to kiln drying.

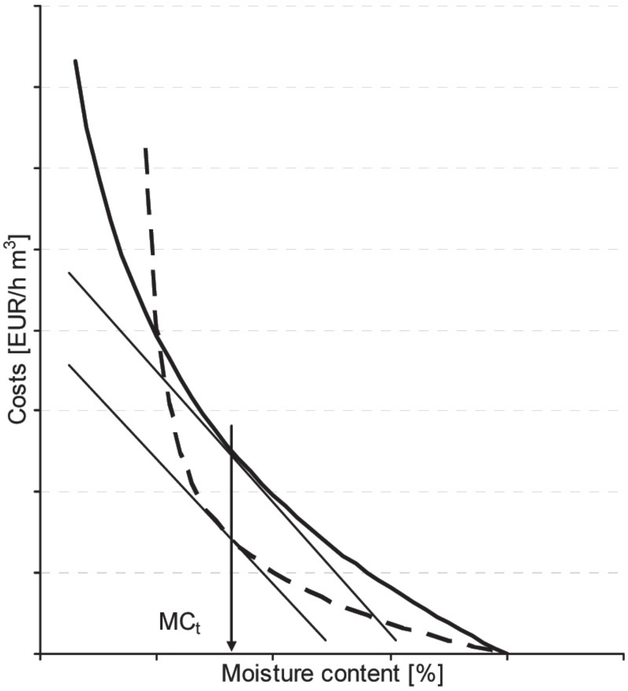


Figure 6: Principle of determining the optimal transition moisture content (MC_t) from air to kiln drying for 38 mm thick beech wood timber

Slika 6 : Metoda določanja optimalne vlažnosti prehoda sušenja iz naravnega v komorsko za 38 mm debelo bukovino

The highest value of the transition MCt (about 40.1%) was reached in winter time (ex. in December and in January). Thereupon, it was decreasing constantly and attained the lowest value in July (23.0%)(Tab. 3). Due to the rainy weather in May, a higher transition MC was calculated.

With air pre-drying (to transition MCt), the kiln drying time is significant reduced; by 29.2% in December and January, and by 49.7% in July; consequently, the kiln drying capacities increase (Tab. 3).

With additional air pre-drying phase, there is also a considerable saving of energy, i.e. from 48.0% in December to 72.1% in July, but the reduction of costs is not so pronounced: from 8.7% in January to 34.9% in April.

4 Conclusions

4 Zaključki

Computer simulation of energy consumption, with included air predrying phase, predicted potential energy savings, significant lowering of kiln drying time and, consequently, rising of available kiln drying capacities as well as lowering of drying costs. With decreasing wood MC, the benefits of air drying were reduced. By analyzing and comparing the costs of both drying processes, we were able to predict the wood MC at which the alteration from air to kiln drying would yield the best results. The model can be also used for optimising the combination of other drying techniques.

Table 3: Calculating the optimal transition MCt from air to kiln drying, reduction of kiln drying time, energy saving and reduction of cost for 38 mm thick beech wood

Preglednica 3: Izračunana optimalna vlažnost prehoda sušenja na prostem v komorsko sušenje, skrajšanje časa sušenja, prihranek energije in zmanjšanje stroškov pri sušenju 38 mm debele bukovine

Period / *Obdobje*	MC of transition from air to kiln drying / *Vlažnost prehoda iz sišenja na prostem v komorsko sušenje* [%]	Reduction of kiln drying time / *Skrajšanje časa komorskega sušenja* [%]	Energy saving / *Prihranek energije* [%]	Reduction of costs / *Zmanjšanje stroškov* [%]
DEC	40.1	29.2	48.0	15.8
JAN	39.5	29.2	48.8	8.7
FEB	33.5	34.8	56.0	18.2
MAR	30.1	40.9	62.3	21.4
APR	25.0	48.1	71.4	34.9
MAY	32.9	37.0	57.2	27.0
JUN	26.4	48.1	71.4	32.5
JUL	23.0	49.7	72.1	33.2

5 Povzetek

Ob vse večjih zahtevah po uvajanju čim krajših tehnoloških postopkov je tehnično sušenje nujna tehnološka operacija v primarni predelavi lesa. Modernim tehnikam navkljub pa ostaja postopek še vedno energijsko zahteven in potraten. Za optimalno izbiro tehnološkega postopka in načina sušenja je zato potrebna širša stroškovna analiza z vidika časa sušenja, porabe energije in doseganja odgovarjajoče kakovosti osušenega lesa. Zaradi vpliva velikega števila dejavnikov, ki so za posamezne odločitve specifične, končna odločitev ni enoznačna, zato je nujen individualen pristop.

Prevladujočim raziskavam možnosti zmanjšanja porabe električne energije (MÜLLER, 1989, SEEGER, 1989) se vse več pozornosti namenja tudi možnosti prihrankov toplotne energije s skrbnejšo analizo izoliranosti komor, z uporabo sistemov rekuperacije energije, z zaporednim delovanjem in povezovanjem več sušilnih komor ipd. (LIPPOLD, 1987). S predlaganimi ukrepi racionalizacije je občutno zmanjšana specifična poraba energije (VILLIER, 1982; BRUNNER, 1987; GUZENDA *et al*., 2004).

Ekonomsko učinkovitost sušilnega postopka je mogoče izboljšati tudi s tehnološkimi ukrepi. Več avtorjev (npr. JAMROZ *et al*. 1996) predlaga uvajanje kombinacije različnih načinov sušenja, prilagojenih posameznim zahtevam postopka. Ohrabrujoči so rezultati zaporednega sušenja na prostem in komorskega sušenja (JAMROZ *et al*. 1996).

Cilj naše raziskave je bil razvoj algoritma za simulacije kinetike in stroškov različnih načinov sušenja. Matematični model analize stroškov naj bi omogočil napovedovanje optimalnih kombinacij različnih sušilnih postopkov in izračunavanje vlažnosti, pri kateri bi s prehodom iz enega načina sušenja v drug način dobili najboljši ekonomski rezultat. Veljavnost modela in izračun prehodne vlažnosti sta bila preverjena na primeru naravnega predsušenja in dosuševanja v konvencionalnih komorah za 38 mm debelo bukovino.

Štiristopenjski algoritem ponazarja bazo podatkov o lesu, klimatskih razmerah, skladišču žaganega lesa (pregl. 1) in vključuje matematični model, ki mogoča izračun tipičnih sušilnih krivulj, časov in hitrosti sušenja ter določitev porabe električne in toplotne energije, specifične porabe energije in energijsko učinkovitost sušilnega postopka. Zadnji del algoritma ponazarja določanje odvisnosti stroškov sušenja odvisno od lesne vlažnosti za različne načine sušenja in izračuna prehodne vlažnosti, pri kateri bi z zamenjavo sušilnega postopka dosegli najmanjše celotne stroške sušenja.

Opazovalno obdobje sušenja na prostem je trajalo od decembra do junija. Eksperimentalne podatke sušilne hitrosti smo prilagodili eksponentni krivulji naravne rasti (en 2). Komorsko sušenje je bilo opravljeno v pilotski eksperimentalni sušilni komori s standardnim sušilnim programom.

Sušenje bukovine na prostem je bilo v opazovanem obdobju zadovoljivo z značilnim vplivom začetne vlažnosti lesa in klimatskih razmer; v zimskih mesecih je bila hitrost sušenja v prvi fazi do 2,1 %/dan, v spomladanskih in poletnih mesecih pa do 5,5,%/dan. Konstantna hitrost sušenja je trajala v zimskih mesecih povprečno 3 tedne, dokler ni vlažnost padla na približno 40 %. V spomladanskih mesecih je bilo trajanje konstantne hitrosti krajše, difuzijska bariera pa se je pokazala že pri vlažnosti 53 %. V nadaljevanju se je hitrost sušenja eksponentno zmanjševala in se ustavila pri doseženi ravnovesni vlažnosti okolice.

Sušenje svežega lesa v komori je zahtevalo višje stroške od sušenja na prostem, vendar so se z nižanjem vlažnosti stroški naravnega sušenja povečevali in presegli sprejemljive vrednosti, ko je nujno les dosušiti s tehničnimi načini. Izračunana prehodna vlažnost, pri kateri bi dosegli v kombinaciji naravnega in komorskega sušenja minimalne stroške, je odvisna predvsem od učinkovitosti sušenja na prostem. Prehodna vlažnost iz sušenja na prostem v komorsko sušenje je najvišja v zimskih mesecih (okoli 40 %) in doseže najnižjo vrednost v juliju (23 %).

Kombinacije sušenja na prostem in komorskega sušenja zmanjša tudi potrebne kapacitete komor, velika prednost pa je v prihranku energije (od 48 % v decembru do 72 % v juliju) in stroškov (8,7 % v decembru in 34,9 % v aprilu).

Algoritem in model optimizacije lahko uporabimo tudi v primerjavah drugih načinov sušenja.

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