OPTIMIZATION OF A WOOD DRYER KILN USING THE MIXED INTEGER PROGRAMMING TECHNIQUE: A Case Study

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Abstract

When wood is to be utilized as a raw material for furniture, buildings etc. it must be dried from approximately 100% to 6% moisture content. This is achieved at least partly in a drying kiln. Heat for this purpose is provided by electrical means, or by steam from boilers fired with wood chips or oil. By making a close examination of monitored values from an actual drying kiln it has been possible to optimize the use of steam and electricity using the so called mixed integer programming technique. Owing to the operating schedule for the drying kiln it has been necessary to divide the drying process in very short time intervals i.e., a number of minutes. Since a drying cycle takes about two or three weeks, a considerable mathematical problem is presented and this has to be solved.

INTRODUCTION

Growing trees contain a large amount of water. In fact, newly felled logs contain many times more water than wood, see Reference [1], where the average moisture content based on oven-dry wood is in the range 34-249 %. This water must be removed. In the case of wood for indoor use in Sweden, a moisture content of about 6 % is recommended in order to achieve equilibrium with the humidity of the surrounding air. If the moisture content is lower or higher this will lead to shrinking or swelling of the wood products. In the furniture industry, broad leaved species such as beech or birch are frequently used. After sawing the logs, the boards are usually stored outdoors for a number of months. Much of the moisture will evaporate, but to reduce the moisture content to below 20 %, artificial drying in kilns is required. Numerous papers and books have been written on the subject of this process, largely because of the advantages of more economical drying and fewer defects in the end product, see e. g. Reference [2]. The two latest studies, Reference [3] deal with a drying kiln using a heat pump for vapor condensation, and with optimized drying schedules, Reference [4].

The optimization technique used here is termed Linear Programming, LP, or when binary variables are used Mixed Integer Linear Programming or MILP, see Reference [5] for details. As recently as ten years ago, solving MILP problems still required very sophisticated computers. With the introduction of modern software and much faster computers, the optimization process is now a minor problem. Nevertheless the mathematical problem must often be expressed strictly mathematically, using the so-called MPS format. This is in fact an ordinary text file containing information on the objective function and the many constraints involved. The present paper deals with the design of these parts on the basis of a number of monitored electricity meter readings from a wood drying kiln.

CASE STUDY

The drying kiln is located at a small carpentry factory, Mörlunda Chair and Furniture Ltd., located about 350 km south of Stockholm, Sweden. The company has been described in an earlier paper, Reference [6], on the subject of load management measures. One of the processes where such measures were considered is the drying kiln. The company uses electricity distributed by Sydkraft Ltd. which applies a time-of-use tariff. In 1997, the total electricity consumption for the company was 341 MWh which cost 247,000 SEK. (One ECU = approx. about 8 SEK, October 1998). About 50 % of the cost relates to actual consumption of MWh. Additional demand fees of about 20,000 SEK were charged since the subscription level of 190 kW was too low. Instead of setting a higher level of about 215 kW, the company may install equipment which turns off machinery not absolutely required at times when peak demand is expected. A suitable process for introducing this economy is the drying kiln since the warm timber stack acts as a thermal storage. It is also possible to use steam as a heating medium, see Figure 1.

This steam is produced in two boilers: one fired with oil and the other with wood residues from the manufacturing processes. The steam is then led to a finned tube where it condenses to hot water. The steam trap, S, ensures that only water is led to the condensate basin. The water is then pumped back to the boilers. The electricity is partly used for five motors each of which operates a fan. There are also five resistance heaters, each with a demand of 2.7 kW. Dampers are opened occasionally and warm, humid air is led outdoors while cold, dry air is transported into the kiln. The air conditions in the dryer must be carefully monitored and regulated in order to obtain boards free of warping and other defects. The electricity consumed during a drying cycle is monitored by a modern meter. This sends a pulse when a certain amount of electricity has passed the meter, the pulse being registered in a memory device. The information is downloaded to a PC once a minute. The electricity consumption during a drying cycle is shown in Figure 2.

The total consumption was 6,560 kWh.

From Figure 2 it is obvious that the demand is at a maximum, about 16 kW, at the beginning of the drying cycle,. It is natural that demand is high in the beginning of the cycle since the temperature must be increased during the initial hours from about 10 °C to 50 °C which is the operating temperature in the dryer. According to Figure 2, about 16 kW could be saved in order to

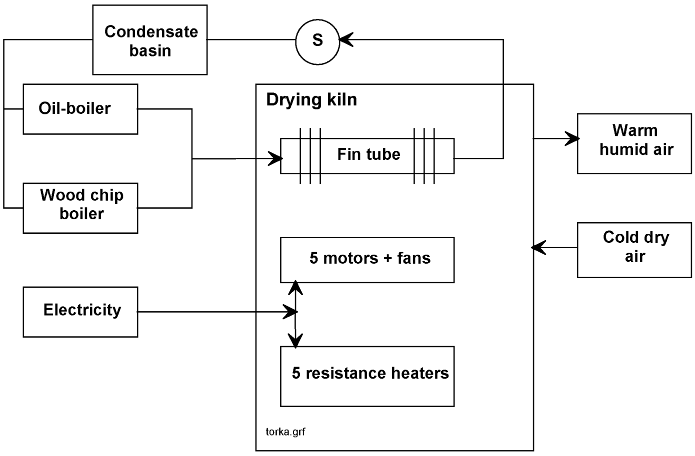

Figure 1: Schematic view of the Mörlunda drying kiln.

reduce the electricity peak. During later hours, this value decreases to about 8 kW. The electricity demand for the heaters and fans, however, adds up to about 20 kW which therefore must be possible to use for load management. The values in Figure 2 are calculated as an average for each hour and there is consequently a need to show the demand in more detail. The shortest time interval for our registrations is one minute: in Figure 3, three hours are shown, starting on May 20.

A closer study of the drying kiln and Figure 3 reveals that the air stream in the dryer is reversed intermittently in order to obtain the correct drying conditions. Three of the motors operate for a few minutes, after which only two of the motors are used. Further, it is shown that the electric resistance heaters are either turned on or off: demand is always increased by about 15 kW when they are in use. Note that each heater has a demand of 2.7 kW.

MATHEMATIC MODEL AND OPTIMIZATION

When an LP or MILP model is to be designed, the first step is to determine the so-called "objective function", i. e. the expression which is to be minimized. In our case, this expression shows the cost for one drying cycle, which depends on how much heat is actually needed and also its source. For the studied cycle, all the heat was provided by the electric resistance heaters, but it was originally possible to use steam from either the oil-fired boiler or the one using wood chips. The steam system in the drying kiln is not in use today as the pipes have been damaged by frost. The result of the optimization will reveal how these sources should be used in order to achieve the lowest possible cost. Naturally, it is then assumed that the pipes have been repaired. Three variables, EH, O and W, are therefore introduced, showing the heat demand in kW for electricity, oil and wood chips respectively. A variable EM is also introduced, showing the

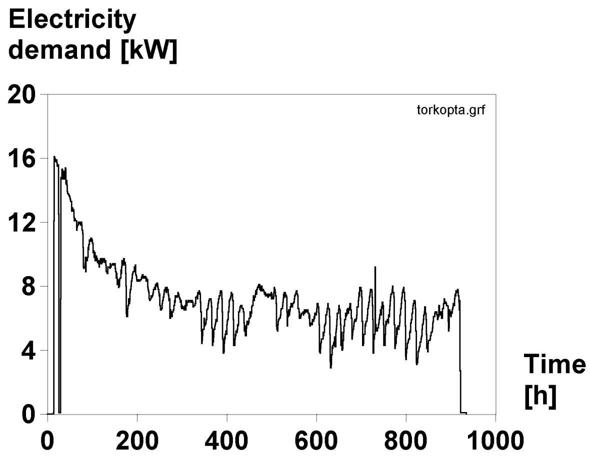

Figure 2: Electricity demand of the drying kiln April 13 to May 25, 1998.

electricity demand for the motors. The company pays for the electricity on the basis of a time-of-use tariff. Unfortunately, we used a five-minute resolution for the initial days. The first working day with one-minute values is therefore April 20, 1998. The humidity of the ambient air has not been monitored, but an average value is 82 % according to Swedish meteorological data. Table 1 shows a number of readings from our electricity meter.

Time	Demand kiln	Demand total	Time	Demand kiln	Demand total	Time	Demand kiln	Demand total
06.00	17.3	197.8	06.10	5.7	179.5	06.20	3.5	177.2
06.01	16.6	179.0	06.11	18.1	194.5	06.21	3.4	152.8
06.02	3.5	167.9	06.12	18.1	189.4	06.22	9.1	168.7
06.03	3.4	166.4	06.13	12.2	194.1	06.23	18.3	170.2
06.04	4.1	173.9	06.14	3.4	173.0	06.24	18.2	167.8
06.05	17.9	179.0	06.15	3.5	170.6	06.25	6.4	158.9
06.06	18.0	189.0	06.16	6.0	178.2	06.26	0.0	159.9
06.07	14.2	192.2	06.17	18.2	185.6	06.27	1.7	156.1
06.08	3.5	179.5	06.18	18.1	188.0	06.28	2.3	157.5
06.09	3.4	177.2	06.19	12.5	206.7	06.29	2.3	158.0

Table 1: Drying kiln and total electricity demand [kW] in the Mörlunda carpentry, April 20, 1998.

The first readings at 06.00 show that 17.3 kW was needed in the kiln, while the total demand for the factory was 197.8 kW. At that time, the price of electricity was 0.275 SEK/kWh, but at 22.00 the price decreases to 0.212 SEK/kWh. The lower price is also valid for the month of May, regardless of the time of day. The company subscribes for 190 kW and this limit is passed within the first

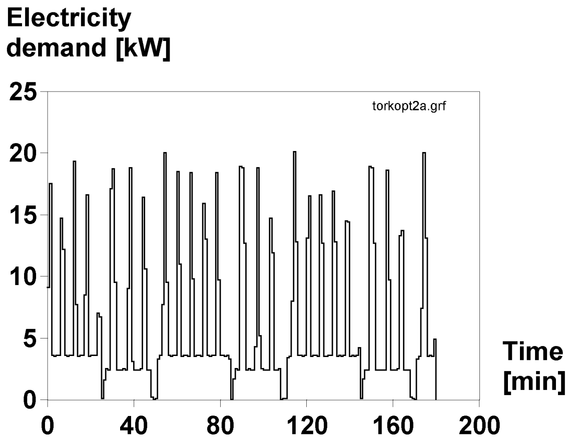

Figure 3: Electricity demand on a oneminute basis, May 20, 1998

minute. The electricity utility, however, calculates an average for one hour, and therefore lower demands during subsequent minutes might save the situation. The demand fee is 174 SEK/kW if demand is lower than 190 kW. During November to March, the demand fee is 420 SEK/kW and the price is doubled for electricity in excess of the 190 kW limit.

The price of oil for industrial use is about 0.2 SEK/kWh, approximately equal to 0.03 USD, because of reductions in energy taxes and CO_2 fees. The oil-fired boiler is assumed to have an efficiency of 0.7.

The price of wood chips is about 100 SEK/m3. The density is approximately 170 kg/m^3, while absolutely dry wood contains 4,500 kcal/kg. Assuming that the moisture content is about 10 %, the heat in one cubic meter will be about 700 kWh, see Reference [1]. The resulting cost for the company is therefore about 0.14 SEK/kWh. Some of these chips are produced in the wood machining processes, but a certain amount has to be purchased elsewhere. The pricing of wood chips might justify further comment. If these chips were in abundant supply, they would have a lower value since the selling price is probably less than the buying price. The fact that the company has to buy chips, however, supports the assumption that the buying price is correct. Energy conservation measures might lead to the opposite situation, which in turn might make some of the measures unprofitable because of the lower monetary value of the chips. The boiler burning wood chips is in a poor state and therefore it is assumed that the efficiency is as low as 0.6. If the energy-related costs alone are considered, the first part of the objective function therefore becomes:

$$\left(\frac{EH_1 \times 0.275}{1.0} + \frac{EM_1 \times 0.275}{1.0} + \frac{O_1 \times 0.20}{0.7} + \frac{W_1 \times 0.14}{0.6}\right)/60 \qquad (1)$$

where the indices show the number of the "time element". The objective must be divided by 60 because this element is only one minute long and the prices are shown in SEK/kWh. The efficiency of the electrical devices has been assumed to be 1.0. Since the model is intended to deal with one full day or 1,440 minutes there are also 1,440 EH, EM, O, and W variables.

If the short objective function (1) is minimised the variables would be set to null and neither heat nor electricity could be used. Hence, a constraint must be introduced. The monitored electricity consumption, showed that 17.3 kW was needed at 06.00. This value includes electricity for the motors as well as the resistance heaters. Each motor must use about 1.15 kW because at 06.28 and 06.29 the demand was 2.3 kW. (At 06.08, 3.5 kW was used, i.e. three motors were running.) The electric motors must either consume electricity or be turned off. The computer "sees" only the values for one minute and it is therefore not easy for it to decide whether two or three motors are running, i. e. if the demand is over 3.5 kW. It is therefore assumed that the demand for the motors equals that value. The EM variables are present in our first constraint and the following applies:

$$EM_1 \leq 3.5 \tag{2}$$

$$EM_1 - 3.5 \times A_1 \geq 0 \tag{3}$$

$$EM_1 + EH_1 + O_1 + W_1 \geq 17.3 \tag{4}$$

A_1 is a binary variable that can only assume the value 0 or 1. If the motors are in operation, i.e. EM_1 equals 3.5 kW, A_1 must be 1 because of constraint (3). If, however, the motors are turned off, A1 equals 0. If optimal, EM_1 will also take that value because of the minimisation of the objective function. If the motors are turned off because of optimal load management, electricity must not be used as a heat source. Therefore, EH_1 should be zero if A_1 assumes that value. This is achieved by the next constraint where M is a number larger than EH_1 will ever assume, e. g. 100 in this case.

$$EH_1 - A_1 \times M \leq 0 \tag{5}$$

The price of electricity is higher than the price of heat from wood chips. In optimization, this leads to zeros in all the EM variables and the air circulation in the dryer will not operate. Assume that the motor must operate for at least 40 minutes each hour. A new constraint must be introduced:

$$A_1 + A_2 + A_3 + \ldots + A_{60} \geq 40 \tag{6}$$

For the next hour, the variables A_{61} to A_{120} must add up to 40, and so on.

The demand fees for electricity must also be considered. As mentioned above, the electricity company applies a fee of 174 SEK/kW as long as demand is lower than 190 kW. If demand is higher, the fee is doubled. The model must therefore include a constraint which calculates the demand for each hour and calculates the maximum value. If this value is higher than 190 kW an extra demand fee must be added to the objective function.

$$(EM_1 + EH_1 + EM_2 + EH_2 + \ldots + EM_{60} + EH_{60})/60 - E_{max1} \geq 0 \tag{7}$$

$$(EM_{61} + EH_{61} + EM_{62} + EH_{62} + \ldots + EM_{120} + EH_{120})/60 - E_{max2} \geq 0 \quad (8)$$

At 07.00 on April 20, the total demand as an average for one hour was monitored as 174.45 kW. At the same time demand from the dryer was 9.52 kW. Therefore 164.93 kW is out of reach for the dryer optimization. At 08.00, this value was 147.67 kW.

$$E_{max} - E_{max1} \geq 164.93 \quad (9)$$

$$E_{max} - E_{max2} \geq 147.67 \quad (10)$$

$$E_{max} - E_{pun} \leq 190 \quad (11)$$

$$E_{pun} \geq 0 \quad (12)$$

In order to cover a full day, 24 equations of type (7) and (9) must be present. E_{pun}, see (11), is added to find the extra penalty fee. This is, however, only applicable during the winter months and for our case study where April and May is considered the extra cost will not apply. In our case, the total electricity demand was never higher than 170.19 kW and hence $E_{pun} = 0$. However, the objective function must include:

$$\ldots + 174 \times E_{maxdr} + \ldots \quad (13)$$

where E_{maxdr} is the maximum electricity demand for the dryer. This value is found by applying constraints similar to (9) where the right hand side equals 0. The value 174 originates from the demand fee.

If the problem above is optimised, the wood-fired boiler should be used all the time because of its low running cost. Electricity is only used for the motors. However, because of the requirements of the fire insurance company the boiler must not be used when there are no employees in the factory. During these hours, the cost for steam heat from wood firing has been set at 100 SEK/kWh which will exclude that source. At Mörlunda, work starts at 06.30 but because of daylight saving time this corresponds to 05.30 in the data files. In Table 1 the values therefore show that the factory was in full use. According to the table demand was 17.3 kW at 06.00. The optimization shows that this demand should be met by using 3.5 kW of electricity for the motors and 13.8 kW of steam from the wood-fired boiler. For times when use of this boiler is prohibited, the oil-fired boiler should be used instead. Electricity should also now be used only for the motors. By turning off these motors for at most 20 minutes the demand expressed as an average for one hour is reduced to 2.33 kW.

Table 1 shows that demand varies between 0 to about 18 kW when electricity is used. This is not very practical when steam from the boilers is to be used. Instead, the heat should be delivered in an even flow. It must be ensured, however, that enough heat is present in order to keep the temperature at a certain level in the dryer. In the data set, it is possible to omit demands higher than 3.5 kW and add the parts that are used primarily for heating. At 06.00, the first minutes result in the following sum, see Table 1:

$$13.8 + 13.1 + 0.6 + 14.4 + 14.5 + 10.7 + \ldots \qquad (14)$$

The energy demand for one hour can therefore be calculated and constraints in the model introduced which ensure that the same amount of heat is delivered to the dryer. Note that constraint (4) must be excluded because it is no longer necessary for demand to be covered for each individual minute. In order to find the lowest possible heat flow, a low cost is introduced in the objective function coupled to the need for steam power. This cost must be chosen with some consideration. If it is too high, e.g. 500 SEK/kW, steam is abandoned for all segments which in turn leads to heating by electricity. The maximum demand in kW will nonetheless be lower than before, 9.1 kW, compared to about 20 kW without optimization.

In this case, the demand cost for steam is very low because all parts of the steam system are already present. If a cost of 0.5 SEK/kW for both oil-fired and wood-fired heat is assumed, the thermal power need in the form of steam is leveled while at the same time electricity is abandoned as a heat source. It is now optimal to use the oil-fired boiler alone and with a demand of 6.6 kW since this device is used during non-working hours. The demand cost for steam must therefore be still lower, say 0.05 SEK/kW, which leads to an oil-fired boiler consumption of 6.6 kW for non-working hours, and steam from wood chips of 6.3 kW when the workers are present. Electricity, 2.33 kW, is only used for the motors. The values are calculated as averages for one hour. It must be noted here that the model contains 1,440 integers and over 7,000 constraints. Consequently, there is not one single optimal solution but instead a number of solutions which supply identical values to the objective function.

The model above contains about 7,000 constraints just for a 24-hour period. If the total drying cycle is to be optimized this number will be about 40 times greater. Such problems will be time-consuming even for modern computers. There is therefore a need for reductions of the input data set. Firstly, the highest electricity demand fees are only applicable during the winter months and, secondly, only day time use is of interest, i. e. from 06.30 to 16.30. Lunch hours and other non-working periods can also be excluded.

CONCLUSIONS

The drying kiln at Mörlunda Chair and Furniture Ltd. is at present heated only with electricity. The maximum demand is monitored at about 20 kW. This leads to the conclusion that it is an appropriate device for load management because the temperature in the kiln will be fairly constant for short reductions of the electricity supply. However, a closer study using the mixed integer linear programming technique shows that electricity is more expensive compared to steam from the oil-fired or wood chip fired boilers. Wood chip fuel is the cheapest source, but cannot be used outside working hours because of fire insurance considerations. During these hours, the oil-fired boiler should be used. Electricity is not used for heating but must be used for the fans. It is assumed that the motors can operate about 40 minutes each hour without any adverse effects on the lumber. This leads to a reduction of the electricity demand from about 16 kW to only 2.3 kW, calculated as an average for one hour. If the owner of the factory acts in this optimal way, the possibility of profitable load management for the rest of the electricity load can be ignored. The maximum demand for the motors is 3.5 kW and only 0.8 kW calculated as an average for one hour can be utilised for this type of demand side management.

References

[1] Kollmann F. and Côté W. *Principles of Wood Science and Technology, Volume I.* Springer-Verlag, 1984. ISBN 3-540-04297-0.

[2] Milota M. R. and Wengert E.M. Applied Drying Technology, 1988-1993. *Forest Products Journal*, 45(5):33–41, 1995.

[3] Bannister P., Bansal B., 'Carrington C. G. and Sun Z. F. Impact of Kiln Losses on a Dehumidifier Drier. *International Journal of Energy Research*, 22(6):515–522, 1998.

[4] Carlsson P., Esping B., Ormarsson S. and Söderström O. Optimization, a Tool with which to Create an Effective Drying Schedule. *Holzforschung*, 52(5):530–540, 1998.

[5] Foulds L. R. *Optimization techniques.* Springer Verlag, New York Inc., 1981.

[6] Gustafsson S. I. Load Management Measures in a Carpentry Factory. *International Journal of Energy Research*, 22(14):1267–1274, 1998.