OPTIMISATION OF DRYING KILN OPERATION

Stig-Inge Gustafsson,
IKP/Energy Systems and Wood Science Technology
Institute of Technology, S581 83 Linköping, Sweden

May 29, 2015

Abstract

When timber is to be utilised in the form of furniture it must be dried. Green timber many times contains more water than wood and if it is placed indoors the water slowly will evaporate. When the fibre saturation point is reached the wooden parts start to shrink and the shape of the details will change. If the wood is dried before it is used for furniture parts this calamity is reduced because shrinking has occurred already in the drying kiln when the raw material was in the form of lumber. This drying process use a lot of heat which is produced by electricity or by firing wood chips or oil in boilers. The cost for these energy sources varies during the season or for electricity also during the day. This paper describes how to optimise the use of energy in two drying kilns located at a small carpentry factory in the south of Sweden. Monitored values from the factory are used in order to describe the process in close detail. These values are then used as a basis for a mathematical model which is designed in the form of a Mixed Integer Linear Program. The method makes it possible to optimise the operating schemes for the two dryers.

Key words: Mixed integer linear programming, Wood drying, Electricity, Boilers, Steam

INTRODUCTION

The wood manufacturing industry in Sweden has not very often been subject for scientific research. The factories are many times located in rural areas and the inhabitants often must move, or commute, to larger cities in order to find work. The County of Kalmar, and funding from the European Community task 5b, have therefore financed studies of this industrial branch in order to help the companies grow and be able to employ more people. Three papers have been published within this project and the first shows how a company uses electricity and heat, and further a number of processes are identified in order to make the energy cost lower, Reference [1]. The second paper deals with the surfacing line in a carpentry factory, Reference [2], while the third paper examines the wood drying process, [3].

OPTIMISATION

The method used here for optimisation, i. e. to find the cheapest way to provide a process with e. g. heat, is called Mixed Integer Linear Programming, MILP. In all such MILP problems there is an objective function which is to be minimised. The objective therefore shows the total cost for the process. The lowest value of this function is, of course, zero but then the process cannot work. Therefore, a number of constraints must be introduced which ensure that, for instance, heat is provided to a sufficient amount. It is not possible to dwell deeper into the details of how to solve such problems and the reader is referred to Reference [4], [5] and [6] for further information. Commercial computer programs are available for MILP optimisation and e. g. CPLEX, LAMPS and ZOOM can be used for this. All these programs need input data and these are presented to the program in the form of a MPS file which is a standard format. This file might include several thousands of lines and, hence, computers are used also for writing this as an ordinary text file. The MPS format just tells the operator how to present the mathematical problem in order for the optimisation program to read it. The main task for the researcher is therefore to construct the computer program which translates an actual process into a mathematical problem.

CASE STUDY

One of the studied companies, Mörlunda Chair and Furniture Ltd., is located about 350 km south of Stockholm. The company was established in 1904 and has now about 20 employees. Electricity is purchased from the Sydkraft company which monitors the amount each hour. These data are after this transferred to a computer located elsewhere. One advantage with this procedure is that data are available on an hourly basis for several years. In Figure 1 the demand of electricity for 1997 is presented in a so called duration graph where the meter readings have been sorted in descending order.

The company has a subscription for 190 kW but during 1997 this level was exceeded by 21 kW. When this happens an extra fee must be paid of 914 SEK/kW. (One US$ equals about 8 SEK.) Hence, an extra fee had to be paid of about 19,000 SEK. This extra fee could be avoided by use of load management measures applied at two kiln dryers, today heated with electricity. A number of other alternatives have also been identified. One of the dryers can be heated with steam from two boilers, one fired with oil and one fired with wood chip residues from the manufacturing processes. The steam system was damaged by frost some years ago and has not been in use since. As a result of this project repairs have now started. The other dryer originally used a heat pump for condensing vapor in the humid kiln dryer air to water. The heat achieved from this process was then led into the dryer via the circulating air. The heat pump, however, has not been used for several years because of some unidentified problem.

Electricity meters have now been set up on strategic spots in the factory and therefore it is possible to use monitored data from these dryers and the total electricity need in order to design a mathematical model. The first time when both dryers were used at the same time, and a peak occurred which exceeded 190 kW, was at November 10, 1998, see Figure 2.

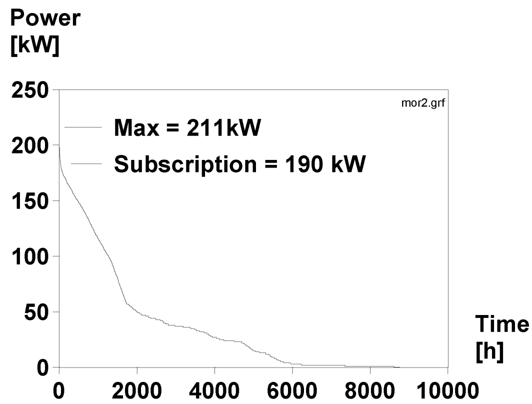

Figure 1: Duration graph of purchased electricity at Mörlunda Chair and Furniture Ltd., 1997, Reference [1].

In Figure 2 the demand is shown for a one minute basis and the maximum total demand 215.6 kW occurred 06.39 and 06.41, i.e. minute no 398 and 400. Sydkraft, however, calculates an average for one hour which was 196.3 kW which occurred for the hour between 07.00 and 08.00. The peak exceeded the subscribed level and this cost the company about 6,000 SEK. For the rest of the day the average demand was lower than 190 kW. It is now of interest to study the peak hour in more detail, see Figure 3.

In Figure 3 it is obvious that both dryers used electricity during the entire hour. The use varies because when a certain temperature is reached the resistance heaters are turned off. The motors for the fans in the dryers seems to operate all the time but for other hours it is shown that they are turned off as well, but only for short periods of time, see Reference [3] where dryer no. 1 is studied in closer detail.

MATHEMATICAL MODEL

The electricity meters installed at Mörlunda Chair and Furniture Ltd. are scanned each minute. Therefore, this basis is used for the mathematical model. For each minute the cost present in the objective function must be elaborated and, further, a number of constraints must be used based on the same time interval. For one full day there are 1,440 minutes each yielding a number of objective function and constraint data. Just for one day the model will therefore include several thousands of variables and constraints. Even for the fast desktop computers available today a model of one full drying cycle, which lasts about two weeks, will be very time consuming to optimise. The model, therefore, is limited to one day, viz. the one where the peak demand of 196 kW occurred. In Table 1 the first values from the most interesting hour is shown.

All MILP models include an objective function. In our case study electric-

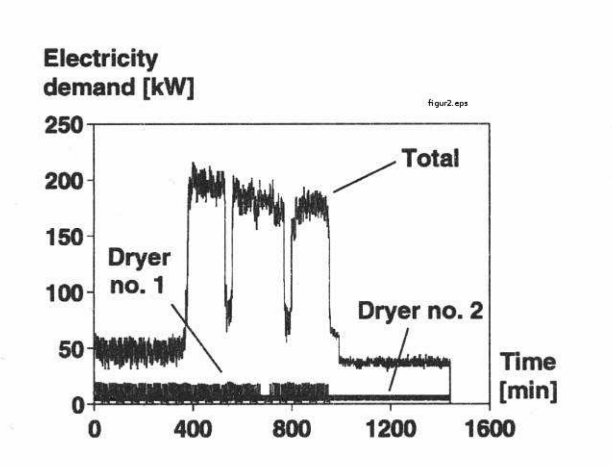

Figure 2: Electricity demand for two dryers and the entire factory, November 10, 1998.

Minute no	Dryer no 1, [kW]	Dryer no 2, [kW]	Total, [kW]
420	3.5	3.7	188
421	8.9	7.5	195.5
422	18	7.5	205.3
423	17.8	7.5	200.6
424	17.8	3.7	205.3
425	17.7	7.5	205.4
426	17.8	7.5	202.9
427	7.4	7.5	194
428	3.5	7.5	188
429	3.5	3.7	188
430	14.6	7.5	196.9

Table 1: Electricity demand in the two dryers and in the total factory.

ity demand in the dryers is of vital interest. Dryer no 1 can be heated with steam from an oil-fired boiler, steam from a wood chip fired boiler or by use of electricity. In Reference [1], it is shown that the dryer use three fans when air circulates in one direction and two fans when the opposite is valid. Each motor use about 1 kW. The first minute in Table 1 shows that no heating occurred and that three motors were used. It must be possible to use the fans when steam heating is optimal and the demand is therefore divided in four parts, $EM1$ for electricity to the motors in dryer no. 1, $EH1$ for electricity heating in dryer no. 1, $WH1$ for steam heating using wood-chips and $OH1$ for steam from the oil-fired boiler. Dryer no. 2 can only use electricity for heating and thus only two variables are needed $EM2$ and $EH2$. Oil for industrial use is now free of tax charges and the price is as low as 0.2 SEK/kWh. It is assumed that the efficiency of the boiler is 0.7 and the price for oil-fired steam is 0.29 SEK/kWh. Wood-chips fired steam is still cheaper and in [3] the price was found to be about

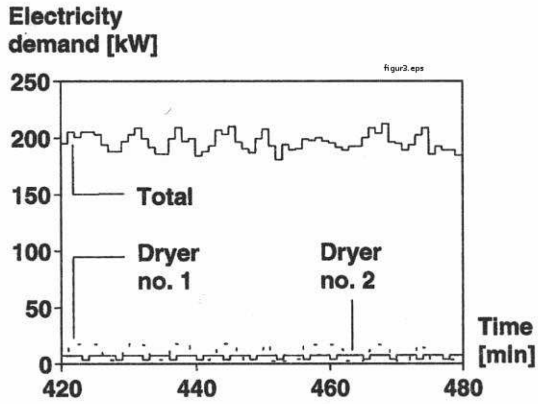

Figure 3: Electricity demand for the peak hour.

0.14 SEK/kWh. The boiler is in a poor state and the efficiency is assumed to be about 0.6 which implies the price 0.23 SEK/kWh. The cost for electricity is very low today because of the deregulated market. The prices are not official and therefore it is assumed that 0.25 SEK/kWh could be used in this case study. We have, however, tested the model with other prices as well. The efficiency for electricity heating is supposed to equal 1.0. The first part of the objective function can now be elaborated.

$$[(EM1_1 + EH1_1 + EM2_1 + EH2_1) \times 0.25 + WH1_1 \times 0.23 + OH1_1 \times 0.29] \times (1/60) \quad (1)$$

The prices are shown in SEK/kWh and hence the objective must be divided by 60. The index 1 shows that this is the first element or the first minute. For one day, 1,440 such cost elements must be added. Note that we do not now in advance how large the variables will become, this will fall out as the result of optimisation. Note that the objective function is linear and that the minimum of it will be zero. This implies that also the values of the variables must be zero which is impossible if the dryers will work. A constraint must therefore be introduced. Load management is supposed to cut off the peaks from the total use in the factory. A certain amount of heat must, however, be present during, for instance, one hour. For dryer no. 1 this leads to:

$$(EH1_1 + WH1_1 + OH_1 + EH1_2 + WH1_2 + OH1_2 +$$

$$\ldots + EH1_{60} + WH1_{60} + OH1_{60}) \times (1/60) \geq 8.2 \quad (2)$$

When the value 8.2 kW was calculated all the readings from the electricity meter which were greater than 3.5 kW have been included, i. e. electricity used for the motors only have been excluded. It shall be noted that it is not necessary to restrict the use to the 24 specific hours present during the day. Instead, 60 consecutive minutes could be used as well starting from e. g. minute no 2 or 3. This leads to over 1,400 equations of type (2). Here, each specific hour is dealt with, leading to only 24 such constraints.

Binary integers are also introduced in the model. If the motors are used for air circulation one of these integers are set to 1. Otherwise it is 0. Adding 60 such consecutive integers must yield a value higher than 40 which implies that the motors could be turned off for 20 minutes. If this is hazardous for the lumber quality the value 40 could be set higher, see Reference [3] for details on these integers.

The model must also include the total electricity demand. Above, it was shown that the maximum was 196 kW. The extra cost for exceeding this level is 914 SEK a value which must be present in the objective function (1). Two new variables are introduced for this, $EMAX$ and ST, and a constraint ensures that ST finds a proper value:

$$EMAX - ST \leq 190 \tag{3}$$

In the objective function, $ST \times 914$ is introduced. Because of the optimization, ST will achieve the lowest possible value but it is important that it is not negative. If the company wants to subscribe for a lower demand it must negotiate with Sydkraft but if the level is set to 190 kW no money could be saved if demand is lower. A lower bound is therefore set so ST always must be ≥ 0. The value of $EMAX$ is calculated by constraints similar to (2), see Reference [3] for all details. ST will then only add a value to the objective when $EMAX$ is higher than 190 kW.

Heat demand in the dryer could be met by using steam. In (2) it is ensured that the need is covered each hour. Only a few minutes with large thermal power will be sufficient but such powerful equipment is not installed. Using three variables which shows the maximum of all the $WH1_n$, $WH2_n$ and $OH1_n$ values and multiplying these with a low cost, e.g. 10^{-4}, in the objective function ensures that the need is leveled at the lowest value.

The optimal solution shows that it is possible to avoid the tariff penalty by using load management in only dryer no 1, see Figure 4.

The average total demand decreased from 196.3 kW to 188.5 kW. Partly this is solved by using steam from the wood-chip fired boiler of 14 kW and partly from turning off the electric motors for the fans for 20 minutes during the peak hour. Above was mentioned that the use of steam should be leveled at the lowest possible value. This is only partly true in Figure 4. For some part of the day 14 kW had to be used and this sets the cost in the objective function. As long as demand of steam is lower no extra cost will occur and hence, 14 kW is used until the need for heat in kWh is covered. After that the steam system is turned off. It must be noted that the optimisation also shows that alternative solutions are available yielding the same cost. Small changes could therefore be made in Figure 4 which will not necessarily increase the cost. Steam from the oil-fired boiler should not be used at all, because of the high fuel cost. Running the dryer without using the fans might be impossible due to the quality of the lumber. If the motors must run for 60 minutes each hour this will only slightly change the optimal solution above. Maximum used demand will only increase from 188.5 to 189.7 kW. If the subscription is decreased from 190 to 185 kW it is no longer possible to avoid the penalty fees by load management in dryer

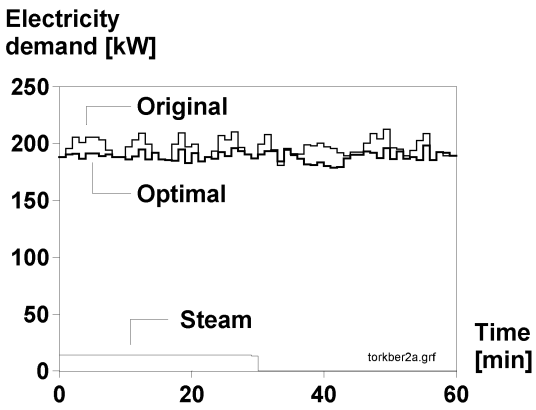

Figure 4: Optimal use of steam and electricity for the peak hour in Mörlunda.

no. 1. The limit is the one found above, or 188. 5 kW.

Dryer no. 2 has a somewhat different load pattern, see Table 1 and Figure 5.

From Figure 5 it is obvious that the maximum demand is about 7.5 kW. It must be noted here that the dryer is not in perfect shape because of the malfunctioning heat pump. The need for electricity, calculated as an average for one hour, is 6.6 kW. The dryer cannot, without some investments, be coupled to the steam system because of its location. For this study it is therefore assumed that the dryer only can be turned off and on and then the monitored electricity demand is used for finding the level each minute. Introducing new binary variables, B_1, B_2 up to B_{60} for each hour and using 60 constraints like:

$$ED_1 - M \times B_1 \leq 0 \tag{4}$$

where ED_1 equals the use of electricity in the dryer the first minute and M is a large number, sets the value of B_1 which is the binary variable showing if the dryer is used or not. If ED_1 is a number greater than zero B_1 must become 1. If ED_1 is zero B_1 can be either zero or one. B_1 is, however, coupled to a cost in the objective and because of the minimisation only zero will apply. It is assumed that the dryer can be turned off for ten minutes without any hazardous effects on the lumber. This can be achieved in the model by use of the following constraint, one for each hour:

$$B_1 + B_2 + \ldots + B_{60} \geq 50 \tag{5}$$

Since there is a cost for using electricity, i.e. the cost for each kWh, it must be ensured that the dryer not always is turned off ten minutes each hour, but instead only when the peak is likely to occur. A cost is therefore introduced in the objective function for turning off the dryer. The cost, which is coupled to a binary variable C which equals one when B assumes the value zero, must be lower than the penalty charged from Sydkraft for exceeding the subscription level. Above it was shown that the maximum demand in the dryer was 7.5 kW.

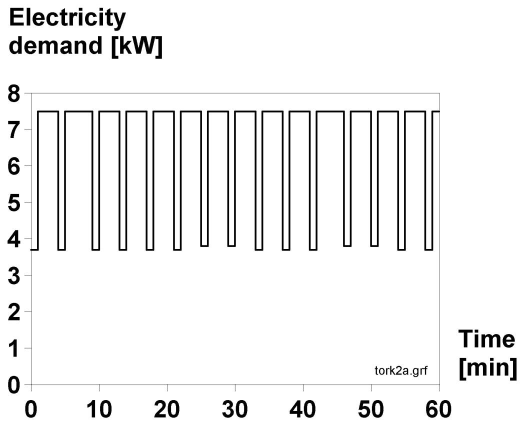

Figure 5: Electricity demand in dryer no 2 for the peak hour at Mörlunda Chair & Furniture Ltd.

Constraint (5) will however restrict the possible decrease of the demand to only 1.25 kW calculated as an average for one hour. One constraint has also been set telling that 6.6 kWh must be delivered to the dryer. If the dryer is disconnected ten minutes this constraint is not met. Instead, the optimal solution shows that the dryer must be connected with 7.5 kW for 52 minutes and one minute with 3.34 kW which adds up to the acquired amount. If the dryer will be a useful tool for load management it must therefore be possible to turn it off for longer periods of time, preferably one hour, or to install steam heating in this dryer as well. By the introduction of several thousands of binary variables the computer time for optimisation is long and the need for computer memory considerable. Our computer, therefore, had some difficulty to evaluate all the nodes in the branch-and-bound tree without getting problems with the amount of memory. A number of solutions exist which yield the same objective function value and still more that are in the vicinity of optimality which aggravates the situation. It was, however, observed that solutions are found within the first 10,000 nodes with an objective function value which probably will not become lower. The branch-and-bound search could therefore be limited to examine only that maximum number of nodes. The process is by that measure not as tedious as was originally expected. This leads to the conclusion that mathematical optimisation by use of the MILP method is possible but not very suitable for processes which has such long schedules as timber drying cycles at least if optimum must be guaranteed. If, for instance, extra insulation of the walls of the drying kiln is considered at the same time as load management on a minute basis, several drying cycles must be examined and preferably over a number of years in order to find profitability for such measures. Even the most sophisticated computer will then be too slow for practical use in optimisation. Using hours as a time basis might solve some of these problems but this will make it impossible to study exactly when the dryers are to be turned off and on.

CONCLUSIONS

It is shown that Mixed Integer Linear Programs, MILP, can be used for optimising load management measures applied in wood drying kilns. In order to find out how much electricity demand can be decreased short time intervals must be used, i.e. minutes. A drying cycle is of the magnitude one or two weeks which leads to programs including several thousands of variables and many of these of the binary type. Further, experience from the optimisation process shows that a number of solutions exist with the same objective function value. This leads to tiresome calculations for even very fast computers if the absolute minimum of the objective function must be guaranteed. Restricting the search to a limited amount of nodes makes the process less tedious and probably one of the optimal solutions will be present in the searched set of the branch-and-bound tree.

References

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

[2] Gustafsson S. I. Energy Usage and Conservation in Surfacing Lines. *Energy Conversion and Management*, 41(15):1649–1669, 2000.

[3] Gustafsson S. I. Optimization of a Wood Dryer Kiln Using the Mixed Integer Programming Technique: A Case study. *Drying Technology*, 17(6):1181–1190, 1999.

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

[5] Nash S. G.and Sofer A. *Linear and Nonlinear Programming*. McGraw-Hill, New York, 1996. ISBN-13: 978-0070460652.

[6] Rardin R. L. *Optimization in Operations Research*. Prentice-Hall, Inc, Upper Saddle River, N.J, 1998. ISBN-13: 978-0023984150.