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Enlarging the Product Portfolio of a Kraft Pulp Mill via Hemicellulose and Lignin Separation – Process Integration Studies in a Case Mill

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Increased energy and raw material prices along with contracting markets for kraft pulp, have highlighted the need for the pulp industry to enlarge their traditional product portfolio with new value-added products via the implementation of biorefinery concepts. In this paper, we have investigated potentials for enlarging the product portfolio of a kraft pulp mill by extracting hemicellulose prior to digesting and in this way, converting to dissolving pulp production.

A case study has been performed on a Swedish kraft pulp mill, in order to evaluate the consequences of the original mill configuration, level of heat integration and choice of by-products produced have on the overall profitability of the mill upon conversion to dissolving pulp production. For the mill studied, the batch digester is identified to be the bottleneck for both kraft and dissolving pulp production. If the digester capacity is increased by e.g. purchasing new effects, the pulp production could be maintained.

The results from the energy study indicate that dissolving pulp production is more heat demanding than kraft production. However, by increasing the heat integration of the mill, it is possible to, not only become self-sufficient in terms of steam, but also to produce significant amounts of excess steam. The steam excess facilitates integration of a lignin separation plant or can be used for power generation.

The net annual profit was evaluated for varying prices of electricity and lignin. For the economic conditions studied, lignin separation was always better than power generation, if lignin can be priced as oil.

1. Introduction

By the end of 2010, the cotton market reached a record high price not seen in several decades. This boosted the popularity of other kinds of textile fibers e.g. rayon. Dissolving pulp can be used for rayon production. Dissolving pulp is mainly produce in sulphite mills but can also be produced at modified kraft mills. Therefore, the growing demand for rayon resulted in traditional kraft pulp manufacturers stepping into an unknown market, the textile market.

In the kraft process, the digester is considered the heart of the mill as the separation of the different wood components is achieved mainly in this equipment. Simplified, most of the cellulose and some of the hemicellulose becomes the pulp product, whereas the rest of the hemicellulose and lignin is burnt to produce steam. In efficient kraft mills, there may be also available excess steam that can be used for e.g. condensing power generation or to facilitate the integration of a lignin separation plant.In the case of dissolving pulp production, the situation is different. Dissolving pulp is cellulose with a very high level of purity. Accordingly, most of the hemicellulose must be removed from the pulp. While this can be done in various different ways, in industrial applications, hemicellulose has been extracted with water prior to digesting (Mateos-Espejel et al., 2013). Due to extraction of hemicellulose and more intensified degradation of cellulose, the pulp yield is decreased from approximately 43 % in an average kraft pulp mill to about 33 %. This means that larger amounts of wood are required to produce the same amount of pulp.

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Alternatively, the pulp production may be reduced if there is equipment at the mill limiting the capacity to handle a larger wood input. Hemicellulose has a promising future in e.g. biofuel production or used as a component in biopolymer formulations (Toledano et al., 2010). Lignin could be used as a fuel or upgraded to e.g. carbon fibers (Maradur et al., 2012).

The conversion of the mill affects the steam and power balance to a large extent. Dissolving pulp production demands more steam and power per ton of pulp produced. On the other hand, the increased wood input to the mill results in an increased amount of organic material that is eventually burned in the recovery boiler, resulting thus, in a larger amount of steam produced. The resulting steam balance for a particular mill depends therefore on its steam demand and its capacity to handle a larger amount of raw material.

In a previous study (Lundberg et al., 2012a), we have used a model representing a modern kraft pulp mill to study the energy consequences of converting to dissolving pulp production. The original excess steam available at the mill decreased significantly upon conversion. However by increasing the heat integration of the mill, it was possible to instead increase the total excess steam and thereby also increase the potential for power generation. For a less efficient converted mill, producing additional steam in an oil boiler, steam saving measures, could result in a decrease oil use (Mateos-Espejel et al., 2013).

The recovery boiler of the mill is usually considered the bottleneck for increased pulp production in kraft mills (Olsson et al., 2006) and in converted mills into dissolving pulp production (Lundberg et al., 2012a). This is however not necessarily always the case. For example, Mateos-Espejel et al. (2013), performed a case study for a Canadian pulp mill. At this mill, the pulp production capacity of the converted mill would be mainly limited by the capacity of the digester plant. By investing in new digesters, the pulp production could be increased. They also identified other critical equipment that could limit the pulp production capacity: evaporation plant, recovery boiler and lime kiln. However, the economic performance of such conversion was not investigated. Hamaguchi et al. (2013) studied the consequences of hemicellulose extraction in a Finnish kraft mill and showed that extensive investments can be avoided if lignin separation is used to debottleneck the recovery boiler of the mill. In this study, however, kraft pulp production (as opposite to dissolving pulp production) was considered.

As a continuation of the previous studies, we have identified the need to further investigate the consequences of the configuration of the original mill on the feasibility and profitability of converting to dissolving pulp production. The aim of this paper is therefore to investigate the energy consequences of converting an existing Swedish kraft pulp mill into dissolving production, and to suggest appropriate steam saving measures that could facilitate the conversion, resulting in a mill self-sufficient in terms of steam, with varying amounts of excess steam available for other purposes. The excess steam could be used e.g. for upgrading hemicellulose, exported to nearby processes, power generation or lignin separation. Moreover, the aim is to investigate the consequences of different levels of heat integration in the overall profitability of the mill, as well as the consequences of using the excess steam for power generation or lignin separation.

2. Method

The conversion of a Swedish kraft pulp mill, producing 425,000 t of softwood kraft pulp annually (~1250 ADt/d) into dissolving pulp production has been studied. In this study, it is assumed that the stream with diluted hemicellulose leaving the extraction unit, so called hydrolysate, might be discharged or it might be exported to a nearby hemicellulose upgrading process. Since many different alternatives for upgrading hemicellulose are possible and the most profitable option is mill specific, the hemicellulose upgrading process has not been defined in this study and consequently considered outside of the system boundaries. The consequences of combusting the hydrolysate in the recovery boiler are investigated in a continuation of this study and will be presented in a future article.

The changes in process streams upon conversion to dissolving pulp production were estimated based on previous studies done by the authors (Lundberg et al., 2012). The changes included modified temperatures or flowrates of certain streams, which resulted in modified heating and cooling demands of certain parts of the mill. The power consumption was increased in order to include the increased power demand of the wood yard as well as the increased pump work necessary for transporting some streams.

Thereafter, Pinch Analysis – see e.g. (Smith, 2005) as a broader source and (Klemes et al., 2010;) as a Process Integration focused souce, has been used to identify opportunities for heat integration. The stream data for the pinch analysis was gathered, when possible, from the internal control system of the mill, for a time period (January 2012) when the production was stable. The period is representative for mild winter conditions with no extreme peaks in the outside temperature in either direction. When data was not available, some temperatures and flowrates have been estimated in collaboration with the mill personal.

Optimization tools were not used to find the most profitable level of heat integration. However, four levels of increasing heat integration were investigated. Of these four, the two simplest resulted in a deficit of steam whereas the two more rigorous resulted in excess steam. In this paper, we present the two levels with highest heat integration: Level 1, the simplest among these two, and Level 2, the most complex one. The potentials for power generation and lignin extraction were quantified for the two levels of heat integration. Finally, an economic evaluation was conducted. Net annual profit, Eq(1), was used as a performance indicator. The annuity factor used was a=0.1, representing a strategic, long term investment.

$$net\ annual\ profit\ =\ annual\ income - operating\ costs - a\ \cdot\ investment\ costs \qquad (1)$$

3. Kraft mill description and conversion to dissolving pulp production

The studied kraft mill has quite unique features since it has undergone several upgrades in the later years which resulted in a potential to increase the existing capacity of most of the critical equipment, see Table 1. Today, the digester plant can be considered the bottleneck of pulp production. If hemicellulose extraction is done as a step in the cooking sequence of the batch digester, the digester plant capacity would limit the pulp production even more. For a constant pulp production, the capacity of the digester plant would have to increase by about 77 % by e.g. purchasing new effects, in order to account for the increased cooking time (extraction step included) and the increased wood input. Under these conditions, the rest of the equipment would still have sufficient capacity to maintain a constant pulp production.

4. Energy analysis

The dissolving pulp demands more steam per ton of pulp produced compared to the kraft pulp. If the digester plant of the mill is debottlenecked, the pulp production can be kept constant and the total steam demand of the mill will increase, as can be seen in Figure 1. This is however compensated by the increased steam production in the recovery boiler, due to increased black liquor production. In the dissolving pulp plant 287 MW (LP and MP) steam is produced, which can be compared with the minimum hot utility demand in the GCC of 211 MW, leaving a theoretical maximum steam surplus of 76 MW.

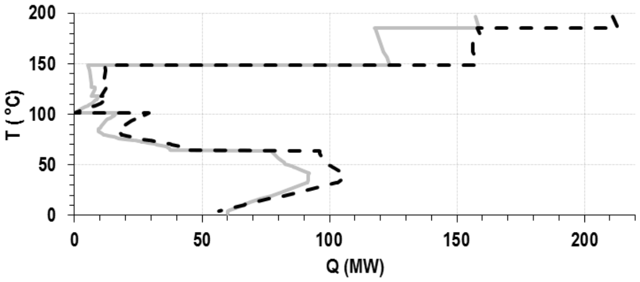

Figure 1: Grand Composite Curves for the kraft (continuous curve) and dissolving pulp mill (dashed curve)

Reaching the theoretical maximum heat integration level is not convenient from a technical and economic point of view. In this paper, two different levels of heat integration are presented. In both cases heat integration with the streams to/from the extraction unit is considered. In practice, it means that the hot hydrolysate, leaving the extraction unit, is used to preheat the extraction water, entering the extraction unit. The main difference between Level 1 and Level 2 is on how the extraction water is preheated prior to the previously mentioned heat exchanger. In Level 1, excess heat readily available at the mill (cooling of surface condenser) is used. In Level 2, extraction water preheating is done stepwise with other sources of excess heat at a higher temperature, which would, in turn, require a more complex design of the heat exchanger network. In addition, in Level 2, additional steam savings are achieved by retrofitting some of the streams at the mill. Most of the retrofits involve modifying the hot and warm water system of the mill to reduce the steam demand for hot water production. These retrofits are independent on the way the extraction water is preheated and could therefore be implemented also in Level 1. The resulting steam savings are presented in Table 2.

Increasing the level of heat integration requires of course greater investments but it also increases the possibilities for producing valuable by-products. At the studied mill, a new pellet factory and a large increase of the existing saw mill is planned for the near future. This would require additional 20 MW of LP steam. Accordingly, this would decrease the potential for power generation and/or lignin separation. In the results presented below, the resulting excess steam has already been decreased by 20 MW to cover the mentioned steam demand. Based on the amount of excess steam left, the case of maximizing power generation by investing in additional back-pressure and condensing turbines is compared against the case of integrating a lignin separation plant. The by-products produced in each case are presented in Figure 2.

Table 1: Potential capacity increase for different process parts at the studied mill

Process equipment	Evaporation	Causticizing	Recovery boiler
Potential capacity increase	86 %	86 %	63 %

Table 2: Summary of steam savings potential

Measure	Level 1	Level 2
Preheating of extraction water	12 MW	17 MW
Retrofitting the mill	0 MW	15 MW
	12 MW	32 MW

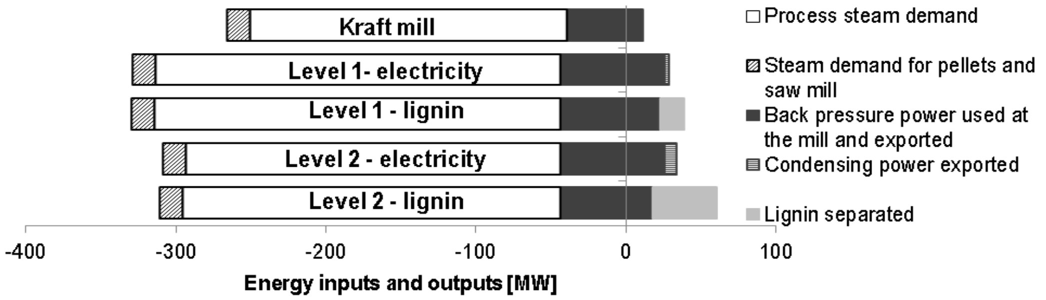

Figure 2: Utility demands (negative values) and energy outputs (positive values) for the different levels of heat integration and type of by-products (electricity or lignin)

5. Economic evaluation

The economic conditions utilized are summarized in Table 3. Individual heat transfer properties of the process streams were considered for heat exchanger area calculations. Conversion into dissolving pulp production requires large investments for debottlenecking the mill, achieving steam saving and for by-products production (e.g. turbines or lignin separation plant). For the studied mill, it was estimated that debottlenecking costs of the digester plant can be as high as 70 % of the total investment costs, see Table 4. This investment is required if the pulp production is kept constant. Alternatively, the pulp production may be decreased, which would result, however, in significant pulp sales losses.

Table 3: Economic conditions: investment costs and operating costs. The investment costs were actualised by using the Chemical engineering plant cost index (CEPCI) for corresponding years

Investment costs			Source
Heat exchangers			
Liquid-liquid	47,907 [€]+479 [€/m^2]		Laaksometsä et al. (2009)
Gas-water/steam	200 [€/m^2]		Laaksometsä et al. (2009)
Air-air	100 [€/m^2]		Laaksometsä et al. (2009)
Back-pressure turbine	$1.09 \cdot P^{0.6}$ [M€]	P= generated power [MW]	Olsson et al. (2006)
Condensing turbine	$1.96 \cdot P^{0.6}$ [M€]	P= generated power [MW]	Olsson et al. (2006)
Lignin separation plant	$5.95 \cdot LR^{0.6}$ [M€]	LR= lignin separation rate [kg/s]	Olsson et al. (2006)
Digester plant	450 [MSEK]	(for a pulp production of 2000 ADt/d)	Delin et al. (2005)
Operating costs			
Lignin separation plant	33 [€/t- lignin]	(equivalent to 5 €/kWh- lignin)	Olsson et al. (2006)

The studied mill has overcapacity in most of the largest equipment and as a consequence only the digester plant needed to be debottlenecked. However, average mills may have one or several bottlenecks.

If any important component needs to be debottlenecked, the investment costs for this would definitely be one of the largest ones upon conversion. In addition, debottlenecking the mill requires a production stop at the plant with significant downtime losses. These costs influence therefore largely the profitability of converting the kraft mill to dissolving pulp production. The decision whether to convert or not needs to be taken considering these aspects as well as the expected revenues from dissolving pulp sales. Once the decision has been taken to convert to dissolving pulp production, a decision must be taken regarding the level of heat integration and the type of by-products produced.

Table 4: Investment costs. The investments can be compared against the estimated investing cost for debottlenecking the digester plant (constant for all cases): 46.4 M€

	Level 1		Level 2	
Retrofits		M€		M€
Required modifications in HWWS for conversion	10 new HX, 2 HX upgrade	3.4	10 new HX, 2 HX upgrade	3.4
Preheating extraction water	2 new HX	4.7	2 new HX	5.0
Retrofitting the mill			3 new HX	1.0
		8.1		9.3
Electricity cases	MW	M€	MW	M€
Back-pressure and condensing turbines	22	9.3	26	13.1
Total investments including retrofits		17.4		22.4
Lignin cases	MW	M€	MW	M€
Back-pressure turbine	16	3.5	11	0.5
Lignin separation plant	16	5.9	43	10.5
Total investments including retrofits		17.4		19.9

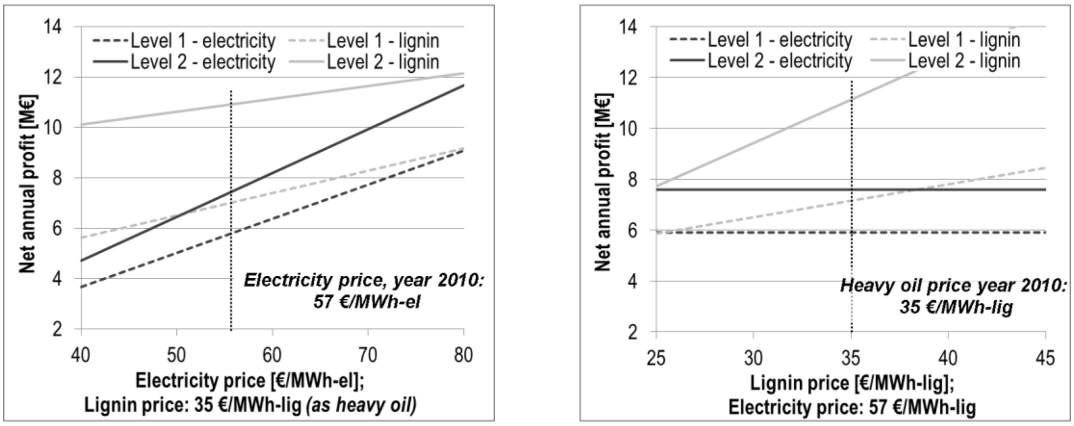

Figure 3: Net annual profit for varying prices of electricity (left side) and lignin (right side). The dashed lines and continuous lines represent Level 1 and 2 of heat integration correspondingly

Sensitivity analyses were conducted to evaluate the profitability of power generation and lignin separation for varying prices of electricity and lignin. The calculated net annual profit considers the investment necessary for energy efficiency measures, the cost for purchasing turbines and/or lignin separation plant and the revenues from the sales of electricity and lignin (cost for debotlenecking the digester plant and the pulp sales are not included, since they are constant for all the cases).

In the left side of Figure 3, the net annual profit is evaluated for varying electricity prices and set lignin price as heavy oil. It is shown that higher levels of heat integration (Level 2) have higher net annual profit than Level 1. Profits are as much as 4 M€ higher for Level 2, for some electricity prices. The performance of both, electricity and lignin cases improve as the electricity price increases, this is due to the fact that back-pressure power is also generated in lignin cases. It is shown that for electricity prices lower than 80 €/MWh-el, lignin separation is always a best alternative.

Today there is no established market for kraft lignin, hence the price is uncertain. The right side of Figure 3 shows the net annual profit for varying prices of lignin and set electricity price. Also in this case, a high level of heat integration gives a higher net annual profit than a lower level of heat integration and for the economic conditions investigated, lignin separation performed always better than power production. A sensitivity analysis was also conducted for lignin priced as low grade fuel (not presented here). In that case, the performance of power generation and lignin separation were similar but the profitability of lignin case increased very rapidly as lignin price increased. These results differ from a similar evaluation done for a kraft mill (Olsson et al., 2006). In that study, lignin was valued as a low grade biofuel and the results favored power production. However, Olsson et.al. (2006) concluded that for an electricity price of 55 €/MWh-el, lignin separation could be better for lignin prices higher than 24-26 €/MWh-lig (as in this study). We conclude that for lignin prices higher than low grade biofuel, lignin separation should be preferred.

6. Conclusions

The energy study showed that efficient heat integration can result in excess steam at the mill. For a simpler design (Level 1), the resulting excess steam was 12 MW. A more rigorous heat integration, (Level 2), resulted in 32 MW.

The largest investments costs in the studied mill are associated with debottlenecking the digester plant (approximately 70 %). Significant losses in pulp production associated with downtime can be also expected. These factors along with the price of dissolving pulp are critical when taken the decision to convert into dissolving pulp production.

The profitability is also affected by the investments and revenues associated with the by-products i.e. the necessary investments in turbines and/or lignin separation plant and the sales of power and/or lignin.

Higher levels of heat integration can give significantly higher net annual profit than lower heat integration, as high as 4 M€. Considering that conversion to dissolving pulp requires anyway a production stop at the mill, it is probably advantageous to take that opportunity to implement ambitious energy saving measures.

For the conditions studied (lignin valued as heavy oil), lignin separation was always more profitable than power production. This price of lignin is reasonable if lignin is used as feedstock for high added value products. The market for lignin is nevertheless uncertain, so for a mill with a positive view on innovation, lignin separation might be more attractive, but on the other hand, power generation might anyway the safest alternative. Note, however, that both alternatives showed positive net annual profit.

For the studied mill, the advantages of either lignin separation or power generation depended exclusively on the associated investment costs and the revenues from by-products sales. This is valid for mills in which the digester plant is the bottleneck for pulp production. Further studies need to be done to evaluate the advantages of separating lignin in mills where the recovery boiler is the bottleneck. For this kind of mills, implementing lignin separation may be extra advantageous since it would allow debottlenecking the recovery boiler, thereby increasing the pulp production.

References

Delin,L., Berglin N., Lundström A., Samuelsson Å., Backlund B., Sivard Å., 2005. FRAM 09: Bleached market kraft pulp mill. STFI, Stockholm.

Hamaguchi M., Kautto J., Vakkilainen E., 2013. Effects of hemicellulose extraction on the kraft pulp mill operation and energy use: Review and case study with lignin removal. Chemical Engineering Research and Design, 91(7), 1284-1291

Klemes J., Friedler F., Bulatov I., Varbanov P., 2010. Sustainability in the Process Industry : Integration and Optimization, 1 ed. McGraw-Hill Professional, New York.

Laaksometsä C., Axelsson E., Berntsson T., Lundström A., 2009. Energy savings combined with lignin extraction for production increase: Case study at a eucalyptus mill in Portugal. Clean Technologies and Environmental Policy, 11, 77-82.

Lundberg V., Axelsson E., Mahmoudkhani M., Berntsson T., 2012a. Energy Analysis for Conversion of a Kraft Pulp Mill into a Dissolving Pulp Mill. Chemical Engineering Transactions, 29, 13-18, DOI: 10.3303/CET1229003.

Lundberg V., Axelsson E., Mahmoudkhani M., Berntsson T., 2012b. Process integration of near-neutral hemicellulose extraction in a Scandinavian kraft pulp mill - Consequences for the steam and Na/S balances. Appl Therm Eng, 43, 42-50.

Maradur S.P., Kim C.H., Kim S.Y., Kim B.-H., Kim W.C., Yang, K.S., 2012. Preparation of carbon fibers from a lignin copolymer with polyacrylonitrile. Synthetic Metals, 162, 453-459.

Mateos-Espejel E., Radiotis T., Jemaa N., 2013. Implications of converting a kraft pulp mill to a dissolving pulp operation with a hemicellulose extraction stage. TAPPI Journal, 12.

Olsson M.R., Axelsson E., Berntsson T., 2006. Exporting lignin or power from heat-integrated kraft pulp mills: A techno-economic comparison using model mills. Nordic Pulp & Paper Research Journal, 21, 476-484.

Smith R.M., 2005. Chemical Process: Design and Integration. John Wiley & Sons, Chichester, England.

Toledano A., Egües I., De Andrés M.A., Llano-Ponte R., Labidi J., 2010. Lignocellulosic biorefinery approach: A challenge for a new world. Chemical Engineering Transactions, 21, DOI: 10.3303/CET1021113