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Process intensification in mechanical pulping

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KEYWORDS: Process intensification, Low consistency refining, High intensity, Softening, Process control, Energy efficiency, Mechanical pulping, TMP

ABSTRACT: Process intensification is a term used in the chemical process industry for major improvements in the process design leading to radical changes in process complexity, equipment size and efficiency. We suggest that a similar approach is applied in the pulp and paper industry. We have focused on the production of mechanical pulp, but a similar approach can be applied to other areas within the pulp and paper industry. Inspired by process intensification methodology, we suggest five principles for development of the mechanical pulping process. Three fundamental principles;

1. Break up the wood and fibre wall structure in the right positions.
2. Give each fibre, of certain morphology, the same processing experience.
3. Optimize the applied mechanical forces and the physiochemical state of the wood and fibre material.

and two system oriented principles;

1. Select wood raw material based on final product specifications.
2. Design the process to facilitate observability, controllability and maintenance.

Implications of these principles on process design and future challenges for mechanical pulping are discussed.

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Introduction

Our intention with this work is to initialize a discussion around fundamental principles in the field of mechanical pulping (MP) resembling the concept of process intensification (PI). Process intensification is a term used in the chemical process industry for major improvements in the process design leading to radical changes in process complexity, equipment size and efficiency.

We focus on the mechanical pulping process, but a similar approach can be applied to other areas of the pulp and paper industry. We introduce the framework of process intensification, since it is to our knowledge not used within the pulp and paper industry. The basic steps of MP are summarised and we suggest fundamental principles for mechanical pulping inspired by PI. We discuss the relevance of the suggested principles based on available knowledge in the field of MP and present some examples of process development that have been made in line with those principles. Finally, we discuss the future challenges of MP in light of the suggested principles.

Process intensification

In the chemical process industry, more compact processes with less equipment, higher yield and lower energy consumption have been developed. When the development is made in an innovative way with large effects on process performance, it is called process intensification (Stankiewicz, Moulijn 2002). Gourdon et al. (2015) stated that PI simply means, "using much LESS to produce MUCH more and BETTER".

The concept of PI was developed during the 1980's and 1990's and in the beginning, the main focus was on reducing production cost (Ramshaw 1995). Later, the definition of PI broadened to include large changes in equipment size and number of process parts, energy consumption, product purity, amount of waste as well as environmental and human safety (Stankiewicz, Moulijn 2000).

Van Gerven and Stankiewicz (2009) summarized much of the previous work in PI and they proposed four fundamental principles defining process intensification:

1. Maximize the effectiveness of intra- and intermolecular events.
2. Give each molecule the same processing experience.
3. Optimize the driving forces at every scale and maximize the specific surface area to which these forces apply.
4. Maximize the synergistic effects from partial processes.

There are overlapping parts in the definition of PI and other concepts for process development such as process system engineering (PSE) and process optimization (Moulijn et al. 2008). The objective of PSE is to improve decision-making for the chemical supply chain, covering the whole process from inventing, designing, manufacturing, and distributing chemical products (Grossmann, Westerberg 2000). PI concerns mainly improvements of the unit operations of the production process, whereas PSE has more focus on system modelling and control (Moulijn et al. 2008). In PI, focus has been on designing new equipment that integrates two or more unit operations such as reactors and separators. It is not the intention to go into details describing the concepts here, but rather to introduce the methods and to point out that there is no strict definition of PI and no distinct border between PI and other chemical engineering skills.

Van Gerven and Stankiewicz (2009) also defined four approaches or domains that any changes in the process can be referred to. The approaches are; *spatial* i.e. creating a structure for the desired processes, *thermodynamic*, which means applying energy in the right form in the right amount at the right position and time, *temporal*, which is utilizing changes in conditions over time and finally *functional*, namely combining different functions to obtain synergy. They also

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structured the material processing equipment according to three scales: *molecular, particle* and finally *macro* scale. The macro scale includes single equipment as well as a whole plant or process.

The concept of PI was developed in an industrial sector that has a different structure than pulp and paper industry. However, we believe that a systematic approach as PI could be useful for development work also in the pulp and paper industry.

The PI principles suggested by Van Gerven and Stankiewicz (2009) can of course be applied to parts of the MP processes as they are. We will not discuss such examples in detail, but rather focus on principles adapted for mechanical pulping.

Mechanical pulping

At a first glance, the mechanical pulping process may look rather uncomplicated; wood is heated and ground in attrition machines called refiners or in grinders. The produced pulp is diluted with water and thereafter unseparated fibres (shives) and coarse fibres are removed and ground again. Pulp is ready and sent to the paper machine.

Pulping based on wood fibres has a starting point that is challenging - the raw material. Wood is an extremely inhomogeneous material, which affects the process all the way to the final product. Despite much research work, the fundamental mechanisms of grinding and refining are still obscured. There are no techniques to separate fibres with high selectivity according to their morphology and thus adapt the treatment for different fractions. Finally, we are still lacking adequate methods to characterise the fibre material at a sufficiently detailed level. Since, at a closer look, the mechanical pulping process is so complex, it ought to be beneficial to have a set of fundamental principles to base the development on.

All mechanical pulp production processes include four basic steps:

1. Selection of wood raw material (e.g. species and part of stem).
2. Pretreatment of wood (e.g. debarking, chipping, washing, heating and impregnation).
3. Defibration (disintegration of wood to free fibres).
4. Fibrillation (flexibilisation and peeling of fibre walls)

These four basic steps are described in more detail below to give a starting point for the discussion of principles for mechanical pulping.

Selection of wood raw material

Concerning the wood, it has been shown in many studies that the quality and choice of wood has a large impact on final product properties and energy consumption. Generally, for a certain wood species, juvenile wood gives a paper with better surface smoothness, higher opacity, and higher brightness but lower tensile and tear strength at certain specific energy consumption compared to mature wood. (Corson 1984; Tyrväinen 1995; Corson et al. 2003; Lundqvist et al. 2003; Persson et al. 2003).

It can thus be stated; *Select wood raw material based on final product specifications.* This might not be considered a principle based on PI, but it is an important factor affecting the product quality. This principle is more in line with process system engineering and should be considered for optimal production of mechanical pulp based products.

Pretreatment of wood

The wood always has to be conditioned, more or less, before fibre separation. Wood is built from natural polymers (mainly cellulose, hemicelluloses and lignin). Hemicelluloses and lignin, which constitute around 60% of softwood trees, are softened i.e. the glass transition temperature is reduced by water and heat (Goring 1963; Back, Salmén 1982; Irvine 1985). It is important for the next phase of the MP process, defibration, that the wood is softened in order avoid excessive fibre rupture and facilitate the further treatment, fibrillation.

In the oldest process for paper production based on wood – Stone Ground Wood (SGW), logs are just debarked, washed and cut to proper lengths before grinding. Therefore, it is crucial to use fresh wood containing natural water for SGW. For refiner-based processes, this is also important but water impregnation of wood chips can compensate, to some extent, for dry wood.

Softening can be enhanced by chemical modification of the wood polymers. Chemicals break the polymer structure and the number of charged groups are increased which increases softening (Höglund et al. 1976; Atack et al. 1978; Salmén 1995). In MP the most utilized chemicals are alkaline sodium sulphite and hydrogen peroxide.

Defibration

Defibration is attained through application of mainly compressive and shear forces to the wood. Defibration has to be made at such conditions that separation occurs in the right position in the wood structure - balancing the applied forces and the softness of the wood (Koran 1967, 1968). It has been shown that the two processes defibration and fibrillation are different (Luhde 1962; Koran 1981) and that they should preferably be performed at different conditions (Salmén, Fellers 1982).

In the machines used today for MP, forces are applied to wood and separated fibres by some kind of structure, either bars as in refiners, *Fig 1*, or grits in grinders.

If the strain is too low, the applied energy will only dissipate as heat (Salmén, Fellers 1982) whereas too high strain will break the fibres. Wood can be characterized as a viscoelastic material, which means that higher strain rate will make it act stiffer and higher temperature will make it softer (Becker et al. 1977). Thus, it is important to find the optimal conditions for transfer of mechanical energy.

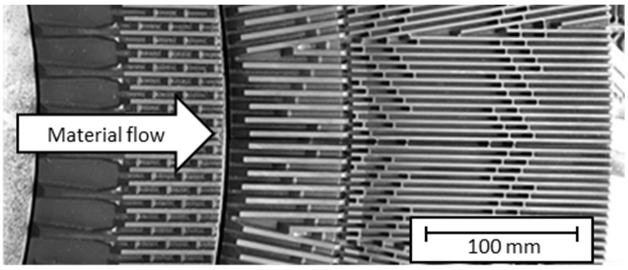

Fig 1 – Part of refiner disc.

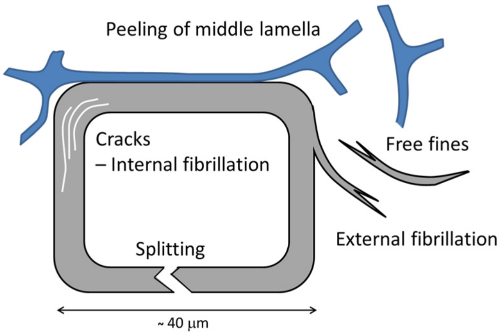

Fig 2 – The mechanical treatment of fibres create internal and external fibrillation as well as free fines particles and fibre wall splitting.

Fibrillation

Fibrillation is here used in a broad sense including the flexibilisation of fibre walls by introduction of micro-cracks, usually referred to as internal fibrillation, as well as reduction of fibre wall thickness through peeling of fibre wall material. The peeling action creates external fibrillation and free fines particles, *Fig 2*. The mechanical treatment can also cause splitting of the fibre wall along the fibre (Reme et al. 1998).

As soon as wood is deformed in order to separate fibres, breakdown of the fibre walls will start. It is therefore impossible to separate the processes of defibration and fibrillation completely in the machines used today. It is however most probable that the processes should be separated as much as possible and forces and force transferring surfaces should be different for the two processes. Fibrillation is more efficient if it is made at higher temperature and intensity than defibration. This was shown for internal fibrillation by Salmén and Fellers (1982) and it has also been shown for fibre development (both internal and external fibrillation) in refiners (Höglund et al. 1997; Sabourin et al. 2003).

Wood fibres have a large native distribution in length, width, fibre wall thickness and fibre wall structure. The variation in fibre cross sectional dimensions is exemplified in *Fig 3.*

Salmén et al. (1997) suggested that earlywood and latewood fibres should be treated separately to improve efficiency and minimize fibre damage. It has also been shown that these two fibre types respond differently to fibrillation; early wood fibres are more easily cut and more often split along the length, whereas late wood fibres maintain the length better and the fibre wall thickness is reduced through peeling of fibre wall material (Mohlin 1995; Kure 1997; Reme et al. 1999). Other fibre dimensions, such as fibre length and width, will probably also affect the optimal conditions for mechanical treatment.

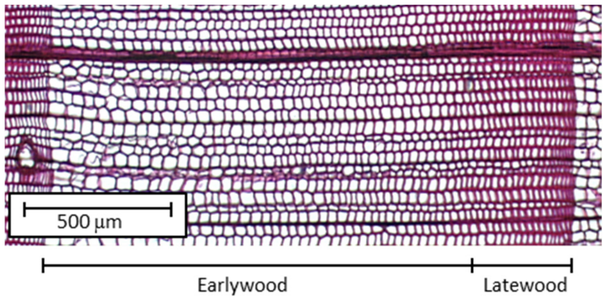

Fig 3 – Cross section of spruce wood showing the large variation in native fibre cross sectional dimensions over one year-ring. Approximate partition of earlywood and latewood is shown.

The mechanical pulping processes used today have very low energy efficiency. The applied energy is transferred to heat in the refiners and grinders, which generates steam. The efficiency of today's processes has been estimated to be lower than 15% according to Salmén and Fellers (1982) and references therein. There is obviously a potential to improve the efficiency of mechanical pulping.

Process intensification principles for mechanical pulping

As mentioned in the introduction, Van Gerven and Stankiewicz (2009) structured process intensification by four principles, four domains (approaches) and three scales. It is somewhat confusing that synergy appears both in principle four and in one of the domains (*functional*). We have chosen to consider synergy from the domain perspective, spanning over all principles and scales, and to not define a fundamental principle based on synergistic effects.

Inspired by Van Gerven and Stankiewicz (2009), we suggest three principles for mechanical pulping:

1. Break up the wood and fibre wall structure in the right positions.
2. Give each fibre, of certain morphology, the same processing experience.
3. Optimize the applied mechanical forces and the physiochemical state of the wood and fibre material.

We will discuss these three principles in relation to the three scales and the four domains. We will not discuss the complete three-dimensional space, but some important aspects and some practical examples. Focus will be on the core of MP - defibration and fibrillation.

Scales

In PI, the scales are associated with the processing equipment, from nano-structured catalysts to whole processes. For mechanical pulping, it is more natural to relate the three scales to the size of the processed material: wood/chips, free fibres and wood polymers.

Molecular scale: The complex wood polymer structure constitutes the molecular scale. From this perspective, the aim is to break up molecular bonds in the wood structure

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in such a way that fibres are separated from the wood matrix and the fibre walls are treated to an extent adapted to the final product. For pure mechanical pulping, it is probably mainly Van der Waals and hydrogen bonds that are broken up, whereas for chemithermomechanical (CTMP) processes also covalent bonds are broken by the chemical treatment. The first MP principle is mainly associated with the molecular scale.

Particle scale: For mechanical pulping, the particle scale is naturally related to fibres and can as well be called the fibre scale. Fibrillation of fibres is the main process on this scale, however more development is needed to better adapt the mechanical treatment to the fibre morphology.

The second MP principle is mainly associated with the particle scale. The statement "same processing experience" in this principle means that the transfer of forces to wood and fibres in the attrition machines should be as similar as possible for each fibre of certain morphology.

Macro scale: From the material perspective, the macro scale includes wood and chips and thus processing steps such as chipping, chip pretreatment and defibration. There is no sharp limit between the macro and particle scales, since wood can be broken down successively into smaller and smaller pieces.

Some process equipment, such as screens and cleaners, can be categorised to both the macro and the fibre scale depending on if they are viewed from the material or equipment perspective. The macro scale also includes the design of parts of, or the whole process. The second and third MP principles are associated with the macro scale.

Domains

Spatial domain: The design of physical structures that enables desired functions in the process, such as force transfer in the defibration and fibrillation stages as well as structures of all other equipment belongs to the spatial domain. Today, similar structures are utilised for treatment on the macro scale (defibration) and fibre scale (fibrillation), which is not necessarily optimal.

On the molecular scale, micromechanical studies by e.g. Berg et al (2009) have shown that loading case affects energy consumption for crack development in the fibre wall. Fratzl et al. (2004), Altaner and Jarvis (2008) and Jin et al. (2015) have all modelled plastic deformation in wood by a detailed description of slip between matrix and cellulosic microfibrils in the fibre wall. These studies are all able to provide ideas for future development of machine structures that efficiently break molecular bonds.

In the third PI principle, driving forces, e.g. temperature or concentration gradients, are considered. It is important to optimize driving forces in parts of the MP processes such as in preheating and impregnation of chips. We do not focus on that aspect since it is covered by the PI principles. For mechanical pulping, it is important to optimise the applied mechanical forces together with the physiochemical state (temperature, water content, chemical environment, etc.) of wood and fibres to get the desired separation and treatment of fibres. It is thus an optimisation connected to all three scales. An example in that direction is the combination of low dose sulphite and high intensity refining (Nelsson et al. 2011).

Ideally, fibres should be individually treated according to their morphology (cell wall thickness, length, width, etc.) and thus force transferring surfaces adapted to the different fibre types.

The third PI principle states that the specific surface area to which the driving forces apply should be maximized; however, there is a very different limit in scale for the mechanical treatment of fibres compared to molecular reactions in the chemical process industry. High specific force-transferring surface area is also desirable in machines for MP but the structures should be adapted to the size of wood and fibres. In practice, this would result in smaller size of equipment at certain production.

Thermodynamic domain: In the machines used today, the fibres are subjected to a large variation in applied energy (Karlström, Eriksson 2014b) resulting in a large distribution in degree of treatment (Reyier Österling 2015). It is probably better to strive for a more narrow distribution of fibre treatment. An example of a step towards more uniform process conditions, on the particle scale, is the new grinding stone design developed by Björkqvist et al. (2006). This design has a more homogenous grit size and thereby also more homogenous mechanical treatment. Tuovinen and Fardim (2015) reported up to 50% reduced electrical energy consumption for wood grinding with this design.

In the processes used today, wood is mainly treated with mechanical energy, but a combination of different forms of energy could be utilized to affect specific molecular structures, which will be further discussed.

Temporal domain*:* Time is important in several ways in mechanical pulping. One example is the time that wood and fibres are exposed to high temperature, balancing wood softening and loss of brightness (Höglund et al. 1997; Sabourin et al. 1997). It is also connected to the strain rate, which has to be optimized together with the physiochemical state of wood and fibre.

Functional domain*:* Within the functional domain, the goal is to find synergistic effects, which can contribute to more efficient and compact process designs.

On the molecular scale, one clear synergy is the addition of chemicals, e.g. peroxide (Harrison et al. 2008), in or just before refining that brightens the pulp and reduces energy consumption.

Another example of a synergistic effect, on the macro scale, is the new Collimated Chipping Technology (Hellström et al. 2011). This chipping technology converts wood to a size that can be handled in the process and at the same time induces a structural change in the wood that reduces refining energy.

Implications on process design

The process development in MP can be looked at from two different perspectives: First, how should a machine look like to be able to break up the molecular structure in an optimal way? Second, how can we modify the existing machines and processes to approach the MP principles? The first approach is out of the scope of this work and thus we will focus on the second approach.

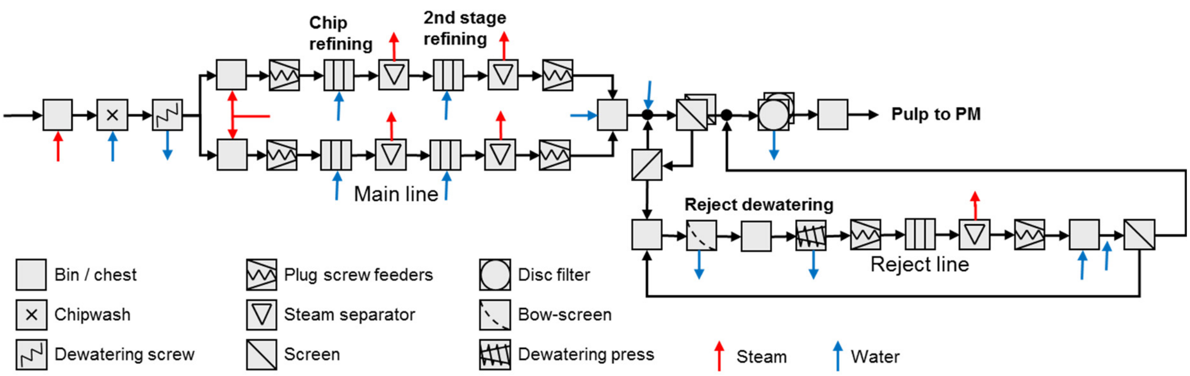

Fig 4 - One of the most common designs of TMP lines from the 1980's.

One of the most common process designs for mechanical pulping is shown in *Fig 4*. This process is still common in mills and it has been used as reference in earlier development work. It contains many unit operations, chests and pumps and consumes a considerable quantity of energy, around 2000 - 2400 kWh/ton (total specific energy for spruce news-grade pulp).

The first principle has, to some extent, permeated the development work in mechanical pulping. It was realised quite early that it is important to control where in the structure the ruptures take place to achieve desired fibre properties (Koran 1967, 1968; Atack et al. 1978). Salmén and Fellers (1982) suggested that defibration and fibrillation should be made separately and at different conditions. For printing paper production, defibration should be made at low strain rate and temperature whereas fibrillation should be made at high strain rate and temperature. This was later confirmed in larger scale (Höglund et al. 1997; Sabourin et al. 2003; Hill et al. 2009). Reported energy reductions are 20-35%.

Utilizing other forms of energy in combination with mechanical energy has been investigated within mechanical pulping. One example is the pretreatment of wood chips with electron radiation (Handke et al. 2014) or laser (Nordström 1996) to break up the molecular structure in specific points. These treatments have usually resulted in loss of fibre length and have not been utilized to a large extent in mill operations, so far. However, there might be a potential for future development in this area.

Chemicals added in or just before refining, can break up the molecular structure, which reduces the mechanical energy demand and simultaneously brightens the pulp in an efficient way due to high temperatures promoting short reaction times (Harrison et al. 2008; Schachtl et al. 2016). It is important for energy efficiency and produced pulp properties that chemicals are added in the right position in the process (Hill et al. 2009).

As mentioned above, Salmén et al. (1997) also suggested that earlywood and latewood should be fibrillated separately, as stated in principle two. Techniques to separate wood fibres into different categories based on length, fibre wall dimensions, fibrillation, etc. and separate treatment of those fractions have been evaluated by Engstrand et al. (1987), Shagaev and Bergström (2005), Ferluc et al. (2007) and Tienvieri and Gummerus (2008), just to mention a few. The reported energy reduction is in the range 10-20%. Today, separation efficiencies are usually low in such processes and the number of unit operations is larger than in a conventional process, which is not in-line with PI. More work is needed to improve the performance of such processes.

Large efforts, mainly related to principle three, have been made to reduce the energy consumption for mechanical pulp production. Most work has been focused on increasing refining intensity (e.g. Miles et al 1991; Sundholm 1993; Sabourin et al. 1997) and/or the wood and fibre softening by means of increased refining temperature or chemical modifications (e.g. Axelsson, Simonson 1983; Petit-Conil et al. 1998; Harrison et al. 2008; Norgren, Höglund 2009; Muhic et al 2010; Nelsson 2016; Meyer et al. 2016). Reported energy reductions are 10-30% compared to the process in *Fig 4*.

One way to make the process more compact and efficient is to utilize single stage high intensity HC refining (Skinnar 1979; Engstrand et al.1987; Strand et al. 1993; Sabourin et al. 1994; Aregger 2001; Muhic et al. 2010). Reported energy reductions are around 15% compared to the process in *Fig 4*. Single stage high intensity refining of slightly chemically treated wood is especially interesting from a PI perspective (Nelsson et al. 2011; Nelsson 2016). This process renders a pulp, directly out from the chip refiner, with low shives content and high tensile index (similar to final pulp properties for newsprint) with around 30% lower energy consumption. Single stage main line refining is also easier to control (Strand et al. 1993).

Sandberg and co-workers (2017) presented a process based on single stage high intensity refining of pretreated chips followed by low consistency (LC) refining. After LC refining, pulp was sent to the paper machine without any screening or reject refining. This concept reduced the number of unit operations and reduced the specific energy with 900 kWh/adt compared to the normal TMP line. That work was inspired by one of the aims of PI – reduction of the number of unit operations in production processes. This is an interesting concept, but more work is needed to be able to apply it to more demanding products than newsprint.

Other concerns

Generally, it is also of great importance to design the process so that it can be easily observed, controlled and maintained. Observability means being able to measure internal process conditions and fibre properties. Examples of processes with poor observability is the high consistency Twin-refiner, where it is not possible (today) to observe–and thereby to control the pulp quality from the two refining zones individually.

Operating the process as close as possible to the lowest acceptable pulp quality reduces energy demand, but a stable process is needed to be able to operate close to that limit. Good control requires good process design. Single stage chip refining makes control easier since only one refiner has to be adjusted and optimized. In two-stage TMP lines disturbances in the chip refiner are amplified in the second stage HC refiner (Hill et al. 1991). One important factor is to have short time delay between refiners and on-line analyser sampling points (Blanchard, Fontebasso 1993), i.e. after each chip refiner pulp should be diluted in a dilution screw connected to a stand-pipe or in a small pulper. In addition, the on-line analysers should not have too many sampling points attached, which also would introduce a time delay (Hill et al. 1979).

It can thus be stated: *Design the process to facilitate observability, controllability and maintenance.*

This statement is very important, but as discussed for the wood selection above, more in line with PSE.

Discussion

Process Intensification is a concept that has been developed within the chemical process industry, in which the processes are rather different from production systems for mechanical pulping. We believe though, that a similar approach could be applied to the development of the mechanical pulping process and other processes in the pulp and paper industry.

A natural question is of course, how can these principles help us in process development for mechanical pulping? Our intention with the suggested principles is to summarize the most important mechanisms that govern mechanical pulping. The principles can be seen as goals in process development.

The first principle is the core in mechanical pulping. More basic research within wood micro mechanics can build the foundation for development of new improved processes.

Principle two is more challenging and requires more development to better adapt the mechanical treatment to different fibre fractions. An example in this direction is the adaptation of segment bar width for LC refining of softwood and hardwood fibres (Lumiainen 1995).

In principle three, the optimisation of applied energy is emphasised. During the defibration in the inner part of the refining zone, wood chips are broken down to match-stick sized particles (pin-chips). These pin-chips are oriented mainly tangentially in the refining zone due to the rotation (Atack 1980), which means that most of the compression and shear forces are applied in the fibre direction. This might not be optimal for fibre separation and might even explain a large part of the fibre length reduction in the first refining stage. Optimising the defibration stage is an area where more research is needed.

We think that it is beneficial to use an approach to mechanical pulping similar to that which Karlström and co-workers are developing (Karlström, Eriksson 2014a) – A well-founded theoretical model of the refining mechanisms that can be utilized to optimise refining conditions. Such a method can be a base for approaching principle three. The two system oriented principles four and five are easier to apply. Wood sorting is used in some mills, which has a clear effect on product properties (Wahlgren, Karlsson 1997) and there is quite a lot of knowledge available in the area of process control.

We have presented a new way to structure the process development of mechanical pulping by proposing fundamental principles. Our intention with this paper is to initialize a discussion in the pulp and paper industry and we hope that this way of working with process development can be useful in this field.

Conclusions

Inspired by process intensification and process system engineering, we suggest five principles for development of the mechanical pulping process. Three fundamental principles;

1. Break up the wood and fibre wall structure in the right positions.
2. Give each fibre, of certain morphology, the same processing experience.
3. Optimize the applied mechanical forces and the physiochemical state of the wood and fibre material.

and two system oriented principles;

1. Select wood raw material based on final product specifications.
2. Design the process to facilitate observability, controllability and maintenance.

The principles relate to the three scales; *molecular, particle* and *macro*. Development work inspired by the principles can be structured according to the four domains; *spatial, thermodynamic, temporal* and *synergistic*.

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