Process Simulation-based Evaluation of Design and Operational Implications of Water-laid Paper Machine Conversion to Foam Technology

Lotta Sorsamäki,[a,*] Antti Koponen,[a] and Eemeli Hytönen [b]

Foam forming technology has attracted much attention during the past few years in the paper industry. Its advantages compared to conventional water forming are a new product portfolio and increased process efficiency. To support the paper industry in pushing foam forming technology forward, process simulation is needed to provide supporting data for strategic decision-making and as a basis for equipment dimensioning. This study examined the conversion of an existing wallpaper machine from water to foam forming technology using process simulation. To determine the required process configuration and parameter changes in the existing process, both published and unpublished data on the foam forming process were collected. This paper also describes modeling of the foam phase in the selected simulation software. The suitability of existing paper process equipment for foam was analyzed. Simulations revealed that undisturbed operation with foam requires some equipment modifications and re-arrangements in water circuits. With foam forming, the water balance in both short and long circulation changes remarkably compared to conventional water forming, leading to a large increase in the long circulation volume flows.

Keywords: Paper machine; Foam forming; Process simulation; Water balance; Process configuration

Contact information: a: VTT Technical Research Centre of Finland Ltd, P.O. Box 1603, 40101 Jyväskylä, Finland; b: VTT Technical Research Centre of Finland Ltd, P.O. Box 1000, 02044 VTT, Finland;
** Corresponding author: lotta.sorsamaki@vtt.fi*

INTRODUCTION

Changes in the global paper industry during the past 10 years have increased the need for more cost-efficient processes and production technologies and even entirely new products. The demand for printing papers is decreasing along with a rapid growth in demand for packaging and tissue products. Papermakers must discover new solutions for their existing production lines. How valuable would it be if an existing production line could be used to produce higher value or even entirely new products? To respond to this challenge, foam forming technology has attracted much attention during the past few years (Lehmonen *et al*. 2013; Kinnunen-Raudaskoski 2017; Kiiskinen *et al*. 2019; Lehmonen *et al*. 2019). Foam forming utilizes small air bubbles (average bubble radius < 100 µm) containing aqueous foam instead of pure water as a process fluid and flowing medium. The fiber-foam mixture is generated by introducing a foaming agent, *i.e.*, surfactant, to the pulp suspension, followed by intensive mixing with air. In the 1970s, foam forming was introduced as a way to replace water in papermaking (Radvan and Gatward 1972; Smith *et al*. 1974; Tringham 1974; Punton 1975a, 1975b; Smith and Punton 1975). The technique was called the "Radfoam process". While some paper machines were modified to accommodate foam forming, the technique was not widely adopted by the paper industry at that time. However, foams have since been used by some manufacturers in the non-woven industry for handling long fibers (Hanson 1977). Generally, foams are widely used in many industrial applications, including the food, petroleum, and gas industries, as well as firefighting (Exerowa and Kruglyakov 1998; Weaire and Hutzler 1999).

The advantages of foam forming compared to water forming include 1) remarkable improvement in end product uniformity (*i.e*., good formation); 2) the possibility of producing highly porous and bulky products, saving raw material and lightening current products; 3) the production of uniform webs from longer and coarser fibers; 4) increased dryness after wet pressing, saving energy during drying (Torvinen *et al*. 2015; Koponen *et al*. 2016; Kiiskinen *et al*. 2019; Lehmonen *et al*. 2020); and 5) high layer purity in stratified forming *e.g.,* in the production of board (Kiiskinen *et al*. 2019). The potential to introduce "difficult" raw materials such as long synthetic or manmade fibers to the papermaking process enables the manufacturing of novel products in an existing production line. Strength properties (both in- and out-of-plane) of water-formed samples are usually better than those made using foam forming. However, the mechanical properties of the foam-formed products may be affected by the different surfactants (*i.e.,* anionic and non-ionic) used in the foam forming process. Lappalainen *et al.* (2014) presented that the effect of the strength additive (cationic starch) in increasing the strength of foam-formed samples was less in the presence of anionic surfactants than with non-ionic surfactants. Both Lappalainen *et al.* (2014) and Zeno *et al.* (2005) pointed out that ionic surfactants were more harmful to sizing than non-ionic surfactants. The conversion of existing production lines from conventional water forming technology to foam forming technology producing higher value products and/or even new products improves the competitiveness of the plant and lengthens the lifetime of the production line.

While the second wave of foam forming has now begun in Finland, foam forming has been explored on a laboratory scale already by many international research organizations. At the pilot scale, all the published studies have thus far been performed at the VTT Technical Research Centre of Finland Ltd. (VTT). Many aspects of foam forming have already been studied, including 1) the generation of foam and resulting foam properties, such as air content, bubble size, and half-life time (Al-Qararah *et al*. 2013, 2015b); 2) the nature and behavior of the foaming agent (Lappalainen *et al*. 2014; Mira *et al*. 2014; Gottberg *et al*. 2019); 3) methods for evaluating the bubble size distribution (Lappalainen and Lehmonen 2012; Koponen *et al*. 2019); 4) the macroscopic properties of foam-formed products (Lehmonen *et al*. 2013; Vähä-Nissi *et al*. 2018); 5) the pore structures of fiber networks of foam-formed fiber suspensions (Al-Qararah *et al*. 2015a, 2016; Koponen *et al*. 2017); 6) foam forming of long fibers (Koponen *et al*. 2016; Asikainen *et al*. 2020); and 7) the operational performances of individual process steps, such as foam generation (Koponen *et al*. 2018), forming (Koponen *et al*. 2016, 2018; Lehmonen *et al*. 2020), pressing (Torvinen *et al*. 2015; Järvinen *et al*. 2018; Lehmonen *et al*. 2020), and drying (Timofeev *et al*. 2016).

Switching from conventional water-laid papermaking to a foam-laid technology does not require replacing the major components of a production machine (Kiiskinen *et al*. 2019). However, the fundamental differences between water and foam that must be considered when designing a foam-forming machine are that 1) foam has a lower density and, by a few orders of magnitude, a higher viscosity than water, 2) foam is compressible, and 3) foam properties are dynamic (Kiiskinen *et al*. 2019). Dynamic here means that, due to drainage and bubble coalescence, the air and water phases easily become separated if the foam is not constantly mixed. All these properties affect the process.

To support the industry in pushing a new technology forward, process simulation is needed. It is a fundamental step in early-stage process design, one that is conducted alongside technology development and is a prerequisite for ensuring the economic sustainability of the process. With modeling and simulation, it is possible to evaluate different strategies for an existing process or a new one and to find the best strategies to decrease the production costs and increase the product's added value. Process simulation and modeling are applied widely in various industries at different stages of the process design. The greatest advantage of simulation models would be obtained if they were built already in the design phase of a greenfield plant implementation project and utilized throughout the whole life cycle of the plant (Blanco *et al*. 2009). Although the pulp and paper industries have used balancing calculations and process control for a very long time, they have been more conservative in the use of computer-based modeling and simulation (Blanco *et al*. 2009). According to Blanco *et al*. (2009), this is largely because of the complex nature of the materials and the high degree of interaction between the various production processes. This statement is even more tenable for foam forming technology than for conventional water forming technology.

The historical perspective and future trends regarding the use of simulation in the pulp and paper industry have been reviewed by Dahlquist (2008) and Blanco *et al.* (2009). According to Blanco *et al.* (2009), steady state modeling of papermaking processes is challenging because papermaking is a process wherein the large amount of water and low efficiency of most of the separation steps make multiple recycling streams necessary. The level of detail in the simulation studies on conventional pulp and papermaking processes reported in the literature ranges from small-scale chemical reactions to mill-wide process calculations and from steady state to dynamic simulations. The steady state simulation studies have focused on 1) optimizing the raw material, fresh water, energy or utility consumption (Bortolin *et al.* 2004; Turon *et al.* 2005; Cardoso *et al.* 2009; Atkins *et al.* 2010; Ruohonen and Ahtila 2010; Jönsson *et al.* 2011; Măluţan and Măluţan 2013); 2) the build-up of dissolved substances (Sorsamäki *et al.* 2019); 3) studying the cost implications of different integrated modernization strategies (Hytönen and Stuart 2012); and 4) studying the chemical state of the plant (Clément *et al.* 2011; Huber *et al.* 2013). Although many studies have focused on dynamic simulation and paper machines, only a few approaches to the dynamics of a paper machine at an industrial scale are available (Blanco *et al.* 2009). These have focused on the transient behavior of wet-end (Orccotoma *et al.* 1997; Yeo *et al.* 2004), the improvement of fault detection (Cheng *et al.* 2008), and the identification of process bottlenecks (Savolainen and Lappalainen 2015). Several software packages exist for flowsheet-based mass balance calculations. When high-fidelity models of single pieces of equipment (*e.g.*, paper machine dryers) are the focus, the models are typically programmed using FORTRAN, C++, or MATLAB and used without flowsheeting tools (Yeo *et al.* 2004; Blanco *et al.* 2009).

Although several studies on the modeling and simulation of conventional paper processes exist, no work to date has focused on the performance of the foam forming process using modeling and simulation. One reason for this may be that in the 1970s, when foam forming was introduced, process simulation was not as common as it is today as a process engineering tool. Currently, there is some industrial activity around foam forming. However, because the production volumes are so far small, and the technology is new and sensitive, the industry prefers not to publish any process data on foam forming. Another reason for the lack of simulation studies on foam forming may be the lack of proper handling of foam in existing simulation software. The nature of foam, like the modeling of it, is challenging. Foam itself is neither liquid nor gas, but it is a more-or-less uniform mixture of air bubbles in the water phase, which could even be called a separate "foam phase." The air content in foam forming is typically 60 vol% to 70 vol%, but recent work has shown that foam forming also works well at as low as 30% to 40% air content (Torvinen *et al*. 2015). Most of the air exists in non-dissolved form as bubbles inside the liquid phase. The amount of dissolved air is marginal. Without proper modeling of the foam phase, the model does not give the true air amounts present in the streams nor the true volume flows of the streams. Without the volume flows, one cannot dimension the pipes or equipment. The volume flows are also needed to reveal any possible differences compared to the conventional water forming.

The main motivators prompting paper manufacturers to implement foam forming technology are the new product portfolio, energy efficiency, and savings in the raw material costs. In addition to the process benefits and product quality improvements verified in several foam forming laboratory trials and pilot-scale runs, process simulation is needed to provide preliminary mass, volume, and energy balances of the foam forming process to create a basis for equipment dimensioning. Together, they will support the process engineering and the strategic decision-making for investing in this new technology. Instead of implementing a greenfield foam forming process, one relevant implementation strategy would be to convert an existing water-laid process to a foam-laid process. In this case, process simulation is needed to reveal bottlenecks in the existing process due to the presence of foam.

Objectives

Because the use of simulation to support engineering has proven beneficial, it makes sense to focus on developing modeling techniques to overcome the shortcomings of commercial simulation tools. Such a focus will enable similar simulation capabilities for foam processes as currently exist for water-based systems. Therefore, this paper presents the required property calculations for describing foam in the used simulation platform. This paper also presents a systematic approach to examine, *via* steady state process simulation, the conversion of an existing paper machine from water-laid technology to foam-laid technology. The overall approach consists of three main steps that are very tightly bound together; 1) modeling of the existing water-laid paper machine; 2) modeling of the conversion of the water-laid paper machine into a foam-laid paper machine; and 3) the model-based, design-based and operation-based comparison of the above two concepts. In the model-based comparison, the authors present the challenges of modelling a foam-laid process in comparison with modelling of a water-laid process, wherein the proper handling of foam phase being the main modelling challenge. In the design-based comparison, the above two concepts are systematically compared to find out whether all parts of the system would be retained or some new parts would be implemented when switching from a water-laid process to a foam-laid one. In the operation-based comparison, the simulation results are utilized to compare these two processes based on their mass, volume, and energy balances with an emphasis on volume flows, foam density levels, and surfactant concentrations throughout the processes. Paper properties were not within the scope of this study. Thus, this three-step approach will reveal the necessary process configuration changes and possible bottlenecks in the existing process. Given these targets, steady state simulation is a sufficient tool, and dynamic simulation is not needed. To justify all the modifications implemented to the reference water-laid process to convert it to a foam-laid process, it was essential to collect all relevant information from the existing literature and experiences in VTT's foam forming laboratory studies and pilot runs. Thus, this paper is both a simulation case study and a review of the foam forming process on a plant-wide level.

EXPERIMENTAL

Overall Approach

The overall approach taken in this study was steady state simulation-based process concept design and evaluation. After defining the scope of the case study, including design- and operation-related questions, ideas for possible concepts to study the questions were defined, and available design and operation data and information were gathered for both the reference water-laid concept and the foam technology. The reference concept simulation model was developed and validated with real process data. The foam technology concept model was developed and used to study the process design and operations to identify any unknown parameters. Pilot plant data was used to validate corresponding parts of the model. Further experimental work was performed to fill in some of the gaps in the datasets. Clarifying experimentally some of the key design parameters would have required major modifications to the experimental setup. The implications of these parameters for the overall design and operation of the foam-based process were studied using separate designs of the concept and possible parameter values were defined based on simulating these designs. After fixing all model parameters, the simulation model results for the final concepts were compared to the reference model results to answer the original questions.

The simulation study was conducted with Balas (v3.3, VTT Technical Research Centre of Finland Ltd., Espoo, Finland), which is a steady state simulation software for assessing chemical processes with an emphasis on pulp and paper, food processing, and biochemical processes. The software uses Microsoft Visio (2013) as a flowsheeting tool and is equipped with a Microsoft Excel (2016) spreadsheet software link. This link allows the user to access all of the simulation software model parameters, manipulate input data, and process the simulation results further within the spreadsheet software.

Case Study Scope

This process simulation study was set up to systematically provide information on the engineering questions related to the technology switch. The specific design-related (#1 to #6) and operation-related (#7 to #9) questions were as follows:

1. How does the existing equipment operate with foam?
2. Is there a need to re-arrange the process streams and/or water circuits?
3. Is there a need for new equipment?
4. Is there a need for changes in the forming section?
5. Do the increased stream volumes necessitate increasing the capacity of the existing equipment?
6. Does the presence of surfactant cause a remarkable increase in the wastewater treatment plant (WWTP) capacity?
7. What are the surfactant concentrations in process waters?
8. What are the foam densities in process waters?
9. Are any savings achieved in drying steam consumption?

Reference Paper Machine

The reference paper machine was a real-life wallpaper machine producing wallpaper from a mixture of softwood and hardwood bleached kraft pulp (SW-BKP and HW-BKP), chemi-thermomechanical pulp (CTMP), and polyethylene terephthalate (PET) fiber. When producing wallpaper, the machine experienced some handling problems with the long PET fiber as well as some quality issues. The most direct advantage of foam forming is the potential to produce quite uniform webs with good formation from longer or coarser fibers. This aspect is one of the main motivators for the reference company to consider converting its existing wallpaper machine to a foam-forming machine.

Figure 1 shows a block diagram of the reference wallpaper machine. It includes the following areas: the stock preparation area; the forming, pressing, and drying zones; the machine white water network; and the wet-broke re-pulping system. The wood-based furnishes (SW-BKP, HW-BKP, and CTMP) are first pulped, cleaned in a high consistency cleaner (HCC), homogenized in a deflaker, and then refined in conical refiners (*i.e.*, "conflos"). Next, the pulped PET fiber is introduced to the process. When long PET fiber is used, the double disc refiners (DDRs) are not used. Before cleaning it in the low consistency cleaners (LCCs) and screening it, the mixed pulp is diluted in several stages with white water (W/W) from the settling tank. Wire water from the white water tank is used for the dilutions in low consistency cleaning and screening. The pulp stream is at 0.75 wt% consistency when it is delivered to the headbox (HB). The Fourdrinier type of former consists of hydrofoil and vacuum boxes. In the press section, there are two single-felted press nips and a smoothing roll. Surface sizing is applied at the size press located between the pre- and after-dryers. Only wet broke ("trim") is recycled. Fiber is recovered from the press water and any surplus wire water with a valveless filter. Chemicals are added to the mixing box and to the size press. Freshwater (here "reuse water") intake to the paper machine occurs through wire and felt showers and cleaning. Rejects from cleaning and screening are treated as the paper machine (PM) effluent in the WWTP.

Modeling Strategy

The modeling strategy of this study was divided into the following five steps:

1. Development and validation of the water-laid concept model
2. Development of the foam-laid process design and concept model
3. Case definition
4. Simulation of the selected cases
5. Comparison of the selected cases

1. Development and validation of the water-laid concept model

Assumptions for the water-laid concept model

The main assumptions for steady state balances for the water-laid process were:

- The chemical components in the model were *Water*, *Pulp* (describing the mixture of SW-BKP, HW-BKP, and CTMP), *PETfibre*, and *Chemical* (describing all types of basic-papermaking chemicals).
- Dissolved and colloidal substances were not modeled.
- No fiber length classification was considered in this study.
- The model was developed at atmospheric pressure.
- The density of the fiber-water suspension was assumed to be constant, 992 kg/m^3.
- The energy balance calculation was less emphasized.

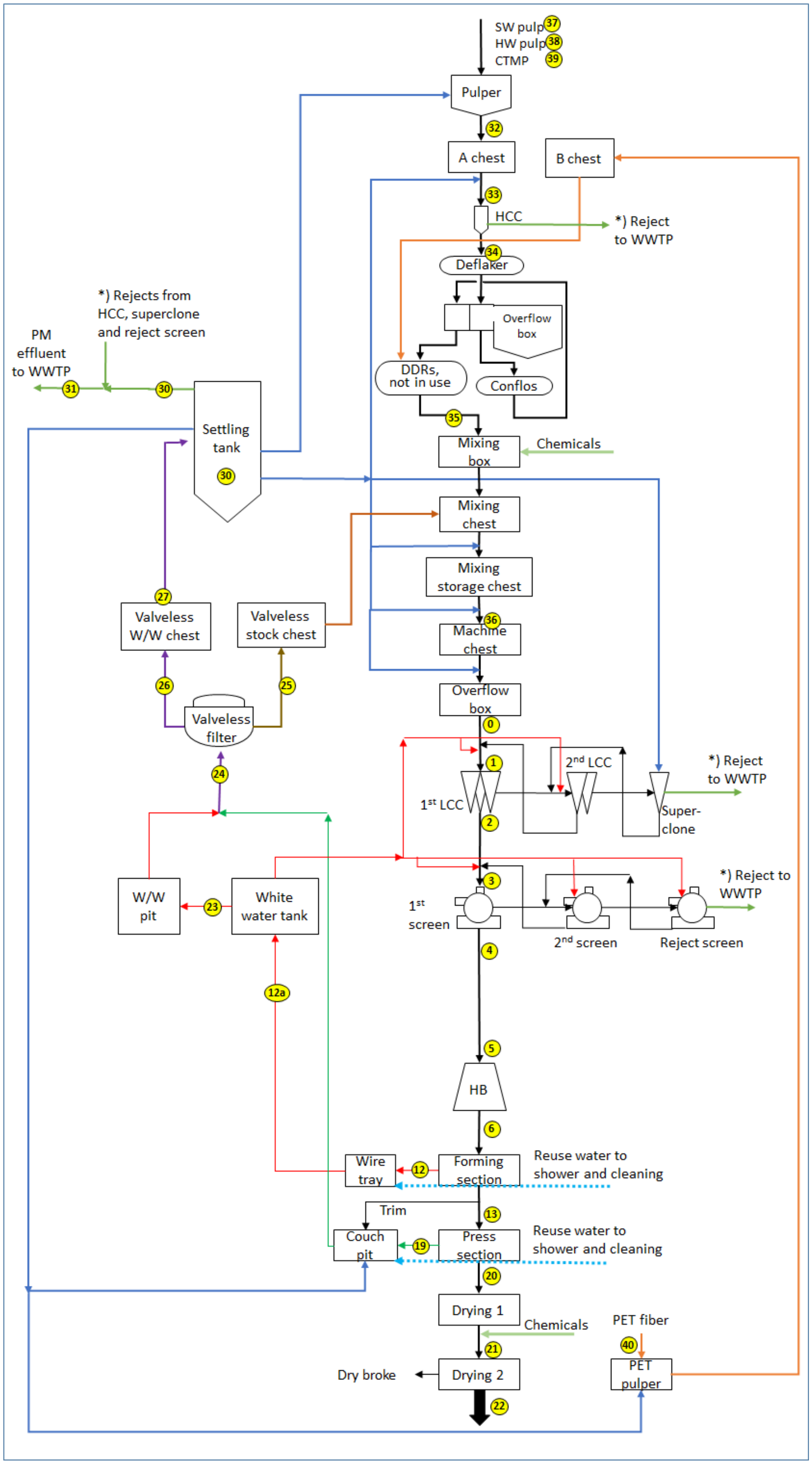

Fig. 1. Block diagram of the reference wallpaper machine. Yellow circles mark the points in the process where the water-laid process is compared with the foam-laid process.

When modeling the system at atmospheric pressure, the mass flows are correct. However, the volume flows are unknown because there is overpressure in the pipes, which decreases the volume flow of a compressible fluid. Pilot runs by VTT suggest that the overpressure is at most a few tens of kilopascals, *i.e.*, much lower than in conventional paper machines. This is due to the machine speed being rather low and because the viscous losses of foam do not increase the pressure levels remarkably. With, for example, 40 kPa of overpressure, the volume of the used foam decreases by only 9%. The fiber-water suspension is thus almost incompressible, and it is justified to assume that no changes in volume flows occur. The volume flows of streams were calculated separately in Excel from the simulated mass flows using the constant density (992 kg/m^3).

The modeling of the energy balance was less emphasized. Only the consumption of steam in the dryers was calculated. The energy consumption of process pumps, drying air compressors, and other process equipment were not considered, nor were heat exchanges between any equipment and its surroundings considered.

Definitions for the water-laid concept model

Figure 2 presents the overall flowsheet of the water-laid simulation model containing four sub-models. In addition to the detailed modeling of the paper machine, freshwater production, the wastewater treatment plant, and chemical preparation were modeled in less detail. This overall flowsheet is identical for both the water-laid and foam-laid concept models.

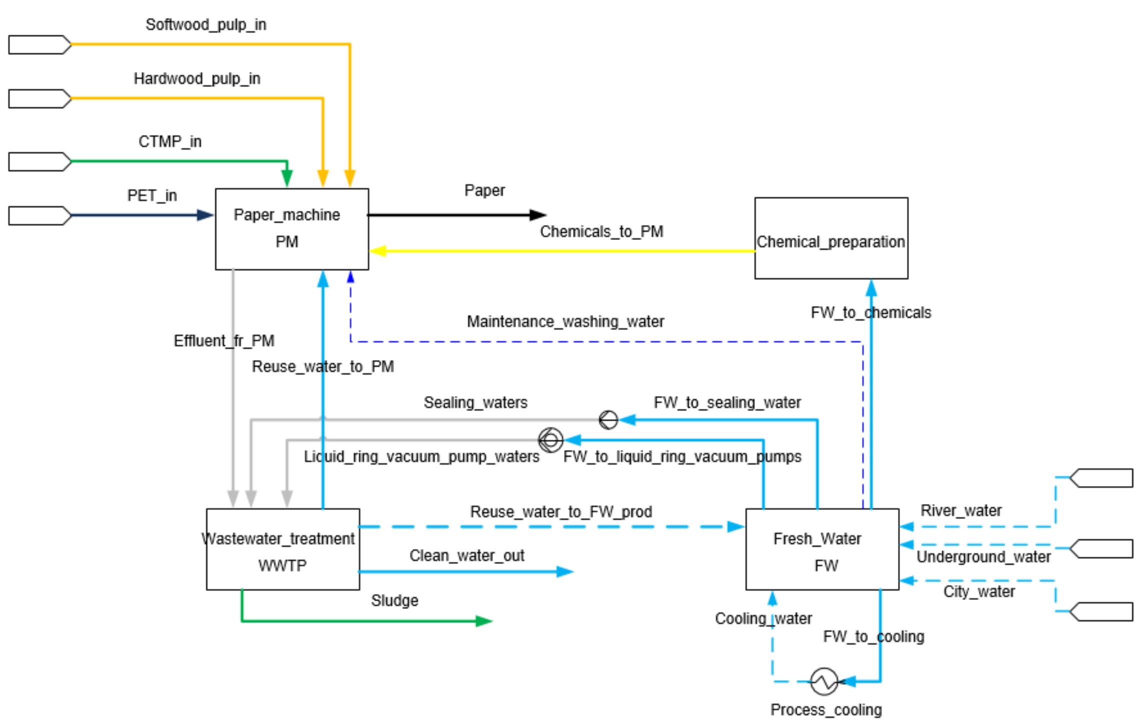

Fig. 2. Overall flowsheet of the simulation model describing the reference wallpaper machine. In addition to the paper machine, freshwater production, wastewater treatment, and chemical preparation were modeled. The overall flowsheet is identical for both forming technologies. The differences in the two technologies are shown in the *Paper machine* sub-model (presented in the supplementary material, Figs. S1 to S3).

The differences in the process configurations (*i.e.*, equipment and stream connections) of these two concept models can only be seen in the *Paper machine* sub-model (Figs. S1 to S3, supplementary material). The rest of the sub-models, *Chemical preparation*, *Wastewater treatment*, and *Freshwater* (Figs. S4 to S6, supplementary material), were identical in both concept models regarding the process configuration. However, there were differences in the process stream data.

The *Paper machine* sub-model included all the unit operations presented in the block diagram for the reference machine. The main parameters defining the water-laid paper machine are presented in Table 1. The targeted basis weight was 95 g/m^2, the annual production capacity was 13 800 tons (1.73 t/h), and the forming consistency was 0.75%. (In paper making, including foam forming, consistency is a key parameter defined as the mass of the pulp fibers to the total mass of the suspension. As the density of air is negligible compared to that of water and cellulose, its mass can be neglected when calculating the consistency of fiber foams used in foam forming.) The *Freshwater* sub-model described the production of freshwater. Freshwater was produced at the mill from several water fractions and used as sealing water, liquid ring vacuum pump water, cooling water, maintenance washing water, and chemical dilution water. Wastewater flows to the *Wastewater treatment* sub-model consisted of sealing waters, liquid ring vacuum pump water, and paper machine (PM) effluent. One third of the treated effluent was discharged from the site as "clean water." Two thirds of the treated effluent was recycled back to the mill to be used either in freshwater production or as reuse water in showers, wire cleaning, and felt cleaning in the paper machine. The modeling of the WWTP was less emphasized because the authors were only interested in the increase in the chemical oxygen demand (COD) in the WWTP feed due to the foaming agent present in the foam forming process. The detailed modeling of different basic papermaking chemicals was not relevant at this point, as it was uncertain how the conversion from a water-laid paper machine to a foam-laid paper machine affects the dosages and activities of the basic papermaking chemicals. In the model, all individual chemical dosages were summed together. Half of this chemical amount was dosed to the mixing box, and half was dosed to the size press. Thus, only the effect of the chemicals on the mass balance, not on paper chemistry, was considered.

The water-laid process model was validated using real-plant process data provided by the reference mill. The selected parameters were temperature, capacity, consistency, flow rate, and dryness level. At points where measured data was lacking, the data were estimated based on general process expertise. Because the provided data were exceptionally good, validation of the model was simple, and the results of the water-laid model were robust. The model predicted the state of the water-laid wallpaper machine quite accurately.

2. Development of the foam-laid process design and concept model

Assumptions for the foam-laid concept model

The main assumptions, in addition to those presented above for the water-laid process, when establishing steady state balances for the foam-laid process were as follows:

- Additional chemical components were *FoamChem* (describing the surfactant) and *Nitrogen&Oxygen* (describing the air).
- The bubble size distribution of the foam was not considered.
- The density of the fiber-water-air suspension was calculated by considering the air density in prevailing conditions and the air content.

- An ideal mixing was assumed everywhere in the model.
- Re-foaming due to geometry (present in pipe angles and pumps), shear forces (cyclones, wire section), or mixing was not considered.
- The fiber retentions in the forming and press sections and the efficiencies of the fiber recovery systems were assumed to be the same for both the water-laid and foam-laid concept models.
- The steady state model did not consider equipment dimensions and material hold-ups.
- Surfactant affects the foam properties and foam generation, but linking surfactant properties to foam density was beyond the scope of this study.

For a compressible fluid like air, as the pressure doubles, the volume is halved. For the fiber-water-air suspension, the assumption of modeling the system at atmospheric pressure is a reasonable simplification because only the air is compressed, and the overpressure in the pipes is relatively low. At this point of the engineering work, the authors were not interested in designing the pipes. Instead, the primary interest was what occurs when the system is at atmospheric pressure. Thus, the calculated volume flows were correct for most of the points. Only those points with minor overpressure were slightly overestimated.

The assumption of ideal mixing is debatable. In reality, a density profile inside the tanks exists, and it depends on gravity, mixing, tank geometry, foam stability (half-life time), and surfactant concentration. It is possible to find several foam fractions with different foam densities inside the same tank. Low-density froth typically piles at the top of the tank, while it is possible to obtain high-density foam, almost to the point of being water, from the bottom of the tank. Re-foaming occurs if a foamable liquid, *i.e.*, a water phase containing enough surfactant, is exposed to mixing or shear forces.

Modeling of foam and density calculation

To achieve the main objective of this study, *i.e.*, creating the basis for equipment dimensioning of the foam-laid process, it is necessary that the used simulation platform contains the needed foam property calculations. In the used simulation software, foam was described as two separate phases, water and air. The presence of air in the foam forming process challenges the material balance calculation in traditional simulation software. All process simulators base their material balance calculation on mass units (*e.g.*, kg/s). This causes no problems with conventional water forming. Because the density of dilute fiber suspensions is approximately 1000 kg/m^3, the mass flows equal the volume flows (1000 kg/s ≈ 1000 L/s). However, in a foam forming process with a foam density of, for example, 500 kg/m^3, the mass flow is the same as in the water-laid process (1000 kg/s), as the mass of air is negligible. At constant stock consistency, however, the volumetric flow is double (2000 L/s), due to the presence of air. (Notice that in water forming, the volume fraction of the fibers depends on the consistency, while in foam forming it depends both on the consistency and the air content of the fiber foam. This has to be taken into account *e.g.* in the calculation of the crowding number of fiber foams (Koponen *et al.* 2016)). For sizing the pumps and tanks involved in the foam forming process, volume flow rates need to be identified. Unfortunately, most simulators do not provide liquid density calculation for the conversion of mass flows into volume flows. Because density was not among the calculated parameters in the used simulation software, a separate calculation procedure was created in the spreadsheet software to calculate the density of air present in the stream in prevailing conditions using the ideal gas law. The density of the fiber-water suspension was assumed to be constant (992 kg/m^3) irrespective of the process conditions, as the temperature changes occurring in the process are moderate. The volume flows for the air phase and the fiber-water phase were calculated based on the mass flows using the density calculated for air and the constant density for the fiber-water suspension. Finally, the foam density was calculated by dividing the total mass of the foamy fiber suspension (weight of air was ignored) by the total volume of the foam, *i.e.*, the combined volume of the fiber-water suspension and air. When modeling foam forming processes, this additional density calculation must be done with all process simulation software that does not already contain it.

Modification strategy

After developing, validating, and simulating the process model for the water-laid wallpaper machine, the model was modified to correspond to the foam-laid process. For modeling and parameterizing the foam-laid process, the authors defined the needed changes in the process configuration and parameters based on theories derived from the laboratory trials, pilot runs, and studies conducted at VTT, as well as knowledge of the steady state operation. The implemented changes in the parameters and process configuration of the water-laid process model when converting it to a foam-laid process model are discussed in detail below.

Modifications to the main parameters

The modifications to the main parameters are presented in Table 1. With foam forming, it is possible to consistently obtain a noticeable improvement in the end product’s uniformity and formation. With foam, improved water removal (see below) in the press section permits the use of lower loads in wet pressing, resulting in lower density (higher bulk) of the end product compared to those produced by water forming (Punton 1975a; Kinnunen *et al*. 2013; Torvinen *et al*. 2015; Kiiskinen *et al*. 2019; Lehmonen *et al*. 2020). A clear increase in bulk, however, is not always noticeable (Koponen *et al*. 2016, 2018). Bulk improvement is greatest with stiff fibers; bulk diminishes with an increased level of refining. For this study, it was assumed that foam forming would yield a 10% bulkier end product with equal quality properties to those achieved with water forming. Thus, the wallpaper basis weight was decreased by 10% from 95 g/m^2 to 86 g/m^2. By keeping the running time (8000 h/a), machine width (1340 mm), and machine speed (225 m/min) unchanged, the same number of square meters of wallpaper was produced with both technologies. Due to the 10% lower basis weight, the mass-based production capacity decreased by 10%, from 1.73 t/h for the water-laid process to 1.56 t/h for the foam-laid process.

In conventional paper and board production, with increased forming consistency, fiber flocculation tends to occur, which weakens the web formation (Lehmonen *et al*. 2019). Foam forming technology, in contrast, permits higher forming consistency and improved formation simultaneously. Various studies (Punton 1975b; Smith and Punton 1975; Lehmonen *et al*. 2013; Torvinen *et al*. 2015; Koponen *et al*. 2016, 2018) have shown that the headbox consistency may even be doubled for foam without any major loss in the formation uniformity. For this study, the headbox consistency in the foam-laid model was assumed to double from 0.75% to 1.5%.

At the beginning of the forming section, the dewatering of foam with hydrofoil boxes is most likely not as effective as the dewatering of water. This was taken into account in the foam-laid model by decreasing the end dryness level after the hydrofoil boxes from 1.9% for the water-laid process to 1.7% for the foam-laid process. Foam forming often increases the effects on the dryness level after the forming section (Koponen *et al*. 2016, 2018; Lehmonen *et al*. 2019), and the difference increases with increasing surfactant dosage mainly due to the reduced surface tension and subsequent decrease of capillary forces (Lehmonen *et al*. 2020). The increase in dryness is typically greater with mechanical pulp than chemical pulp. However, VTT's pilot trials have occasionally shown no improvement in the dryness level after the forming section. For example, Lehmonen *et al*. (2019) observed no improvement in the dryness level with a foam density of 600 kg/m^3. To be on the safe side in this study, the dryness level after the forming section remained unchanged in the foam-laid model compared to the water-laid process.

The dryness levels are often higher after the press section with foam forming compared to water forming (Torvinen *et al*. 2015; Koponen *et al*. 2016, 2018; Lehmonen *et al*. 2020). The increase in dryness may be due to foam forming increasing the number of large pores in the sheet, which leads to increased sheet permeability (Koponen *et al*. 2017). Pilot trials at VTT with a single extended nip press have shown that with foam forming, 2-percentage-point to 8-percentage-point higher dryness levels after the wet press are usually achieved, depending on the furnish type. Notably, the press type used in the pilot trials differs from the press type used on the industrial scale. The increases in dryness levels after the press section are noticeable with mechanical pulp, while for chemical pulp, the effect of foam forming on the dryness is smaller (Lehmonen *et al*. 2019). With VTT's pilot machine, the dryness levels after the press section have even exceeded 50% for stiff natural fibers. When long synthetic fibers have been included, dryness levels as high as 60% have been obtained. The increased dryness leads to remarkable energy savings during thermal drying. For this study, the dryness level after the press section in the foam-laid model was assumed to increase by 5 percentage points compared to the water-laid process. The dryness levels after the pre-dryer and after-dryer were assumed to be the same for both forming technologies. The surface sizing applied at the size press between the pre- and after-dryers decreases the dryness level temporarily.

Table 1. Basic Parameters Defining the Water-laid and Foam-laid Processes

	Water-laid Process	Foam-laid Process
Basis weight (g/m^2)	95	85
Machine speed (m/min)	225	225
Capacity (t/h) Capacity (m^2/h)	1.73 18 200	1.56 18 200
Forming consistency (%)	0.75	1.5
Dryness level after the vacuumless part of the forming section (%)	1.9	1.7
Dryness level after the forming section (%)	19.4	19.4
Dryness level after the press section (%)	45.6	50.6
Dryness level after the first dryer (%)	96.9	96.9
Dryness level after the second dryer (%)	97	97

The recipe in both processes was the same: a mixture of SW-BKP, HW-BKP, CTMP, and PET fiber. The nominal freshwater consumption (m^3 / t paper) and dosage rates for basic papermaking chemicals (t / t paper) remained unchanged compared to the water-laid case. These are, however, debatable assumptions, as it is uncertain how the presence of foam and surfactant affects the process purity and the activities of the basic papermaking chemicals compared to conventional water forming. Lengthier pilot trials are required to determine whether the accumulation of impurities will increase or decrease, causing a corresponding increase or decrease in the fresh washing water consumption rate. It is also unclear if, for example, the dosage of wet strength chemicals would need to be increased.

New main parameters

The fiber-foam mixture is generated by introducing a foaming agent, *i.e.*, a surfactant, to the pulp suspension followed by intensive mixing or injection of air. An ideal surfactant should produce foam rapidly, provide the desired air content and sufficiently small bubble size (bubble diameter less than 100 μm), be cost-efficient, not have any harmful interactions with other process chemicals, and give additional functionality (wet/dry strength, porosity) to the foam-formed product (Gottberg *et al*. 2019). Mira *et al*. (2014) used seven surfactants in lab-scale foam forming tests and Lappalainen *et al*. (2014) used three surfactants belonging to different surfactant classes. Surfactants used in pilot-scale foam forming trials include sodium dodecyl sulfate (SDS) and polyvinyl alcohol (PVA) (Gottberg *et al*. 2019). The surfactant concentration in the process depends on the end application. As surfactant concentration increases, the produced foam's stability also increases, and, consequently, bulkier products may be achieved. Typical SDS concentrations in VTT's pilot trials have been 10 ppm to 290 ppm (Koponen *et al*. 2018), 40 ppm to 200 ppm (Koponen *et al*. 2016), or even up to 400 ppm, depending on the foam density level. The lowest concentrations (< 50 ppm) can only be used with inline foam generation when the foam's half-life time is quite short. For this study, SDS was selected as the surfactant, and the SDS concentration at the headbox was set to 100 ppm (100 mg/L).

Typical foam densities in VTT's pilot trials have been 400 kg/m^3 to 600 kg/m^3 (Koponen *et al*. 2016), 250 kg/m^3 to 700 kg/m^3 (Koponen *et al*. 2018), or 400 kg/m^3 to 800 kg/m^3 (Lehmonen *et al*. 2019). As foam density increases, the efficiency of water removal in the forming section also increases, and the required amount of surfactant decreases. For this study, the foam air content at the headbox was set to 40%, which means that the foam density was 600 kg/m^3. With this foam density, a sufficient improvement in the formation was assumed to be achieved.

New equipment

The properties of the foam are a key issue affecting not only the performance of the forming process but also some important properties of the end product, such as the formation. Foams can be generated *via* either tank generation (Lappalainen and Lehmonen 2012; Al-Qararah *et al*. 2013; Jäsberg *et al*. 2015; Kouko *et al*. 2020) or inline generation (Koponen *et al*. 2018; Jabarkhyl *et al*. 2020a, 2020b). A tank generator consists of a stirring tank with a turbulent mixer without air injection. With inline generation, compressed air is injected into a pipe and mixed with water. The foam generation method affects the foam density, foam stability, and bubble size distribution (Al-Qararah *et al*. 2012; Kouko *et al*. 2020). Bubble size distribution is also affected by the amount of foaming agent and by the mixing energy (Jabarkhyl *et al*. 2020b; Kouko *et al*. 2020). An increase in the specific energy consumption decreases the bubble diameter (Al-Qararah *et al*. 2013; Kouko *et al*. 2020). An increase in the foaming agent dosage decreases the foam density and bubble diameter (Kouko *et al*. 2020). Inline generators generate a wider bubble size distribution with a greater share of large bubbles than tank generation. So far, foam generated with inline generators has not been as stable as foam generated in tanks (Koponen *et al*. 2018). The main advantages of producing the foam with inline generators located as close to the headbox as possible are smaller surfactant dosages than in tank generation and a restriction on the spreading of foam to all circulations. Tank generation with an adequate surfactant dosage generates a stable and uniform foam that has a narrow bubble size distribution with a large share of small bubbles (Al-Qararah *et al*. 2012, 2013; Koponen *et al*. 2018; Kouko *et al*. 2020). It is suitable for applications where high bulk is desired. For this study, it was assumed that with the foam-laid process, the foam would be generated with an inline generator. The inline generator is located on the approach pipe before the headbox. Air and surfactant are fed to the generator.

Surfactant recovery and recycling are essential for three reasons: 1) to increase the cost-effectiveness of the process by reducing the chemical costs, 2) to guarantee undisturbed operation of the WWTP, and 3) to avoid problems when using surfactant-rich water or a mixture of water and foam in the process. The recovered surfactant can be recycled back to the process to substitute for the makeup surfactant. With surfactant recovery, it is possible to obtain a surfactant-lean stream that can be used in positions where foam is not tolerated. Without surfactant recovery, the surfactant concentration in all water circuits would be virtually the same as at the headbox. In addition, a notable amount of surfactant would be lost along with the effluent to the WWTP. The most suitable methods for treating large amounts of surfactant-rich water are foam fractionation (Lee and Maa 1986; Boonyasuwat *et al.* 2003; Burghoff 2012) and membrane separation (Kowalska *et al.* 2004; Fernández *et al.* 2005). Fiber removal before the surfactant recovery step is crucial. Otherwise, there will be a frequent need to clean the surfactant recovery units. To guarantee a low total suspended solids (TSS) concentration in the feed to the recovery units, cartridge filters or bag filters may be used before introducing them. For this study, foam fractionation was selected as the surfactant recovery method. In foam fractionation, a surfactant-rich filtrate from the fiber recovery system (here “valveless filter”) is fed to a foam fractionation vessel where air is blown into the surfactant solution from the bottom of the vessel. Surfactant molecules attach themselves to the surface of the air bubbles and rise to the top of the vessel, where the surfactant-rich concentrate overflows into a foam resolution unit where foam is collapsed mechanically. Mechanical methods for collapsing foam include; 1) slowly rotating perforated centrifuges; 2) a rotating basket made of stainless steel; 3) discharging the foam on to a rotating disk; and 4) a suction device (Leonard and Blacyki 1978; Lee and Maa 1986; Burghoff 2012). The surfactant-rich fraction is recycled just before reaching the headbox to substitute for a major part of the makeup surfactant. The surfactant-lean fraction is removed from the bottom of the vessel. The acceptable surfactant concentration for the recovered lean fraction depends on the surfactant type. For SDS, the target concentration is less than 20 ppm of SDS. Based on laboratory trials performed at VTT, water containing less than 20 ppm of SDS should not re-foam even if exposed to mixing or shear forces. With 100 ppm of SDS in the feed to the surfactant recovery system, the target concentration for the surfactant-lean fraction is achieved by positioning two foam fractionation vessels in series. The surfactant-lean fraction is led to the white water tower (here “settling tank”) and further used as dilution water. The volume reduction ratio (VRR) and the recovery degree in each foam fractionation vessel were adjusted based on laboratory trials performed at VTT. A VRR of 10 was used. This means that 10 vol% of the feed was taken as a concentrate from the top of the fractionation vessel. The surfactant recovery degree depends on the surfactant concentration of the feed. As the surfactant concentration in the feed increases, the recovery degree over one unit decreases.

Froth build-up in tanks is an unavoidable and unwanted phenomenon, especially in the short circulation. Froth piles up at the surfaces of the tanks, accounting for notable tank volume and eventually leading to an undesired overflow of foam/froth on the floor. The wire pit, which may contain air more than 50% of its volume, is the most problematic regarding the froth. The residence time in the wire pit is not sufficient to collapse the foam. Thus, the foamed liquid ends up in fiber recovery. Depending on the device used for fiber recovery, small amounts of foam/froth may even end up in the white water tower, which provides the dilutions for thick stock preparation and refiners at the beginning of the process. Froth may be collapsed with, for example, mechanical foam breakers, which are used in brown stock washing and black liquor oxidation systems. In this study, mechanical collapsing of froth was implemented in the foam-laid model to remove part (20%) of the air present in the white water tank.

Modifications to the existing equipment and water circuits

The conversion of existing paper machines to foam technology requires some changes in the existing equipment. For several years now, VTT has studied the running and operation of the unit operations in the short circulation with foam. Because VTT's pilot environment does not include refiners, hydrocyclones, or fiber recovery systems, how they will function with foam remains uncertain. Only limited public information is available on how existing paper process equipment tolerates foam. The equipment suppliers would be a reliable source of information, but they were not contacted for this study. Based on the best existing knowledge and not using data based on systematic tests or physical laws, Table 2 was compiled to present the suitability of existing paper process equipment for foam when producing paper-like products (25 g/m^2 to 150 g/m^2). The re-arrangement of the process streams in the foam-laid process was conducted based on the assumptions presented in Table 2.

Refiners, hydrocyclones, headbox, and forming section were identified as the most critical paper process equipment when considering converting a water-laid process to a foam-laid process. Foam presents challenges in adjusting the refiner pressure. Hydrocyclones, meanwhile, may or may not work with foam, depending on the furnish type. The headbox may require some modifications, and the vacuum capacity of the forming section must be increased. Preliminary simulations of the foam-laid concept model revealed that, from the standpoint of mass and volume balance, the questionable operability of hydrocyclones with foam is the most crucial issue. Option for overcoming this challenge would be to skip the hydrocyclones entirely. However, this is possible only when the quality of pulp is not an issue. In greenfield foam-laid processes, it might even be possible to pass the pulp through a hydrocyclone system in the pulp mill before it is introduced to foam in the paper mill. In this study, it was assumed that the hydrocyclones retain in their place, and their possible malfunction when exposed to foam is solved by changing the source of their dilution water. In the water-laid process, dilution waters for hydrocyclones are taken from the short circulation, *i.e.*, from the white water tank. In the foam-laid process, the white water tank most definitely contains foam (foamed liquid) or foamable liquid (water phase with high surfactant concentration), which causes more foaming and results in malfunction if used as dilution water in the hydrocyclones.

Table 2. Suitability of Existing Paper Process Equipment for Foam When Producing Paper-like Products

Equipment	Suitability for Foam When Producing Paper-like Products (25 g/m^2 to 150 g/m^2)			
	As Is	No	With Modif.	Reasoning
Hydrocyclones	X	X		Hydrocyclones may or may not work depending on the furnish type. Even if hydrocyclones tolerate foam/air, the original cleaning function may suffer. According to Stoor (2008), small volumes of air (less than 5%) have an insignificant effect on the cleaning performance, but air reduces the dwell time and the capacity of the hydrocyclone in proportion to its volumetric ratio. The removal of small air bubbles with hydrocyclones in conventional papermaking processes is difficult. Because small bubbles are a prerequisite in foam forming, it seems most probable that hydrocyclones do not act as foam separators.
Refiners		X		Foam present in refiners makes it difficult to adjust the refiner pressure. It is advisable not to feed foamed liquid into the refiner.
Pressure screens	X		X	Based on VTT's pilot trials, pressure screens seem more likely to clog up with foam than with water. They work without any modifications at a certain foam density level. When the air content exceeds approximately 50 vol% (foam density < 500 kg/m^3), the screens start to clog up. The clogging tendency depends also on the furnish type and the basis weight. The mechanism causing the clogging is unclear. The clogging must be tackled, *e.g.*, by adjusting the gap size.
Headbox	X		X	Depending on the headbox type, furnish type, and fiber length, some adjustments to the headbox may be required. An increase in the fiber length or in the share of long fibers (>20%) will likely clog the turbulence generator. The handling of flowrate changes and presence of air must be tackled. Profile adjustments may be accomplished by changes in the slice jet or by dilution control (increasing the stock bypass ratio). When targeting the same consistency in both foam forming and water forming applications, the slice opening must be larger (or the slice jet increased) with foam forming.
Forming section			X	The dewatering of foam in the forming section is poorer/slower than the dewatering of water. To achieve the same dewatering rate in both cases, greater vacuums or lower machine speeds are used with foam forming. The high vacuums used in the suction boxes tend to suck the foam into the vacuum system. To prevent this, the vacuum system must be equipped with extraction pumps. The forming section may also necessitate the optimization of forming fabrics, or it may need to be equipped with edge guides, because foam tends to spread at the beginning of the forming board due to its viscous nature.
Press section	X			The press section works fine with foam. Greater dryness levels are achieved with foam than with water. Press load levels have to be optimized for foam-formed web.
Dryers	X			Drying of foam-formed, paper-like products (25 g/m^2 to 150 g/m^2) is possible with the same equipment as the drying of water-formed products.
Disc filter	X		X	Disc filters may need some minor modifications, like lower running consistencies, if a foamed liquid is fed to them. Disc filters mechanically collapse the foam.
Dissolved air flotation	X			Dissolved air flotation works fine with foam. It mechanically collapses the foam.
Pumps			X	All pumps need re-dimensioning. Centrifugal pumps must be equipped with air removal option.

Modif. – modification

To avoid this refoaming problem in the foam-laid concept model, the dilution waters for the first and second LCCs must be taken from the long circulation, *i.e.*, from the settling tank, because the settling tank contains non-foamable, surfactant-lean (SDS < 20 ppm) water from the surfactant recovery that should not foam even if exposed to shear forces or mixing. This re-arrangement of the dilution water mixes the water balance between the short and long circulations and results in increased volume flows from the short to the long circulation, leading to increased capacity for the existing equipment in the long circulation. The fiber recovery system (*i.e.*, valveless filter) as such was assumed to mechanically collapse the foam due to the suction and rotation. Thus, the filtrate exiting the valveless filter was assumed to be in the water phase, whereas the recovered fiber fraction was assumed to contain some foam. To prevent the foamy fiber fraction from entering the LCCs, it is recycled after the first LCC to the feed of the first pressure screen, not to the mixing chest, as is done in the water-laid process.

Modifications to the modeling of the forming section

Dewatering in conventional papermaking is widely studied and quite well understood (Baldwin 1997; Hubbe and Heitmann 2007; Åslund and Vomhoff 2008). However, the dewatering of foam differs considerably from the dewatering of water. The viscosity of foam is typically a few orders of magnitude greater than that of pure water (Jäsberg *et al*. 2015). Due to the greater viscosity, the dewatering of foam in the forming section is poorer/slower. To reach the same dewatering rate in both cases, greater vacuums or lower machine speeds need to be used in foam forming.

For modeling the forming section of the foam-laid wallpaper machine, the authors studied foam removal in the forming section of VTT's pilot machine as a function of the vacuum level, foam density, and web consistency. Altogether, six trial points were run, either by varying the foam density at the headbox (400 kg/m^3, 500 kg/m^3, or 650 kg/m^3) and using constant vacuum profiles through the forming section or by keeping the foam density at the headbox constant (650 kg/m^3) and varying the vacuum profiles through the forming section. Because only one type of furnish and surfactant was used, their effects on the dewatering were excluded.

The VTT pilot machine (Fig. 3) consists of an approach system with different kinds of containers; a forming section that can be run in gap, hybrid, or Fourdrinier mode; and a press section, which consists of a single extended nip press. In these trials, the pilot machine was run in the hybrid-forming mode (Fig. 4). The machine speed in the trials was 500 m/min. The pilot machine's forming section is divided into four foam removal sections, each having two to four foam removal units and its own degassing pump feeding the wire water tank. This division into four sections was also applied in the model describing the forming section. By modeling the forming section in stages, it is possible to estimate the volume flows and the foam densities of the exiting wire water fractions from each section separately and further use this data for dimensioning the degassing pumps. To estimate the water and air removal efficiency in each section, the authors created mass balances for water and air over each section based on the pilot trial data.

The other, more simplified method to model the forming section is to describe it as a black box with a fixed end dryness level (*i.e.*, fix the water removal) and assume that water and air are removed at the same ratio. By using this approach, however, one only obtains estimates of the volume flow and density level of the combined wire water flow. Thus, it is not possible to obtain data for the wire water fractions from different parts of the forming section. Both approaches have the same outcome regarding the water balance: The web exits the forming section with a fixed end dryness level and with a corresponding amount of water. The rest of the water originally present in the web ends up in the wire water tank. However, the air balance differs. By using the stagewise modeling and experimental data describing both water and air removal, the air balance through the forming section can be modeled in more detail.

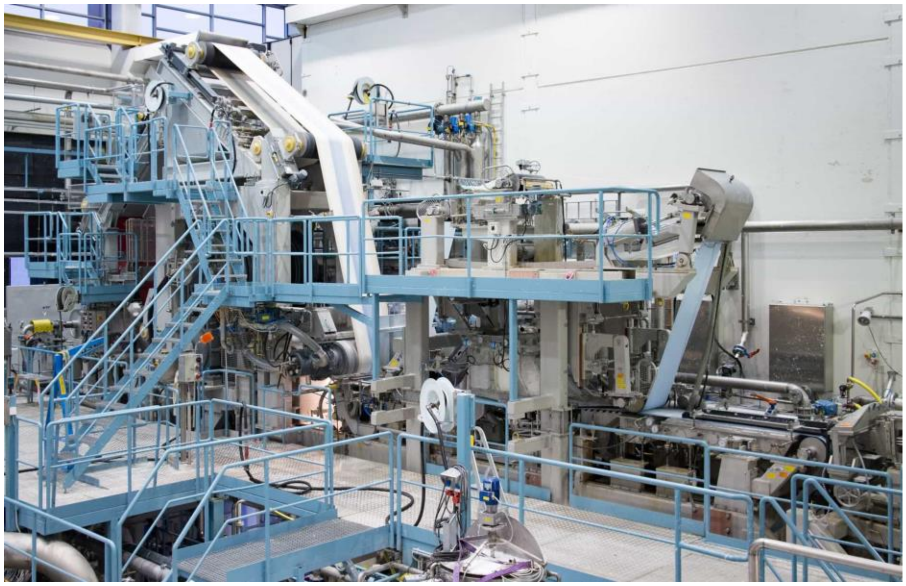

Fig. 3. Foam forming pilot machine at VTT (Jyväskylä, Finland)

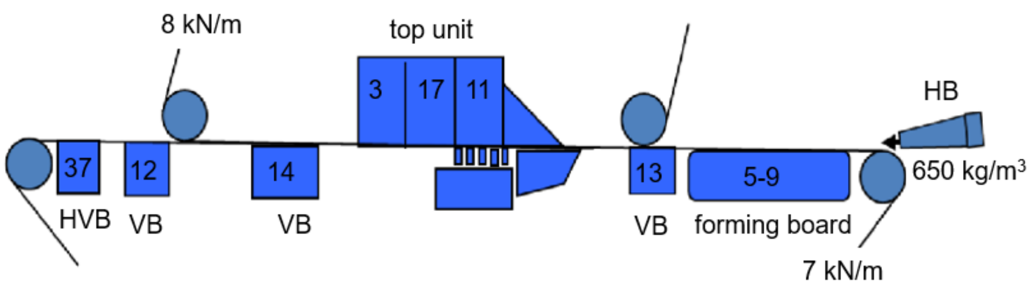

Fig. 4. Hybrid former section of the pilot plant (schematic diagram, not to scale). HB = headbox, VB = vacuum box, HVB = high vacuum box. The forming board consists of five vacuum boxes. The top unit consists of three vacuum boxes and loadable blades under one vacuum box. Typical wire tension values are shown. The vacuum levels (in kPa) presented are for the trial point at which a moderate vacuum profile was used and the foam density at the headbox was 650 kg/m^3. The vacuum and web consistency increase along with the forming section.

Achieving an understanding of foam removal and the modeling of foam removal were difficult with the limited number of available trial points. When moving along the forming section, the foam removal was different and also affected differently by the vacuum and foam density. With web consistencies less than approximately 15%, air and water were removed at roughly the same volumes. In the high vacuum box with higher web consistencies, the volume of removed air was only approximately 40% of the volume of removed water. Subject to possible measurement errors, foam forming behaves quite differently than water forming: After the water line (or dry line), there is noticeable flow of external air through the web (Hubbe *et al*. 2020). The reason for this difference is likely that the foam effectively seals the sheet with higher consistencies due to capillary forces acting between the bubbles and the fibers. If this is the case, compression dewatering, where water is expelled from the web due to applied pressure decreasing its volume, should be more important in foam forming than displacement dewatering, in which the water held within a web is displaced by air. Generally, as the vacuum increased, the efficiency of the foam dewatering also increased. With identical vacuum profiles, as foam dryness increased, foam removal occurred further along the forming section. Dry foam (400 kg/m^3 to 500 kg/m^3) removal occurred mainly at the end, whereas wet foam (600 kg/m^3 to 700 kg/m^3) removal mainly occurred at the beginning of the forming section. The effective foam removal of wet foams at the beginning of the forming section might be explained by their clearly lower viscosity compared to dry foams.

Figure 5 presents the modeling of the forming section in the foam-laid case. By imitating the structure of the VTT pilot machine's forming section, the forming section of the reference wallpaper machine was divided into four dewatering sections (*DW0*, *DW1*, *DW2*, and *DW3*), each having one to two vacuum boxes. The length of each of the four dewatering sections in the reference wallpaper machine was half that of the VTT pilot machine's corresponding dewatering section. In addition, the speed of the reference wallpaper machine was half that of the pilot machine's speed. If the machine speed is halved, and the vacuum level is kept constant in the dewatering section, the length of the dewatering section may be halved to maintain the same impulse due to the pressure difference throughout the foam removal unit. Thus, it is justified to apply to the wallpaper machine the same vacuum level profile that was tested in the pilot machine and shown to provide sufficient foam removal. It seemed that the amount/length of the existing vacuum boxes in the reference wallpaper machine would be enough for sufficient foam removal if the machine speed does not exceed 250 m/min. However, if the dewatering remains insufficient, it is possible to substitute some of the hydrofoil boxes with vacuum boxes.

In addition to the vacuum-aided dewatering sections, the forming section of the reference machine contained one dewatering section with hydrofoils (*Hydrofoil boxes*) just after the headbox. The dryness levels after the first (*Hydrofoil boxes*) and last (*DW3*) dewatering sections were fixed to 1.7% and 19.4%, respectively. The simulation model calculated backwards the required water removal efficiency (wt% of water removed from the incoming) to achieve the fixed dryness levels. These efficiencies were 15.5% for *Hydrofoil boxes* and 50.7% for *DW3*. The water removal efficiencies in the second (*DW0*), third (*DW1*), and fourth (*DW2*) foam removal sections were fixed based on the pilot trial data points, the vacuum profile of which is presented in Fig. 4. Thus, the same kind of water removal trend along the forming section was assumed as was observed in the pilot trial. The water removal efficiencies in the second, third, and fourth foam removal sections were set to 45%, 50%, and 55%, respectively. The simulation model calculated the corresponding dryness levels of the web. To estimate air removal in each dewatering section, a correlation derived from the pilot trials was used. It revealed that until a certain web consistency (approximately 15% to 20%), air removal is 97% that of water removal. However, at high web consistencies (>15%), air removal is only approximately 40% that of water removal. The air removal efficiencies in the five foam removal sections were set to 15.0%, 43.7%, 48.5%, 53.4%, and 20.3%.

The attempt to create a general and consistent model to describe the consistency profile (*i.e.*, foam removal) in the forming section of a foam-forming machine failed because of the limited trial data. Still, it is notable that successfully predicting the consistency profile in the forming section of a conventional water-laid paper machine is extremely challenging. An exact modeling of the forming section is crucial only when estimates of the required vacuum levels or dimensioning data for the vacuum pumps are needed. For preliminary mass and volume flow balances, the approach used in this study is sufficient.

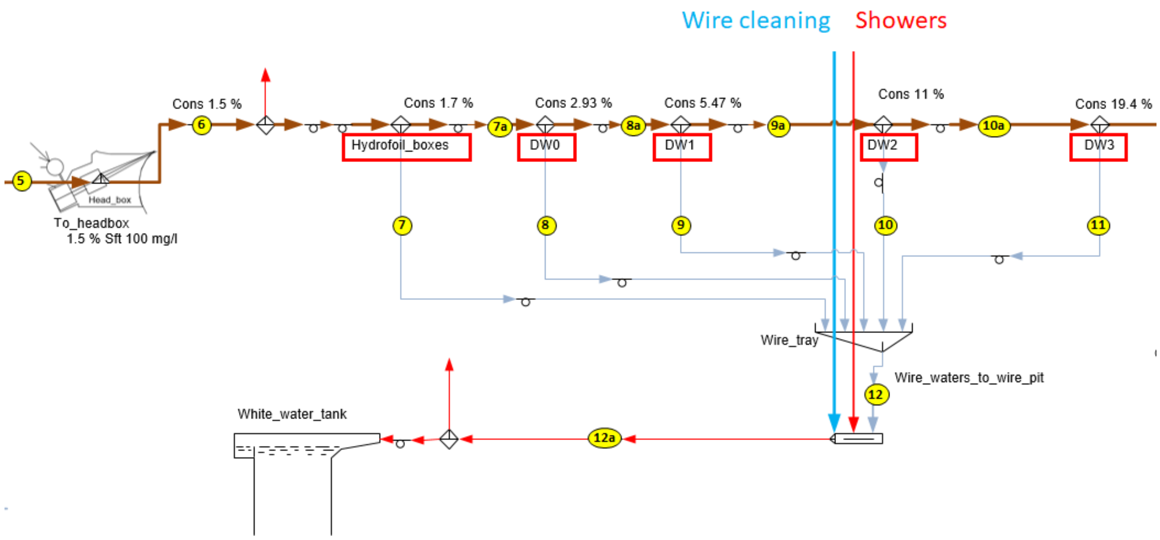

Fig. 5. Modeling of the forming section of the foam-laid wallpaper machine. The forming section is divided into one vacuum-less (*Hydrofoil boxes*) and four vacuum-aided (*DW0*, *DW1*, *DW2*, and *DW3*) foam removal sections to estimate the volume flows and densities of the different wire water fractions.

Modifications to the modeling of the press section

The modeling of the press section was kept simple because the density development of the web during the wet pressing was not of interest. The press section was modeled with three pressing rolls (*DW4*, *DW5*, and *DW6* in Fig. 6). The solids content profile in the rolls mimicked the solids content profile observed by Järvinen *et al*. (2018) in laboratory tests, in which three parallel long-pulse tests for both water- and foam-formed wet sheets were used. The solids contents after the three rolls were 33.0%, 42.7%, and 45.6% in the water-laid case and 37.7%, 47.0%, and 50.6% in the foam-laid cases. Exact modeling of the air balance during wet pressing is challenging due to the lack of experimental data. When pressing the web, some of the air present in the web remains in the web, while some is removed along with the press water, and some escapes into the surroundings. In the foam-laid model, it was assumed that the density of the press waters removed from each of the rolls was 800 kg/m^3, *i.e.*, the press waters contained 20% air. The authors assumed that the rest of the air remains in the web until the last roll (*DW6*). After the last roll, the rest of the air present in the web was modeled as if leaving the system. This assumption did not prove correct, but it was accurate enough at this point, as the density of the web entering the drying section was not of interest. From the standpoint of total air balance, only the amount of air present in the press waters is crucial.

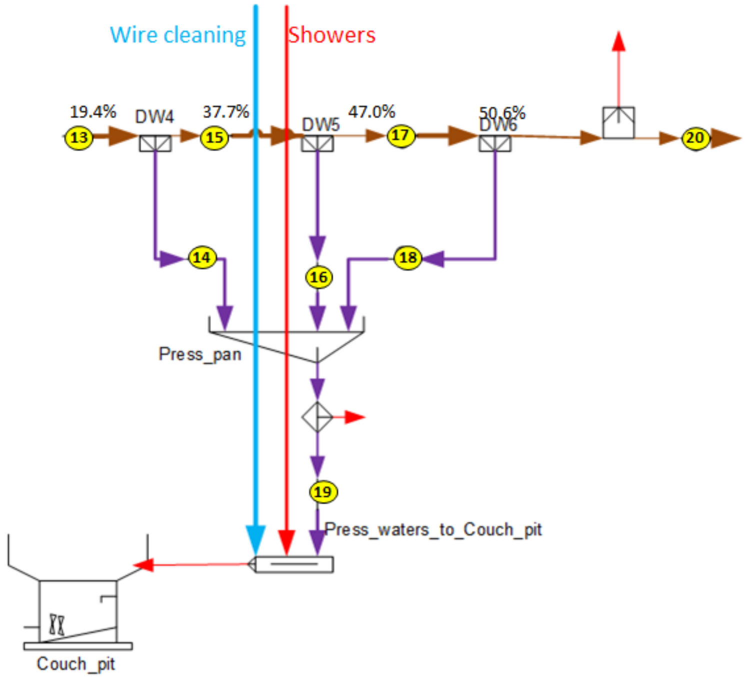

Fig. 6. Modeling of the press section of the foam-laid wallpaper machine. The press section is divided into three pressing rolls (*DW4*, *DW5*, and *DW6*).

3. Case definition

The concept for the foam-laid process was not fixed at the beginning of the simulation study. Instead, it changed along with the nature of the research work. After making the process configuration changes to the water-laid concept model to convert it to the foam-laid concept model, the foam-laid model was simulated for the first time. The results showed that the process configuration change related to the dilution water of the hydrocyclones had a remarkable effect on the total water balance. Because the reasoning behind this particular process configuration change was somewhat questionable, it was decided to study two different cases of the foam-laid concept and compare them to the water-laid concept. Thus, the selection of the foam-laid cases was the result of a concept study.

4. Simulation of selected cases

The water-laid model was simulated to obtain the steady state mass, volume, and energy balances of the wallpaper machine producing wallpaper based on conventional water forming. The two different cases of the foam-laid concept model were simulated to obtain the steady state mass, volume, and energy balances of the wallpaper machine producing wallpaper based on the new foam forming technology.

5. Comparison of the selected cases

The main object of the simulation study was to compare the water-laid and foam-laid processes based on the mass, volume flow, and energy balances. Using the output from the concept models for the three evaluated cases, consistency, mass flows, and volume flows were compared at almost 40 points in the process.

RESULTS AND DISCUSSION

Evaluated Cases

As discussed above, because the operation of the hydrocyclones with foam is questionable, the water-laid case was compared with two foam-laid cases. The foam-laid cases differed from each other in how the dilution of the hydrocyclones was arranged. The two evaluated foam-laid cases were as follows:

- *Foam-laid, Ref*: It was assumed that the first and second LCCs do not tolerate foam. The dilution water for these units needs to be taken from the settling tank, unlike in the water-laid case.
- *Foam-laid, Mod*: It was assumed that the first and second LCCs tolerate foam. The dilution water for these units may be taken from the white water tank, as in the water-laid process.

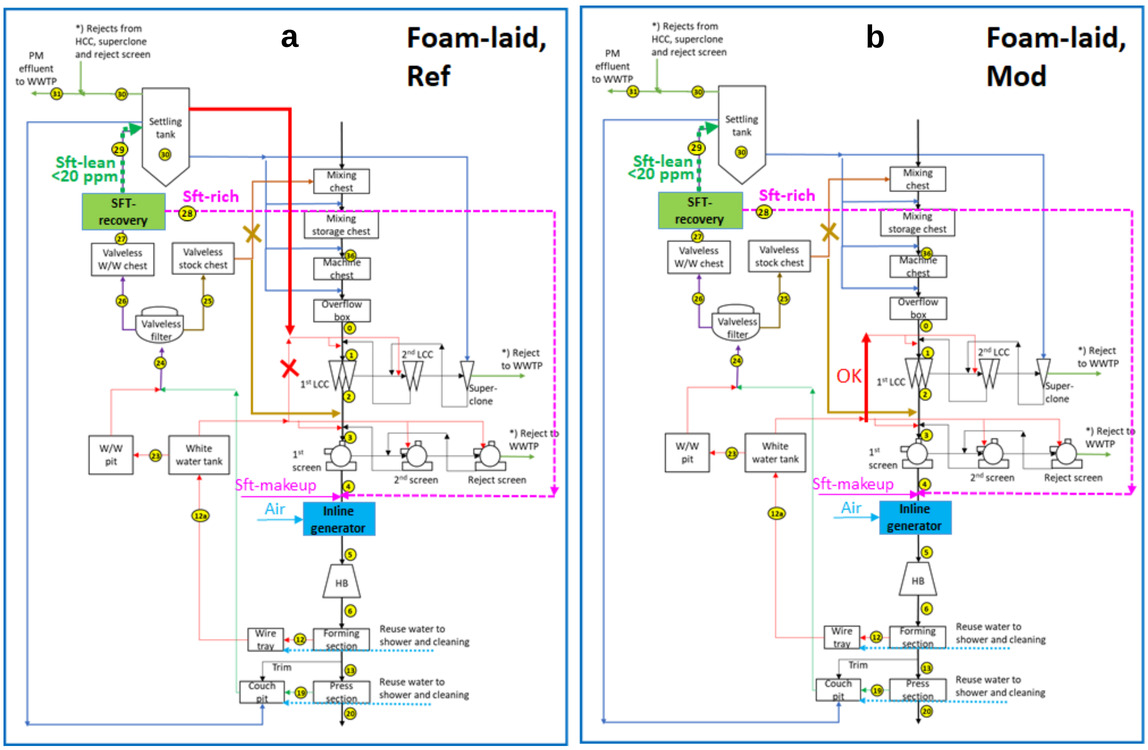

Fig. 7. The two evaluated foam-laid cases: (a) the foam-laid concept with the assumption that hydrocyclones do not tolerate foam (*Foam-laid, Ref*) and (b) the foam-laid concept with the assumption that hydrocyclones tolerate foam (*Foam-laid, Mod*)

Figure 7 shows the main process stream re-arrangements and additional equipment used in the two foam-laid cases, compared to the water-laid case presented in Fig. 1. The flowsheets for the *Paper machine* sub-model for both evaluated foam-laid cases are presented in the supplementary material (Fig. S2 and Fig. S3).

Comparison of Water-laid and Foam-laid Cases

The authors used the case studies to answer the nine design- and operation-related questions presented as part of the overall approach. Question #4 was studied, but it turned out to be too challenging at this point in the research work. The aim was to model foam removal in the forming section using experimental data and to use the outcomes to design the necessary vacuum profile in the forming section. However, the study remained incomplete due to the inadequate experimental data.

The main objective of the simulation study was to compare the water-laid and foam-laid processes from the standpoint of mass and volume flow. Based on the output from the simulation models for the three evaluated cases, consistency, mass flows, and volume flows were compared at almost 40 points in the process. For the foam-laid cases, the simulation model also gave the foam densities and SDS concentrations at the same 40 points. Figure 1 shows the locations of the points at which the two technologies were compared. The doubled forming consistency, the presence of air, the re-arrangement of dilution water streams, and the recycling of the surfactant-rich fraction to the approach line of the headbox caused the following changes in the consistencies and process flows of the foam-laid process compared to water-laid process.

Consistency

In the foam-laid case, the doubled forming consistency caused an increase in the consistency of all process steps before the headbox. In the water-laid case, the pulp suspension was gradually diluted from a pulping consistency of 5.2% (point #32 in Fig. 1) to a machine chest consistency of 3.5% (#0). In both foam-laid cases, the consistency decreased gradually from 5.2% to the range of 3.7% to 3.9%. In the water-laid case, the first and second stages of the first LCC operated at consistencies of 1.5% and 1.3%, respectively. In the foam-laid cases, the consistencies in the first LCC were 1.9% to 2.2% at the first stage and 1.4% to 1.5% at the second stage. A typical operational consistency for LCCs is between 0.5% and 2.0%. The consistency of the first LCC in both foam-laid cases did not radically exceed this range.

In the foam-laid cases, the consistencies of the first and second pressure screens and the reject screen increased compared to the water-laid case. The consistencies of the screens in the water-laid case were 0.8% to 0.9%, whereas in the foam-laid cases they were 1.3% to 2.0%. A typical operational consistency for mid-consistency pressure screens is 1% to 4%. The consistency in both foam-laid cases was still within this range.

Figure 8 depicts the changes (%) in the consistencies of both foam-laid cases throughout the process compared to the water-laid case. These are some explanations for the differences:

- #0 to #4: The higher operational consistencies in the overflow box, first LCC, and pressure screens resulted from the doubled forming consistency.
- #5 to #6: The forming consistency was doubled.
- #12: The fiber amount (kg) in the wire waters in the foam-laid case was 90% of the amount in the water-laid case due to a 10% smaller mass-based production rate. Instead, because of the doubled forming consistency, the mass flow of the wire water in the foam-laid case was approximately 50% smaller than in the water-laid case, leading to a 106% to 107% greater consistency. Consistency is expressed as fibers in water volume, not as fibers in foam volume.
- #19: The fiber amount (kg) in the press waters in the foam-laid case was 90% of the amount in the water-laid due to a 10% smaller mass-based production rate. The dryness after the press section was 5 percentage points higher for foam than for water. This would result in a 5-percentage-point greater mass flow of press water.

However, the 10% smaller production capacity rate compensated for the increase due to the higher dryness level, leading to a 7% smaller consistency.

- #20: The dryness after the press section was 45.6% for the water-laid case and 50.6% for foam-laid case, *i.e.*, 11% higher.

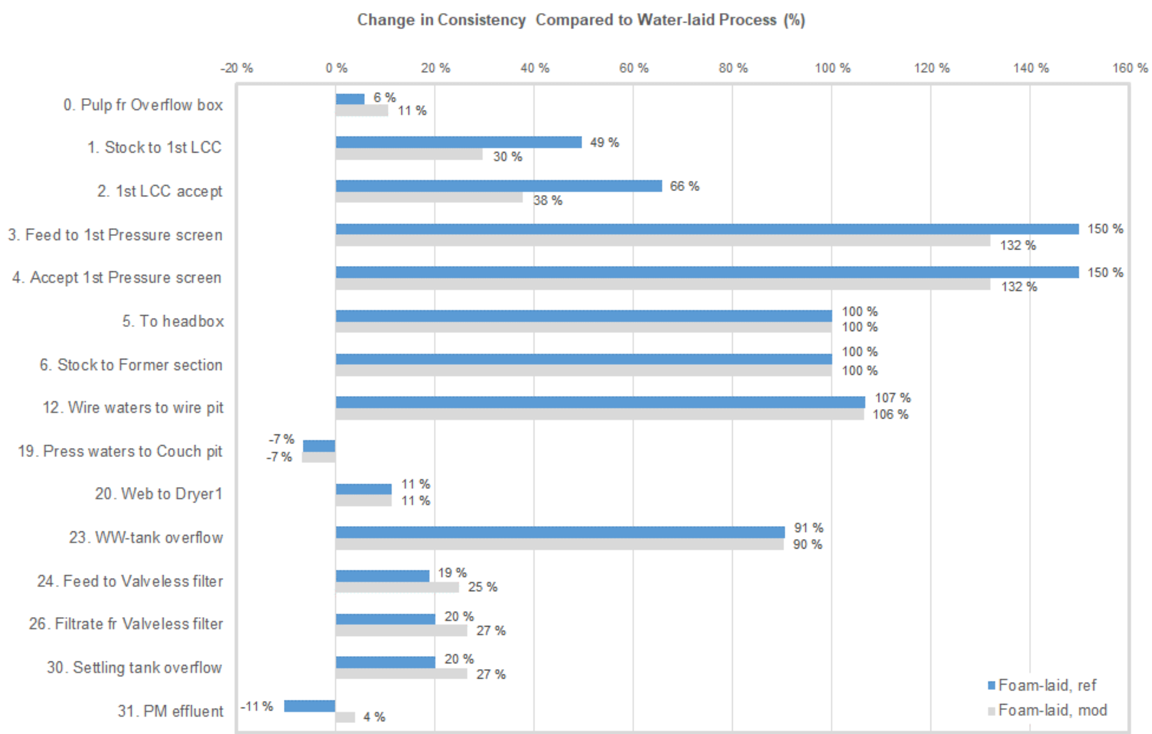

Fig. 8. Changes (%) in the operational consistencies of both evaluated foam-laid cases compared to the water-laid case. The observation point numbers refer to Fig. 1.

Raw material and freshwater balances

It was assumed that foam forming would produce a 10% bulkier end product with the same quality properties as those achieved with water forming. Thus, the wallpaper basis weight was decreased by 10% (exact value 9.5%). Due to the 10% lower basis weight, the mass-based production capacity in both foam-laid cases compared to the water-laid case decreased by 10% (exact value 9.5%). In the *Foam-laid, Ref* case, this led correspondingly to a 9.5% reduction in furnish consumption. In the *Foam laid, Mod* case, however, the reduction in furnish consumption was only 8.4%, which had to do with the greater fiber loss *via* the reject from the superclone to the WWTP. The fiber loss *via* this reject was greater in the *Foam-laid, Mod* case than in the *Foam-laid, Ref* case because the dilution of the cyclone was done with the “fiber-rich” wire water instead of “fiber-lean” white water. The main advantage of foam forming is the lightweighting effect, *i.e.*, the same number of square meters of paper may be produced from a lesser amount of raw furnish. As a result, the material and logistical costs decrease.

Because the nominal freshwater consumption (m^3/t paper) and the basic papermaking chemical consumption (t/t paper) were the same as in the water-laid case, and the mass-based production capacity of wallpaper was decreased by 10%, both the freshwater (m^3/h) and chemical (t/h) consumption rates were decreased by 10% in the foam-laid cases.

Surfactant and wastewater balances

Surfactant leaves the system *via* two streams: product and PM effluent. The retention of surfactant on fibers will define the surfactant loss *via* paper. The surfactant was assumed to follow the water phase in the forming section and not to be retained on fibers. In the press section, however, the surfactant retention on fibers was estimated based on VTT's laboratory trials: 0.33 g/kg bone-dry paper for an SDS concentration of 100 ppm at the headbox. Surfactant that is retained on the fiber is lost with the paper product. In the foam-laid case, 40% of the surfactant ended up in the product. The amount of surfactant loss *via* paper was notable. The possibility to save on surfactant costs and limitations on the amount of surfactant residues in food or skin-contacting products (Viitala 2018) encourage finding means to reduce the surfactant content in the product. The amount of SDS residues in the product is affected by the dry matter content before the drying step and the amount of precipitated dodecyl sulphate (DS) (Viitala *et al*. 2020). The anionic SDS precipitates as salts with divalent cations, such as calcium and magnesium that cause hardness of the water. Calcium and magnesium salts of dodecyl sulphate are weakly soluble (unlike SDS), and hence precipitate out from an aqueous solution. Dodecyl sulphate (DS) remains in the final product as a salt when the water evaporates. Therefore, the amount of surfactant remaining in the product can be reduced by removing the maximum amount of water mechanically and by preventing the precipitation of the surfactant (Viitala *et al*. 2020). Precipitation can be effectively prevented by using surfactant mixtures (Fan *et al*. 1988).

The rest of the surfactant (60%) leaves the paper machine along with the effluent. The increase in the COD load to the WWTP due to the SDS can be estimated as follows: 1 mg / mg of SDS is equal to 1.8 mg / mg of COD (Mortazavi *et al*. 2008). The aeration capacity of the existing WWTP may constitute a bottleneck when considering conversion to foam forming technology. Thus, it is important to minimize the additional COD load caused by the surfactant *via* effective surfactant recovery. In both foam-laid cases, the SDS content of the PM effluent was less than 20 ppm, corresponding to an additional COD load of approximately 1.5 kg/h to the WWTP. With efficient precipitation chemicals, such as ferrous sulfate ($FeSO_4$) or polyaluminum chloride (PAC), approximately 40% to 80% of the SDS may be precipitated already in the primary clarifiers of the WWTP. Thus, the COD load for the subsequent aerobic treatment was only 20% to 60% of the incoming, approximately 0.3 kg COD / h to 0.9 kg COD / h.

Savings in drying steam consumption

Pilot trials at VTT have shown that with foam forming, it is possible to obtain 2-percentage-point to 8-percentage-point greater dryness after the press section compared to water forming. The effect of the dryness level on the drying steam consumption was evaluated using three different dryness levels for the foam-laid case.

Table 3. Effect of Dryness Level (%) after the Press Section on Drying Steam Consumption When Compared to the Water-laid Case

	Dryness after Pressing (%)	Savings Compared to Water-laid (%)
Water-laid	45.6	0
Foam-laid, Ref	47.6	13.4
Foam-laid, Ref	50.6	18.2
Foam-laid, Ref	53.6	22.5
Foam-laid, Mod	50.6	18.3

Table 3 shows the drying steam savings in each case compared to the water-laid case. If the dryness level in the foam-laid process after the press section was even 8 percentage points higher than in the water-laid process, a savings of 22.5% in drying steam consumption could be achieved.

Changes in process stream mass and volume flows

There were noticeable changes in the mass and volume flows of the foam-laid process compared to the water-laid process. The reasons for this result include 1) the presence of air as the carrier phase and the flowing medium, 2) the doubled forming consistency, 3) the introduction of the surfactant recycle to the approach line of the headbox, and 4) the re-arrangement of dilution water sources around the hydrocyclones.

Figures 9 and 10 depict the changes (%) in the process mass flows and volume flows of both foam-laid cases throughout the process compared to the water-laid case. These are some explanations for the differences:

- #0 to #4: The overflow box, first LCC, and pressure screens operate at a higher consistency level than in the water-laid process, which led to 23% to 64% smaller mass flows. The air content at this point in the process is not yet high (<20%), so the volume flows were 20% to 60% smaller than in the water-laid case.
- #5 to #6: The forming consistency is doubled. This, together with the 10% smaller mass-based production capacity, led to 55% smaller mass flows at the headbox. The volume flows were only 25% smaller because the air content at this point is 40%.
- #12: Because of the doubled forming consistency, the mass flow of the wire water was 56% smaller than in the water-laid case. The volume flows were only 28% smaller because the air content at this point is 40%.
- #19: The dryness after the press section is 5 percentage points higher for foam than for water. This would lead to a 5-percentage-point greater mass flow of press water. However, the 10% smaller mass-based production capacity compensates for the increase due to the higher dryness level, leading to 3% smaller mass flows. The volume flows of the press waters are 20% higher compared to the water-laid process because the press waters are assumed to contain 20% air.
- #23: There was a 99% larger overflow from the white water tank to the long circulation in the *Foam-laid, Ref* case because the dilution water to the first LCC and second LCC is not taken from the white water tank. Because the air content at this point is 30%, the volume flow is as much as 190% higher than in the water-laid case. In the *Foam-laid, Mod* case, the increases in the white water tank overflow were not as drastic: 25% for the mass flow and 80% for the volume flow. The increases were due to the higher operational consistency before the headbox, which leads to smaller dilution need from the white water tank.
- #24 to #26, #30: The increased mass and volume flows around the valveless filter and from the settling tank derive directly from the increased overflow of the white water tank. The increased overflowing of the white water tank acts on the upcoming process units like a snowball effect.
- #32 to #35: The decrease in the mass and volume flows derives from the 10% smaller production capacity.

- #36: The decrease in the mass and volume flows derives from the 10% smaller production capacity and from the higher operational consistency in the machine chest.

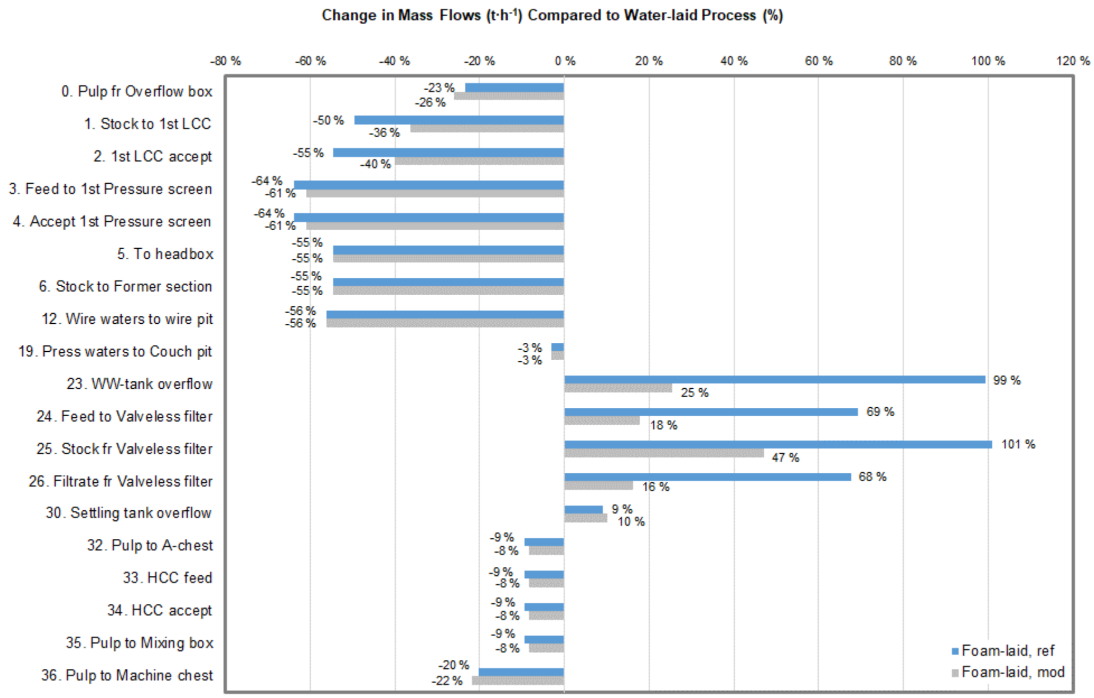

Fig. 9. Changes (%) in the process mass flows of both evaluated foam-laid cases compared to the water-laid case. The observation point numbers refer to Fig. 1.

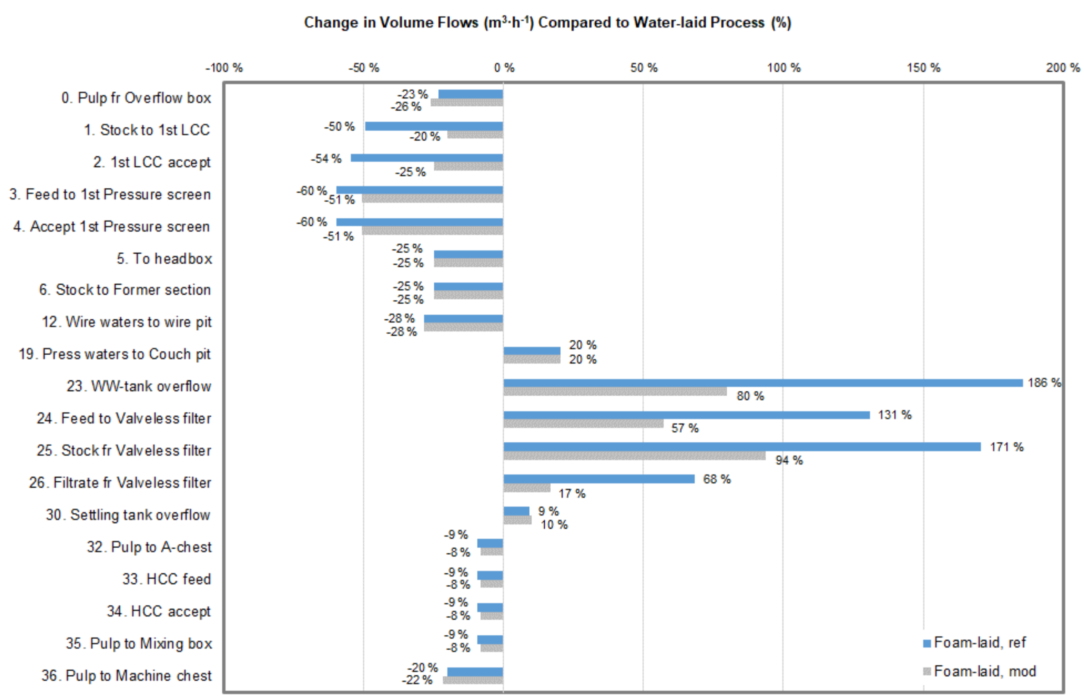

Fig. 10. Changes (%) in the process volume flows of both evaluated foam-laid cases compared to the water-laid case. The observation point numbers refer to Fig. 1.

Figure 11 summarizes the consistencies (%), volume flows (m^3/h), foam densities (kg/m^3), and SDS concentrations (ppm) for the three evaluated cases and the changes (%) in the volume flows compared to the water-laid case at the most critical points in the process. As speculated above, even though the operational consistencies in the feed to the first LCC and first pressure screen increased in the foam-laid cases, they should still remain within an acceptable range for these devices. Compared to the water-laid case, where the consistency remained constant between the outlet of the pressure screen and the inlet of the headbox, in both foam-laid cases, the addition of surfactant just before the headbox decreased the consistency by 14% to 20%. Due to the doubled forming consistency, the volume flows before the headbox in the foam-laid cases were 20% to 60% smaller than in the water-laid case. The conversion from a water-laid to a foam-laid process has the most impact on the volume balance of the white water tank. In the foam-laid cases, the amount of dilution water taken from the white water tank into the approach line was 60% to 87% less than in the water-laid case. Even though the feed to the white water tank was about one-fourth smaller in the foam-laid cases, the overflow from the tank towards the long circulation was almost double or triple that of the water-laid case. In the foam-laid cases, the feed to the valves filter was 1.6 to 2.3 times greater than in the water-laid case. Due to the removal of the surfactant-rich fraction from the surfactant recovery system, the feed flow to the settling tank in the *Foam-laid, Ref* case was 1.4 times greater than in the water-laid case. It was almost the same in the *Foam-laid, Mod* case as in the water-laid case. This remarkable capacity increase in the long circulation must be accounted for when evaluating the suitability of existing process equipment for foam forming technology.

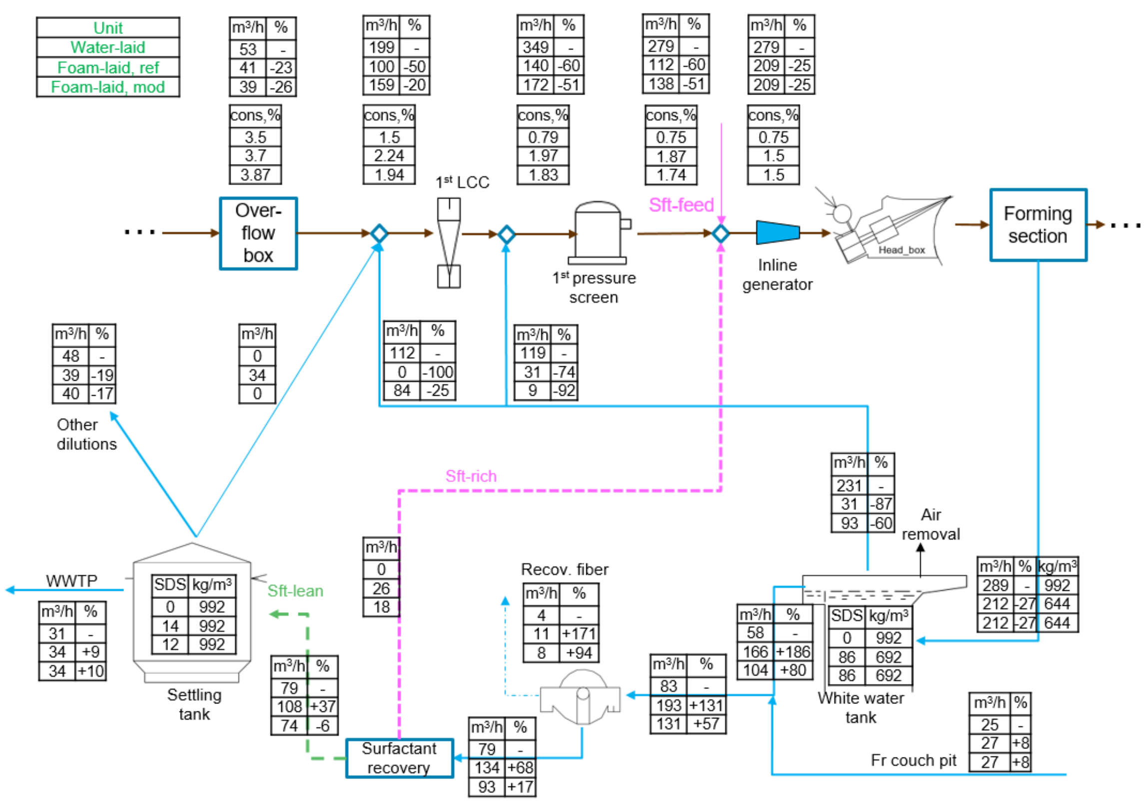

Fig. 11. Comparison of the consistencies, mass flows, and volume flows at the most critical points of the process for the three evaluated cases

Foam density level and SDS concentration in process streams

Figure S7 in the supplementary material presents the foam density levels throughout the process for both foam-laid cases. The foam density of wire waters and press waters ranged between 600 kg/m^3 and 800 kg/m^3. The foam density in the white water tank was 690 kg/m^3, and in the settling tank it was 990 kg/m^3.

Figure S8 in the supplementary material shows the SDS concentrations throughout the process for both foam-laid cases. From the headbox until the press section, SDS was assumed to follow the water phase, and the SDS concentration in all streams was the same as at the headbox (100 ppm). In the press section, the retention of SDS on fibers increased the SDS concentration of the webs leaving the pressing stages. The press waters were very SDS lean. The SDS-rich and SDS-lean fractions from the surfactant recovery contained approximately 300 ppm of SDS and less than 20 ppm of SDS, respectively.

CONCLUSIONS

Foam forming technology offers several advantages compared to conventional water forming technology. To support the paper industry in pushing this new technology forward, process simulation is needed. No work has so far been published on studying the performance of the foam forming process with modeling and simulation. One of the reasons for this may be that the existing simulation software does not deal well with foam. To overcome this obstacle, this paper presented the development of necessary foam property calculations in the used simulator platform. It also presented a systematic approach to study, *via* process simulation, the conversion of an existing wallpaper machine from water-laid technology to foam-laid technology, to reveal the needed process configuration changes and possible bottlenecks in the existing process and to create a basis for equipment dimensioning. The conversion work consisted of a conceptual stage process design combined with steady state process simulation using simulation software.

1. The concept model describing the reference process, *i.e*., wallpaper production with water forming, was validated with real process data. For parameterizing the concept model describing the future process, *i.e*., wallpaper production with foam forming, the required process changes and new parameters were defined based on knowledge derived from laboratory trials, pilot runs, and studies conducted at VTT.
2. When converting conventional water-laid papermaking process to the foam process, investing in a foam generator and a surfactant recovery system as new equipment is unavoidable. To determine whether the conversion phase requires replacing or modifying some major components of the production machine, the operability of the existing equipment with foam was analyzed based on knowledge obtained from pilot runs. The refiners, headbox, forming section, and hydrocyclones were identified as the most critical paper process equipment for conversion. Foam causes challenges in adjusting the refiner pressure. The headbox may call for some modifications depending on the furnish type. The vacuum capacity in the forming section must be increased to achieve the same dewatering rate as in the water-laid process. However, from the standpoint of water balance, the questionable operability of hydrocyclones with foam is the most crucial issue. Depending on the furnish type, hydrocyclones may or may not work with foam. To guarantee their undisturbed operation, their feeds should not contain foamed or foamable liquid. This necessitates re-arranging their dilution water

supply from foamy and surfactant-concentrated short circulation water to non-foamable, surfactant-lean long circulation water. This re-arrangement may double or even triple the volume flows from the short to the long circulation, necessitating capacity growth in the existing equipment in the long circulation.

3. Mass, volume, and energy balances of the wallpaper machine for both forming technologies were created and compared. In the foam-laid model, it was assumed that a 10% bulkier end product with the same paper quality properties as in the water-laid process could be produced. It was also assumed that in the foam-laid model, the forming consistency could be doubled, and a 5-percentage-point higher dryness level after the wet press could be achieved. These, together with the re-arrangement of the water circuits and the presence of air, had a joint effect and caused, compared to the water-laid process, the following: 1) growth in the operational consistency of all process steps before the headbox, 2) increased process water consistency throughout the process, 3) a 10% savings in the furnish raw material, basic papermaking chemicals, and freshwater consumption, 4) a small additional COD load to the WWTP due to the surfactant, 5) an 18% savings in drying steam consumption, 6) smaller process volume flows until the headbox and in the short circulation, and 7) greater process volume flows in the long circulation.
4. The benefits of using simulation in support of engineering are noticeable. The created mass and volume balances for the new foam forming process provided the required data for revealing possible bottlenecks in the existing process and for dimensioning new equipment.

Future work should include more research related to the operation of refiners and hydrocyclones with foam to increase the reliability of the simulation model and should implement pressure dependence of density and more realistic mixing rules for the model to enable its scalability.

Data used in this study was mainly collected from the VTT pilot machine. All machine and short circulation components were supplied by major machine suppliers. In a production scale, all machines are somewhat different, and results obtained at pilot scale may not be directly transferrable to a larger scale due to differences in machinery.

ACKNOWLEDGMENTS

The authors thank Timo Lappalainen and Baranivignesh Prakash for providing input regarding surfactant and foam generation studies, Mikko Jegoroff for developing the simulation models, and Harri Kiiskinen and Jaakko Asikainen for providing comments.

Funding

This study was conducted as part of the Future Fibre Products 2020 (FFP2020) project, which is funded by the European Regional Development Fund (Grant Nos. A73089 and A73092), VTT Technical Research Centre of Finland Ltd., and 32 industrial partners.

Conflicts of Interest

The authors declare no conflicts of interest.

REFERENCES CITED

Al-Qararah, A. M., Hjelt, T., Kinnunen, K., Beletski, N., and Ketoja, J. (2012). "Exceptional pore size distribution in foam-formed fibre networks," *Nordic Pulp & Paper Research Journal* 27(2), 226-230. DOI: 10.3183/npprj-2012-27-02-p226-230

Al-Qararah, A. M., Hjelt, T., Koponen, A., Harlin, A., and Ketoja, J. A. (2013). "Bubble size and air content of wet fibre foams in axial mixing with macro-instabilities," *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 436, 1130-1139. DOI: 10.1016/j.colsurfa.2013.08.051

Al-Qararah, A. M., Ekman, A., Hjelt, T., Ketoja, J. A., Kiiskinen, H., Koponen, A., and Timonen, J. (2015a). "A unique microstructure of the fiber networks deposited from foam–fiber suspensions," *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 482, 544-553. DOI: 10.1016/j.colsurfa.2015.07.010

Al-Qararah, A. M., Hjelt, T., Koponen, A., Harlin, A., and Ketoja, J. A. (2015b). "Response of wet foam to fibre mixing," *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 467, 97-106. DOI: 10.1016/j.colsurfa.2014.11.034

Al-Qararah, A. M., Ekman, A., Hjelt, T., Kiiskinen, H., Timonen, J., and Ketoja, J. A. (2016). "Porous structure of fibre networks formed by a foaming process: A comparative study of different characterization techniques," *Journal of Microscopy* 264(1), 88-101. DOI: 10.1111/jmi.12420

Asikainen, J., Saharinen, E., and Koponen, A. (2020). "Dispersion of 24-mm staple fibers with foam," *Journal of Engineered Fibers and Fabrics* 15, 1-8. DOI: 10.1177/1558925020946441

Åslund, P., and Vomhoff, H. (2008). "Dewatering mechanisms and their influence on suction box dewatering processes – A literature review," *Nordic Pulp & Paper Research Journal* 23(4), 389-397. DOI: 10.3183/npprj-2008-23-04-p389-397

Atkins, M., Morrison, A., Walmsley, M., and Riley, J. (2010). "WinGEMS modelling and pinch analysis of a paper machine for utility reduction," *Appita Journal* 63(4), 281-287.

Baldwin, L. (1997). "High-vacuum dewatering," *Paper Technology* 38(4), 23-28.

Blanco, A., Dahlquist, E., Kappen, J., Manninen, J., Negro, C., and Ritala, R. (2009). "Use of modelling and simulation in the pulp and paper industry," *Mathematical and Computer Modelling of Dynamical Systems* 15(5), 409-423. DOI: 10.1080/13873950903375387

Boonyasuwat, S., Chavadej, S., Malakul, P., and Scamehorn, J. F. (2003). "Anionic and cationic surfactant recovery from water using a multistage foam fractionator," *Chemical Engineering Journal* 93(3), 241-252. DOI: 10.1016/S1385-8947(03)00043-3

Bortolin, G., Borg, S., and Gutman, P. O. (2004). "Modeling of the wet end part of a paper mill with Dymola," *Mathematics and Computers in Simulation* 65(1-2), 31-38. DOI: 10.1016/j.matcom.2003.09.005

Burghoff, B. (2012). "Foam fractionation applications," *Journal of Biotechnology* 161(2), 126-137. DOI: 10.1016/j.jbiotec.2012.03.008

Cardoso, M., de Oliveira, K. D., Costa, G. A. A., and Passos, M. L. (2009). "Chemical process simulation for minimizing energy consumption in pulp mills," *Applied Energy* 86(1), 45-51. DOI: 10.1016/j.apenergy.2008.03.021

Cheng, H., Nikus, M., and Jämsä-Jounela, S.-L. (2008). "Fault diagnosis of the paper machine short circulation process using novel dynamic causal digraph reasoning," *Journal of Process Control* 18(7-8), 676-691. DOI: 10.1016/j.jprocont.2007.12.003

Clément, S., Gouiller, A., Ottenio, P., Nivelon, S., Huber, P., and Nortier, P. (2011). "Speciation and supersaturation model in papermaking streams," *Process Safety and Environmental Protection* 89(1), 67-73. DOI: 10.1016/j.psep.2010.08.005

Dahlquist, E. (2008). "Process simulation for pulp and paper industries: Current practice and future trend," *Chemical Product and Process Modeling* 3(1). DOI: 10.2202/1934-2659.1087

Exerowa, D., and Kruglyakov, P. M. (1998). *Foam and Foam Films: Theory, Experiment, Application*, Elsevier, Amsterdam, the Netherlands.

Fan, X.-J., Stenius, P., Kallay, N., and Matijević, E. (1988). "Precipitation of surfactant salts: II. The effect of nonionic surfactants on precipitation of calcium dodecyl sulfate," *Journal of Colloid and Interface Science* 121(2), 571-578. DOI: 10.1016/0021-9797(88)90459-6

Fernández, E., Benito, J. M., Pazos, C., and Coca, J. (2005). "Ceramic membrane ultrafiltration of anionic and nonionic surfactant solutions," *Journal of Membrane Science* 246(1) 1-6. DOI: 10.1016/j.memsci.2004.04.007

Gottberg, J. M., Lappalainen, T., and Salminen, K. (2019). "Polyvinyl alcohol as foaming agent in foam formed paper," *Tappi Journal* 18(8), 475-485. DOI: 10.32964/TJ18.8.475

Hanson, J. P. (1977). "What's going on in non-wovens," *Pulp & Paper* 51(11), 97-102.

Hubbe, M. A., and Heitmann, J. A. (2007). "Review of factors affecting the release of water from cellulosic fibers during paper manufacture," *BioResources* 2(3), 500-533. DOI: 10.15376/biores.2.3.500-533

Hubbe, M. A., Sjöstrand, B., Nilsson, L., Koponen, A., and McDonald, J. D. (2020). "Rate-limiting mechanisms of water removal during the formation, vacuum dewatering, and wet-pressing of paper webs: A review," *BioResources* 15(4), 9672-9755.

Huber, P., Nivelon, S., Ottenio, P., and Nortier, P. (2013). "Coupling a chemical reaction engine with a mass flow balance process simulation for scaling management in papermaking process waters," *Industrial & Engineering Chemistry Research* 52(1), 421-429. DOI: 10.1021/ie300984y

Hytönen, E., and Stuart, P. R. (2012). "Early-stage design methodology for biorefinery capital appropriation," *Tappi Journal* 11(4), 9-23. DOI: 10.32964/TJ11.4.9

Jabarkhyl, S., Barigou, M., Badve, M., and Zhu, S. (2020a). "Rheological properties of wet foams generated from viscous pseudoplastic fluids," *Innovative Food Science & Emerging Technologies* 64. DOI: 10.1016/j.ifset.2020.102304

Jabarkhyl, S., Barigou, M., Zhu, S., Rayment, P., Lloyd, D. M., and Rossetti, D. (2020b). "Foams generated from viscous non-Newtonian shear-thinning liquids in a continuous multi rotor-stator device," *Innovative Food Science & Emerging Technologies* 59. DOI: 10.1016/j.ifset.2019.102231

Järvinen, M., Pihko, R., and Ketoja, J. A. (2018). "Density development in foam forming: Wet pressing dynamics," *Nordic Pulp & Paper Research Journal* 33(2), 226-236. DOI: 10.1515/npprj-2018-3031

Jäsberg, A., Selenius, P., and Koponen, A. (2015). "Experimental results on the flow rheology of fiber-laden aqueous foams," *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 473, 147-155. DOI: 10.1016/j.colsurfa.2014.11.041

Jönsson, J., Ruohonen, P., Michel, G., and Berntsson, T. (2011). "The potential for steam savings and implementation of different biorefinery concepts in Scandinavian integrated TMP and paper mills," *Applied Thermal Engineering* 31(13), 2107-2114. DOI: 10.1016/j.applthermaleng.2011.03.001

Kiiskinen, H., Salminen, K., Lappalainen, T., Asikainen, J., Keränen, J., and Hellén, E. (2019). "Progress in foam forming technology," *Tappi Journal* 18(8), 499-510. DOI: 10.32964/TJ18.8.499

Kinnunen, K., Lehmonen, J., Beletski, N., Jetsu, P., and Hjelt, T. (2013). "Benefits of foam forming technology and its applicability in high MFC addition structures," in: *Proceedings of the 15th Fundamental Research Symposium*, Advances in Paper Research, Cambridge, UK, pp. 837-850.

Kinnunen-Raudaskoski, K. (2017). *Foam as a Carrier Phase – A Multipurpose Technology for Industrial Applications*, Ph.D. Dissertation, Aalto University, Espoo, Finland.

Koponen, A., Torvinen, K., Jäsberg, A., and Kiiskinen, H. (2016). "Foam forming of long fibers," *Nordic Pulp & Paper Research Journal* 31(2), 239-247. DOI: 10.3183/npprj-2016-31-02-p239-247

Koponen, A., Ekman, A., Mattila, K., Al-Qararah, A. M., and Timonen, J. (2017). "The effect of void structure on the permeability of fibrous networks," *Transport in Porous Media* 117(2), 247-259. DOI: 10.1007/s11242-017-0831-2

Koponen, A., Jäsberg, A., Lappalainen, T., and Kiiskinen, H. (2018). "The effect of in-line foam generation on foam quality and sheet formation in foam forming," *Nordic Pulp & Paper Research Journal* 33(3), 482-495. DOI: 10.1515/npprj-2018-3051

Koponen, A., Eloranta, H., Jäsberg, A., Honkanen, M., and Kiiskinen, H. (2019). "Real-time monitoring of bubble size distribution in a foam forming process," *Tappi Journal* 18(8), 487-494. DOI: 10.32964/TJ18.8.487

Kouko, J., Prakash, B., Luukkainen, V.-M., Jäsberg, A., and Koponen, A. I. (2020). "Generation of aqueous foams and fiber foams in a stirred tank," *Chemical Engineering Research and Design*, in press.

Kowalska, I., Kabsch-Korbutowicz, M., Majewska-Nowak, K., and Winnicki, T. (2004). "Separation of anionic surfactants on ultrafiltration membranes," *Desalination* 162(1-3), 33-40. DOI: 10.1016/S0011-9164(04)00024-4

Lappalainen, T., and Lehmonen, J. (2012). "Determinations of bubble size distribution of foam-fibre mixture using circular hough transform," *Nordic Pulp & Paper Research Journal* 27(5), 930-939. DOI: 10.3183/npprj-2012-27-05-p930-939

Lappalainen, T., Salminen, K., Kinnunen, K., Järvinen, M., Mira, I., and Andersson, M. (2014). "Foam forming revisited. Part II. Effect of surfactant on the properties of foam-formed paper products," *Nordic Pulp & Paper Research Journal* 29(4), 689-699. DOI: 10.3183/npprj-2014-29-04-p689-699

Lee, J., and Maa, J. R. (1986). "Separation of a surface active solute by foam fractionation," *International Communications in Heat and Mass Transfer* 13(4), 465-473. DOI: 10.1016/0735-1933(86)90009-6

Lehmonen, J., Jetsu, P., Kinnunen, K., and Hjelt, T. (2013). "Potential of foam-laid forming technology in paper applications," *Nordic Pulp & Paper Research Journal* 28(3), 392-398. DOI: 10.3183/npprj-2013-28-03-p392-398

Lehmonen, J., Rantanen, T., and Kinnunen-Raudaskoski, K. (2019). "Upscaling of foam forming technology for pilot scale," *Tappi Journal* 18(8), 461-471. DOI: 10.32964/TJ18.8.461

Lehmonen, J., Retulainen, E., Paltakari, J., Kinnunen-Raudaskoski, K., and Koponen, A. (2020). "Dewatering of foam-laid and water-laid structures and the formed web properties," *Cellulose* 27(3), 1127-1146. DOI: 10.1007/s10570-019-02842-x

Leonard, R. A., and Blacyki, J. D. (1978) "Multistage bubble fractionator," *Industrial & Engineering Chemistry Process Design and Development* 17(3), 358-361. DOI: 10.1021/i260067a026

Măluţan, T., and Măluţan, C. (2013). "Simulation of processes in papermaking by WinGEMS software," *Environmental Engineering and Management Journal* 12(8), 1645-1647.

Mira, I., Andersson, M., Boge, L., Blute, I., Carlsson, G., Salminen, K., Lappalainen, T., and Kinnunen, K. (2014). "Foam forming revisited Part I. Foaming behaviour of fibre-surfactant systems," *Nordic Pulp & Paper Research Journal* 29(4), 679-688. DOI: 10.3183/npprj-2014-29-04-p679-689

Mortazavi, S. B., Khavanin, A., Moussavi, G., and Azhdarpoor, A. (2008). "Removal of sodium dodecyl sulfate in an intermittent cycle extended aeration system," *Pakistan Journal of Biological Sciences* 11(2), 290-293. DOI: 10.3923/pjbs.2008.290.293

Orccotoma, J. A., Paris, J., Perrier, M., and Roche, A. A. (1997). "Dynamics of white water networks during web breaks," *Tappi Journal* 80(12), 101-110.

Punton, V. (1975a). "Fibre distribution in foam and foam-laid paper," in: *International Paper Physics Conference*, New York, NY, USA, pp. 135-139.

Punton, V. W. (1975b). "The use of an aqueous foam as a fibre-suspending medium in quality papermaking," in: *Proceedings of a Symposium Organized by the Society of Chemical Industry*, London, UK, pp. 179-194.

Radvan, B., and Gatward, A. P. J. (1972). "The formation of wet-laid webs by a foaming process," *Tappi Journal* 55(5), 748-751.

Ruohonen, P., and Ahtila, P. (2010). "Analysis of a mechanical pulp and paper mill using advanced composite curves," *Applied Thermal Engineering* 30(6-7), 649-657. DOI: 10.1016/j.applthermaleng.2009.11.012

Savolainen, J., and Lappalainen, J. (2015). "Identification of process bottlenecks with global sensitivity analysis, an application to papermaking processes," *Nordic Pulp & Paper Research Journal* 30(3), 393-401. DOI: 10.3183/npprj-2015-30-03-p393-401

Smith, M. K., and Punton, V. W. (1975). "Foam can improve formation," *Pulp & Paper Canada* 76(1), 55-58.

Smith, M. K., Punton, V. W., and Rixson, A. G. (1974). "The structure and properties of paper formed by a foaming process," *Tappi Journal* 57(1), 107-111.

Sorsamäki, L., Grönroos, A., Tukiainen, P., Prasse, S., Huber, P., Fourest, E., Lemercier, J., Deschamps, C., Vleeming, H., van der Pol, E., *et al*. (2019). *Selected Scenario Simulation for Process and Cooling Water Reuse in the P&P Industry* (Report D3.2), (http://www.spotview.eu/docs/filesProject/6/48365817-0B94-BA9C-C2C097648B571681.2-VTT-final.pdf), Accessed 30 November 2020.

Stoor, T. (2008). "Air in pulp and papermaking processes," in: *62nd Appita Annual Conference and Exhibition*, Rotorua, New Zealand, pp. 207-214.

Timofeev, O., Jetsu, P., Kiiskinen, H., and Keränen, J. T. (2016). "Drying of foam-formed mats from virgin pine fibers," *Drying Technology* 34(10), 1210-1218. DOI: 10.1080/07373937.2015.1103254

Torvinen, K., Lahtinen, P., Kiiskinen, H., Hellen, E., and Koponen, A. (2015). "Bulky paper and board at a high dry solids content with foam forming," in: *Proceedings of PaperCon 2015*, Atlanta, GA, USA, pp. 757-766.

Tringham, R. (1974). "New developments in the Radfoam process," *Paper Technology* 15(5), 288-294.
Turon, X., Labidi, J., and Paris, J. (2005). "Simulation and optimisation of a high grade coated paper mill," *Journal of Cleaner Production* 13(15), 1424-1433. DOI: 10.1016/j.jclepro.2005.05.024
Vähä-Nissi, M., Lappalainen, T., and Salminen, K. (2018). "The wet strength of water- and foam-laid cellulose sheets prepared with polyamideamine-epichlorohydrin (PAE) resin," *Nordic Pulp & Paper Research Journal* 33(3), 496-502. DOI: 10.1515/npprj-2018-3056
Viitala, J. (2018). *Determination of Surfactants from Foam-formed Products,* Master's Thesis, University of Jyväskylä, Finland.
Viitala, J., Lappalainen, T., and Järvinen, M. (2020). "Sodium dodecyl sulphate (SDS) residue analysis of foam-formed cellulose-based products," *Nordic Pulp & Paper Research Journal* 35(2), 261-271. DOI: 10.1515/npprj-2019-0058
Weaire, D., and Hutzler, S. (1999). *The Physics of Foams*, Oxford University Press, New York, NY, USA.
Yeo, Y.-K., Yi, S. C., Ryu, J. Y., and Kang, H. (2004). "Modeling and simulation of wet-end white water system in the paper mill," *Korean Journal of Chemical Engineering* 21(2), 358-364. DOI: 10.1007/BF02705420
Zeno, E., Carré, B., and Mauret, E. (2005). "Influence of surface-active substances on AKD sizing," *Nordic Pulp & Paper Research Journal* 20(2), 253-258. DOI: 10.3183/npprj-2005-20-02-p253-258

Article submitted: December 17, 2020; Peer review completed: January 31, 2021; Revised version received: February 17, 2021; Accepted: May 12, 2021; Published: May 28, 2021.
DOI: 10.15376/biores.16.3.5148-5186

APPENDIX

Supplementary Material

Figures S1 to S3 present the *Paper machine* sub-model of the simulation model for all three evaluated cases, with the mass flows (t/h), consistencies (%), and SDS concentrations (mg/L = ppm) shown for the observation points (marked with yellow circles in the figures). Figures S4 to S6 present the three other sub-models, *Chemical preparation*, *Wastewater treatment*, and *Freshwater preparation*, for the water-laid case. These sub-models were identical regarding the process configuration in all evaluated cases. Deviations in process flow data do exist, though. The resolution of the figures is high when zoomed.

Figure S7 presents the foam density levels throughout the process for both evaluated foam-laid cases. The differences in the foam density before the headbox (#1 to #4) may be explained by the re-arrangement of the hydrocyclones' dilution water. In the *Foam-laid, Ref* case, the dilution water used for the hydrocyclones was nearly air-free water from the settling tank (990 kg/m^3). In the *Foam-laid, Mod* case, the density of the dilution water taken from the white water tank was 690 kg/m^3. From the headbox (#5) until the last foam removal unit in the forming section (#10a), the foam densities of both wire waters and webs remained constant (600 kg/m^3) because water and air are removed in the foam removal units *DW0*, *DW1*, and *DW2* at almost the same ratio. The foam density of the wire water (#11) removed from the last water removal unit (*DW3*) was higher (780 kg/m^3) because in this foam removal unit, the air removal efficiency was only 40% that of the water removal efficiency. Because the air balance in the press section was modeled such that only air escaping from the last roll (*DW6*) into the surroundings was included, the retention of air in the web after the first two rolls was too high. This resulted in overly low web densities: 380 kg/m^3 after the first roll (#15) and 330 kg/m^3 after the second roll (#17). The density of the web after the last roll, when entering the drying section, was 980 kg/m^3 (#20). The densities of the press waters (#14, #16, and #18) were 800 kg/m^3. The foam density in the feed to the white water tank was 640 kg/m^3 (#12a). Because it was assumed that the mechanical collapsing of froth removes 20% of the air present in the white water tank, the density inside and in the outlet of the tank was 690 kg/m^3. The valveless filter as such was assumed to mechanically collapse the foam. As a result, the density in the settling tank and at the beginning of the process was 990 kg/m^3.

Figure S8 presents the SDS concentrations throughout the process for both evaluated foam-laid cases. The differences in the SDS concentration before the headbox (#1 to #4) were due to the re-arrangement of the hydrocyclones' dilution water. In the *Foam-laid, Ref* case, the dilution water used for the hydrocyclones was surfactant-lean water from the settling tank (14 ppm of SDS). In the *Foam-laid, Mod* case, the dilution water was surfactant-rich water from the white water tank (86 ppm of SDS). From the headbox (#5) until the press section (#13), SDS was assumed to follow the water phase, and the SDS concentration in all streams was same as at the headbox (100 ppm). In the press section, retention of SDS on the fibers occurred, which can be observed as the high SDS concentrations in the webs leaving the three pressing stages (#15, #17, and #20). The press water streams (#14, #16, and #18) from the three pressing stages were very SDS lean. The concentrated fraction from surfactant recovery contained approximately 300 ppm of SDS (#28). The surfactant lean fraction from the surfactant recovery contained less than 20 ppm of SDS (#29).

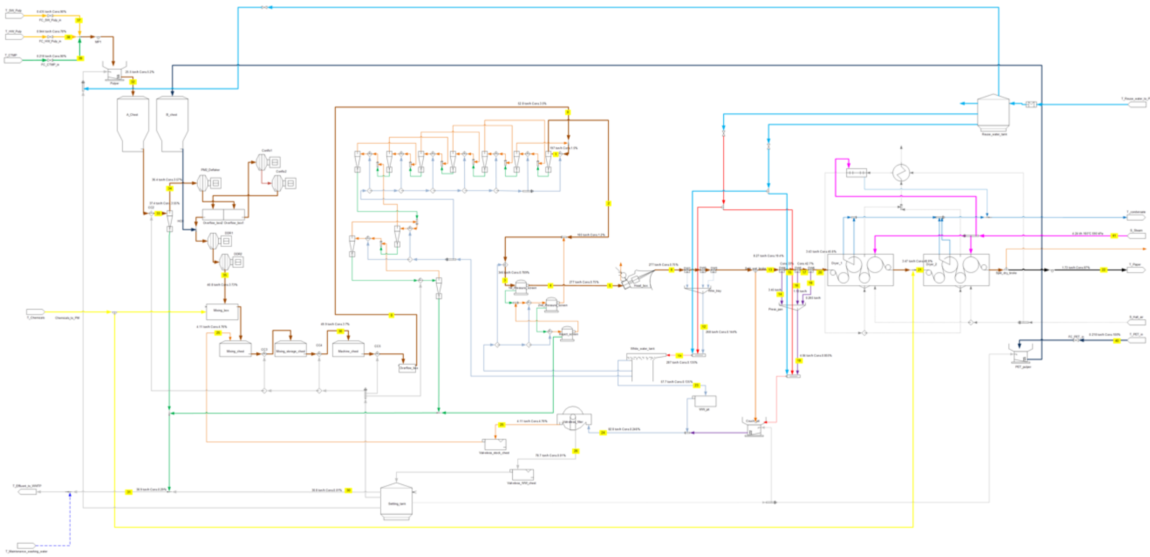

Fig. S1. The *Paper machine* sub-model for the *Water-laid* case

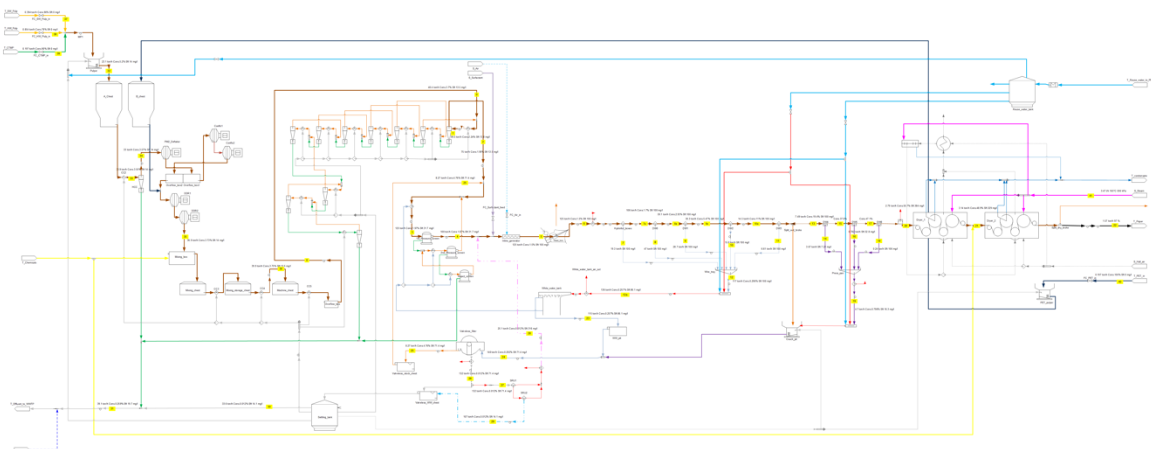

Fig. S2. The *Paper machine* sub-model for the *Foam-laid, Ref'* case

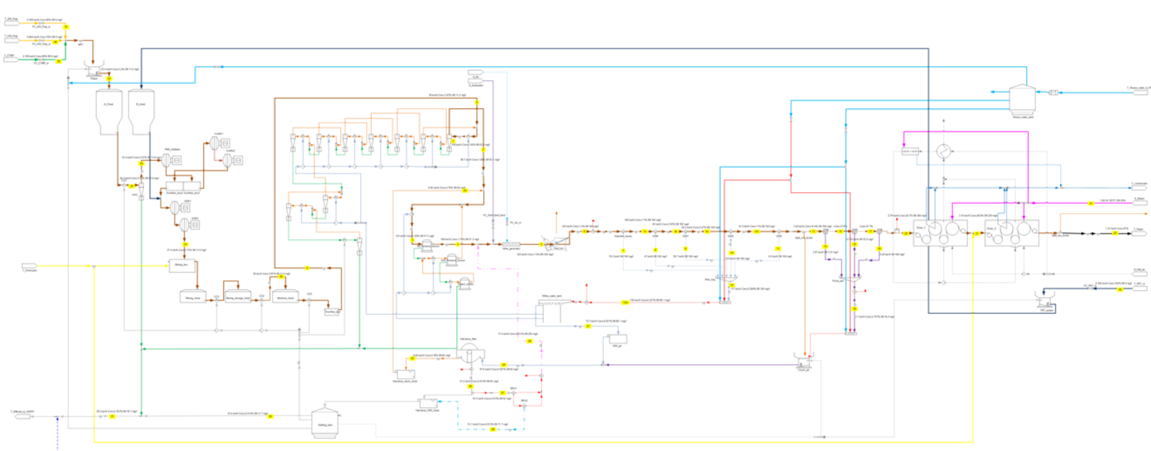

Fig. S3. The *Paper machine* sub-model for the *Foam-laid, Mod* case

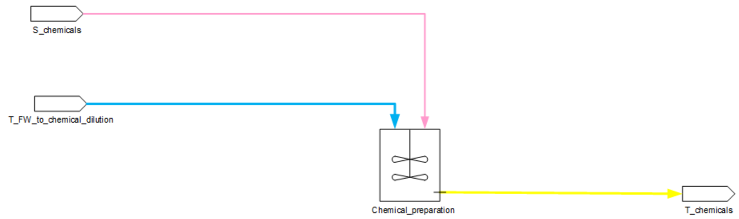

Fig. S4. The *Chemical preparation* sub-model for all cases. The configuration is identical in all cases; deviations in flow data exist.

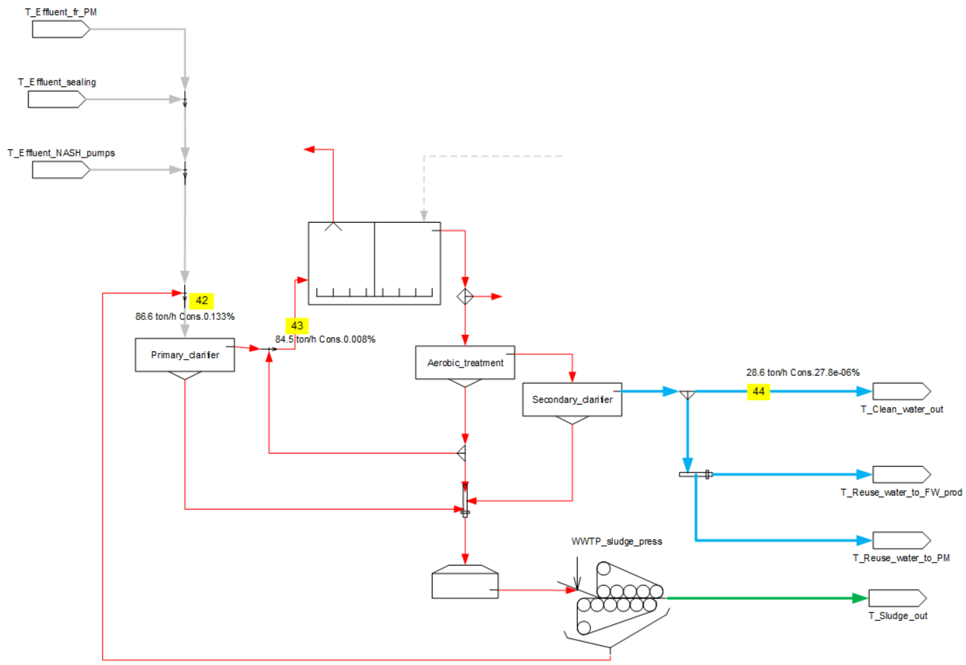

Fig. S5. The *Wastewater treatment* sub-model for the *Water-laid* case. The configuration is identical in all cases; deviations in flow data exist.

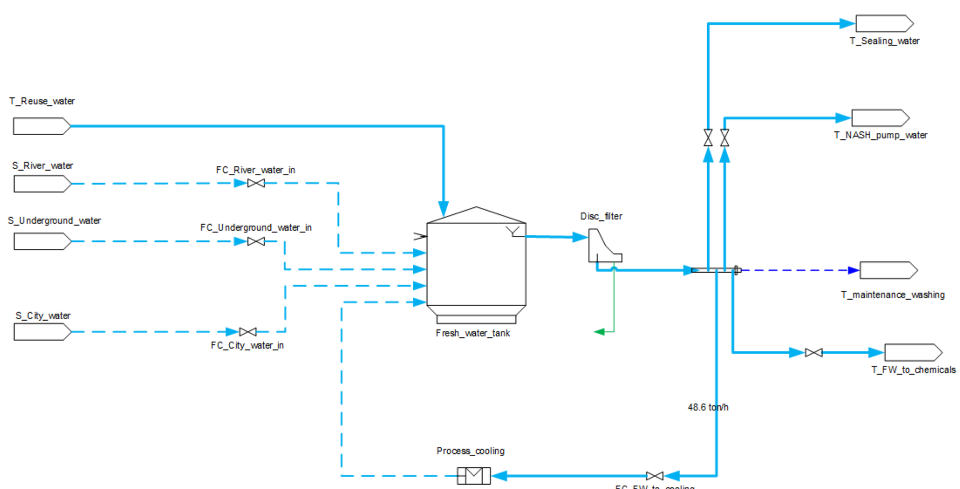

Fig. S6. The *Freshwater preparation* sub-model for all cases. The configuration is identical in all cases; deviations in flow data exist.

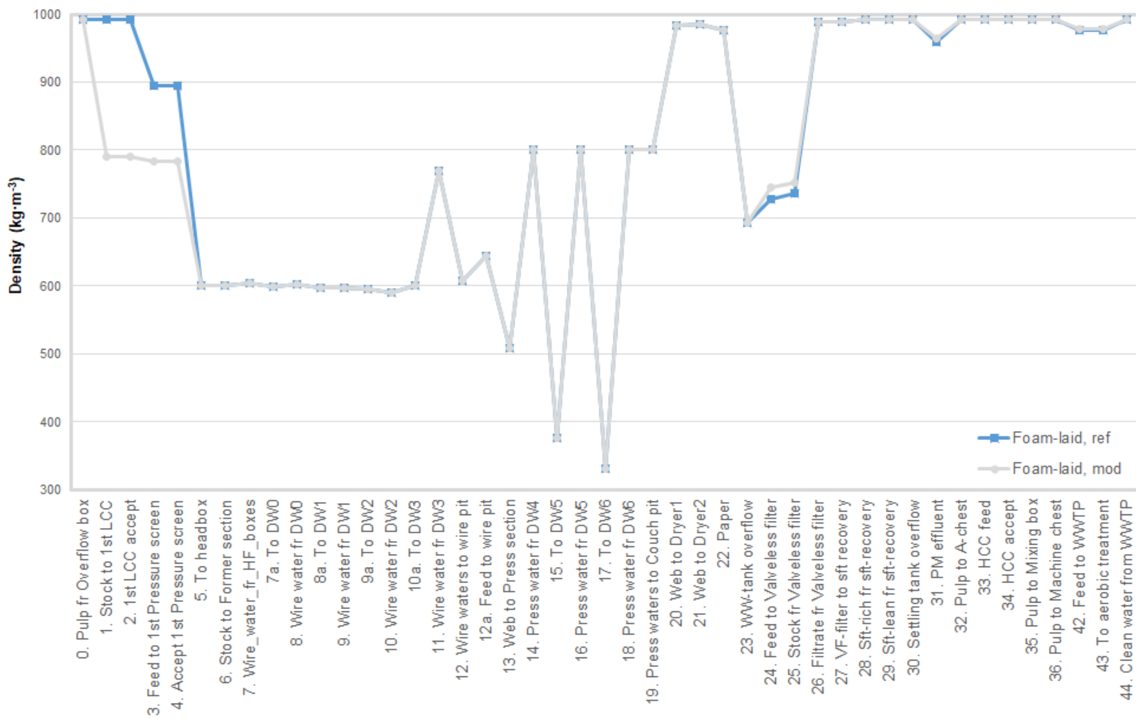

Fig. S7. Foam density levels throughout the process for both evaluated foam-laid cases. The observation point numbers refer to Figs. S2 and S5.

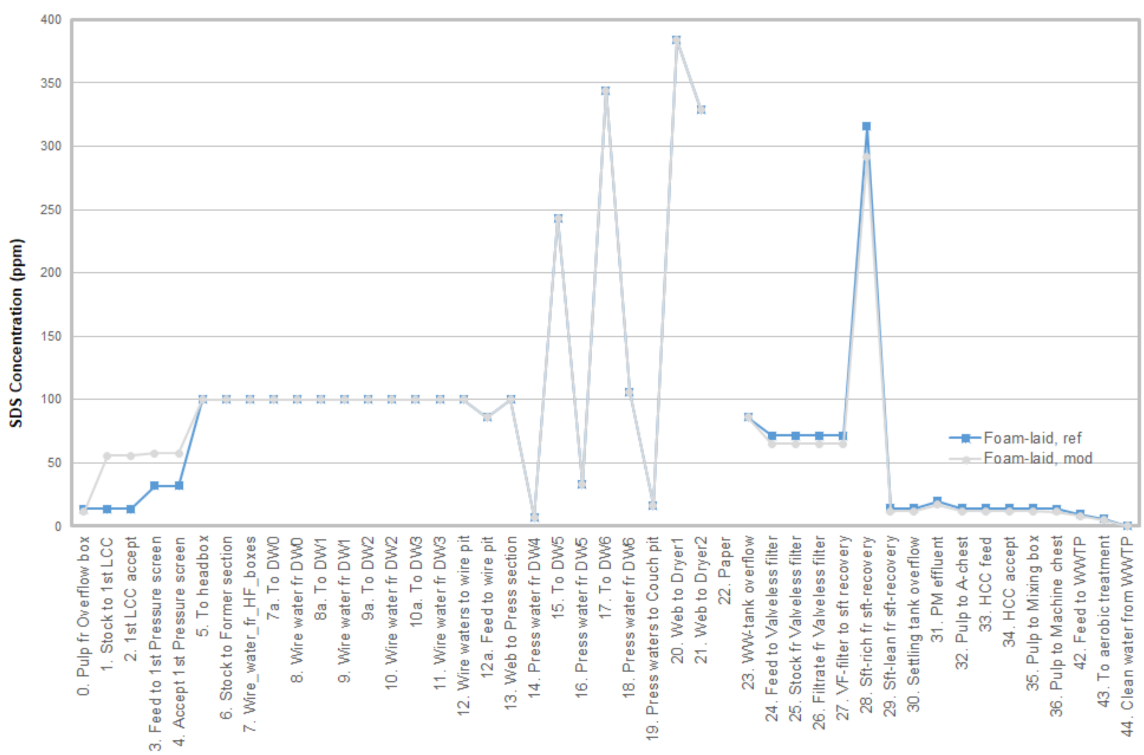

Fig. S8. Sodium dodecyl sulfate (SDS) concentrations throughout the process for both evaluated foam-laid cases. The observation point numbers refer to Figs. S2 and S5.