DEVELOPMENT OF A SALES PHASE TOOL FOR DUCTWORK ESTIMATION IN PAPER/BOARD MACHINE

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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Development of a sales phase tool for ductwork estimation in paper/board machine

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Keywords: Paper machine, board machine, ductwork, estimation, tool, sales phase

Air systems play a significant role in the operation of paper and board machines. In the former and press sections of the machine, the primary and most important task of the systems is to remove excess moisture and thus improve the driving conditions. Moving to the drying section, the systems consist of numerous runnability and pocket ventilation devices. These are aimed at ensuring uninterrupted paper web run on cylinders and maintaining uniform air conditions inside the hood. Air systems are also required in various air dryers and many others machine areas. Well-functioning air systems in machines require extensive ductwork to transport air flows.

In this thesis, a calculation tool is developed for Valmet's air systems unit to determine the ductwork quantities for paper and board machines. The purpose of the tool is to determine the amount of ducts with sufficient accuracy for pricing purposes in the sales phase. In addition, the adoption of the tool establishes a uniform pricing method for the department and eliminate differences in previous methods.

The tool was tested on two projects to determine its accuracy. The results obtained from the tool were compared to the planned weights of the projects' ductworks. Based on the tests, the tool was further developed, and its calculation models were adjusted for accuracy. The final accuracy of the tool was determined by comparing its results to the project's reference weights. The results obtained from the tool were 3.7% and 2.3% lower than the reference weights of the projects.

TIIVISTELMÄ

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Työkalun kehittäminen myyntivaiheeseen paperi/kartonkikoneen kanavistotarpeen määrittämiseksi

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Ilmajärjestelmillä on merkittävä rooli paperi- ja kartonkikoneiden toiminnan kannalta. Koneen viira- ja puristinosalla järjestelmien pääsääntöinen ja tärkein tehtävä on ylimääräisen kosteuden poisto ja näin ajo-olosuhteiden parantaminen. Kuivatusosalle siirryttäessä järjestelmät koostuvat lukuisista ajettavuus- ja taskutuuletuslaitteista. Näillä pyritään varmistamaan paperirainan katkeamaton kulku sylintereillä sekä tasaiset ilmaolosuhteet huuvan sisällä. Ilmajärjestelmiä tarvitaan myös erilaisissa ilmakuivaimissa ja monissa muissa koneen laitteissa. Paperikoneiden hyvin toimivat ilmajärjestelmät vaativat laajat kanavistot ilmavirtojen kuljettamiseksi.

Tässä diplomityössä kehitetään laskentatyökalu Valmetin ilmajärjestelmien yksikköön paperi- ja kartonkikoneiden kanavamäärien määrittämiseksi. Työkalun tarkoituksena on määrittää riittävällä tarkkuudella kanavien määrä hinnoittelua varten myyntivaiheessa. Tämän lisäksi työkalun käyttöönotolla valjastetaan osastolle yhtenäinen hinnoittelumenetelmä, minkä myötä aikaisempien menetelmien erot poistuvat.

Työkalua testattiin kahteen projektiin sen tarkkuuden määrittämiseksi. Työkalusta saatuja tuloksia verrattiin projektien kanavistojen suunniteltuihin painoihin. Testien perusteella työkalua jatkokehitettiin ja sen laskentamalleja muokattiin tarkemmiksi. Valmiin työkalun antamia tuloksia verrattiin vielä projektien vertailupainoihin, jonka perustella saatiin työkalun lopullinen tarkkuus. Työkalun tulokset jäivät 3,7 % ja 2,3 % vajaiksi projektien vertailupainoista.

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Fellow students, thank you for the time we had together and for the memorable moments we made. You made the academic years so unforgettable. Mom and Dad, I wouldn’t have made it this far without your encouragement and support, big thanks to you. In addition, warm thanks to all the loved ones who proofread this thesis. Making of this thesis has been a long process and I’m glad that I have been able to finish it.

In Jyväskylä 5th of April 2024

SYMBOLS AND ABBREVIATIONS

Roman characters

C_{vi}	exhaust point coefficient	[m^2/m]
C_{vt}	temperature correlation coefficient	[-]
qv	volume flow rate	[m^3/s]
v	velocity	[m/s]
L	length	[m, mm]
x	humidity	[kg H_2O/kg d.a.]
p	pressure	[bar, Pa]
T	temperature	[K, °C]
qm	mass flow rate	[kg/s]
D	diameter	[m, mm]

Greek characters

ρ	density	[kg/m^3]

Constants

π	pi	3,14

Subscripts

d.a.	dry air
h.a.	humid air
vi	exhaust point coefficient

vt	temperature correlation coefficient
H_2O,E	evaporated water
H_2O,v	outgoing water by runnability VacRolls
H_2O,c	outgoing water by runnability components
d.a, v	outgoing dry air mass flow by VacRolls
d.a, c	outgoing dry air mass flow by runnability components
e	exhaust air

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1 Introduction

Over the past decade, the paper and board industry has faced various challenges due to declining demand, and there is greater caution in investing in new machine lines. Machine suppliers must develop products and processes to be more efficient and cost-effective to meet today's market conditions. Air systems are an essential part of paper and board machines, necessary for moisture removal, paper drying, and maintaining optimal conditions throughout the production process. As a result, they play a crucial role in production efficiency and product quality. Well-functioning air systems for paper machines require extensive ductwork to transport airflows. The aim of this thesis is to develop an automated calculation tool for Valmet's Air Systems unit. The purpose of the tool is to accurately determine the amount of air ductwork needed for machines in the sale phase and to obtain more precise figures for the estimated costs of ductwork. The new tool is expected to expedite and streamline the sales process and create a unified price and quantity estimation for ductwork.

Initially, the thesis introduces the role and significance of air systems in machine operation in different parts to provide an understanding of the various air devices used and why they are essential for efficient machine operation. The former, press, and drying sections and the air equipment used in them, along with their operating principles, are presented as separate entities. The drying section's air equipment are divided into several sub-sections. The development section of the thesis describes the tool's development process, explains the calculations based on which the ductwork is dimensioned, and explains how the total mass of the ductwork is formed. The experimental part of the thesis remains only in client' use, which is why more detailed information about the air devices and the development of the tool cannot be provided.

Additionally, the thesis tests the developed tool on two projects to determine its accuracy. The tests are conducted using previous or ongoing projects where the planned weights of the project's ductworks are available. The weights of the project's ductworks are compared to the results provided by the design tool, and based on any discrepancies, the tool's calculation models are further developed to better match reality. This ensures that the tool is usable and can be implemented. Finally, the thesis provides brief instructions for using the tool and for further development. More detailed instructions are included in the tool itself.

2 Paper and board machine ventilation

Air systems play a significant role in the uninterrupted operation of machines. They are crucial for tasks such as removing moisture in the wet end and drying section, drying paper with separate dryers, improving web runnability, and maintaining a consistent air balance in the drying section. As a result, air equipment is necessary in every area of the machine.

The wet end (headbox, former and press section) of the machines requires well-designed ventilation systems to ensure optimal production efficiency and reduce quality errors in web. The exhaust system for the former and press section directly removes hot and moist air from various sources, preventing deterioration and corrosion, and enhancing working conditions. (Enerquin 2024.) In addition to the exhaust system, the ventilation systems for the former include dewatering and fabric conditioning equipment, which help remove water from the pulp and fabric, directly impacting production capacity and quality. (Valmet 2024a.)

The ventilation of the drying section includes supply and exhaust systems to maintain the correct humidity and temperature requirements within the hood. The purpose of the intake air is to supply hot, dry air to the hood, while the exhaust air removes the moist air evaporated from the paper web during the drying process. Typical intake systems include various blow boxes, pocket ventilators, and additional blowing devices. The exhaust system primarily consists of vacuum rolls and exhaust points located in the hood ceiling (Sarli 2018).

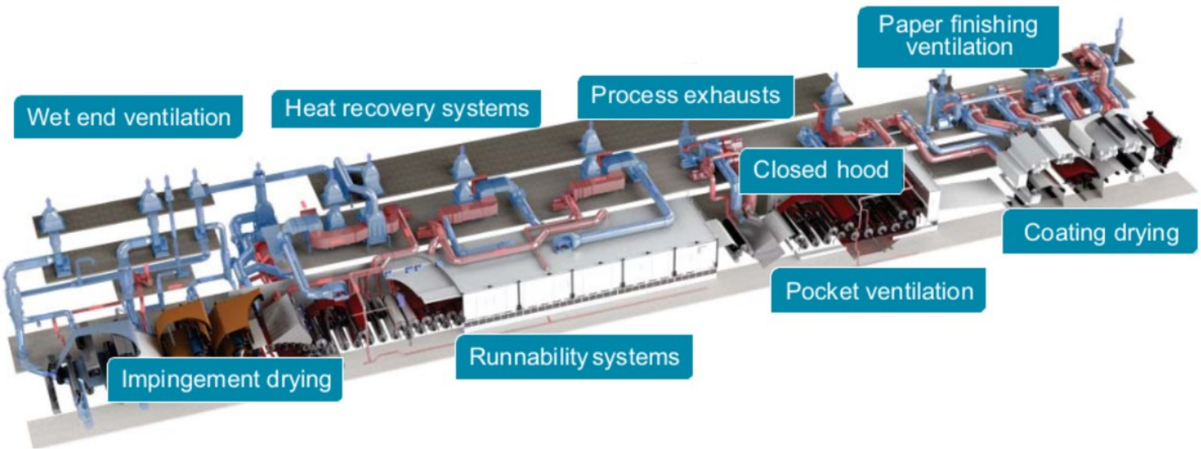

Figure 1. Machine ventilations (Valmet Technologies 2017d.)

Figure 1 shows illustrative image of machine ventilations. In addition to the wet end and drying section, air ventilation is also required for various other parts of the machine, including pulpers, reel, and sizer. Ventilation is also essential for coating drying air dryers and paper finishing area, but these have been excluded from the scope of this work. However, the work includes impingement dryers, which are used to dry the web before it enters the drying section or at the end area of drying section.

2.1 Forming section

The formation of paper/board starts on the headbox/forming section, where stock flow from headbox is spread on to wire. At this point, the consistency percentage of the flow is typically less than one, so there is more than 99% water. The main principle in the forming section is to "form" the fibers into the right structure for the final product and increase the consistency percentage to 15-25% by removing water from the pulp. (ForestBioFacts 2020a.)

There is comprehensive selection of different former applications for paper and board machines. Choosing the right former type mainly depends on the desired board/paper species, quality, and machine speed and width. However, application solutions can be divided into three main sections; gap formers, hybrid formers and fourdriniers, which can be modified according to the customer's needs. (Valmet 2023a.) By this, the needed ventilation equipment also varies with the former models, but all air equipment can be divided into exhaust, fabric conditioning and dewatering equipment. Figure 2 shows some ventilation point of a type of hybrid former.

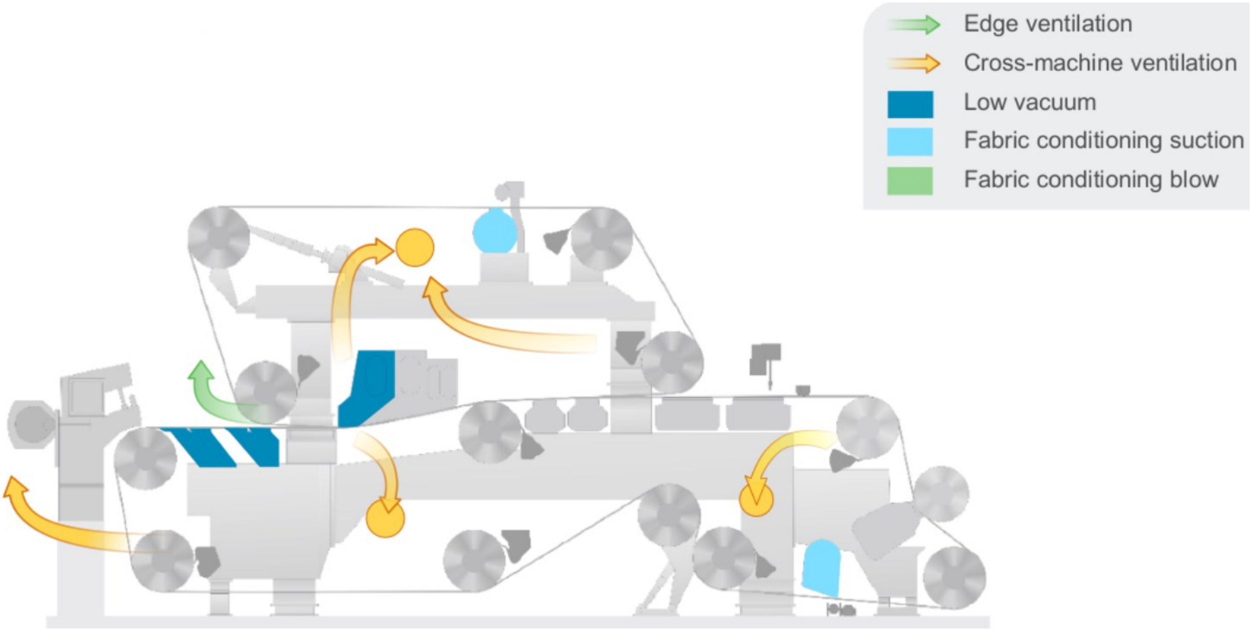

Figure 2. Example of former ventilation points (Valmet Technologies 2021.)

The yellow and green arrows indicate the locations of the former's exhaust points. Fabric conditioning equipments are presented by light blue shapes, while dewatering devices are presented by dark blue shapes. Exhaust ventilation has been designed to remove effectively mist and humidity which develops in the forming section and to decrease dirt build-up. Depending on former type, size and speed, warm and humid air have to exhaust several places. Especially as the machine speed increases, the exhaust locations multiply. A common example of an exhaust location is under the headbox.

Fabric conditioning equipment consist of Mist Collector/Ventilator, Vacuum Fabric Cleaner and Blow Cleaner, and they are used to clean and condition the fabric and to collect water mist created by HP (high pressure) showers. BlowCleaner dries the fabric for a uniform moisture profile with an air blow and eliminates possible water streaks caused by HP showers. Vacuum Fabric Cleaner removes the water mist produced by the high-pressure shower and dries the fabric with the suction box. Mist Collector and Ventilator remove the water mist penetrating through the fabric. Mist Ventilator can replace Mist Collector case by case or they can be used together in larger formers. Basically, the Mist Collector/Ventilator is not used together with the BlowCleaner, only either solution is chosen. In largest formers, e.g. a fourdriner with three or four headboxes, both solutions can be used simultaneously.

To remove fibres and water from the air in the exhaust ducts, Mist Collector/Ventilator and Vacuum Fabric Cleaner are equipped with water separators and droplet separator.

Dewatering equipment include Vacuum deflector, VacuShoe, VacuBalance, Vacufoil boxes and Wet suction boxes. The operation of the equipment is based on under pressure, whereby moisture is removed from fabric. Depending on the type of former and the desired characteristics, specific dewatering equipment is required. For example, boxes are typically used in larger formers, like in multifourdriniers.

2.2 Press section

The main task of the press section is to remove water by wet pressing. Wet pressing aims to get the web as dry as possible before the drying section in order to achieve the best driveability there. Water is removed from the wet web in nip formed by two rolls or a roll and a shoe. The water obtained from the web moves either to the cavities on the surface of the roll or to the wet fabric. The 15-25% dry matter content previously obtained in the former section is aimed at getting 40-50% with the press section. The press unit typically consists of 2-4 separate nips. (ForestBioFacts 2020b.)

Valmet mainly uses two different press concepts: OptiPress Center and Linear. Two nips Linear is excellent for paper grades, while the Center with a central roller base is preferred for cardboard production. (Valmet 2023b.) Air system of the press section consists of exhaust ventilation and runnability equipment. With both press types total air amount is in the same scale. Figure 3 shows exhaust points of linear press.

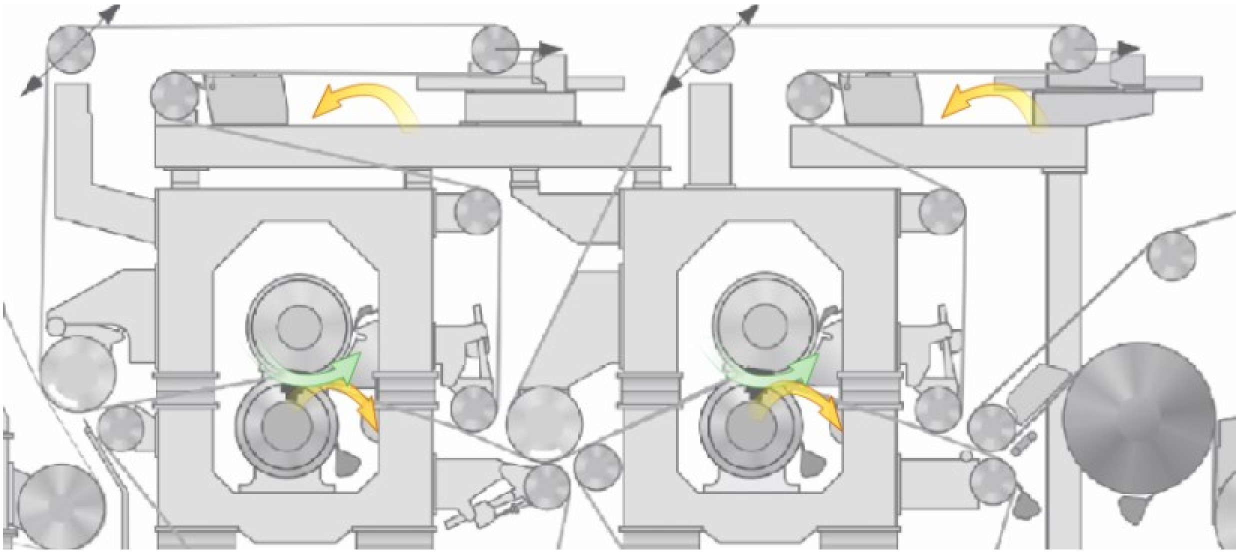

Figure 3. Exhaust ventilation points of linear press (Valmet Technologies 2021.)

If the machine speed is low enough, there may not be a need for exhaust ventilation at all on the press. However, when the machine speed is sufficiently high, ventilation becomes necessary, first above the nips (green arrows in the image). At even higher speeds, ventilation is required below the nip and from other parts of the press (yellow arrows). Exhaust ventilation task is removing humid air from the press section to reduce the formation of mist. Like in former section exhaust ventilation, ductwork has equipped with droplet and water separators.

For better quality and higher driving speeds, two different blow box principle using driveability components can be used in the press section to support runnability: Press Nip Web Stabilizer and Press Run Web Stabilizer. In figure 4 is shown both stabilizers, Press Nip in left and Press Run in right.

Figure 4. Press Nip and Press Run Web Stabilizers (Valmet Technologies 2020.)

The purpose of Press Nip Web Stabilizer is to prevent air bubbles in the nip. Blow box is placed before the press nip and the vacuum created by it prevents the web from fluttering and the appearance of wrinkles by holding the web in the press felt. Stabilizer is especially necessary in new and open press felts. The function of the Press Run Web Stabilizer is to support the passage of the web, remove free draws and improve runnability before the web moves from the press to the drying section. The blow box creates the necessary under pressure so that the web remains well supported on the drying fabric. (Valmet Technologies 2012a, 8-10.)

2.3 Drying section

Undoubtedly, the most common drying method in the paper and cardboard industry is to use steam cylinders, which transfer heat from the cylinder to the web. Cylinder drying has several advantages, such as its energy efficiency, the possibility of controlled web transport, low toxicity, and easy portability. Additionally, modern paper mills can be part of a larger mill integration, where there is also a pulp mill that provides steam as a byproduct. (Slätteke 2006, 22.) The drying section of the machine consists of cylinder groups, of which there are typically 5–10 in a modern machine. The most common configurations for cylinders are double-felted and single-felted fabric systems, but cylinders can be arranged in many other ways as well. (Ahtila et al. 2010, 80.)

To support and transport the paper web in the drying section, there are used drying wires. In addition to transportation, another crucial function of the wires is to press the web against the cylinder to enhance heat transfer. As the name suggests, the double-felted configuration consists of two drying wires, where one passes the bottom cylinders and the other the top cylinders. In this configuration, the paper moves from one cylinder to another without support, which can lead to issues such as wrinkles and sheet breaks. (Slätteke 2006, 23–24.) The advantage of the double-felted configuration is the increased number of drying cylinders compared to the single-felted configuration, providing more drying surface area. However, this assembly does not offer sufficient support for the web at higher machine speeds. In Figure 5 shows both configurations, with the double-felted configuration at the top and the single-felted at the bottom. In the upper image, dashed lines represent wires, and in both the black line represents the web or the web and wire together.

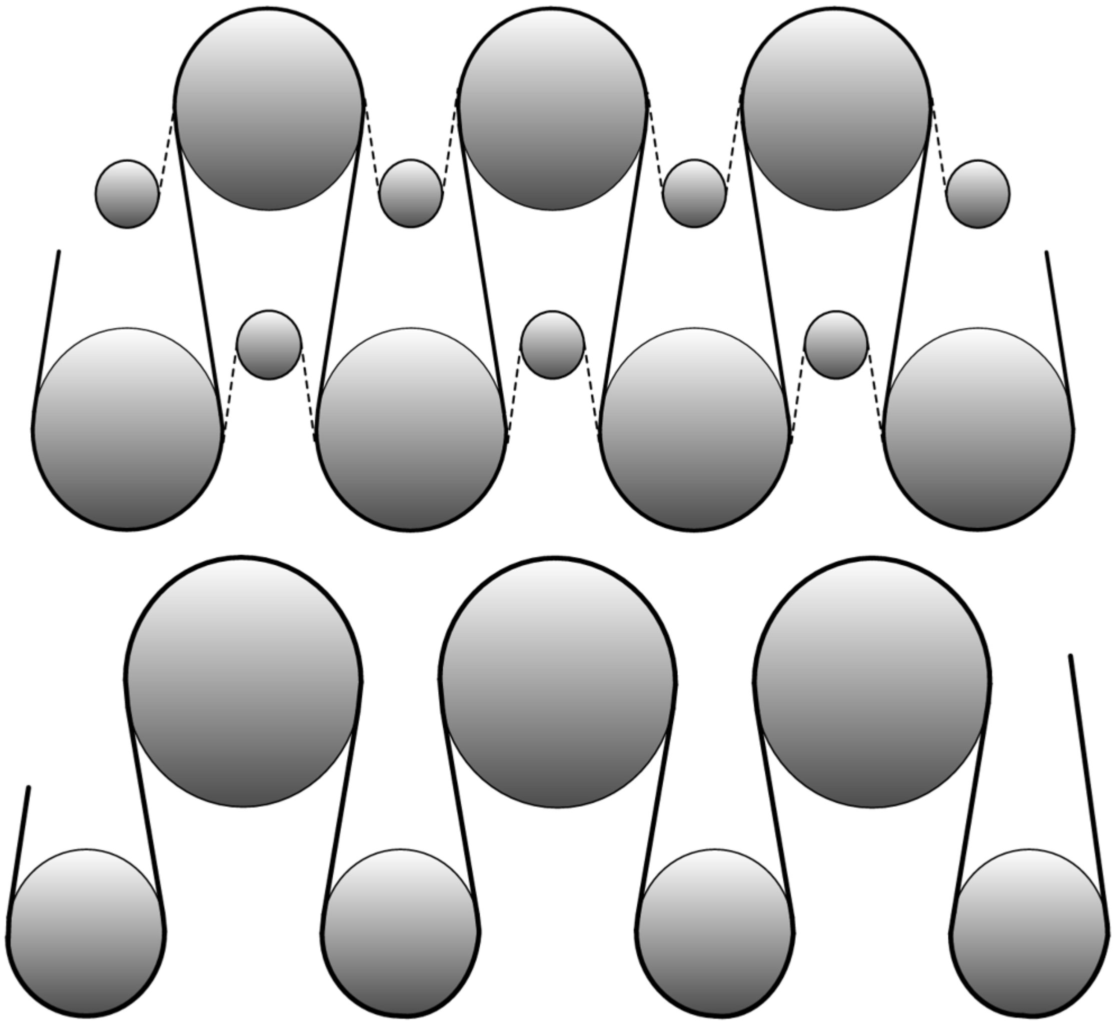

Figure 5. Double- and single-felted configurations of drying cylinders (Slätteke 2006, 23-24.)

The use of the double-felted configuration becomes problematic at high machine speeds, especially in the wet area of the drying section due to the low wet strength of the paper. In such cases, the single-felted configuration is employed, allowing better runnability and web control as the wire supports the web throughout the entire path. Since the fabric is between the web and the bottom cylinders, there is no significant drying happening in that space. Therefore, the lower row of cylinders is replaced with smaller suction rolls, improving runnability and preventing the web from dropping. (Ahtila et al. 2010, 81–82.)

Nowadays, drying section solutions consist of three main concepts: single-fabric dryer sections, double-fabric dryer sections, and hybrid drying sections, which are a combination of the first two. In a hybrid drying section, there is a single-fabric configuration at the beginning and a double-fabric at the end. The single-fabric dryer section provides excellent runnability and productivity with consistent quality, and it is a typical solution for the predrying section of high-speed paper machines. The double-fabric drying section enhances drying efficiency and is typical solution in the after drying section. The hybrid section is used mainly in predrying section, and it combines the best features of both solutions. In addition, there are triple-tier dryer sections designed for heavy board machines, usually used in rebuilds when space is limited. Regardless of the concept, a comprehensive ventilation system is needed in whole drying section. The concept only determines the types of air equipment that can be installed for each group. However, in all machines, the drying section requires own ventilation system for blow boxes, pocket ventilators/other blow applications, vacuum rolls, and hood exhaust air. (Valmet 2024b.)

2.3.1 Hood supply and exhaust air

All paper machine dryer sections are equipped with a closed hood. Hoods were originally developed to improve working conditions by keeping heat and moisture out of the machine hall. However, today they play a crucial role in influencing the drying efficiency and energy economy of the machine. To ensure the most efficient drying of the web, a sufficient amount of air must be supplied to the hood to prevent condensation and keep pocket humidity low. At the same time, air must be continuously removed from the hood to create a uniform moisture profile, because moist air is constantly generated. Balance for a closed hood in a modern machine is good to be close to 0.8, meaning that the amount of supply air is 80% of the exhaust air. If the hood balance is too high, it leads to steam leakage into the machine room, while too low a balance causes sweating, runnability issues, and quality defects. To achieve the optimal hood balance, it is essential to have a precise understanding of evaporation rates depending on the paper grade and production volumes, as well as the desired moisture content of the exhaust air. As seen in Figure 6, maintaining the hood at a higher moisture level brings significant advantages. With higher air moisture in the hood, smaller supply and exhaust air volumes are sufficient, and there is greater potential for heat recovery. However, the moisture level in the hood cannot be raised too much, as this would slow down the drying of the web. (Ghosh 2010, 558–560.) In addition, raising humidity reduces the need for exhaust air and this is lowering the difference between temperature supply air and dew point. Maintaining a significantly higher dry-bulb temperature than the dew point is crucial to prevent moisture condensation, which could be detrimental to paper quality and potentially lead to web breaks. (Kong 2016, 1648.)

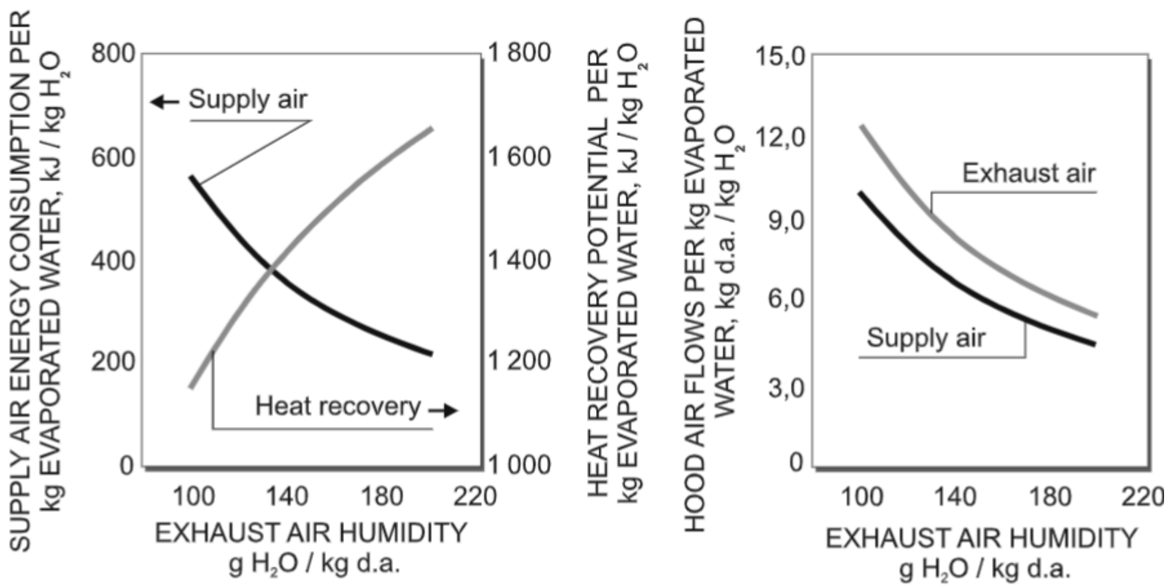

Figure 6. Influence of exhaust air humidity on energy consumption and air flows of the hood (Ahtila et al. 2010, 460)

Most of the dry and warm air to the hood comes through blow boxes and pocket ventilators. Air is also entered into the hood through various blowing mechanisms and the rest air enters the hood as leakage air from the lower part of the hood. Some of the moist air is removed directly through vacuum rolls and the suction side of blow boxes, but the majority of the air is removed through the roof. Hood exhaust air is utilized in heat recovery towers, for example, to heat the hood supply air or process water. (Ahtila et al. 2010, 439.)

2.3.2 Blow boxes

Paper machines have been continuously developed to be faster and more productive, but the increasing speed of the machine brings problems which are related to runnability such as paper web flutter, quality defects and wrinkles. At high driving speeds, the air currents cause the paper web to detach from the drying fabric or press felt in the nip areas. Especially in drying cylinder opening nip, due the effecting under pressure, paper web tends to detach from the surface of the drying fabric and tends to follow the surface of the drying cylinder. (Valmet Technologies 2012a, 5-6.)

Blow boxes are runnability components which are placed in the upper pockets formed between rolls to improve machine runnability. With upper pocket is meant space above bottom roll and between upper drying cylinders. Bottom pocket respectively means space under upper drying cylinders and between bottom rolls. The purpose of the boxes is to create a vacuum area between the box and the drying fabric, which sucks the web to the fabric. Vacuum area is created as a result of the Coanda effect when the box nozzles blow air at high speed. (Valmet Technologies 2012a, 4-5.) Figure 7 shows example one type of blow box and critical points for runnability. The opening nip of the drying cylinder, where negative pressure tends to pull the web off the fabric according to the drying cylinder and the closing nip of the lower roll (vacuum roll in the picture) is formed overpressure, which tends to push the web off the fabric. As well as the web rotates around the lower roller, the centrifugal forces tend to drop it off the fabric and in the closing nip of the drying cylinder, the air flows between the paper and the fabric cause the paper to detach and the flutter edge of the web. (Valmet Technologies 2023c.)

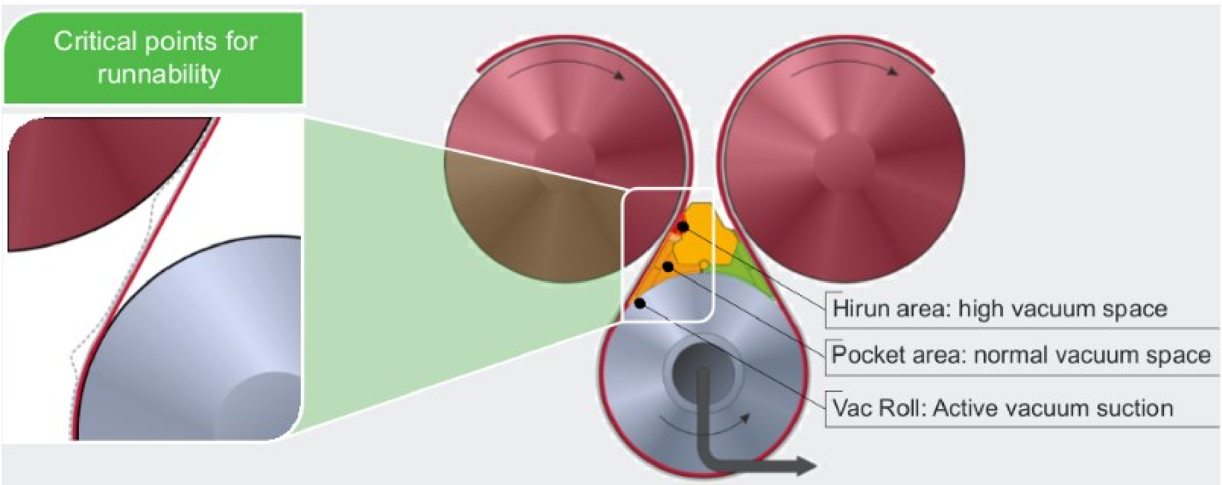

Figure 7. Hirun Web Stabilizers operating principle (Valmet Technologies 2023c.)

Various blow boxes have invented to fulfill drying groups' different requirements. HiRun Web stabilizers has been created to reduce runnability problems in the first group(s) of single-fabric sections. In the first groups, web is still really wet and dries slowly, so it can be difficult to control the web in increasing machine speed. Thus, the required negative pressure and air amount is biggest in the first pockets in order to control the web. (Valmet Technologies 2017c.) After web is slightly dried and its control is easier, instead of HiRun, Web Stabilizer SRE/SR is used remaining single-fabric cylinder groups. Operating principle and intended use is however same as HiRun. Blow box principle is also used in impingement dryers and in the previously presented wet end runnability equipment in Press Run/Nip Web Stabilizers.

2.3.3 Pocket Ventilators

Pocket Ventilators purpose is to increase ventilation and also balance air flows and humidity profiles in pockets by blowing warm and dry air into the pocket as well as same time stabilize the web run and intensify drying capacity. Figure 8 shows example placement of Pocket Ventilators in single- and double fabric groups. In single-fabric groups Pocket Ventilators are placed to bottom pocket and in double-fabric groups Ventilators are placed in both bottom and upper pocket. (Valmet Tecnologies 2012a, 12-16.)

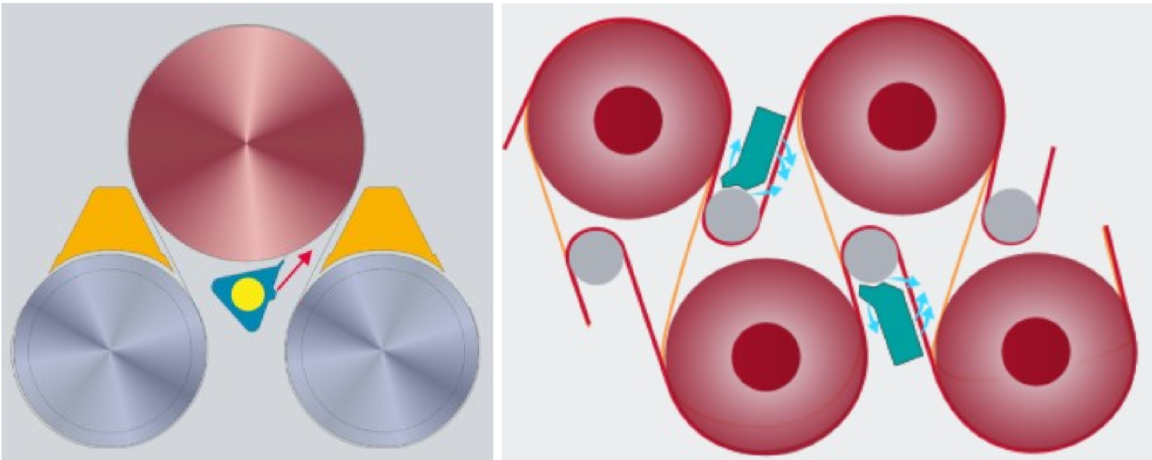

Figure 8. Ventilation Doctor in single-fabric section in left and Web Stabilizer TR in double-fabric section in right (Valmet Technologies 2020)

Type of Ventilator is chosen depending on the paper/board grade and speed of the machine. Pocket Ventilator UR and Ventilator Doctors are used single-fabric groups. Pocket Ventilator UR is designed just blow air to pocket but Ventilator Doctor combine air blowing and roll cleaning. Pocket Ventilators for double-fabric groups are Dryer Pocket Ventilator, Dryer Pocket Ventilator B and Web Stabilizer TR. Ventilator B is created for board grades to get large air flows and high drying capacity. At higher machine speeds also in double-fabric section, stabilizing is needed for web runnability. In addition to ventilation TR creates a negative pressure area against the fabric by blowing, which helps the web stay in controlled manner on the fabric so at the same time it is also a blow box. (Valmet Tecnologies 2012a, 12-16.)

2.3.4 VacRolls

At higher machine speeds, smooth rolls are no longer able to keep the web attached to the drying fabric. As a result, machines use grooved and drilled suction rolls. Roll internal suction within the grooves creates an under pressure that helps the web adhere to the drying fabric, and thus preventing runnability issues such as fluttering. Earlier in the blow box section, critical points for runnability were presented. Closing and opening nip on the bottom roll need additional support for runnability in addition of blow box, and thus, the vacuum areas are designed so that the supporting effects of the suction roll are highest at edge areas. VacRoll rolls are always used in single-fabric groups as a bottom roll with a blow boxes. In Figure 4, VacRoll is shown with the HiRun blow box. In addition to the drying section, VacRoll is used in impingement dryers, and in the press section a transfer suction roll is used which is like VacRoll. (Valmet Technologies 2017b.)

2.3.5 Impingement dryers

Paper and cardboard industry has a long-standing characteristic of making machines more and more productive, achieved by simply increasing machine speeds. In addition to the challenges related to drivability, which increased speed of the machine brings, insufficient drying capacity is a notable issue. Cylinder drying has many advantages, but as machines are developed to be faster, the heat transfer time between the drying cylinder and the web decreases. Consequently, to achieve sufficient drying, the drying section needs to be extended, leading to significant additional investments. To enhance productivity, a better solution is seen in integrating impingement dryers into the drying process. (Hashemi S.J. & Murray Douglas W.J 2006, 2488-2499; Hashemi S.J. et al. 2006, 2526.) Dryers not only enable to increase machine speed, but due to their high drying efficiency, the number of cylinder groups can be reduced, thereby shortening the length of the machine. The use of air blowing also allows for much faster adjustment of drying conditions compared to cylinder drying, improving quality control, and enabling quicker and more efficient grade changes. The steam used in drying cylinders cannot be efficiently raised to a high enough temperature to heat the air for the dryers. Therefore, a common solution for heating the blowing air is to use gas burners. (Karlsson 2001, 724–725.)

Valmet has developed three types of Impingement dryers: OptiDry Vertical, Horizontal, and Twin. In figure 9, is shown Vertical dryer and its air system.

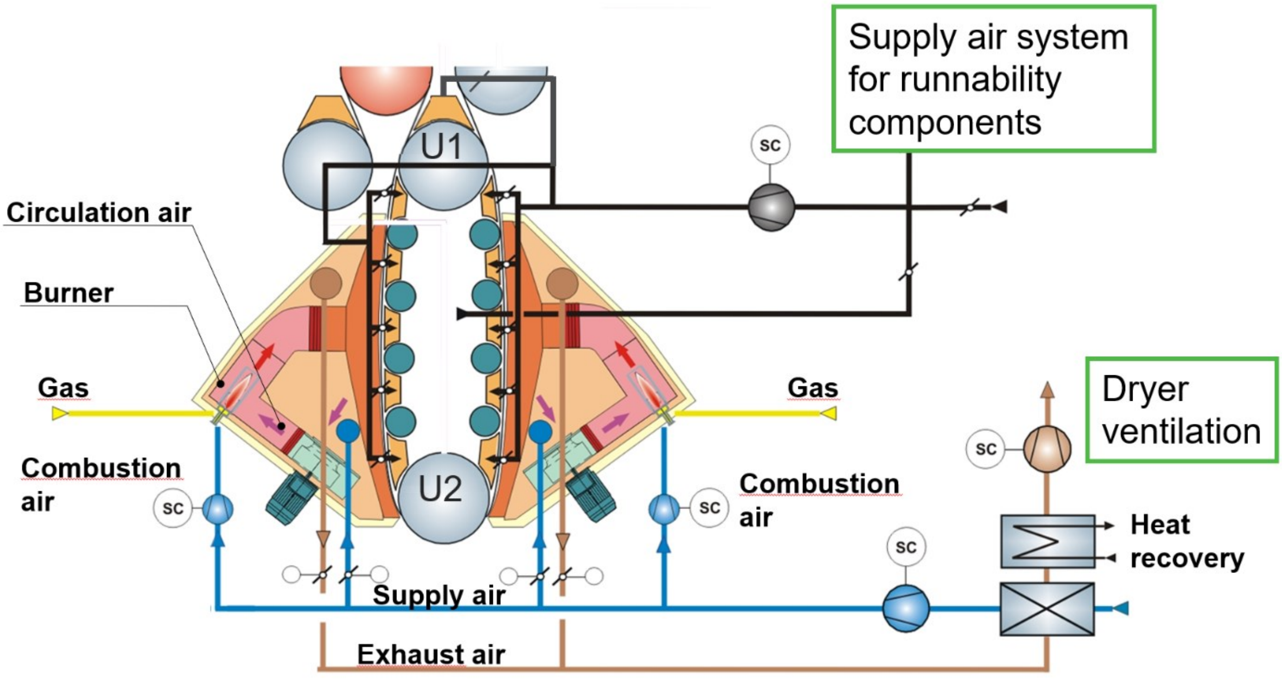

Figure 9. Air system for OptiDry Vertical impingement drying unit (Valmet Tecnologies 2012b.)

The Vertical dryer unit in the picture consists of two vertical dryers between which the web runs. Vertical dryer is a convenient solution for rebuild projects as it can be positioned easily below the drying group. The Horizontal unit comprises a single dryer placed horizontally above the group towards the end of the machine's drying section. The purpose of this placement is to prevent web curling, ensuring that one side of the web is dried last. The Twin unit is a combination of these two, with a horizontal dryer located above the vertical one. Twin is used as a boost the drying immediately at the beginning of the drying section.

All drying techniques are based on blowing hot air at high speed towards the web. Each dryer has multiple burners and circulation air fans that heat and circulate the air within the dryer. As seen in the figure, the dryers have a very extensive air system relative to their size when compared to other areas of the machine. Each dryer requires inlet air for combustion, circulation, cooling, and drivability components, as well as exhaust air from the dryer and vacuum rolls. (Valmet Technologies 2012b, 7–10.)

3 Tool development

The purpose of this thesis is to develop calculation tool for Valmet's Air Systems unit, which enables the automated determination for the amount of ductwork on the sales phase for paper and board machine lines. The tool provides results that are indicative estimates of how much ductwork is required for a machine line, but accurate enough to be used in the pricing of quotation during the sales phase. In addition to more accurate pricing, the development of the tool aims to integrate and expedite the pricing methods used. The tool standardizes a common pricing practise for sales, eliminating differences between various ones.

The tool operates based on user inputs, through which it determines the required amount of ductwork for each section of the machine. Inputs include basic machine numerical specification and the types and quantities of various optional components included in the machine. For some inputs, typical reference values can be used, which are pre-set on the input tab. However, the more precise values the user can set, the more accurately the tool determines the ductwork requirement. The calculation of duct sizes is based on determining the volume flows, lengths, and diameters of the ducts, from which the tool calculates the required masses for the ductwork. The calculation also defines how many and what types of duct sections are needed in the machines and how they change with variations in the input data.

The development process of a successful tool requires careful planning to ensure its user-friendliness and efficient operation. The initial steps in the development involve familiarizing oneself with the requirements of paper machines and the technical characteristics of air systems. This is essential to gain the necessary understanding of the purposes and functions of various air devices as part of the machine line. This knowledge forms the basis for creating calculation models for "products," taking into account relevant variables. After creating the models, the focus shifts to designing the user interface. The goal of a user-friendly tool is to provide an easy and intuitive way to input necessary information, considering the users' needs. This ensures that the results from the tool can be utilized as efficiently as possible. Finally, it is crucial to verify that the tool functions as expected and provides reliable results in various usage scenarios. Taking user feedback and test results into account, the calculation models of the tool are refined before its implementation.

During the evaluation of thesis scope, it was agreed that alternative development platforms were not considered. From the beginning, the decision was made to use Microsoft Excel as the basis for the tool. An essential factor in this decision was to consider who are the tool users and what kind of platform would be familiar to them for tool usage. Excel was well-suited for this purpose, because it is a widely known and used software. This facilitates the adoption and smooth use of the tool, as users do not need to learn something new. Excel provides a user-friendly interface, and even inexperienced individuals can quickly grasp its operating principles. From the developer's perspective, Excel was an excellent choice as the foundation for the tool. It is a highly familiar software used in studies, work, and daily life. Its versatile and user-friendly formulas and functions expedite tool development by offering various calculation options. Additionally, even the most challenging aspects of tool automation can be addressed using the VBA programming language. Looking ahead, the current model can be easily modified and updated to meet evolving needs.

3.1 Dimensioning

Dimensioning the ductwork is a crucial element in the development of the tool. Creating the calculation basis and its automating requires careful work to avoid errors in the tool. The tool dimensions more than half a thousand individual ducts, and each one based on determining their specific air needs. Consequently, small errors may be challenging to notice when reviewing ductwork models later. These small errors can be deceptive in the overall calculation because, even if they don't affect the size of an individual small duct, several small ducts together can impact the main duct where they converge. An increase in the size of such a duct can significantly raise the total mass of the ductwork. In addition to air volume, the tool defines the diameter and thickness for the ductwork. The diameters and thicknesses are standardized sizes that depend on the air volume flow and the air velocity. All straight ducts are dimensioned as round ducts with longitudinal seams. The most common material for ducts is galvanized or aluzink steel, especially used in the drying section and the other dry areas of the machine. In addition to these, stainless steel is a common material for ducts, particularly in the former and the press section. In extremely hot ducts, such as in parts of OptiDry, corten steel can be used. Ducts still need to have appropriate lengths determined and coefficients for additional ducts elements are created, contributing to the overall mass of the ductwork.

3.1.1 Determining air volume flows

Air volume flows are mainly obtained from equipment data, where the required air quantity is specified. The air requirement is typically expressed in units of m^3/h/m, meaning cubic meters of air per hour per width. There are also many areas where the air volume flow cannot be determined solely based on width, but it serves as the foundation for all calculations. Examples of such areas include former section and press exhaust air, OptiDry dryers, hood exhaust air, and pulpers. To ensure optimal performance of all air devices, ducts are oversized by ten percent.

In the wet end, the required exhaust air for the former section and press depends on the machine speed and stock temperature, in addition to the width. To each exhaust point is pre-defined coefficient C_{vi}, [m^2/m] which describes the exhaust area per meter of width. The effect of stock temperature is considered as a coefficient C_{vt} when the temperature is above 50 °C. In this case, each degree above 50 increases the required exhaust air by 2%. Equation 1 below represents the exhaust volume flow rate qv [m^3/s] for the former section and press.

$$qv = C_{vi} * C_{vt} * v * L \tag{1}$$

, where v [m/s] is the machine speed and L [m] is the width of the former section. The specific air requirements per width are notified for the former section's Fabric Conditioning and Dewatering devices, as well as for the press's runnability components and suction rolls. The air volume flow for these components can be calculated by multiplying the requirement by the width of the fabric.

Also in the drying section, the specific air requirements for all runnability components, vacuum rolls, and pocket ventilators are notified. Only for the OptiDry dryer, the supply, combustion, exhaust, and cooling air quantities is determined differently. The intake, combustion, and exhaust air for the OptiDry dryer depend on numerous factors, making their determination potentially too laborious for the development of this tool. Since these values can be obtained directly from a separate calculation program, they are not individually defined in the tool but requested as input. The cooling air for the dryers can be calculated based on amount dryer blocks and recirculation fans. Each dryer block and recirculation fan have a constant cooling requirement. The number of dryer block depends on the type of OptiDry dryer, and the number of fans depends on the machine's width.

Outside the wet end and drying section, air is used for web threading in the reel, sizer supply and exhaust, and pulpers exhaust. The reel and sizer also have specified air requirements relative to their widths. The exhaust air requirement for pulpers is based on the opening area, surface speed, and mass temperature coefficient. Opening area refers to the total surface area of the pulper opening, surface speeds are individually defined design speeds for each pulper, and the mass temperature is noticed as a coefficient in the same way as in the wet end when the temperature is above 50°C.

3.1.2 Hood balance: Exhaust and circulating air volume flow

Moist air is extracted from the closed hood through the hood roof. Determining the quantity of exhaust air requires consideration of the balance between the air volume and humidity in the hood. To maintain this balance, the humidity content of the exhaust air from the hood must be equal to the sum of the humidities of the incoming air to the hood and the difference in the humidities of the air leaving the hood through other means. Moist air is removed directly by vacuum rolls and runnability components with suction sides, while the remaining moist air is extracted through the hood roof. Air enters the hood as supply air for runnability components, pocket ventilators, and other blowings, as well as leakage air from the lower part of the hood. In a high-performance hood, the typical humidity of the exhaust air is 0.160–0.180 kg H_2O/kg d.a.(dry air), with a temperature of 80–90 °C and a leakage air quantity of 10–30% of all incoming air (Ahtila et al., 2010, 444). In the after-dryer, these reference values for humidity and temperature are slightly lower because there evaporates much less water than in the pre-drying section, but the leakage air quantity typically increases.

To determine the quantity of exhaust air from the hood, it is initially necessary to define the amount of water being removed with the vacuum rolls and runnability components. The amount of water formed from the paper drying in the hood kg H_2O/s is get as input data to the tool. The humidity and temperature of the air leaving through the vacuum rolls and runnability components depend on the number of fans, and these values are not the same for each fan. If there is only one exhaust fan, the average humidity and temperature of the exhaust air are used as the values. If there is more than one fan, the humidity and temperature of the exhaust air for the first fan is reduced from the average values, and the values for the last ones fans are elevated.

The average humidity of the hood exhaust air is requested as input data in the tool because it has a significant impact on the calculation and can vary depending on the project. Even though it could be determined based on the paper grade and maximum steam pressure, it is crucial to ensure its accuracy, especially since it might deviate from typical values. The average temperature of the exhaust air is directly proportional to the maximum steam pressure, which is also provided as input data. The density of exhaust air ρ [kg/m3] can be calculated using equation 2 (Ahtila et al. 2010, 442).

$$\rho = \frac{216{,}67 * p * (x + 1)}{T * (x + 0{,}622)} \tag{2}$$

,where p is pressure [bar], x air humidity [kg H_2O/kg air] and T temperature [K]. The pressure used is the standard atmospheric pressure of 1,013 bar. The dry air mass flow $qm_{d.a.}$ [kg/s] of the total mass flow can be calculated using equation 3.

$$qm_{d.a.} = \frac{qv_{h.a.} * \rho}{1 + x} \tag{3}$$

, where $qv_{h.a.}$ (humid air) is the volume flow rate of humid air, which is the amount of air removed by the equipment and is determined based on the amount of equipment. Thus, the mass flow rates of waters removed by the equipments qm_{H2O} [kg/s] can be calculated for each equipment area using equation 4.

$$qm_{H2O} = \sum qm_{d.a.} * x \tag{4}$$

The volume of hood exhaust air can be determined through the balance, considering the moisture generated within the hood, incoming moisture to the hood, and outgoing moisture from the hood. The humidity of the air supplied to the equipment, and the leakage air remains constant. On the right side of the equation, factors include the moisture generated in the hood and the incoming flows to the hood. On the left side, there are the outgoing flows from the hood. The incoming flows are expressed using outgoing flows with the humidity of dry air since the volume of air entering the hood must equals the volume that is exiting.

$$qm_{H20,E} + x_{d.a.} * \left(qm_{d.a,v} + qm_{d.a,c}\right) + x_{d.a.} * qm_{d.a,e} = qm_{H2O,v} + qm_{H2O,c} + x_e * qm_{d.a,e}$$

, where $qm_{H2O, E}$ is the amount of generated water [kg H_2O/s] due to evaporation in the drying section., $x_{d.a.}$ humidity of the dry supply and leakage air, $qm_{d.a.. v}$ dry air mass flow exiting through the vacuum rolls [$kg_{d.a.}$/s], $qm_{d.a. c}$ dry air mass exiting through the runnability components. [$kg_{d.a.}$/s], $qm_{d.a. e}$ dry exhaust air leaving the hood [$kg_{d.a.}$/s], $qm_{H2O v}$ water exiting through the vacuum rolls. [kg H_2O/s], $qm_{H2O c}$ water exiting through the runnability components [kg H_2O/s] and x_e exhaust air humidity. The dry mass flow rate of the hood exhaust air can be obtained with equation 5.

$$qm_{d.a,e} = \frac{qm_{H20,E} + x_{d.a.} * (qm_{d.a,v} + qm_{d.a,c}) - qm_{H2O,v} - qm_{H2O,c}}{x_e - x_{d.a.}} \tag{5}$$

After this, the density of the hood exhaust air can be calculated using Equation 2 and the volume flow rate using equation 3.

Circulation air is the air taken from the hood's roof, which is mixed with supply air to supplement the required air volume for blow boxes. The amount of new supply air is typically 70% for the predrying section and 60% for the afterdrying section of total exhaust air volume. When here subtracting the air volumes needed for pocket ventilators and other blow applications, the remaining air volume may not be sufficient for the blow boxes. The remaining supply air for blow boxes is distributed to HiRun, SymRun, and TwinRun boxes based on their total need as follows:

$$qv = \frac{qv_n}{\sum qv_n} * qv_l \tag{6}$$

, where qv_n is the total air demand of either HiRun, SymRun ja TwinRun blow boxes, $\sum qv_n$ is the total air demand of all blow boxes and qv_l is the remaining supply air for the blow boxes. The amount of circulating air is then calculated by subtracting the available air demand for the blow boxes from their total air demand. There may be cases where the air need for pocket ventilators and other blows is so large compared to the amount of supply air that is available that supply air for blow boxes consists almost entirely of circulating air. In such cases, it is advisable to increase the percentage of supply air.

3.1.3 Diameter and thickness

The diameters of the ducts are standard sizes, and each section has its own thickness requirements based on the diameters and the material used. Each air equipment ductwork has reference limits for air velocities. The lower limit velocities in the recommendations are intended for ducts with smaller diameters, and the upper limits are for ducts with larger diameters. In the recommendations, there is one diameter limit, and the air velocities for ducts smaller than this limit are recommended to be at the lower limit, while velocities for larger ducts should be at the upper limit. Air velocities used in the calculation are derived from the reference limits, such that the lower velocity for smaller ducts is slightly higher than the lower limit, increased by 20% of the difference between the limits. Higher velocities for larger ducts, a slightly lower than the upper limit, decreased by 20% of the difference between the limits. The diameters D of the ducts is determined as follows

$$D = 2\sqrt{\frac{qv}{v * \pi}} \tag{7}$$

, where qv is the air volume flow in the duct [m^3/s], and v is the air velocity in the duct [m/s]. However, before determining the diameter, it is not known whether the diameter should be determined with a higher or lower velocity. Additionally, a problem arises when the volume flow is at the threshold, that using a higher velocity would result a diameter below limit value, requiring the use of a lower velocity, and with a lower velocity, the diameter increases above the limit. Therefore, we determine what the volume flow rate is with a higher velocity at the diameter limit. This flow rate is used as a threshold, with values below it uses a lower air velocity and values above uses a higher air velocity. Based on the result obtained from Equation 6, the closest larger standard diameter is selected as the duct diameter. Based on the diameters, an appropriate thickness is chosen for the duct. Each component class has its own thickness requirements for the duct. In some cases, the material may also matter, but for the most part, the materials that can be chosen for the area ducts have the same thickness requirements.

3.1.4 Determining lengths

In the tool, the lengths of the ductworks are primarily based on inputted constant values, and only in some instances are they determined through calculations. Standardized values pose a challenge as they remain constant unless adjusted for specific projects. Altering these values for each new project would be laborious and would compromise the idea of an automated tool. Therefore, determining the lengths of the ductworks is a challenging aspect of the tool's development, especially since the aim is to create models that fit all projects. Construction of new machines is always line-specific, making it difficult to anticipate the layout constraints in the machine hall and the potential obstacles that might require circumvention. This poses challenges, particularly in the former section, press section, and OptiDry area, where there are numerous ductworks and fans, and the ducts may need to navigate around each other. However, in the drying section, ducts inside the hood are designed based on the same principles, remaining consistent from one project to another. Outside the hood, different projects may exhibit slightly varied solutions in the placement of fans and heat recovery towers, posing a minor challenge in determining lengths, but the differences are not so significant that a central model cannot be developed.

In the wet end, the lengths of ducts have been set constant for each model. There are nine different models for the former section and two for the press section. These models remain relatively consistent across different projects, so constant values for duct lengths have been defined for them. The only exception involves ducts going under or inside the former, where the duct length must also consider the width of the machine. To determine reliable lengths for each former and press model, several projects with the respective former type were examined. By reviewing drawings, suitable lengths for all duct lines could be determined. However, for some former types, it was noticed that the designed ducts varied slightly from each other's. Variations were observed in the placement of exhaust fans and the distribution of exhausts. For these, it had to be considered what would be the most common and sensible way to form the ducts distribution for the fans. Developing a more detailed calculation for duct lengths, taking into account precise fan locations and exhaust distributions, is challenging. Such an effort for all models could be extremely time-consuming and would require asking a lot of more inputs from the tool user. Moreover, the requested information might ask that kind of details to which the user might not be able to provide a sensible answer during the sales phase. Therefore, the best solution is to create as universally applicable lengths as possible for the ducts.

Determination of lengths in the drying section is much more accurate than in the wet end, and they can be very precise. This is due to their simpler structure, the fact that they remain very similar in all projects, and that, in determining these lengths, the dimensions of the hood can be used as reference measurements. The lengths of longitudinal ducts are defined based on the hood length and the cylinder gap. The lengths of the short ducts leading to the blower boxes, pocket ventilators, and vacuum rolls remain almost the same in every project, making them easy to determine accurately from the drawings. As mentioned earlier, for external ducts outside the hood, depending on the project, differences in lengths are created by the placement of blowers and towers. Like wet end models, requesting additional inputs is not a reasonable solution, so generic lengths need to be created for them.

For the OptiDry dryers as well, standard lengths need to be established because creating calculations for their bottoms is extremely challenging. The duct requirement for the dryers is the largest among the machine areas and, at the same time, the most confined in terms of space. Ducts for supply air, combustion air, exhaust air, runnability components, vacuum rolls, and cooling need to be drawn from the sides of the dryer. The ducts have to navigate around each other, and in their design, it is impossible to think that they could be drawn in the straightest possible path to the blowers. In terms of the tool's results, this area may experience the most deviation from actual weights.

3.2 The formation of the ductwork system

Formation of the ductwork is based on approximately 100 inputs from the user, depending on the selected forming, press, and dryer types. These inputs determine the overall extent of the ductwork. While the number of inputs may seem high, all are essential for the calculations. A significant number of them involves specifying the amount of runnability components and pocket ventilators. Some inputs, such as the dimensions of structural elements, air velocities, and the choice between multiple components, only affect the required air volume. However, the majority of inputs dictate the number of various ductworks needed.

In the wet end, the first influential factor is the selection of the forming section and press type. Each type of former requires a specific number of exhausts from different locations. The longer the forming section is and the more head boxes it includes, the more exhaust points are needed, which also result in an increase in the number of fans. Press types have similar exhaust points, but there are a few differences. In particular, the number of nips introduces additional exhaust points. The second factor influencing the number of exhausts is the speed and width of the machine. For the forming section, exhaust is not needed in a few locations if the machine speed and width are low enough. For the press, the necessity of exhaust depends on the speed and grade. If the grade is board, the need for exhausts becomes substantive at lower machine speeds, and for paper grade, they are necessary at slightly higher machine speeds. Fabric conditioning and Dewatering devices in the forming section are mostly optional, used if deemed necessary. In many forming section types, at least one of the Fabric conditioning equipment, Mist Collector or Blow Cleaner, is in use. If Blow Cleaner is not selected, Mist Collector is automatically used and vice versa. In former types where dewatering devices can be used, a choice is made between VacShoe and Vacuum Deflector. Other equipment are optional and used as needed. For the press, all additional equipment are optional.

In the drying section, the extent of the ductwork is determined almost entirely by the number of blowing boxes, pocket ventilators, and vacuum rolls, along with the associated fan amounts. Additionally, a few different additional air supply options can be selected, such as impulse blowing under the machine or blowing above the lift doors. In total, around twenty different equipment can be chosen, but not all are used in any given project; typically, over half of the selections remain empty.

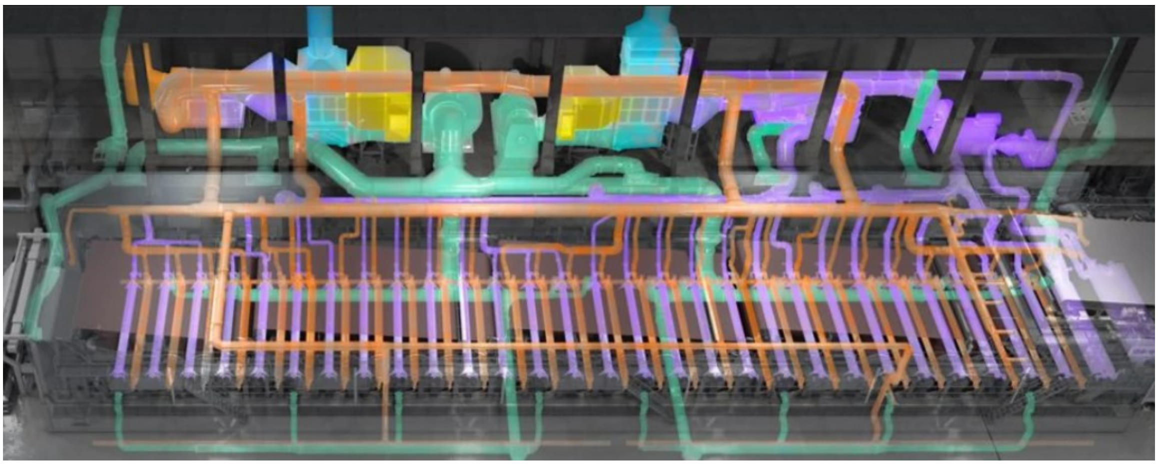

Figure 10. Ventilation ductworks of pre-drying section (Valmet Technologies 2024c.)

However, there are several separate ductworks because, for example, blowing boxes such as HiRun and SymRun require their own ductworks, and pocket ventilators and vacuum rolls each have their own ductworks. Figure 10 shows separate ductworks with different colours. The ducts in purple are for Hirun equipment, the orange ones are for the hood supply air and pocket ventilators, the green ones are for the suction of the vacuum rolls, and the blue and yellow ones are heat recovery towers. Moreover, vacuum rolls have suction on both sides of the machine, requiring ductwork on both the drive side and the tending side. Also, if HiRun boxes are in use, which have both blowing and suction sides, separate ductworks are needed for these on the machine's tending side. The more equipment used, the larger air volume is required, increasing the number of fans and, consequently, the number of ducts.

3.3 Ductwork total weight

The tool primarily dimensions the ducts as straight cylindrical tubes. Rectangular ducts are dimensioned only for heat recovery towers, silencers, fans, and air intake chambers for hood exhaust and recirculation. In reality, the ducts are not only straight cylindrical tubes; they can have bends and various shapes, and when the duct size changes, conversion cones may be needed in between. In addition to these, additional weight is added by duct supports, fastening accessories, and reinforcements. It is extremely challenging to account for all the shapes deviating from a straight duct during dimensioning. The calculation would need to somehow specify all the bends in each duct, and determining the exact quantity of them is difficult. The quantities of bends are always project-specific, and it's unlikely that anyone would have the time to add the quantity for each duct when using the tool. Therefore, in the tool, the weight obtained from dimensioning a straight duct is allocated between straight ducts and shape piece. Dividing these doesn't however affect the total weight, instead they are allocated separately for pricing purposes.

The weights of supports, transition cones, and fastening accessories are taken into account through separate coefficients. The coefficients are expressed as sector-specific percentages share, representing the additional weight to add on top of the basic weight of the duct. Assistance in determining the coefficients for supports is obtained from the weight data of the tool's test. The total weights and weights without support were extracted from the 3D-models of the ducts, which can be used to determine suitable percentage allocations for supports. The table below presents the total weights from the models, weights without supports, the share of weight of supports, and the designed coefficients for the tool.

Table 1. Determining supports coefficients

Position	Total weights [kg]	Weights without supports [kg]	Share of supports	Designed coefficients
Former section	17600	16400	6,82 %	15 %
Press section	9200	7500	18,48 %	30 %
Drying section inside hood	31000	26350	15,00 %	25 %
Drying section outside hood	44800	32150	28,24 %	40 %
OptiDry	44000	29200	33,64 %	55 %
Reel	500	200	60,00 %	200 %
Pulpers	9900	8300	16,16 %	25 %
Sizer	1900	1250	34,21 %	50 %
TurnFloat	1700	1550	8,82 %	15 %

The coefficients have been designed on a section-by-section basis because it was deemed more reasonable for the former, press, and OptiDry sections to have only one set of coefficients that cover the entire area. For drying section there are own coefficients for duct outside and inside hood because typically more supports are needed outside of the hood. There are not presented coefficients for hood exhaust duct in the table because there was a design error for the supports in the model so their weights can't be used. Same coefficient can be applied to them as used for the drying section ducts outside hood. The 'share of supports' in the table represents the proportion of the weight attributed to supports in the total weight obtained from the models. In the tool, however, the coefficients are added on top of the basic weight of the duct. To ensure that the weight of the supports is appropriate, the coefficients must be greater than the share of supports in the table. However, the share of supports is only a rough estimate based on one project. If the share of supports were examined across multiple projects, the coefficients could be more accurately determined.

The coefficient for conversion cones depends heavily on how much variation in duct size occurs in the ductwork. There are no direct results for determining the coefficient as with supports, but by examining drawings and models of the ductwork, their proportions can be roughly estimated. Additionally, with the help of the tool's tests presented later, the coefficients for transition cones can be adjusted. When the basic weight of the duct and other coefficients are known, the remaining coefficient for transition cones can be adjusted so that the results provided by the tool correspond to the weights obtained from 3D-models. Fastening accessories typically have an additional 10% coefficient on top of the basic duct weight.

In round ducts, flanges are used as reinforcement and in rectangular ducts flat bars are used. Reinforcement flanges are necessary when the pressure in the duct is sufficiently high. However, this high pressure is only achieved on the blowing side of HiRun ducts and in the former section's fabric conditioning and dewatering device ducts. The weights of the flanges are constant and depend on the diameters of the ducts and they need to be installed at certain interval of distance. In rectangular ducts, reinforcements are required when there is enough of unsupported area. In such cases, flat bars are used to create lattice support on top of the duct, and their weight increases with the bigger free area in the duct.

In the table 2, an example is provided to illustrate the formation of the weight of the HiRun's ductwork in pre-drying section outside of the hood.

Table 2 An example of ductwork total weight formation

HiRun PD outside hood	weight [kg]
Basic weight	4804,59
Share of straight duct (90 %)	4324,13
Share of shape piece (10 %)	480,46
Additional parts	
Supports (40 %)	1921,84
Conversion cone (25 %)	1201,15
Fastenings (10 %)	480,46
Round duct reinforcements	366,30
Rectangular ducts reinforcements	37,73
Total	8812,07

Base weight is divided into 0.9 share for the straight duct and 0.1 for the shaped piece. In addition to this, 40% of the base weight is added as the weight of the supports, 25% as the weight of the conversion cones, and 10% as fastening accessories. In the HiRun blowing side, there is sufficiently high pressure so that reinforcement flanges are needed for the round ducts. Additionally, for the circulation air intake, there are rectangular-shaped suction chambers in the hood's ceiling that require their own reinforcements. As seen from the table, the total weight of the ductwork is almost double compared to its basic weight. There must be careful when setting the coefficients as they have a significant impact on the final weight of the ductwork.

4 Testing tool accuracy

Testing the tool is important before its implementation to determine its accuracy and reliability. The results obtained from the tool have no value if we do not know how close they are to the actual weights. By visually inspecting the results, we can assess whether they are even close to what they should be, but we don't precisely know whether the weight goes significantly over or far below. The tool was tested using past or ongoing projects for which duct models are available. Reference weights are taken from 3D-models using a design tool that calculates the exact weight for the ductwork. Project information is input into the tool, and the obtained results are compared to the weights designed for the project. However, planned weights are ideal, and in reality, there may be some differences between the planned and delivered weights. For example, suppliers of ducts may have to choose another material or thicker thickness for the duct based on material availability. In such cases, the actual weights are somewhat higher than planned. It would have been best if the tool could have been tested directly against the actual weights, but it was difficult to obtain them, and their reliability cannot be fully ensured. However, using the weights obtained from the design tools can ensure that the tool's base system is functioning correctly, and the results are reliable. Afterward, adjustments can be made, such as increasing material thicknesses or coefficients, to better match the weights with reality.

4.1 First project test

The first test project was an ongoing project where the ductwork has already been delivered. The extent of the ductwork in the project can be described as moderately sized. The type of former used is one of the smallest, resulting in a relatively small ductwork compared to other types. All exhaust ducts were in use, but there were only two Fabric Conditioning devices and one Dewatering device in the project. More value to the project gives the OptiDry dryer, which is not present in nearly every project. The drying section itself is somewhat different, as it does not have a double-felted configuration, which can be explained by the high speed of the machine. Additionally, except for a few initial drying section blow boxes, all HiRun boxes are Compact models, meaning they have suction instead of blowing. This creates an unusual air balance in the hood since there is less supply air due to the Compact models, and they increase direct air exhaust through equipment. This leads to a lower-than-normal exhaust air from the hood through the roof. Furthermore, TwinRun cannot be tested because double-felted drying doesn't exist. For the rest, the project covers all the areas that can be tested.

Table 3 presents the comparison weights obtained from the design tool and the results provided by the tool when the project was tested first time whit tool and after that when modifications had been made to the tool based on the initial results. Each position has its own row, and total kilograms are calculated for the areas. Additionally, the percentage of deviation from the designed kilos is indicated. The background is green when the weight deviation is below 10%, and orange when the 10% deviation is exceeded.

Table 3. The comparison weights obtained from the design tool and the results provided by the tool of first test project

Position	Comparison weight [kg]	Weights provided from tool first time [kg] and deviation		Weights provided from tool after modifications [kg] and deviation	
Former section					
Exhaust	14900	11856	- 20,4 %	13216	- 11,3 %
Fabric conditioning	1600	2253	+ 40,8 %	1675	+ 4,7 %
Dewatering	1100	1385	+ 25,9 %	1032	- 6,2 %
Total	**17600**	**15494**	**- 11,9 %**	**15923**	**- 9,5 %**
Press section					
Exhaust	5200	4579	- 11,9 %	4378	- 15,8 %
PressRun, Suction roll	4000	1333	- 66,7 %	3365	- 15,9 %
Total	**9200**	**5912**	**- 35,7 %**	**7743**	**- 15,8 %**
Drying section PD					
Hirun					
Inside hood	5600	6708	+ 19,8 %	5303	- 5,3 %
Outside hood	8700	7996	- 8,1 %	8065	- 7,3 %
Total	**14300**	**14404**	**- 0,7 %**	**13368**	**- 6,5 %**
SR					
Inside hood	1300	1694	+ 30,3 %	1537	+ 18,2 %
Outside hood	1900	921	- 51,5 %	1866	- 1,8 %
Total	**3200**	**2615**	**- 18,3 %**	**3403**	**+ 6,3 %**
Hood supply & pocket vent.					
Inside hood	6700	6555	- 2,2 %	7156	+ 6,8 %
Outside hood	10700	5287	- 50,6 %	10648	- 0,5 %
Total	**17400**	**11842**	**- 32,0 %**	**17804**	**+ 2,3 %**
VacRoll					
Inside hood	5500	6110	+ 11,1 %	4752	- 13,6 %
Outside hood	8300	6636	- 20,1 %	8840	+ 6,5 %
Total	**13800**	**12746**	**- 7,6 %**	**13592**	**- 1,5 %**
Drying section AD					
Hirun					

Inside hood	3100	3316	+ 7,0 %	3316	+ 7,0 %
Outside hood	3500	2754	- 21,3 %	2754	- 21,3 %
Total	**6600**	**6070**	**- 8,0 %**	**6070**	**- 8,0 %**
SR					
Inside hood	1200	1425	+ 18,8 %	960	- 20,0 %
Outside hood	1700	694	- 59,2 %	1732	+ 1,9 %
Total	**2900**	**2119**	**- 26,9 %**	**2692**	**- 7,2 %**
Hood supply & pocket vent.					
Inside hood	4500	4687	+ 4,2 %	4553	+ 1,2 %
Outside hood	5800	3649	- 37,1 %	6268	+ 8,1 %
Total	**10300**	**8336**	**- 19,1 %**	**10821**	**+ 5,1 %**
VacRoll					
Inside hood	3100	4131	+ 33,3 %	3628	+ 17,0 %
Outside hood	5750	3160	- 45,0 %	5691	- 1,0 %
Total	**8850**	**7291**	**- 17,6 %**	**9319**	**+ 5,3 %**
OptiDry Twin					
Runnability	11500	6737	- 41,4 %	6922	- 39,8 %
VacRoll exhaust	6100	6572	+ 7,7 %	6476	+ 6,2 %
Supply	5500	1883	- 65,8 %	6890	+ 25,3 %
Exhaust	14000	6473	- 53,8 %	11438	- 18,3 %
Combustion	1900	689	- 63,7 %	2563	+ 34,9 %
Cooling	1700	711	- 58,2 %	807	- 52,5 %
Total	**40700**	**23066**	**- 43,3 %**	**35095**	**- 13,8 %**
Hood exhaust					
PD	13000	3829	- 70,6 %	13173	+ 1,3 %
Vacuum exhaust	20000	14717	- 26,4 %	19854	- 0,7 %
AD	7000	2279	- 67,4 %	6303	- 10,0 %
Total	**40000**	**20824**	**- 47,9 %**	**39329**	**- 1,7 %**
Sizer	500	386	- 22,8 %	835	+ 67,0 %
TurnFloat	1700	1100	- 35,3 %	969	- 43,0 %
Web threading at reel	500	188	- 62,4 %	204	- 59,2 %
Pulpers	9900	9139	- 7,7 %	9590	- 3,1 %
Project total	197450	140542	- 28,8 %	187393	- 5,1 %

The results show that the most significant deviations occur in the ducts outside the hood, especially in the hood exhaust and pocket ventilators/hood supply ducts, and as anticipated, there is a significant deviation in the OptiDry dryer. Consequently, areas with deviations were examined more closely, and based on that, models were either further developed or refined for accuracy. In the former section, lengths were examined more closely, and coefficients were adjusted slightly. The ducts inside and outside hood for HiRun and VacRoll was modified so that the ducts from the tendings side to the drive side does not go on inside the hood but outside instead, balancing the differences between outside and inside ducts. Dryer ducts thicknesses and materials were reviewed, and a small error was found, which, when corrected, balanced the weights in some areas. In addition, missing ducts were added to the heat recovery towers, which significantly smoothed out the difference in hood exhaust air results.

In hood exhaust duct and pocket ventilator ducts outside of hood, the deviation was so significant that there were doubts about the results obtained from the design tool. The weight structure of the 3D-models of the ductwork was examined more closely and in some of these 3D-models revealed an error where supports had modelled as too heavy, potentially adding 100% extra weight to those models. Subsequently, all 3D-models were revisited, and only a few were found to be incorrect. For these areas, the comparison weight has been presented without weight of supports and it is compared corresponding weight obtained from the tool.

The results after the changes can be considered great, although there is still some deviation in certain areas. Models of the former and press sections may need slight refinement for accuracy, but the changes can be done after another project test since in that is used the same types in former and press. In the drying section, there is deviation in a few ductworks inside hood and one outside ductwork, but the total weights for these areas are relatively small, and a 10% difference can form from a few hundred kilograms. OptiDry seems to be a challenging area for development, and achieving accuracy is difficult when weights vary above and below reference weights in different areas. However, excluding OptiDry, the results of other large and heavy ductworks are accurately and as a result, the total weight of the project's total ductwork is only 5.1% below the reference weight.

4.2 Second project test

The scope of the second test project was quite similar to the first test project. The types of former and press are the same as in the first test project. The only difference in wet end is that press has fewer exhaust points in this project. The number of exhausts is not the same as would generally be designed for the press with this speed, width, and grade. This immediately highlighted a development area in determining the number of press exhaust if it is not deemed necessary to use all the exhaust that the design guide would specify. Additional selection was added to the input tab, allowing the definition of how extensive exhaust ventilation the user wants for press nips. In this project, the air balance of the drying section is slightly more normal compared to the first project since instead of HiRun Compacts regular blowing boxes are utilized. As a result, the exhaust air volume from the hood is also larger, approximately 1.5 times for both drying sections compared to the first project and at the same time the amount of circulating airs increase. Additionally, the after-drying section has one double-felted cylinder group which enables testing of TwinRun.

In the project, only basic design has been done for all ducts outside the hood because these are not included in Valmet's scope of supply. The weights of these ducts are significantly lower than reality, possibly even half of the actual weights. However, this has its advantages. Now we can see how close ducts basic design without additional parts is to the weights of the design tool. This also helps determine whether the coefficients are too large or too small if the weights of the basic design do not match. The test results are presented in Table 4.

Table 4. The comparison weights obtained from the design tool and the results provided by the tool of second test project

Position	Reference kilograms [kg]	Tool kilograms [kg]	Weight deviation
Former section			
Exhaust	10300	8010	- 22,2 %
Fabric conditioning	1600	931	- 41,8 %
Dewatering	800	555	- 30,6 %
Total	**12700**	**9496**	**- 25,2 %**
Press section			
Exhaust	1300	1373	+ 5,7 %
PressRun, Suction roll	900	903	+ 0,4 %
Total	**2200**	**2277**	**+ 3,5 %**
Inside hood			
Hirun PD	6900	6588	- 4,5 %
SR PD	1300	1533	+ 17,9 %
Hood supply and pocket vent. PD	5900	6476	+ 9,8 %
VacRoll inside hood PD	6100	6824	+ 11,9 %
SR&TR inside hood AD	2100	1811	- 13,8 %
Hood supply and pocket vent. AD	1200	1338	- 11,5 %
VacRoll AD	1200	1082	- 9,8 %
Total	**24700**	**25652**	**+ 3,9 %**
Outside hood			
Total	**46100**	**41578**	**- 9,8 %**
Reel	150	78	- 47,7 %
Pulpers	5700	6093	+ 6,9 %
Project total	**91550**	**85175**	**- 7,0 %**

Drying section ducts outside of the hood and the hood exhaust ducts are presented as a combined weight because heat recovery towers air inlet and the exhaust ducts from the towers are scattered across different 3D-design models. This is because there are less air intake ducts to hood supply/pocket ventilator from towers and less hood exhaust ducts to the towers than there is heat recovery towers. As a result, the exhaust ducts for a tower might be example in the VacRoll design models and the intake ducts to the tower in the SR design model. In the tool, the tower ducts are accounted for on the exhaust side in the "hood exhaust" ducts and on the supply side in the "hood supply and pocket ventilator" ducts, because it is hard to know in advance in which design model the remaining ducts of the towers will be. This would cause significant differences between the test areas, so it is best to only compare total masses with each other since individual areas cannot be made comparable.

Due to the identified errors in the bracket design in the first project, the masses taken from the design tool include the weight without supports. However, this only applies to the comparison of ducts inside hood because basic design models are already used to compare ducts outside hood. In the former section, the total weights are about 25% below the reference weight so the basic design weight in the tool could be slightly increased. Since both projects have a similar former section, the coefficients are slightly too high, as increasing the basic weight would result in excessively high results for the first project. The basic design for the press section is appropriate cause the results are very accurate. However, the coefficients need to be adjusted slightly to bring the results of the first project closer to the reference values. In the drying section, there are minor variations in ducts inside hoods by areas and with some areas deviating by over 10%. These variations are moderate, and since the total weight deviation is less than 4%, and the weights were accurate in the first project, major changes in this regard may not be necessary. However, the ducts outside hood fall a little more short of the target, nearly 10%. It is challenging to pinpoint the areas of deviation when considering only the total mass. For the first project, the deviation in the combined weights of same ducts was only 1.5% below the reference weight. Consequently, a similar solution should be applied to the ducts as will done for the former section.

4.3 Results

The tests conducted for the tool were a crucial part of the development process. They provided comparison data for the tool's results and enabled further development based on their outcomes. The tests were important because they highlighted some errors that had formed during the tool's development, which might have gone unnoticed without them. There are numerous solutions for machine ventilation ductwork, making it challenging to develop a tool that display excellent results for every project. The testing of the tool took surprisingly much time for one project, leading to a relatively small number of tests. Based on two tests, the tool can already be further developed, and we can see in which areas it is most accurate and where discrepancies are more common. Ideally, there would have been more tests, covering diverse scenarios to observe the tool's operation comprehensively.

Tests from just two projects already revealed numerous areas for improvement, leading to a more precise development of the tool. Of course, the major areas for improvement become apparent immediately and more tests would be done, the expectation is that the number of improvement areas would decrease with each test. The table below shows the deviation in the results identified in tables 3 and 4 after the tests and the new deviations with the ready fitted tool settings when the same developed settings are applied to both projects.

Table 5. Deviations after the tests and with the ready fitted settings.

Position	Project 1		Project 2	
	After the test	Fitted setting	After the test	Fitted settings
Former section				
Exhaust	- 11,3 %	- 4,7 %	- 22,2 %	- 11,1 %
Fabric conditioning	+ 4,7 %	+ 5,5 %	- 41,8 %	- 31,9 %
Dewatering	- 6,2 %	+ 4,3 %	- 30,6 %	- 7,5 %
Total	**- 9,5 %**	**- 3,2 %**	**- 25,2 %**	**- 13,5 %**
Press section				
Exhaust	- 15,8 %	- 8,7 %	+ 5,7 %	+ 6,4 %
PressRun, Suction roll	- 15,9 %	- 9,8 %	+ 0,4 %	+ 2,3 %
Total	**- 15,8 %**	**- 9,2 %**	**+ 3,5 %**	**+ 4,8 %**
Drying section inside hood				
Hirun PD	- 5,3 %	- 2,3 %	- 4,5 %	+ 9,1 %
SR PD	+ 18,2 %	+ 21,9 %	+ 17,9 %	+ 19,8 %
Hood supply and pocket vent.PD	+ 6,8 %	- 2,6 %	+ 9,8 %	+ 3,8 %
VacRoll inside hood PD	- 13,6 %	- 3,7 %	+ 11,9 %	+ 6,6 %
Hirun AD	+ 7,0 %	+ 8,9 %		
SR&TR inside hood AD	+ 20,0 %	- 17,2 %	- 13,8 %	- 1,5 %
Hood supply and pocket vent. AD	+ 1,2 %	- 4,3 %	- 11,5 %	+ 16,7 %
VacRoll AD	+ 17,0 %	+ 17,1 %	- 9,8 %	- 8,3 %
Total	**+ 0,6 %**	**+ 0,6 %**	**+ 3,9 %**	**+ 4,2 %**
Drying section outside hood				
Total	**- 0,6 %**	**+ 1,0 %**	**- 9,8 %**	**- 5,6 %**
OptiDry Twin				
Runnability	- 39,8 %	- 5,7 %		
VacRoll exhaust	+ 6,2 %	- 15,3 %		
Supply	+ 25,3 %	+ 23,3 %		
Exhaust	- 18,3 %	- 8,6 %		
Combustion	+ 34,9 %	- 2,4 %		

Cooling	- 52,5 %	- 66,9 %		
Total	**- 13,8 %**	**- 9,6 %**		
Sizer	- 67,0 %	- 6,1 %		
TurnFloat	- 43,0 %	- 43,0 %		
Web threading at reel	- 59,2 %	- 2,4 %	- 47,7 %	- 21,6 %
Pulpers	- 3,1 %	- 3,1 %	+ 6,9 %	+ 6,5 %
Project total	**- 5,1 %**	**- 3,7 %**	**- 7,0 %**	**- 2,3 %**

After the improvements made to the tool, there are still areas where the results obtained from the tool do not precisely match the reference values. In the case of the Former section, there is still some deviation in the second project, although it has been reduced to almost half of the original difference. For the Press section, the results in both projects are in good area. In the drying section, there seems to be a problem when as one area gets closer to the reference value, the other area deviates slightly further. However, the overall deviations in weight for the drying section are excellent. In the optidry ductwork, changes were made to get the total weights under a 10% deviation, but in half areas, a significant deviation remains. Considering the tool's purpose for more accurate and consistent pricing, the overall weight discrepancies in projects are 3.7% and 2.3% indicate that the tool provides reliable results, and it can indeed be used as a basis for pricing ductwork in projects.

5 The use, updating, and future development of the tool

Instructions for using the tool have been created in Excel, so this section does not cover all the details in it. However, it highlights the key points for using the tool and provides important information for maintenance and future development. Products are constantly evolving, and as a result, the tool is developed accordingly. Minor changes, such as adjusting airflows, air velocities, thicknesses, or lengths, are relatively straightforward. However, if new former, press, or optidry type are introduced in the future, they will require more work with the tool.

Coefficients for duct weights

Results-sheet includes weight coefficients for additional duct part for each area. For pricing, the calculated weights from the dimensioning-sheets are divided into percentages for straight duct and shape piece. These percentages can be freely adjusted for different areas based on estimations of the distribution. Other coefficients: supports, conversion cone, and mounting, add set percentage of additional weight to the basic weight of the ductwork. Supports and conversion cones has developed as area-specific and for mounting, a constant 10% additional weight is used. These coefficients can also be changed for a project-specific, and it is recommended to improve their accuracy in future development.

Adding new duct row

The duct dimensioning is divided into nine sheets: Former, Press, HiRun, Other Runnability, Pocket Ventilator & Hood Supply, OptiDry, VacRoll, Hood Exhaust and Others. Each sheet contains ductwork of its area, and every kind of duct is in its own row. Other Runnability-sheet, include SymRun and TwinRun ducts as they can share a common ductwork. The Others-sheet includes Reel, Pulpers, Sizer, and TurnFloat. To add a new duct row, simply use "Insert new row" and copy any existing calculation row to the new one. The user needs to set the amount, the length either based on calculations or as free input and the air volume flow of the duct which usually based on the machine width but can also be set directly. The quantity must be linked to the input-sheet. Other information comes automatically from tables or through calculations. The diameter and thickness take values according to the requirements of the area, like what used in the copied row. For future development, it would be beneficial to have a macro-based selection for adding a new row to prevent user errors. However, such development could take a considerable amount of time.

Setting the over dimensioning

For each duct dimensioning sheet, there is a cell where the ducts for that area can be oversized. A percentage value is set in the cell to indicate how much the ducts in that area should be oversized. This increases the airflow of the air devices in the area by the specified amount, which may then potentially affect larger ducts if the limits are exceeded.

The amount of exhaust points on the former and press section

For the Former models, there are no separate direct selections for the amounts of removals; by default, all removals are included. The only exception is for the largest former types, where the user is asked whether the former includes a top former unit or only a fourdrinier and also is there primary or secondary gap or both. In addition of these, of course, the exhausts from the head boxes are included when the width and speed are high enough. For the Press section, there are a few direct input selections asking about the extent of exhaust. If you want to manually adjust the amount of exhaust, you need to go to the former and press sheets and set the "pieces" column to the desired number of removals, in practise 1 or 0. For each project, it is advisable to verify whether the amount of exhaust in the tool corresponds to the actual situation.

Updating tables

Tables-sheet contains tabulated standardized values utilized in calculations. This includes diameters and thicknesses of ducts, air velocities by areas, material densities and length of opening and face velocities for each pulper, as well as the weights of reinforcement flanges. It is advisable to update this information whenever new guidelines for these are released. Additionally duct thicknesses can be adjusted on a project-specific basis if for example, it is known that the duct supplier uses thicker material than recommended in the design guidelines.

Adding new ”products”

Air devices are continuously developed to be more efficient and advanced, and new products are introduced. When devices are updated, if their airflow values change, you only need to change them on the corresponding product's duct calculation row. Also, it is advisable to update the product name on both the input and the products sheet. For entirely new products, a dedicated input selection needs to be created on the input-sheet, and a new row must be added to the products-sheet. The pieces column should be linked to its input. This is easy to implement for all drying section equipment. When an entirely new product group is introduced, it is recommended to create a new sheet for it and copy the template from the corresponding product sheet.

For new former, press, or optidry types, adjusting the tool requires a bit more effort. New types can be placed on existing sheets, and their ductwork template can be copied from another type. For all ducts need to determine lengths and set airflow values according to the model's design guidelines. Additionally, it is crucial to check all the links to ensure they point to the correct cells. These areas have macro-based input selections to keep input amount on the input-sheet in moderation. For new types, a macro-based selection must also be created. This is best achieved by copying the code from another type and modifying it for the new one. The macro code for input selections can be found in the VBAProject of the tool file under "Sheet2 (Input).

Basic principle of tools’ macrocode

The operation of input-sheet macros is based on the "worksheet_change" main program which is automatically called when a change occurs in a specified cell. For example, when a new selection for the former type is made on the input-sheet, the main program calls the "InputFormer" subprogram. The "InputFormer" subprogram consists of case selections where each case corresponds to a one of former types. The case selection chooses the appropriate case based on the choice made on the input-sheet. Each case is defined to open specific additional inputs on the input-sheet. Some made additional selections may start the main program again to call other subprograms, whose task is to automatically fill in the selection for additional equipment. There are ten of these subprograms and they are placed in the code after the "InputFormer" subprogram. Apart from the former-related subprogram, there is one subprogram for the press and one for optidry dryers. The main program calls these when a selection is made for the press or optidry type. Some comments have been left in the VBA code to assist the user in understanding what certain code segments do.

6 Summary

In this master's thesis, the goal was to develop an automated calculation tool for Valmet's Air Systems unit, aiming to enable precise estimation of ductwork quantities for paper and board machine lines during the sale phase. The air systems of different parts of the machine are crucial for its operation. Their design and operation directly affect the production efficiency of the machine and the quality of the end product. The central idea of the tool is to determine the scope of required air equipments and optimize the ductwork structure for each area of the machine based on the user-inputted data.

Creating the new tool wasn't as straightforward as initially thought. The development of the tool required considering a vast array of factors and contemplating various possible combinations for the ductwork structure. As a result, the calculation tool contains a massive amount of if-conditions and cell links. However, the tool serves its development purpose as an automated tool. The user is asked for a large number of inputs, but beyond this, the tool doesn’t require any additional work, and the results are generated directly based on input information.

An important part of the development process was testing the tool to ensure its accuracy and reliability. Through testing, it was ensured that the results obtained from the tool are close enough to real situations. The tool was tested on two different machine line projects, where the results obtained from the tool were compared to the planned weights of the ductworks in the projects. Testing revealed areas where discrepancies occurred, and based on these, models were further refined to be more precise. The goal of the tests was to achieve discrepancies of less than 10% regionally, which was mostly achieved, but there were still a few areas where this 10% threshold couldn't be reached. However, when comparing the weights of the entire projects' ductworks, the results provided by the tool were only 3.7% and 2.3% short of the reference weights, which are excellent results.

Overall, the master's thesis succeeded in demonstrating that the development of the automated tool was successful and met its objectives and it also was put into use for pricing of one project even before it was completely finalized. The tool will be a valuable addition to estimating the ductwork quantities of paper and board machines, streamlining the bidding process, and pricing. The adoption of the tool also creates a basis for a unified pricing method for sales, eliminating the previously used pricing practises and their differences. Additionally, this work lays the groundwork for future development and improvement of the topic.

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