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Development of a system for the production of self-adhesive foils

CBI Project Course Spring 2020

Executive Summary

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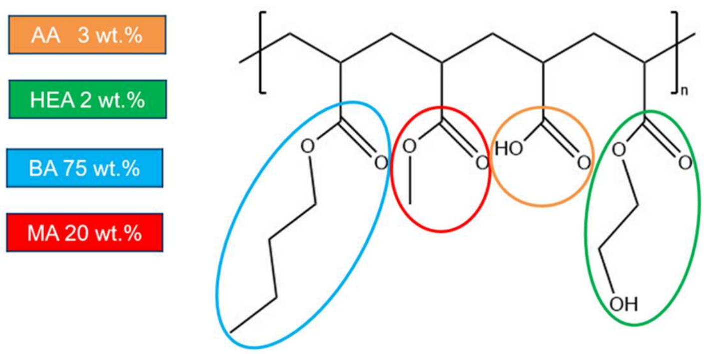
The partner of the CBI project course in spring 2020 is a company in Germany that offers **self-adhesive films** in its product portfolio. Over the last few years, the demand for printable films has risen sharply, especially in the advertising and automotive industries. To meet the increase in demand, the company is now planning to expand its production and build a new plant. The production of the 1.6 m wide films is divided into two processes. In a first, separate production step, a carrier film is made from a PVC organosol. The film is then coated with a wet adhesive film in a coating process, which enables adhesion to the substrate after drying. The adhesive currently used is based on organic solvents and is transparent or translucent. As part of a **sustainable corporate policy**, the use of organic solvents is to be minimized in the future. In the long term, the aim is to develop a solvent-free adhesive variant, although this will not be possible for several years due to development constraints. For this reason, the new system is to be designed with two adhesive variants or coating technologies. On the one hand, with organic solvents and, on the other, with a solvent-free hotmelt variant that can be retrofitted with as little investment as possible. The process for coating and producing the adhesive film is to be designed for an annual capacity in which approx. 1000 kg h^{-1} of adhesive is processed in 15-layer operation at a web speed of 100 m min^{-1}. For the solvent-based variant, 50 wt.% solvent can be assumed.

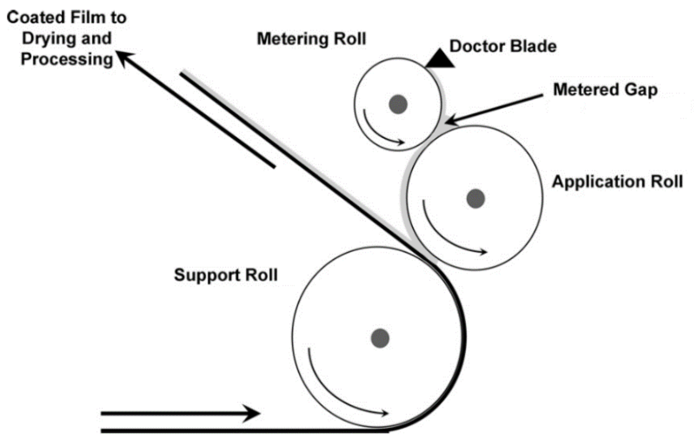
The **solvent-based pressure sensitive adhesive** (SBPSA) is a common conventionally used wet adhesive. Ethyl acetate (EA) was chosen as solvent. The adhesive consists of four monomers: butyl acrylate (BA, soft monomer), methyl acrylate (MA, hard monomer), acrylic acid (AA, improves adhesive strength and elasticity) and hydroxyethyl acrylate (HEA, improves weather resistance). The solution polymerisation is initiated by adding a small amount of azobisisobutyronitrile (AIBN). As the polymerisation is statistically distributed, there only can be model assumptions on what the polymer may look like, on option is shown here. Cross-linking of the sidechains create the specific properties, which can be varied by adjusting the amounts of the different components to better suit the



intended application. Positive aspects of this adhesive system are its UV- and aging resistance, quick drying, high transparency, good adhesion to non-polar surfaces and thus, a high bond strength to plastic. Negative aspects are its low initial adhesive strength (full strain on the bonded objects can only be applied after a certain time has passed), its low environmental friendliness due to the solvent contained and its petroleum-based educts, its low shear rate, low cohesion and thus low stability, flammability and toxicity (during the process). The chosen

hot melt pressure sensitive adhesive (HMPSA) consists of two copolymers – ethylene vinyl acetate (EVA, increases adhesion, flexibility, lowers softening point), styrene ethylene butylene styrene (SEBS, transparent, UV-stable, high aging resistance, good cohesion) – and the tackifier rosin ester resin. Additional paraffin oil serves as stabiliser (lowers melting point). Positive aspects of the HMPSA are that it is solvent-free (more environmentally friendly, no drying step needed), its short setting time, its immediate adhesion to surfaces and that it is easily removable by applying heat. Negative aspects are its temperature sensitivity (above the melting temperature detachment is likely) and its higher viscosity. Further research into **biobased HMPSA** yielded no suitable adhesive system yet but may be possible in the future.

As the task requested a **modular setup** that can easily be transformed from using SBPSA to using HMPSA, a solution for both variants was searched for. Measurement technology and adjustments in the ongoing operation were needed to guarantee only minimal deviations of the film thickness. Several processes were compared, only the **reverse roll coating process** met all criteria demanded by the project. A brief explanation of the apparatus shown below: the PVC-foil is unrolled and lead to run over the support roll; on top of the support roll, the application roll is located, which is coated with the proper amount of adhesive to provide a uniform film thickness; the metering roll is responsible for precisely dosing the adhesive to coat the application roll; the adhesive is provided from storage in the case of SBPSA; a wiper ensures that no excess adhesive drips down from the metering roll to the coated foil; the foil is coated by convergence of the application roll and the support roll, with the foil in between; the coated foil leaves the coating apparatus towards the dryer.

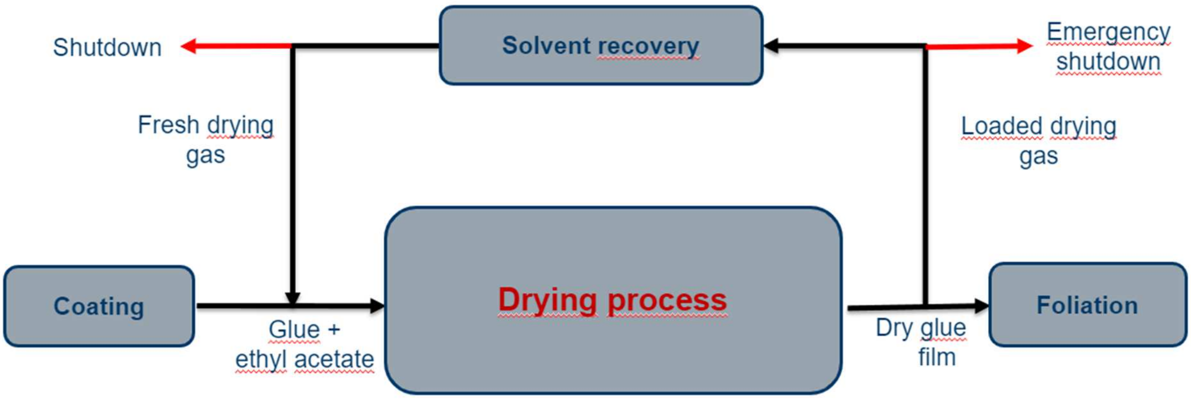


A housing around the apparatus filled with nitrogen prevents any formation of explosive atmospheres. The solvent-containing nitrogen would be fed into the nitrogen loop of the plant, in front of the dryer. In the case of HMPSA, different aspects need to be addressed as the adhesive needs to stay hot enough in order to successfully bond to the foil. In order to ensure a **uniform melt process** that also has a short start-up time, an extruder was chosen to provide the heat for melting the granular adhesive. It also has the benefit of conveying the melted adhesive directly to the coating rolls. Thus, additional pipes can be avoided and there is no danger of clogging when the process is halted due to usual shut-down or an emergency. In order to keep the adhesive hot (160°C application temperature), the application roll and metering roll were designed to have an integrated heating system (resistance heating). To account for thermal expansion, the space in between the rolls adjustable. To meet the specification of the assignment of using 1000 kg adhesive per hour, the plant is configured to have two production lines (two coating apparatuses and two dryers). According to the material properties of the adhesives, different layer thickness occurs. In the case of SBPSA, the adhesive film is designed to be 57 µm thick on the finished product. In the coating process, the solvent must be accounted for, so when the foil leaves the coating apparatus, the wet adhesive film is 116 µm thick. In the case of HMPSA, the layer thickness of the adhesive on the finished product is 53 µm, equal to the freshly coated adhesive layer.

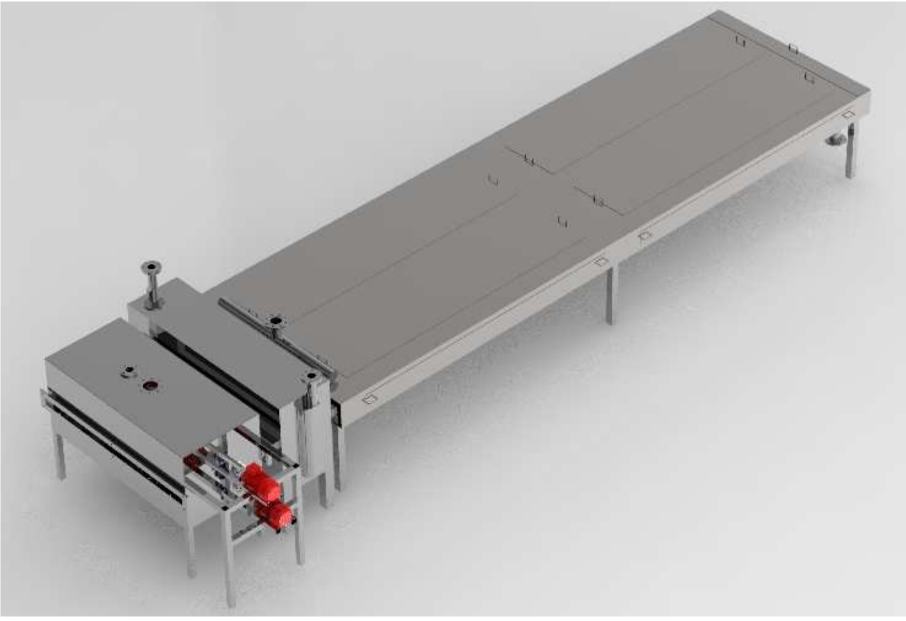
For the process involving SBPSA, **drying** is the next step in the production process. In one dryer, 500 kg of solvent need to be removed per hour. In this apparatus, explosions were to be avoided as well, therefore it was flooded with nitrogen similar to the coating apparatus. A thermal drying option was chosen due to the structure of the foil. Convection drying was selected over the expensive radiation drying and conduction drying (for this task unsuitable because of the heat sensitivity of the foil); to keep the uniformity of the adhesive film, flotation drying was set as the solution chosen. The dryer consists of several chambers; the number was determined by estimations of the drying process. Because no data on the evaporation behaviour of EA in nitrogen comparable to a Mollier-h-x-diagram could be found, analogies had to be used in order to design this apparatus. As benzene shares similar properties to EA, a psychrometric chart of the system benzene-nitrogen was consulted. Extrapolation of the temperature range was necessary in order to determine the state of the mixture and the coated foil at the end of every drying chamber. It was also assumed that the wet layer consists purely of solvent in order to generate data that other groups could use for their calculations. Additionally, it was decided that co-current flow was to be used in this operation, even though counter current flow was better suited to handle the mass transfer, because many variables needed to be estimated, other design choices needed to be made, and no reliable data could be found. At the start of each chamber, hot (170°C) nitrogen is led to flow parallel to the foil and evaporate the solvent from the wet adhesive. When the mass transfer starts to slow down, the nitrogen is taken out of the chamber and heated again. In the last chamber, the temperature of the nitrogen converges to that of the foil. The product exits the apparatus after about 67 m and 40 s with about 1 vol% of humidity left in the adhesive film. At least 53 kW of power are needed per dryer unit. The nitrogen mass flow was set to be 424 kg per hour per unit and after the drying process, one kilogram of nitrogen would contain 1.2 kg of EA, which would then be transported to recover the included solvent.

The initial approach of **solvent recovery** was to use condensation as a technique to retrieve the dissolved EA from the nitrogen, which would then be reused in the drying process. Further literature research yielded a combined application with a membrane module. The recovery process can be summarised: the loaded nitrogen is compressed to 3 bar, which enables a great portion of the EA to be removed from the gas stream in the condenser; afterwards, the residual load of the nitrogen is reduced until there are only 32 g per kilogram of nitrogen left (this concentration is needed to ensure a good drying effect; additionally, there is a trade-off between the purity of the nitrogen and the amount of membrane modules; further purification would demand significantly more membrane modules and is therefore not economical); the permeation is promoted by an additional vacuum pump, which conveys the solvent-enriched stream back to the nitrogen stream that originated from the dryer in order to further promote the condensation. The condenser is designed to be a tube bundle condenser with a heat transfer surface of 30 m² with a potential cooling load of 199 kW. The membrane module was designed to retain the nitrogen and let the solvent permeate. A surface of 80.2 m² would be required, totalling 22 membrane modules (excluding additional modules for maintenance etc.). Further optimisation of the concept is possible: Direct condensation of EA was considered but was rejected early on as in the starting phase of the project no cooling unit was intended to be included in the plant. Additionally, the pressure ratio could be further optimised to reduce the required membrane surface.

Heat recovery & exhaust air treatment focused on the exhaust air predominantly, since the amount of heat to be recovered was insignificant. In the case of usual operation, nitrogen is fed into a loop after solvent recovery. For shutdown, the plant is flooded with ambient air to allow for easy access e.g. for maintenance. The nitrogen that is simultaneously released into the environment needs to be treated in order to be free of any solvent or other impurities that may have accumulated over the course of the work process. A decision was made to recover the residual load of the nitrogen stream instead of using destructive methods. For this, adsorption was chosen as the means of purification. The two adsorbers work redundantly to ensure the requirements even in the case of failure of one adsorber. For any shutdown, be it usual or emergency, the nitrogen stream passes the adsorbers in one direction. During each start-up, the adsorbers are passed by fresh nitrogen from the other direction that regenerates the adsorbent and is fed back into the nitrogen loop in order to create a non-explosive atmosphere in the apparatuses again. In order to select a fitting adsorbent, Langmuir isotherms, price, temperature rise, and bulk density were compared for select zeolites and activated carbon. 13 X exhibited parameters that were fit for this purpose, therefore the design of the adsorbers could be made using this zeolite. For the case of an emergency shutdown, the usual solvent recovery is bypassed, and the solvent-containing nitrogen is released directly to the adsorbers. Therefore, the adsorbers need to be able to handle the load of solvent that is still included in the coating and drying apparatuses (which is significantly more than the usual amount led to the adsorbers) while still meeting the purity requirements, and thus dimensioning was based on this mode of operation. Including a safety factor of 2, the adsorbers were designed to be 0.29 m long with a diameter of 0.89 m.



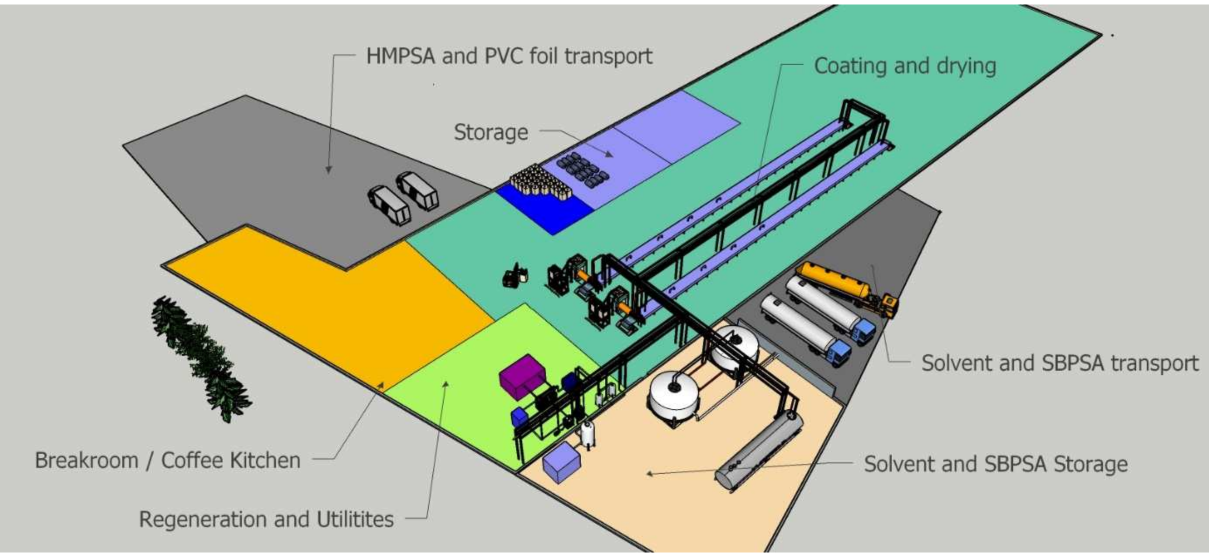
The exact layout and specifications needed for every apparatus that is specific for the plant were planned out by **Apparatus Design**, especially the coating system and the belt dryer. For this, CAD models and technical drawings have been created with the software *Creo 5.0.* Mechanical strength and temperature resistance of the materials have been taken into consideration for the dimensions. Modular design choices enable the combination of the structural elements with nitrogen partition units and extension of the dryer length. The coating system is designed as a reverse roller coating system with hollow rollers (support, application and metering roll), which are each stabilised by a solid shaft running through the centre, connected by four braces. The dryer unit is designed with five separate chambers, of which the last is significantly longer than the others but can also be built by combination of the same modular units. At the intake of each chamber, nitrogen is introduced through an inlet flange and split into six separate flows. It is then redirected by a baffle plate for an approximately laminar flow that is parallel to the foil. The nitrogen is lead out through



two outlet tubes at the bottom end of the chamber. The foil is transported over small rolls, which ensure that as little friction as possible is applied to it. Easy access for maintenance is given by opening the covers of the dryer. Stainless steel has been chosen as material to prevent corrosion for every part that comes into direct contact with the solvent-containing adhesive or the solvent-containing nitrogen. The transport rolls inside the dryer consist of aluminium. The sealings of the flanges and maintenance covers are made of PTFE, the support roll is coated with PDME. The outer housing of the dryer consists of regular steel. In the case of using HMPSA, the assembly can still be used. As nitrogen is no longer needed, the dryer length can be used to let the hot adhesive cool down to room temperature. The rolls of the coating system are heated, their position adjustable to account for thermal expansion.

The task of **Heat Management** was to find ways to heat and cool process streams. For this, the plant was analysed and heat sinks or sources were identified in order to estimate the applicability of a pinch analysis. It was not practical to couple the hot and cold streams, as there were only few apparatuses that needed heating (dryer and adsorber) and cooling (condenser) for the case of the SBPSA process and for the HMPSA, only heating (extruder and heated rolls) was needed. For the SBPSA process, even though there were hot and cold streams, they could not be coupled. Thus, every apparatus needed to be heated and cooled separately. For heating, several options were discussed and rejected: hot steam was not available on site; flue gas was available, but the generated heat would be too excessive; thermal oil would need an additional infrastructure and every heat transfer step would result in loss of efficiency. Therefore, electrical heating was chosen to apply heat in the exact amount and location where it would be needed. As the infrastructure could be easily modified, it was the ideal approach for the modular and adaptable design of the plant. The heating was implemented in the form of inline electrical process heaters (for heating the nitrogen stream before it is led into the dryer chambers or before the desorption process; two 50 kW and eight 25 kW heaters) and electrically heated jacket rolls for the HMPSA process. For cooling, also several refrigeration methods were discussed: cold process water was not available on site; ambient air was too unreliable (too warm in summer); adsorption refrigeration was only sensible with a heat source, not practical in this case. Two options were available: compression refrigeration as a conventional means of cooling and *TerraCool* as an innovative method. The latter was discarded because no information was available regarding the geological structure of the ground on site (as the ground remains at a constant 10°C below a certain depth, that cooling power would have been used). Thus, a recirculation chiller with compression refrigeration was chosen to cool the condenser, fed with drinking water from a closed circuit (needs to be treated with biocide and water softener; 245 kW cooling power of the chiller).

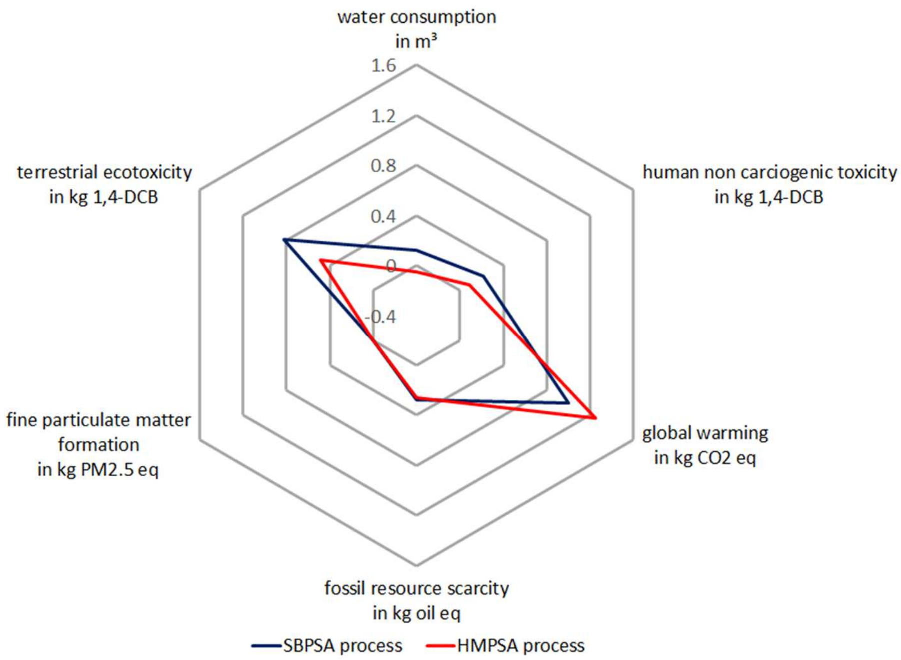
Piping System & Layout combined the knowledge of all material and media flows with the designed apparatuses. The goal was to achieve an overview over the model plant, to minimise piping lengths and direct material flows in an efficient way. For the design of the pipe dimensions, media and process properties have been considered. Some of these properties include viscosity, density, corrosion properties, volume flow, maximum temperature difference and the required pressure at the target. To calculate the pipe dimensions, the pressure drop due to dissipation and also the pressure changes by sudden changes in the operation were taken into account. Thermal expansion and natural frequencies were also calculated for the piping design. As a material choice, everything in contact with the solvent EA were designed to be made of stainless steel to prevent corrosion. Water pipes were chosen to be made of copper and mineral wool would be used as isolation material. To combine this information into one visual model of the plant, the software *SketchUp* by *Trimble Inc.*, along with third-party plug-in programs, was used. Pumps were chosen: a gear pump with a magnetic clutch for the SBPSA; a screw compressor for the nitrogen loop; centrifugal pumps for ethyl acetate and cooling water; a roots vacuum pump for the membrane module; screw conveyors for the granulated HMPSA; every pump is to be doubled to account for redundancy.



To ensure a smooth operation of the plant, **Automation** specified control tasks for the plant and planned an automated system start-up and shutdown routine. In the following, a few control tasks of the SBPSA process are described. In the coating apparatus, a uniform coating must be ensured; over the width of the PVC-foil, three sensors are installed to measure the film thickness by optical means; if there are any irregularities, the speed of the metering roll will be adjusted in order to increase or decrease the film thickness. In the dryer, several control tasks must be fulfilled: regulating the temperature of the nitrogen stream by measuring the temperature inside the chambers; ensuring that there is no pressure build-up; ensuring a steady speed of the foil; monitoring the O_2 concentration and triggering an emergency shutdown if it is too high. Solvent recovery also demands several control tasks: ensuring that the right pressure is set for the condenser; adjusting the cooling power of the condenser by regulating the flow of cooling water; controlling the pressure difference at the membrane module. The nitrogen loop also involves control tasks: maintaining a sufficient recycle stream; adjusting the pressure; splitting the streams and ensuring a separate operation of both lines (if one must be shut down, the other line can remain in normal operation mode). For the start-up of the system, several work processes are combined into automation programmes, e.g. the position of the valves to switch from flooding the production line with ambient air to flooding it with nitrogen until the concentration of oxygen is low enough, starting the heating and eventually starting the operation altogether. The same was done for emergency and normal shutdown routines, also detailed with sensor information and differently timed steps, ensuring a safe and efficient work environment. For the HMPSA process, the number of control tasks is greatly reduced as the drying unit, solvent recovery and exhaust air treatment are no longer needed: the amount of adhesive fed into the coating apparatus is regulated by the speed of the extruder and of the rotary valve; the temperature needs to be regulated by the temperature of the application rolls; the layer thickness is regulated as described for the SBPSA process.

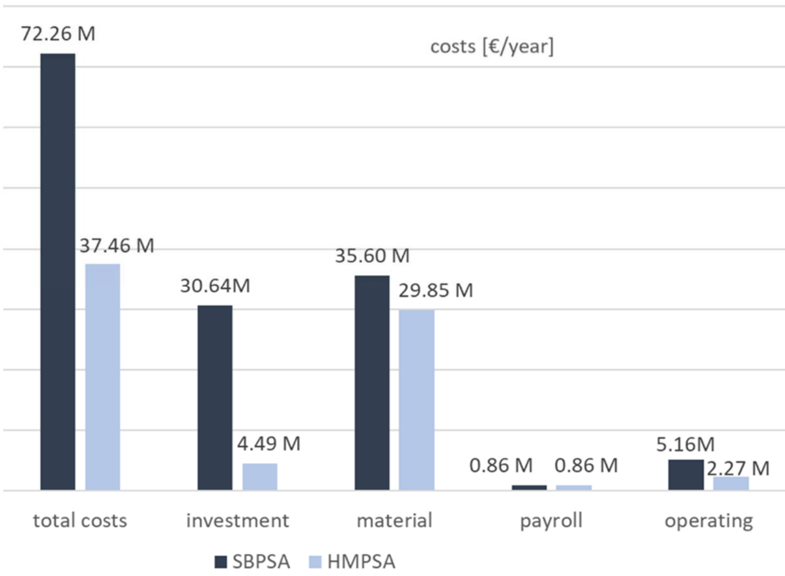
Several tasks were fulfilled by **Location – Permit – Safety**. The first priority was to find a fitting site to build the plant. As there already is a production site of the company in Germany, a possible location in proximity to this factory was searched. In an industrial park, in about 1.5 km distance to the existing plant, there is a lot with an empty industrial hall that can be purchased and has similar access to infrastructure as the other site. There is access to gas, electricity and drinking water, but noise limits must be complied with. The next step was to research the legal framework. Several laws must be observed, e.g. Bundesimmissionsschutzgesetz (Federal Immission Control Act), Wasserhaushaltsgesetz (Water Resources Act), Brandschutzregelungen NRW (Fire Protection Regulations specifically for the federal state North Rhine-Westphalia), to name a few. It is expected that after handing in all relevant forms and data, about 7 months are needed for a decision of the authorities. After that, there is an objection period, in which the residents can object to building the site at this location. Other important aspects to be observed are the occupational safety and the environmental safety, which are also regulated by several laws regarding e.g. rules for hazardous substances, air quality, noise control, etc. To meet the requirements, constructive measures (double-walled storage tanks), technical measures (regulation of the air around the dryer), organisational measures (restricted access in certain areas) or safety training of the workers (how to handle dangerous substances) are to be implemented. Special attention was given to prevent fires and explosions, e.g. using nitrogen for drying purposes and to keep an inert atmosphere). An incident analysis has been executed in close collaboration with the other groups in order to assess possible dangers that may occur and the relevant counter actions to ensure a safe work environment.

With a **Life Cycle Assessment,** the effects of the different adhesive systems with the two process variants on the environment were researched. As a functional unit, 1 m^2 of coated PVC-foil is used in order to enable a comparison between the two processes. The system boundary of the process at the company envelops coating and drying of the foil and exhaust air treatment. The system boundary of the entire life cycle is extended to PVC foil and adhesive production, foliation and, as an end-of-life scenario, incineration. An inventory analysis was done in order to assess the amount of every material and energy flow entering and leaving the process. The third step of the LCA is the impact assessment, in which both processes were assessed according to the following impact categories: global warming potential (GWP), water consumption, human non-carcinogenic toxicity, fossil resource scarcity, fine particulate matter formation and terrestrial ecotoxicity. The results of the impact categories were calculated with the *openLCA* software, which uses the *ecoinvent* database. In summary, the assessment yielded that the environmental impact of the HMPSA process is lower in water consumption, human non-carcinogenic toxicity, fossil resource scarcity and terrestrial ecotoxicity. Fine particulate matter formation displayed no significant impact for both processes and GWP was slightly higher for the HMPSA process. The reason is that the adhesive is purely based on thermoplastic materials which have a higher amount of carbon in their molecular structure than the relatively oxygen-rich SBPSA and can therefore produce more CO_2 in the incineration process. From the analysis, it can be deduced that the majority of the GWP can be allocated to the production of the foil, the adhesive and the end-of-life treatment of the product. For SBPSA, 0.018 kg CO_2 eq. (or 1.8% of the entire process) are allocated to the process at the company; for HMPSA, this amount is reduced to 0.002 kg CO_2 eq. (or 0.2% of the entire process). CO_2-certificates will have to be bought to cope with the amount of CO_2 released to the environment (for the process involving HMPSA 2’100€ (2020) or 4’200€ (2030) will have to be paid vs. 24’400€ (2020) or 48’900€ (2030) for SBPSA)). Additionally, the total energy consumption is 40% lower for the HMPSA process, compared to the SBPSA process. Therefore, a conversion to using HMPSA is reasonable.



Flowchart and Costs combined all information from the other groups into a single flowchart. As it is too extensive, it will not be shown in this short report. Besides the flowchart, costs were analysed. The total costs can be grouped into investment costs, raw materials costs, payroll costs and operating costs. The investment costs involved e.g. equipment, pipes, control mechanisms and their installation, construction, engineering and lawyer’s fees. The costs were then multiplied by a factor that was calculated by summing up the "weight" of different contributions, resulting in total investment costs of 30.6 Mio. € (SBPSA) and 4.5 Mio. € (HMPSA). Raw material costs were obtained by multiplying the costs of PVC-foil and adhesive per m² and assuming a production of 53.01 Mio. m² of product per year. A total of 35.6 Mio. € (SBPSA) and 29.9 Mio. € (HMPSA) raw material costs were determined. For payroll costs, 37.5 h per week of work time with four workers for production (1 technician, 2 production workers, 1 forklift driver) in 3 shifts and one administrator and one production engineer for work in the office were assumed (simplification). Including bonuses, insurances, etc. the payroll costs total to 860'000€ per year.

Operating costs involving e.g. electricity, waste water treatment, insurances, transport costs, sum up to 5.1 Mio. € (SBPSA) and 2.3 Mio. € (HMPSA), respectively. Ultimately, the total costs add up to 72.3 Mio. € (SBPSA) and 37.5 Mio. € (HMPSA). Production costs were calculated by using a linear depreciation of the plant.



A dynamic pay-out time analysis was implemented to determine the estimated sales price and the resulting pay-out time. For the SBPSA process, with a sales price of 1.5€ per m² of product, the pay-out time amounts to about 4.5 years and for the HMPSA, a sales price of 0.8€ per m² of product was assumed, resulting in about 3 years of pay-out time. As the production costs for the HMPSA variant are significantly lower, the profit margin is considerably bigger, therefore the pay-out time can be reduced to a few months, assuming a higher sales-price of the product.