**Abbildung 2:**

The X Link is currently applicable to EVA. Spot tests also suggest applicability to crosslinking polyolefins. The research needed to extend this to other materials, encapsulation, but also backsheet films such as for bifacial module types, is being done in EVAPLUS (LayTec, CSP). There is also a known dependency with the micro-structural properties of the backsheet film that needs to be explored for successful deployment of the system. This is done in EVAPLUS by LayTec, CSP and HSA. The influences of the measurement process and material combinations, e.g., initial temperature, backsheet structure or thickness are currently not understood. This research problem is being addressed by HSA through the development of a digital twin of the measurement process. A formal uncertainty analysis, as is common in metrology, is needed to prove the reliability of a measurement method.

One goal is to make the X Link suitable for in-line process control in manufacturing. This requires an acceleration of the measurement process. LayTec is aiming to halve the measurement time here (<30s). However, a pure process control would not exhaust the potential of this technology. Currently, production only ensures that the degree of crosslinking is above a minimum and maximizes the temperature of the process, as these speeds up the process. The state of the art in quality control is that, at best, a module is occasionally tested destructively. As discussed above, this is not practical from a reliability perspective and can also lead to a reduction in process yield, as a process that is too fast can lead to bubbling in the encapsulation and similar abnormalities. To complicate matters, the input material can also vary greatly, as shown in Figure 3. However, the investigation shown here [11] would need to be applied again to modern films (HSA, Sunset). Here, HSA will develop a method for optical determination of the relevant parameters. A test run will be carried out at Sunset and possible marketing by LayTec will be investigated.

**Abbildung 3:**

This requires a continuous evaluation of the input films, which is being developed by HSA. Based on transmission spectroscopy coupled with artificial intelligence, this supports the correlation analysis for microstructural and crosslinking degree relevant properties of the backside or encapsulation film. Together with LayTec and Sunset, we are looking at how this can be implemented in an Industry 4.0 environment in production. LayTec will work here on a method for tool-to-tool matching.

The development of the required BAT for own projects (ABO) or as a service (PIB) requires detailed preliminary investigations such as an FMEA (CSP, ABO, PIB) and an expectation value for problem identification and frequency (ABO, PIB). This is needed to develop statistically relevant test scenarios that provide an acceptable probability of problem identification at minimal cost. This requires detailed studies of the expected value (ABO) of current production. PIB will contribute knowledge of typical production environments, ABO will perform correlation analysis with performance measurements.

he reliability of laminates depends on the film used. There are currently several studies dealing with the backing films, the encapsulation itself is currently less investigated. Encapsulation has often been investigated in the past due to the yellowing that can be observed, e.g. [12]. This problem can be controlled with the help of targeted additivation. Other problems include the release of acetic acid in EVA encapsulations [13], leading to corrosion of the active elements. However, the encapsulation must also perform other functions, such as electrical insulation, mechanical protection, equalization of thermal stresses between different materials in module, and protection of the inside of the back sheet from UV radiation. These properties depend largely on the additivation of the films and, of course, on the homogeneity of these additives. In this regard, there are the studies by Ehrich and Schulze [11], who determined the distribution of crosslinking peroxides with DSC, but the production processes and volumes have changed a lot since then. There continues to be significant scatter in e.g., gel content measurements, but a systematic study is being conducted in EVAPlus. A critical parameter for the quality of the final product is the gel content, which also allows conclusions about the production process to a certain extent. EVAPlus will provide the tools needed to measure this two-dimensionally. The gel content can be determined using Soxhlet. The method is simple, cheap and can provide an absolute number of the actual crosslinking degree. However, the long experimental duration, destructive sample preparation, work with solvents and result dependence on the type of solvent used make the method less attractive [14]. An alternative method for crosslinking degree determination is DSC, which was already mentioned in connection with Figure 3. DSC is much faster than Soxhlet, but also requires destructive sample preparation. Moreover, one always needs an uncross linked starting film as a reference to quantify the degree of crosslinking by relating the residual heat of crosslinking to the total heat of crosslinking from the starting film [11]. The above-mentioned distribution of all possible low molecular weight additives can be determined by GC-MS. The method will be used within the project for the calibration of the optical methods, which are also suitable for the purpose [15], [16].

Nowadays, the quality of films is mainly examined by destructive methods. Investigations consist of cutting open the backing film and extracting material and examining it using various methods. Various thermal, mechanical, and chromatographic methods are used for this purpose. The thermal methods mainly include the above-mentioned DSC and TGA [17]-[19]. DSC can determine the degree of crystallinity after lamination, which is reflected in light transmission and can ultimately be used to optimize the cooling phase of lamination. TGA is sensitive to degradation processes in the polymer chain and is primarily used for tracking vinyl acetate cleavage, as it leads to corrosion in the form of acetic acid. Among mechanical methods, DMA and TMA are often used. DMA can be used to optimize the parameters of the lamination process such as temperature and time, since the storage module responds immediately to the changes in network structure [11]. TMA can be used to determine thermal expansion coefficients, the knowledge of which is particularly important for new encapsulation materials, since too high expansion coefficients can lead to the formation of mechanical stresses in PV modules in the field and ultimately to delamination [20], [21]. Chromatographic methods (GCMS, HPLC) can be used not only to determine the above distribution of additives, but also to follow degradation processes of polymer chains and additives during aging. Non-destructive methods are currently under development. Film qualities are investigated using micromechanical indenters, such as LayTec's X-Link. This approach is currently the most advanced in commercialization. Competing approaches are Raman spectroscopy [22], luminescence spectroscopy [15], [23] but also simpler methods like UV fluorescence [24]. None of these methods is currently able to evaluate the manufacturing process in a depth as it is possible using the X Link. Therefore, the X Link method is used in EVAPlus to improve the lamination quality throughout the value chain.

Although it would make a lot of sense to carry out a detailed incoming goods inspection of the encapsulation films, as shown above, the current state of the art is a rather superficial investigation. At best, the documents are sifted to see whether the same film was really supplied and perhaps an off-line check of e.g., transparency of the film is carried out in isolated cases. It is not checked whether the additives also correspond to the order or whether the film was also manufactured homogeneously. Non-destructive optical metrology is not used, and the use of indenter-based methods can also be expanded. Thus, the proposed quality assurance in the incoming material department of the module producer Sunset is extremely innovative and requires the scientific support of the consortium in order to be practicable.

The outgoing goods, i.e., the control of the polymer quality of the finished laminate or module, is not common. In rare cases, isolated modules are tested with the X-Link. process, but the number of modules is not even in the single-digit per mille range of production. This is only possible because there is also no stringent incoming goods inspection of the processed polymers on the end customer's side and thus no market pull for such processes. The reasons for this are many, but the lack of non-destructive testing methods and also the understanding of the risk due to poor polymer quality play an important role. This circumstance is fundamentally remedied by EVAPlus, so that a contribution to the energy industry in general can be achieved.