Pragmatic organic integration of Industry 4.0 in the PV industry

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Abstract

Industry 4.0 has often been discussed and investigated in relation to its benefits for the PV industry. Many solutions require the set-up of a complex complete system for the entire manufacturing process and possibly even for the raw materials. Particularly for existing manufacturing operations or for ramp-up, such complex solutions are often out of the question. The aim, therefore, is to discuss in this paper what approaches from the digitalization field can be used quickly and easily to accelerate ramp-up, to analyse overlapping data and to improve production either manually or automatically. The concept of a scalable, strictly modular system that works with any hardware and leaves the choice of application to the user is presented. All data will reside in a database, from which they can be retrieved with, for example, Excel, jmp or other statistical/monitoring or management software. In addition, standards for wafer tracking are proposed, and a way of integration with current digital twin standards is suggested so that the system can be easily extended. The concepts described are part of a FlexFab system: RCT and ISC are working together on a factory concept in which different cell and module designs (here, bifacial n-type back-contact ZEBRA and PERC) can be manufactured in parallel. In the production process, it is possible to continuously vary the proportion of different cells as required.

Introduction

How does digitalization and Industry 4.0 benefit PV? An organic way of realizing a meaningful digitized PV factory will be discussed, where equipment, measuring devices and environmental sensors are equipped with digital twins or minimal digital twins. These virtual representations communicate autonomously using open standards that are recognized throughout industry. The data can be accessed with almost any software. 'Minimal' means that only the necessary data are collected and can be easily expanded.

Benefits for ramp-up

The ramp-up process is arguably the most complex operation that any PV factory will ever experience. Each individual plant presents its own start-up difficulties: facilities such as ventilation, clean water and automation will have just been set up and will therefore be more prone to errors than after operating continuously for some time. Operators also need to be trained and may make frequent mistakes until they are fully qualified. In the light of these conditions, the complex equilibrium of a stable – and, as far as possible, efficiency-optimized – manufacturing process for solar cells needs to be reached during ramp-up and the system broken in.

"Ramp-up generally still takes place manually in many factories."

Despite the drawbacks, ramp-up generally still takes place manually in many factories: the settings of individual systems and the measurement results, such as sheet resistance, finger width and *I–V* parameters, are noted down and transferred to Excel tables or read out from the individual systems. Engineers then laboriously analyse the dependencies of individual process steps and environmental influences.

As an example, in one project large fluctuations in cell voltage and efficiency were observed; the cause of this was not readily apparent at first, until a technician noticed that the results always improved after a rainfall. It transpired that filters in the ventilation system were defective, allowing metal particles to enter the clean room (Figs. 1 and 2). However, when the rain had cleaned the outside air, the air in the clean room was also clean and the results were significantly better.

The efforts to find the source of the problem were enormous: all the data had to be collected, and many other hypotheses tested and discarded before the problem was eventually solved. It would have clearly been a huge help had all the data already been made available automatically at the start of ramp-up, such as measurement results, device parameters and also seemingly aberrant environmental data. If, in addition, statistical methods had been used to automatically check for correlations, the issue would probably have been detected much earlier.

Of course, steps like those described above can be carried out using a manufacturing execution system (MES) – provided such a system has been commissioned and is already fully functional before ramp-up begins. Alternatively, each individual plant, each measuring device and each sensor could be equipped with a digital interface right at the point of commissioning, and a 'minimal digital twin' created, which would allow each device to be queried uniformly. The data can be written into databases or directly used by programs of the customer's choosing, for example Excel or statistical analysis programs. In this way, the application is isolated from the data provision.

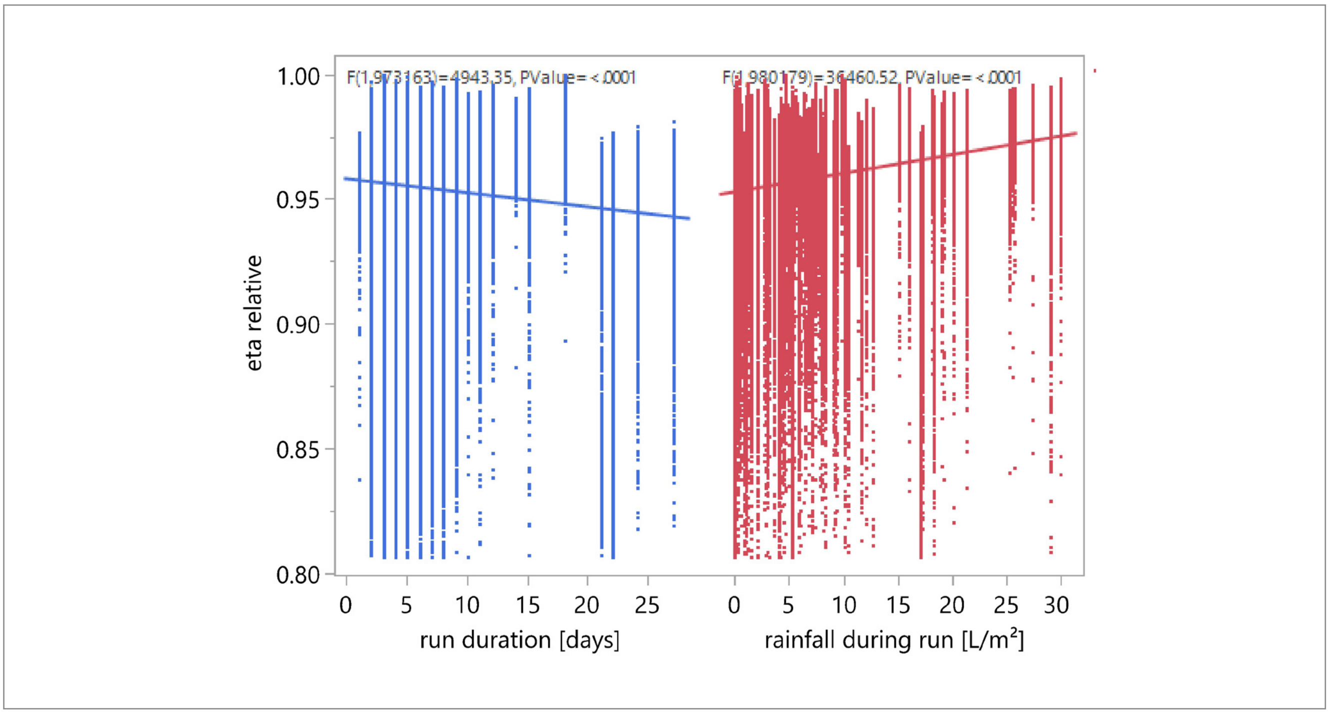

Figure 1. Strong dependency of efficiency on rainfall in a ramp-up project. It was found that a defective filter led to metal-containing dust in the clean room. After a rainfall, the outside air was clean and therefore no contaminated air entered the clean room.

Benefits for manufacturing reports

In an operational PV production set-up, different parts of the operation need different information. The *shift supervisor* must have a continuous and up-to-date overview of yield and the most important cell parameters; they must be able to see at least the current errors from the plants, and preferably even more parameters as needed. The *operator* needs to be informed about tasks. The *management* should be able to query yield, uptime and quality of the cells or modules at any time and for any period.

Each of the three levels of operation mentioned above may wish to use different software. Quality assurance requires the development of, for example, an Excel tool into which data are fed. The operator might use an in-house-developed app for their cell phone or smartwatch to automatically advise them to go to a specific plant at any time. The accounting department will probably want to integrate results directly into accounting software.

An MES, of course, can achieve this variety of software needs; however, this type of system involves complex, centralized software. Digital twins and the use of Industry 4.0 technologies would mean more

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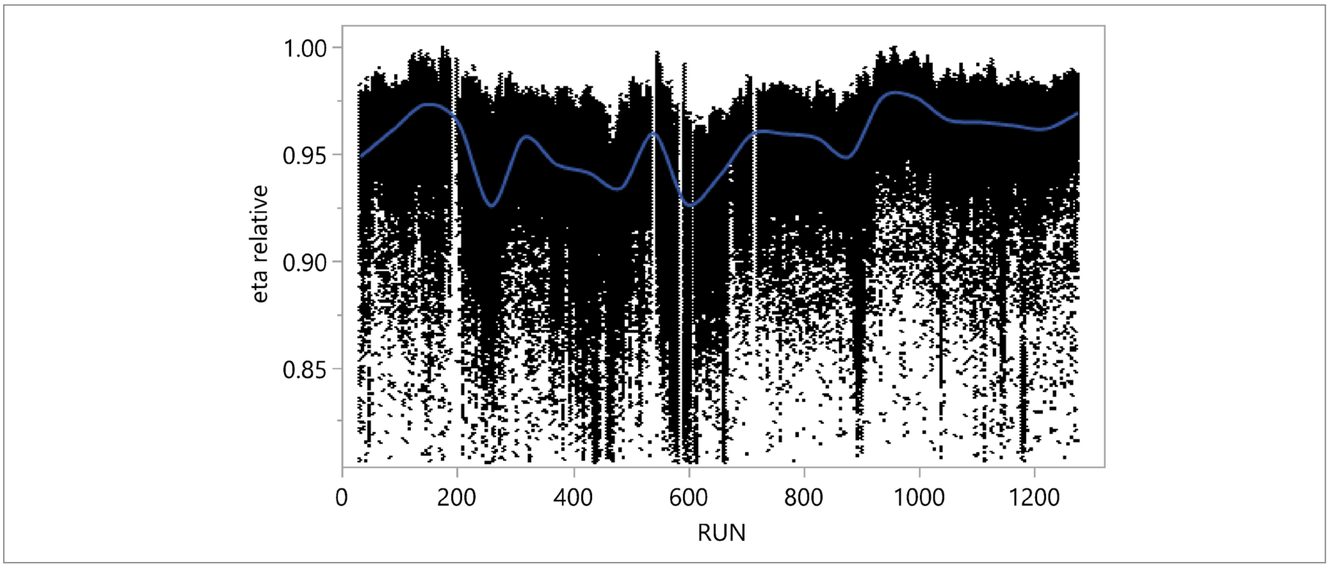
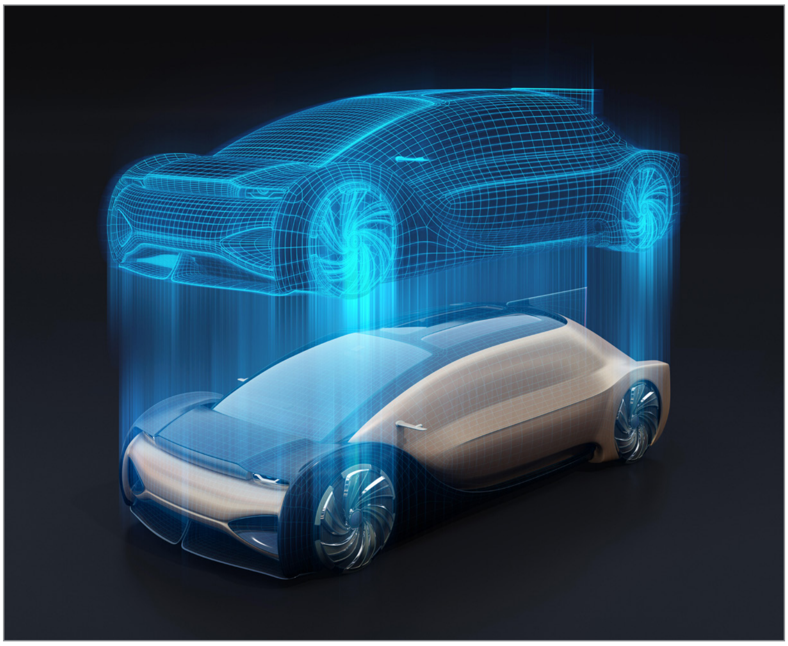


Figure 2. Sample start of a factory ramp-up, with 1 million wafers. The variations in efficiency highlight the different obstacles encountered during the ramp-up process.



Credit: Haiyin Wang/Alamy Stock Photo.

Figure 3. Digital twin representation of a car, using CAD drawings, operating details and even every screw.

self-organization: each digital twin of a plant can be addressed individually or it reports individually, with a minimal higher-level structure.

Benefits for organic line improvements

If standard interfaces or digital twins are used, data can be provided in a standard format and the devices can be linked very easily. Analyses can then be performed with software selected by the user. External experts of the user's choosing can help quickly, because they can use their own tools – uniformly for all data on the line.

The scope of the data can be expanded easily and, if desired, by the user's own digital experts. The data will form a good basis for the use of artificial intelligence (AI), be it for error analysis or for self-learning algorithms. The solutions have to be as simple as possible, even for different systems: large machines and small ones, such as sensors, must be easily hooked up.

Minimal digital twins and expansion

Digital twins can reproduce a device almost exactly: they can include computer-aided design (CAD) drawings, all components, important process parameters, manuals and much more (Fig. 3). Alternatively, only minimal information might be stored, such as the direction and current speed for a car, or etch removal and measured reflectivity for a chemical wet bench. If only alarms, etch removal and reflectivity are required, only these data need to be available. Should more data become available later, the twin must be easily expanded in due course.

"A cross-industry standard for digital twins that can be integrated with existing libraries would be desirable."

This all sounds quite complicated to implement and to coordinate among all the players in PV manufacturing. A cross-industry standard for digital twins that can be integrated with existing libraries would be desirable.

Digital twins in PV – use of a unified, cross-industry standard

The concept of digital twin in manufacturing dates back to 2003, when Michael Grieves [1] introduced it in his course on product life-cycle management. According to Grieves, a digital twin model consists of three parts: 1) the real product; 2) a virtual copy of the real product; and 3) the connections, in the form of data and information, between the real product and the virtual product.

The amount of information a digital twin might contain is wide ranging. At one end of the spectrum, there is the *rich digital twin*, which contains all available information about the product. At the other end, there is the *lightweight digital twin*, which carries only the information needed for the actual task, thus reducing the size of the model and allowing faster processing.

Digital twins are used to visualize and simulate products and systems, but they are also used to share information within the supplier's network. On the physical side, more and more data about the physical product are collected. For the greatest benefit, the real product and the virtual product should exchange information continuously throughout the product's entire life cycle. In this case, digital twins can be used to build a virtual factory replication, which constantly monitors and displays the state of the real factory.

Grieves' definition of a digital twin, consisting of a real product, a virtual representation and the connections between the two, is quite broad. The set of implementations that fall under this definition of digital twin is therefore quite diverse. And to make matters worse, there exist other concepts, such as the 'digital shadow' [2], which overlap with Grieves' definition. Kritzinger et al. [3] note that this diversity and ambiguity leads to misunderstandings, since different people have different understandings of these concepts.

Consequently, Kritzinger et al. define a classification of digital representations based on the level of integration between the physical object and the digital representation. Three classes are defined: digital model, digital shadow and digital twin. According to this classification, a *digital model* is a representation of a physical object without any automated data exchange between the digital representation and the physical object. A *digital shadow* is a digital representation of a physical object with an automated data flow from the physical object to the digital object. The digital representation is called a *digital twin*, if the automated data flow is in both directions, from the physical object to the virtual object and vice versa.

For a broad introduction of digital twins in Industry 4.0, it is necessary to have not only a consistent understanding of terminology, but also standards for the implementation of digital twins. In Germany the Plattform Industrie 4.0 [4] is developing such a standard for digital twins, called the *Asset Administration Shell (AAS)* [5]. However, in this context the term 'digital twin' is used quite broadly; specifically, a *digital twin* is defined as a 'digital representation, sufficient to meet the requirements of a set of use cases' [6]. As such, this definition covers all three classes defined by Kritzinger et al., from a pure digital model up to a fully-fledged digital twin.

The AAS concept is described in a technologically neutral form in terms of the unified modelling language (UML), in which every asset has an associated AAS. Assets can be physical assets such as machines or products, or they can be non-physical assets such as processes or computer programs.

An AAS consists of a header and a body: the header contains information to identify the AAS and the asset, whereas the body contains the data about the asset. The structure of the body is characterized by so-called *submodels*, representing different aspects of the asset. Submodels can contain properties and operations, which can be hierarchically structured. In principle, the equipment vendor or user is free to define submodels as needed, but a certain amount of standardization is beneficial. Plattform Industrie 4.0 has so far standardized the *Nameplate* submodel, which contains essential information about the asset, such as the manufacturer, serial number and year of construction [7], and the *Technical Data* submodel, which contains the sections labelled *General Information*, *Product Classification* and *Technical Properties* [8]. The implementation of a digital twin of an inline wet bench in the lab at ISC Konstanz is shown in Fig. 4.

Submodels do not have to be contained in the corresponding AAS; it is possible for them to be hosted externally, and only a reference to each submodel stored in the AAS. In addition to the submodels, the AAS concept defines a registry in which AASs and submodels can be registered. This registry allows an easy look-up of the registered AASs and submodels.

The AAS standard is accompanied by a reference implementation, which is part of the Eclipse BaSyx factory automation platform [9,10]. BaSyx is an open-source platform under the Eclipse Public License 2.0 (EPL 2.0). BaSyx provides software development kits (SDKs) for the AAS in the Java and C# languages; there is also an SDK available for C++, but this is only intended to be used for integrating existing devices.

In terms of the classification developed by Kritzinger et al., Part 1 of the AAS standard [6] defines a *digital model*. Part 2 of the AAS standard [11] defines an API for interacting with the model; this API provides the functionality for reading data from the AAS, so it can be used as a *digital shadow*. In addition, the API provides functionality for invoking operations on the AAS, thus acting as a *digital twin*. In order to fully define a digital twin, however, the interaction between the AAS and the physical asset has yet to be standardized. This gap is bridged by the Eclipse BaSyx platform, which already contains the necessary functionality. Thus, with BaSyx an AAS can be used to operate a device [10].

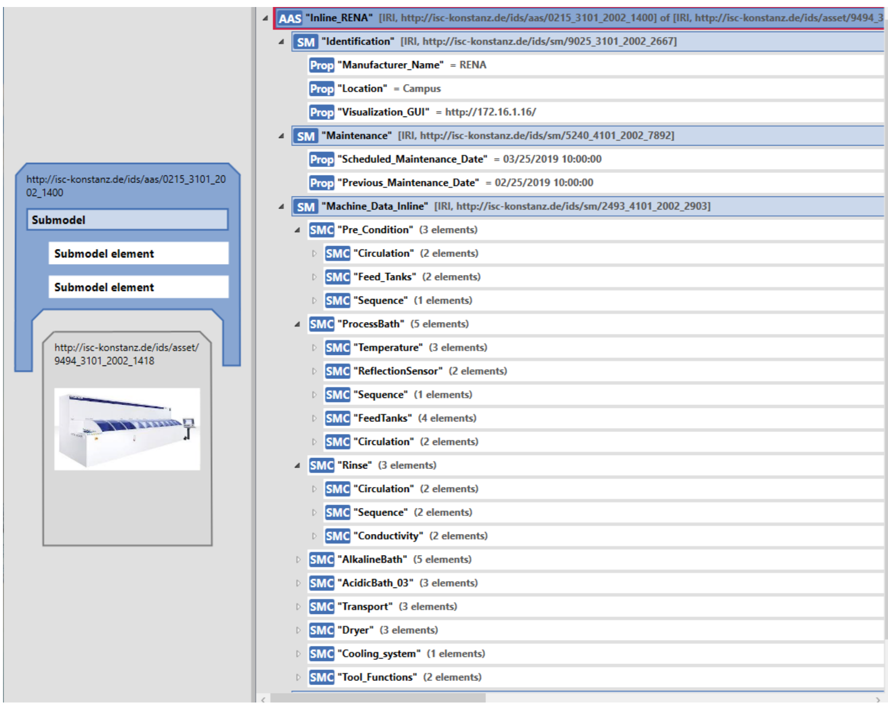


Figure 4. Implementation of a digital twin of an inline wet bench at the ISC Konstanz lab.

A twin in every machine

Every machine builder and measurement device manufacturer should offer the digital twin as standard with their products. Since the twin is based on any interface, the machine builder only has to create a twin on their PV2, OPC-UA or xml-based interface. The AAS according to 'Plattform Industrie 4.0' described above for digital twins in PV manufacturing is proposed as a standard. A minimal twin contains the nameplate, the most important alarms and the most relevant process parameters.

For demonstration purposes, all cell manufacturing facilities in the ISC Konstanz lab are currently being equipped with digital twins as part of the FlexFab 2 project. This is intended to demonstrate the control of flexible manufacturing of different cell concepts.

Additional benefits of digital twins in PV manufacturing

With digital twins, manufacturing data can be read and recipes can be changed. But there are many more applications available through the standardized structure. For instance, manuals and other documents can be regularly called up, and virtual training for operators or engineers can be carried out at the plants. Remote support is also conceivably made easier if remote maintenance software is given access to the digital twin.

Factory ramp-up can be done virtually if the digital twins have been interconnected to form a virtual factory. In addition, the factory can be operated as a 'silent factory': tasks, alarms and information are sent directly to those responsible, such as the operator's cell phone or the shift manager's smartwatch, and escalation and forwarding can be easily set up.

MES providers offer corresponding but different types of system: a 'simple' system with the connection of all equipment and access to the measurement data and data of the production plants. This can be to the extent of complete networking of manufacturing, data analysis, personnel planning, enterprise resource planning (ERP) and much more.

Ramp-up and experiments without an MES

Without an MES, ramp-up and experimentation on the line must be done entirely manually, with run sheets and transfer to Excel spreadsheets or statistical process control (SPC) tools. This may be necessary if an MES has not been purchased for a new production, if existing factories do not have an MES, or if the MES is not yet fully functional when the factory is commissioned. However, the effort required for data collection without an MES can be significantly reduced by means of a minimal integration of interfaces and databases. For ramp-up or inline experiments, samples of (for example) 100, 1,000 or 10,000 wafers are used. All data are stored, as far as possible, automatically in a central database, which can take the form of a simple SQL database.

- All plants and sensors must synchronize their clock times, which is easily accomplished automatically if they are all connected to the Internet. Otherwise, the clock times of the plants must be regularly checked.

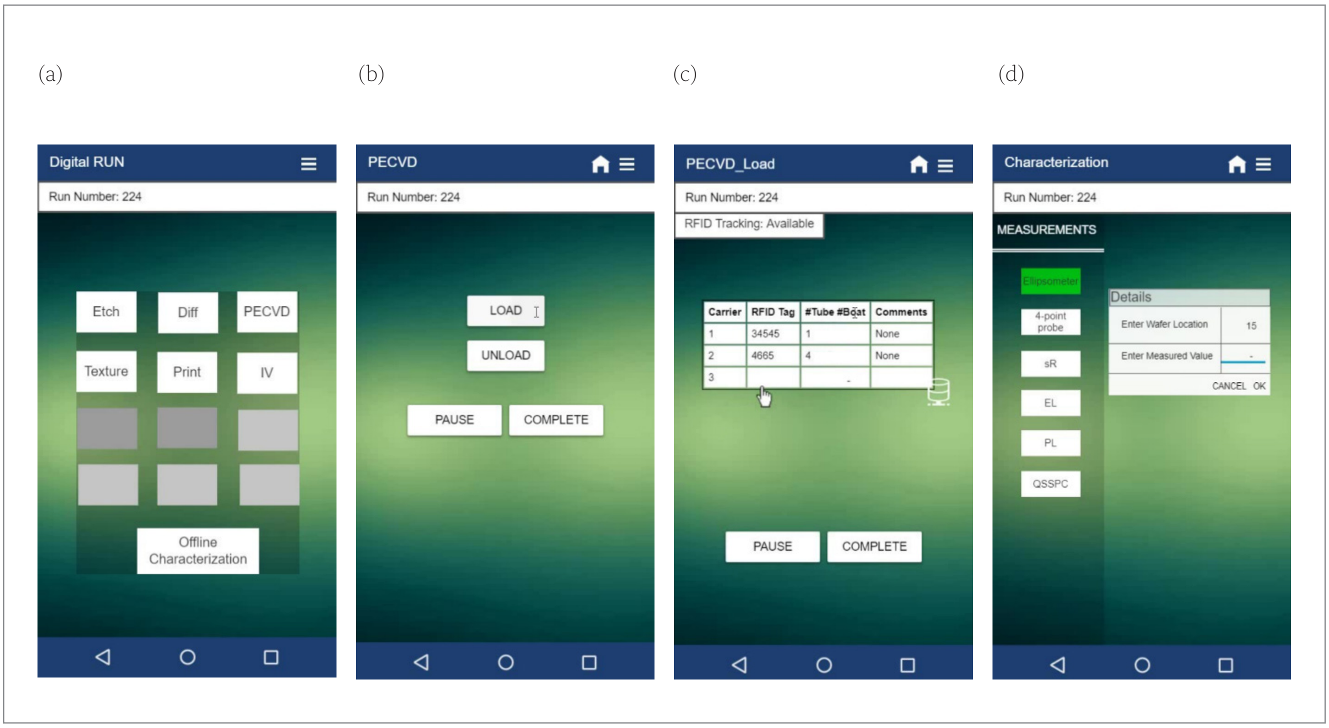


Figure 5. App developed by ISC Konstanz to follow wafers in an experiment in the absence of an MES. The tablet travels with the wafers, and operators enter values via the tablet. Screenshots: (a) choose process step; (b) load/unload form process; (c) enter details for process; (d) enter values for offline characterization.

- All equipment that generates important data (e.g. *I–V* measurement data) should be equipped with a digital interface. The data can then be easily transferred to the database using a script.

- The loading and unloading of equipment must be stored with the timestamps. For that equipment which transfers data to the database, the assignment to the experiment can be made in this way. Otherwise, data can be assigned later.

- Manually measured values are transferred to the database by hand, with assignment to the experiment and the groups.

- The transfer of measured values and the assignment of times to processes/experiments can be handled by an app that each operator runs on a tablet. ISC Konstanz has developed an app for this very purpose, which can be used during ramp-up (Fig. 5). The tablet travels with the wafers – a digital docket. However, the app must be very easy and quick to use; otherwise, operators in the factory will fail to perform the task, or they may do it carelessly and the data will be worthless. If the carriers are equipped with radio-frequency identification (RFID) tags, these can be read immediately by the tablet, thus avoiding assignment errors.

Basic MES

Basic MES options with limited functionality are available that can be used for ramp-up and experimentation; these simpler systems work much faster and are more reliable than manual solutions. The factory operator must be willing to invest in a basic MES, and the MES must be available, ready and working at the time of commissioning.

Such a basic MES must have interfaces for all systems and measuring devices and be able to store the acquired data centrally in a database that is freely accessible to the user. Some types of MES already offer virtual wafer tracking in the simplest version, which can significantly accelerate and improve ramp-up and experimentation. Self-learning algorithms and automatic experiment planning can be implemented.

It is very important that the MES works when the equipment is put into operation. To ensure this, it is best to agree when purchasing the equipment that it will be accepted and commissioned together with the interface for the MES.

The possibilities offered by a fully-fledged MES will be discussed in the section on modularization later.

Necessary standards

If all the equipment in a PV factory could be accessed in a standard fashion, the work entailed in reading data would not be very difficult. Ideally, each equipment builder supplies a digital twin of its plant in a standardized format. This standard must be recognized across industry, and so the AAS according to 'Plattform Industrie 4.0' is proposed. The digital twin can be a minimal twin, through which only important values and information about the equipment can be accessed.

When a digital twin format is not standard, the digital interface properties should at least be defined: in addition to the PV standard PV SECS/GEM, this could be according to OPC-UA or MQTT protocols.

In addition, database schemas could be prescribed for important data, which would once again significantly simplify the connections to tools for evaluation purposes.

Applications

No matter how the data are provided, the customer should be free to choose the application with which they access the data. This application must only be able to communicate with the database. The customer can then use Excel, jmp, a self-written web application or anything else, or even multiple applications in parallel, in the way that best benefits manufacturing, evaluation or ramp-up.

Growth, or what can be achieved in PV production with today's technologies

In the following two sections, the technical possibilities of digitization in PV manufacturing will be discussed. To this end, the individual possibilities of currently available MESs will be examined. In addition, the latest digitalization concepts that can be used to optimize manufacturing processes will be considered.

Fig. 6 shows the core of an MES in solar cell manufacturing, consisting of the equipment connection and manual input possibilities to allow process control and overall equipment efficiency (OEE). The advantage of this is the central material tracking of wafers. Initial extensions are quality control (QC) and SPC based on the core, which allows more detailed reports. Other components can be added later or connected as modules via interfaces.

The scalability and the flexibility to grow from a simple data-collection system (the 'basic MES' discussed above) with rough data output for central report requirements are suited to a fully data-driven business [12]. For newcomers or new factory locations in the solar industry, a balance needs to be struck between cost, effort, qualification, time and return of investment. In the case of newcomers, the complexity of the production control is often disregarded.

Preferably, the virtual factory part is built in parallel with the real factory. However, the MES is often seen by managers as less important compared

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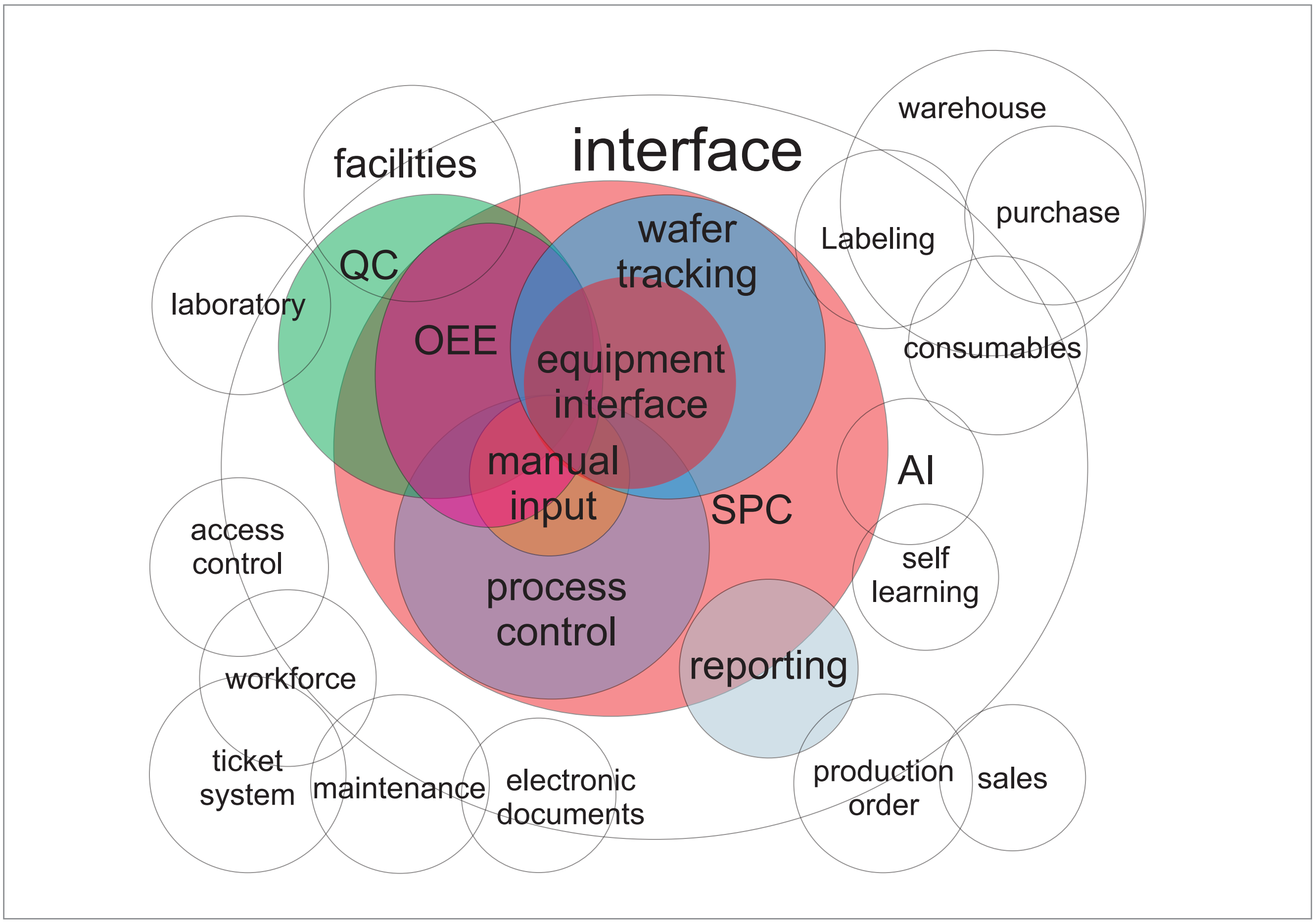

Figure 6. The core of an MES in solar cell manufacturing, with initial extensions and possible later additions or connections of other components via interfaces.

with, for example, the machines, so that not the full potential is exploited. Therefore, the core aspect of a solar cell MES, collecting SPC and OEE relevant data from each piece of production equipment, should be the initial focus. With a traditional monolithic MES, strongly coupled to the database, the selection of the database and database system is crucial, as it is unlikely that the limitations of the database structure can be overcome at a later stage. With a modern modularized approach to software development, the initial choice of database is less important, because the abstraction layers decouple the application from the underlying database.

As a full MES solution is so much more than just SPC and OEE monitoring, each vendor and industry has its own definition of beneficial add-ons and divisions between individual modules inside the MES, the ERP system above and the supervisory control and data acquisition (SCADA) systems below. In the case of full modularization and database separation (as discussed in the next section), it is possible to shift software modules between these systems or to add modules later on, depending on individual requirements. The basis for this is the possibility of running each module, or at least the core modules, separately and provide standardized interfaces between them.

The major argument against this approach is the often-feared so-called *heterogeneous IT landscape*.

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In times of virtualization, interface libraries and outsourcing, this argument is overthrown by the advantages of taking, for example, specifically the best database regardless for each individual purpose.

Modularization – how far can PV production go with digitalization?

One of the basic requirements for current IT systems is their flexibility in the face of rapid development, limited resources at the beginning of a project, and unforeseen new requirements. The traditional approach for MES is a closed system from a single vendor with out-of-the-box functionality. Prima facie, the advantage of this is clear: one vendor alone is taking the risk and responsibility for the system, which is preferable, considering the numerous vendors that are already part of consortiums and projects. On the other hand, the single-vendor approach rapidly leads to a vendor lock-in. Even more likely is a system lock-in, as obviously there is no easy way of transferring the whole MES to a new system from the same vendor, if the vendor switches to using a new architecture.

On closer inspection of the data paths, it becomes clearer that these already include several different vendors and interfaces. In a classic MES, the data are most likely generated initially by analogue sensors. These signals are digitalized and transmitted via a machine internal bus to a programmable logic controller (PLC). The PLC communicates via an additional interface (either built into the PLC itself or installed as an external additional data card, box or separate HMI PC) with vendor-specific line controllers or directly with the MES. The MES then reports to the ERP system. Each of these levels of processing goes hand in hand with a data reduction and filtering stage.

The core of a classic MES is a vendor-specific relational database system (RDBMS). The flexibility and scalability are limited by the database, the onsite server capacity and the features of the MES platform. The output is then most likely limited to SPC and central recipe control, thereby leading to a reduction in onsite manpower. There is much more that can be gained from the data, depending on the specific task: external experts for data analysis could provide support if they could simply get access to the data in a freely selectable format. Recent developments in the fields of data science and analysis, such as AI, are complex and require a special approach.

A modular MES is shown in Fig. 7: while the central MES database provides compressed core information, each device registers itself in the registry. The registry stores information about data type, connection type and data storage location. Other devices can request details of data sources from the registry and directly communicate with the data source. Latency and network and server load are minimized.

Four fields in modular digital PV manufacturing can be identified. In field number one, a modular MES breaks down the single, central MES into smaller modules which have standardized interfaces in between and work more independently than software that is monolithic in nature. A monolithic MES selects and offers data to allow data handling.

Software parts are programmed in independent modules which can be run in virtual environments. Examples of modules are a piece of equipment with an interface, a digital twin, a data processing engine, an AI, an SPC system, a report system or a single industrial internet of things (IIoT) device. Each defined module, as part of the modular MES, runs in a virtual machine, independently of the hardware base. The modules are connected via standardized interfaces, with this standard being independent of vendors and preferably open source. The MES, as a central system, has to provide the hardware and storage pools, either on the premises or in the cloud. Standardized interfaces allow simple replacements of individual modules of the same type, or even parallel processing and comparison. The interface also allows the data source behind it to be easily replaced.

The second field includes modular data transformation steps, data buffer systems, predictions for data and so on; these can be intermediate modules between the original data source and the final recipient in an unlimited row. The data from sensors with more complex functions are modified, transformed, predicted or replaced by pure software code in additional modules. Instead of a direct access to the sensor data, an analysis module uses the transformed data in advance. A data source module is then a source and a recipient at the same time on the data path.

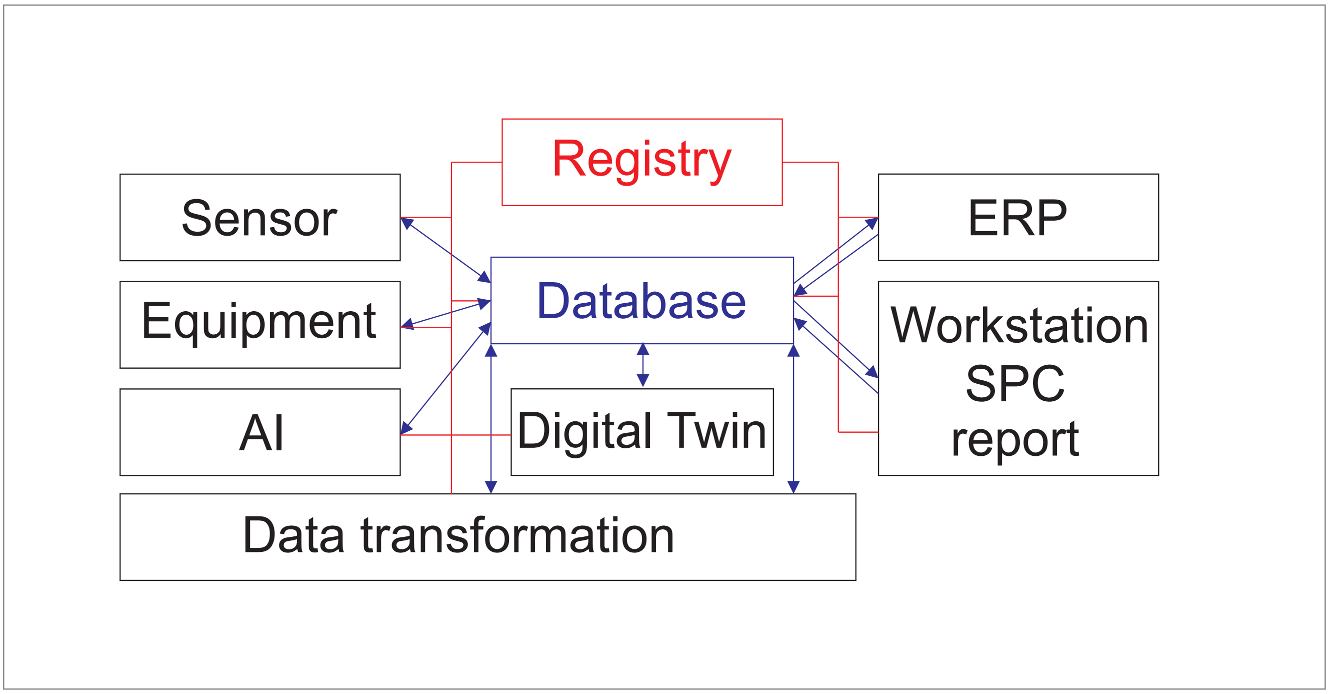

Figure 7. A modular MES.

As a consequence, it no longer matters whether physical or virtual production equipment is being run, feedback and optimizations are acquired from a human via an SPC module, or recipe adjustments are received for every batch, even during processing, via an AI [13].

In the third field, the big step forward will be the transfer from a central database to a real cloud-based system. This concept utilizes the following components. The single MES database, as the core, is divided into several databases connected together in a network of databases. Microservices, independent software instances with modules, are state of the art in many IT systems [14]. The cloud concept does not necessarily mean taking resources completely or partly from one of the three main players – AWS, Azure or Google cloud. It could also be a scalable, virtualized and flexible hardware and software resource system which is hosted locally (on the premises), but which is scalable and independent of hardware and software.

The hierarchical structure of a production sequence, from sensor to ERP system, is thereby broken down. Every module participating in the production can be both a recipient and a data source. The industrial IIoT concept describes this conversion in small steps. Each module is equal and part of a larger network. Data are equally converted, modified or generated and consumed by each player in the network. Large, spanning all sectors, active big-data specialists, such as Palantir, and/or large cloud players have defined interfaces and data structures to address the challenges of data mining.

The fourth field handles the identification of digital twins. In the future, a machine will be delivered with a digital twin as a matter of course. The digital factory will recognize it, and one will be able to easily perform a digital ramp-up that will quickly identify possible configuration errors of the complete factory.

Current standards in the solar industry – such as SECS/GEM, EDA or OPC-UA – still mainly target the SPC as the final data output, which is fine for manual data mining. A big-data approach, however, needs to go one step further. In addition to the current interfaces, a direct pathway between data source and recipient has to be defined.

The complete transformation of an MES into a modular system allows additional freedom in design and data flow. A modular virtualized system not only includes existing standards, but also guides real-time data from sensors and other players into a data pool. This system makes use of cloud-compatible interfaces, thereby generating an up-to-the-minute system. It benefits from modular Industry 4.0 steps with digital twins, AI and further current developments [15]. This system could directly register communication channels and request metadata such as communication protocols from the central MES core. Each participant is therefore recorded in the registry, either manually or automatically in advance. Subsequently, the digital twin of, for example, a diffusion furnace is automatically recognized as such and integrated into the infrastructure with all connections, just as if it were physically placed in the line. By means of a direct pathway between any sensor in the furnace and the AI, even pure, unstructured sensor data will be available and can be fetched as needed by the AI. Therefore, a direct connection to the machine internal network will be established without limitations by digital interfaces.

Only through an overall transition of an MES as proposed in these four fields can the development from a pure measurement collection system to a platform take place, and the rapidly increasing data pool be transformed to allow data mining and to generate an efficient and rapid 'digital payback'.

Wafer tracking: real and virtual

The most interesting part in an MES for solar cell factories is the material flow and its tracking. Besides all secondary material flows from chemicals, water, pastes, etc. there is one linear main material flow. The wafer is a clearly defined unit going through all the steps and conversions in solar cell production, starting from polysilicon up to panel installation on a roof. The wafer is therefore the primary material to follow and track in cell production. Batch tracking, where a batch may consist of 1,000 to 40,000 wafers, is the minimum requirement for all productions worldwide.

Some advanced factories adopt the approach of single-wafer tracking, in which each individual wafer is tracked at each production step. All measurement data are coupled either directly or via timestamps to the wafer ID. Two different ways of tracking are possible. In the first method, each wafer is marked by laser individually on the front or back side (as described by Q CELLS [16]), while the second option involves marking the edges of the wafer in the silicon brick. In each production step, both possible types of wafer mark can be read out by cameras. The tracking accuracy is claimed to be above 95% over the full production process, and even in the final module the wafer marks can be read out several years after production. Although this system allows total traceability based on hardware marks over a long period of time, it requires specialized hardware, and is only feasible if the data is required to be available for many years or if the data is to be used to significantly improve cell and PV module quality.

Another approach is to only track wafers virtually, in which case the wafer marks are not mandatory, but still helpful for checks and adjustments. Virtual wafer tracking requires the tracking of all transportation steps inside and outside of all

> "The most interesting part in an MES for solar cell factories is the material flow and its tracking.

production equipment, handling and measurement systems, and of external and internal transportation. In this way, small batches of about 100 wafers are tracked by IDs in the form of barcodes, QR codes or RFID chips in carriers or boxes.

A physical wafer that is acknowledged by a piece of equipment for the first time receives an ID from that equipment; this will most likely occur during the incoming inspection. The ID, together with position and timestamp information, is reported to the virtual wafer tracking instance (usually the MES). Simultaneously, the equipment transfers the wafer ID to the connected automation. The automation then binds the wafer ID to the position inside the batch, herein defined as the carrier and the carrier ID. The position of the wafer is now defined. Measurement data, recipes or other sensor data are transferred separately and coupled virtually to the wafer ID.

In the next step, the equipment which processes complete carriers without any wafer handling just manages the carrier ID and informs the MES about all the process steps. Equipment that either processes individual wafers or requires specific boats for wafers has its own particular automation. The automation involves opening the batch both physically and virtually, and requesting the wafer ID and position of each ID in the carrier after reading the RFID code on the carrier. A virtual copy of the automation then handles each wafer ID in registers. These registers represent belts, robots, buffers or even boats inside the process equipment. The wafer ID is thereby treated like the real wafer; this requires full access to all automation information, which is best provided by the automation manufacturer itself. After all the steps, the wafer is returned to a carrier with an ID. The automation thus binds wafer position and ID to a carrier ID once again and closes the batch.

In inline processes, such as wet-chemical inline equipment, the wafer ID is handed over with a timestamp and position, in this case in the lane at the entrance, to the process equipment. The process equipment then takes over the responsibility for the wafer ID itself, as it automatically transfers the wafers at a well-known speed to the exit. The equipment subsequently transfers the information back to the automation. In this method, the MES does not follow the wafer itself, but only gets informed of the wafer ID's process timestamp.

The MES is independent of the equipment binding the process information to the wafer ID. Only measurement values from single wafers are directly bound to the wafer ID. Wafers that are absent because of breakage, delays or mismatch are treated as lost, and this information is stored for a certain period of time. A wafer that is rediscovered somewhere along the line without a wafer ID is assigned a wafer ID by the equipment itself; each piece of equipment is therefore allocated a unique range of IDs for this purpose.

The disadvantage of virtual wafer tracking is the dependency on each single automation and process in order to carry out the internal wafer tracking properly, as there is no control stage. At the same time, the identification of a single cell inside a PV module on a roof is also only virtually possible, requiring virtual wafer tracking, even between the different production steps of the cell and module and within the module production. To the authors' knowledge, this has not been achieved until now. The accuracy of the virtual wafer tracking approach can also be more than 90%, depending on the accuracy of each piece of equipment and production flow.

Outlook into the factory of the future

Individual paths of each wafer

Industry 4.0 is used for manufacturing individual products in other industries (Lot Size One). At first, this would seem an outlandish approach for solar cells and modules. Individual prediction and individual pathfinding, however, can also be useful in PV manufacturing, such as in the preparation of wafers from ingot areas with lower lifetimes in processes with optimized conditions (e.g. in a diffusion with better gettering properties). Q CELLS, in particular, has demonstrated the advantages of wafer tracking: typically, the position of the wafer in an ingot has a bearing on the final efficiency of the solar cell [16].

Currently, all process steps in solar cell production aim for a homogeneous result. Dosing in wet-chemical equipment is adjusted to target homogeneous etching, texturing or cleaning results over the bath lifetime and from bath to bath. Tubes in thermal equipment are designed in such a way as to guarantee that the result over the full boat is as homogeneous as possible. Target values with tolerances for wafer interior, wafer to wafer and batch to batch definitions aim for an acceptable amount of deviation over the full production.

In the sorter at the beginning of the line, during the incoming inspection, wafers can be separated into different classes. These classes are preferably already treated slightly differently in the later processes, otherwise the expectations of cell efficiency in the corresponding campaigns are lower. At the end of the line, the sorter separates the cells according to their efficiency or colour into bin classes. The obvious goal is to obtain homogeneous results with even treatments using a single recipe set; in reality, however, the results are more heterogeneous. Depending on the process, between 5 and 10% of wafers are produced with different base resistivities, treated differently in wet-chemical baths and within the average values for wafers from different positions within the boat (wafer to wafer over the boat).

Current MESs track and can even select the correct recipes for batches. The next step is to optimize each recipe and, depending on the results after each process cycle, make adjustments to the recipe. The optimization of each recipe and each tube by SPC, as well as by AI, on the basis of the optimum conditions for each batch is already close to being realized.

The following step is to not only track each wafer, but also actively guide the wafer through the production. Instead of binning groups, each wafer is treated individually. On a complete decision matrix there would be an optimum process flow for each wafer, which is of course adjusted after each process step. The MES creates groups of wafers which are processed together in batch processes, but the position of each wafer in the batch is not random. On the basis of the trend in baths and boats, each wafer is individually assigned its position in each process step. Buffers and bins in the automation are used to manipulate the wafers actively into the perfect position. Some examples are given next.

On the assumption that the first and last wafers in a diffusion boat are more likely to yield a lower cell efficiency and will be sorted out in the sorter after printing, it might be advantageous to already put in this position a wafer that is almost out of spec because of its base resistivity. Therefore, a low-quality wafer will also be allocated a low-quality position in the diffusion. As the risk of low printing quality is higher when a screen change in the printer is imminent, this particular wafer could also be printed during this period. In this way, low-quality wafers are given low-quality positions, and the risk of good wafers going to waste is reduced. In contrast, the best-performing cells are created by always putting the best cell in the best position. An alternative goal could be to keep the efficiency distribution as narrow as possible, thus, conversely, to process bad wafers in further-optimized processes.

The additional benefit of this system of actively positioning the wafers will be that the recipes for each group of wafers can be optimized on the basis of their needs. Process windows, which currently have to match a higher bandwidth of incoming wafer conditions, can be significantly tightened in the case of granular bin sorting before each process step. This benefit can already be realized, with positive SPC results. It is achieved via clear rules, replacing the assignment of bin classes to single recipes by mathematical factors for time, temperatures and other process parameters. The flexible boundaries create an unlimited number of flexibly defined bins and batches with different recipes. Instead of bins with predefined boundaries, bins of a defined size with minimized scattering are created for each process step. When a large number wafers are being considered, the total scattering will become small.

The next logical step would be to use this flexibility in AI concepts. A virtual wafer is passed in advance through a virtual cell factory. Each wafer is then guided in its preferred batch with optimized recipes at each step for deciding the best place for it.

“A self-learning PV factory can independently improve its production.”

Self-learning factory: physical models vs. AI concepts

A self-learning PV factory can independently improve its production. On the one hand, it can improve the quality of individual cells or modules, while, on the other, it can improve throughput and yield. Physical models or AI can be used for this purpose – or a mixture of the two.

For instance, a physical model can match the thickness of the silicon nitride layer to the reflective properties of the wafers, which have different properties as a result of the different saw damage after etching. In contrast, AI can be used to investigate which influencing parameters have an impact on the cell results. The common outcome of these two scenarios is that the manufacturing process can be dynamically adjusted.

An example of self-learning manufacturing is the use of automated experiments in production lines: in other words, a system that can independently suggest and perform a statistically significant design of experiment (DOE). This will allow, for example, new metallization pastes or new metallization screens to be investigated quickly and in an optimized manner. For this purpose, boundary conditions are defined for the system, such as the limits of the snap-off or the permitted firing parameters. Thus, the line independently plans the experiment, carries it out and outputs the optimum possibilities of a new paste or an alternative screen for the current cell concept. It conducts the experiment in the shortest possible time and with the minimum loss of yield in the current production.

Self-learning FlexFab

RCT and ISC are working together on a factory concept in which different cell and module concepts can be manufactured in parallel. The proportion of the respective solar cells fabricated is required be variable, so that more solar modules of one type or of the other can be produced, depending on the request. For example, a FlexFab can produce passivated emitter and rear cells (PERCs) for the mass market and n-type back-contact ZEBRA cells for the rooftop market.

The wafers follow individual paths in a FlexFab, and production is monitored and controlled by digital twins. This type of manufacturing is currently being implemented at ISC Konstanz on a pilot-line scale. Self-learning aspects are considered in a FlexFab, so that the performance of the modules and factory throughput are constantly improving.

It is important to always be mindful of the manufacturing costs. The paths of the wafers are optimized and the manufacturing processes are combined to such an extent that the additional cost for the FlexFab production of PERC cells is only 0.6%, compared with a purely PERC production.

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