Performing experiments in photovoltaic manufacturing using knowledge management technologies

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ABSTRACT

Supporting a smooth application of new wafer materials and handling equipment into photovoltaic mass production requires extensive testing of new wafers and equipments under a range of potential operating conditions. The management of such experiments, both in laboratory and production environments, demands the integration and management of a multitude of differing information. This includes static data-like equipment, specifications and experiment settings, online machine data regarding process signal and events – but also unstructured human knowledge, which is available in manual and test reports. To efficiently deal with these kind of complex environments, knowledge management techniques have proven to be a promising approach in various industrial applications.

This paper depicts, by means of a photovoltaic wafer-testing platform at Fraunhofer IPA, how the application of automation systems and knowledge management techniques leads to more effective experiment management. More precisely, the gathered knowledge from the wider range of information included in the analysis of experiments can be re-used during future experiments and the manual effort is significantly reduced.

Introduction

Effective and accountable experiment management is essential for a smooth transition of new wafer materials and handling equipment in mass production environments. As a prerequisite for the start of production, new wafer materials and equipment need to be carefully assessed under a variety of future production conditions. Therefore, simulation tools – and more importantly physical testing environments – need to be applied.

In such testing environments, the gathering, analysis and re-use of the wide range of available information like parameters, machine data and human experience during experiments, have proven to be a major challenge. The complexity of a formal approach for experiment management is based on the fact that the relevant information is represented in very different ways: documents, databases, spreadsheet tables, machine-data and data available on the internet. Transforming human knowledge into a machine-understandable format and interconnecting it to other data is especially challenging when using only traditional data management technologies.

In general, managing knowledge inside companies and making it re-usable is a challenge for any organization. According to Fraunhofer IAO [1], companies estimate that more than 50% of their added value is a direct result of knowledge. However, 50% of these companies state that they only use 20–40% of this information. Knowledge management systems are widely expected to leverage efficiencies in a multitude of application fields.

This paper depicts a concept for a knowledge management system (KMS) to support experiments in the photovoltaic industry. The concept will be based on semantic technologies and interconnects static data, online machine data and human knowledge. Any information gained during an experiment will be systematically stored and will be available for re-use in future analysis.

In the following, the concept will be described using the photovoltaic testing and demonstration platform at Fraunhofer IPA which serves to evaluate different wafer types and automation equipments like grippers, actuators and sensors.

In the first section, the underlying business cases for performing experiments and for applying experiment management systems in both laboratory and production environments are investigated. The photovoltaic testing platform at Fraunhofer IPA and the data items occurring during experiment management are then described in more detail. In addition, the requirements for an ICT system to automatically execute and track experiments as well as for a complementary knowledge management system are defined.

Furthermore, existing knowledge management technologies and tools are looked at with respect to their suitability for the described business cases. In particular, the potential of semantic technologies for the integration of information from different sources and domains is highlighted. Finally, the formal concept for a knowledge management system to manage experiments in photovoltaic manufacturing is described, which is currently in development at Fraunhofer IPA.

Motivation and business cases

Experiment management in photovoltaic manufacturing

Today, the photovoltaic industry is strongly characterized by short innovation cycles. Products, production processes, and equipment is continuously adapted to improve the process quality and to cut down the overall production cost. The reduction of photovoltaic wafer thickness and the optimization of the throughput of production lines are just two such major leverage factors.

At the same time, wafer breakage needs to be prevented in order to ensure stable production processes. Therefore, the optimization of production parameters and automation solutions needs to work alongside careful investigation of their effect on quality and scrap rates [2]. A systematic testing of new wafer materials and handling equipment needs to be conducted to ensure a smooth transition to mass production environments. Besides the use of material and process simulation models, the execution of experiments in physical testing systems under a variety of test conditions can play a key role.

Knowledge management for experiments

During such experiments, a variety of static data-like equipment, material and product specifications, experiment settings like machine parameters, online machine data like process signal and events are available as well as a large amount of unstructured

Figure 1. Automated test and demonstration platform for wafer handling experiments.

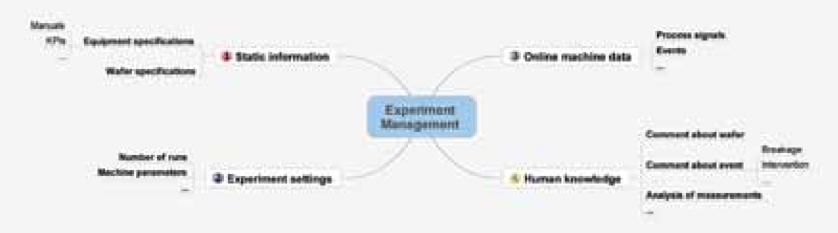


Figure 2. Data items of the PV test platform.

information from engineers such as observations about incidents during an experiment. Traditionally, only a subset of this data is structured and used for the experiment analysis.

Unstructured human knowledge about materials, equipment and events is highly important information for the analysis of experiments and for the re-use of the analysis results in the future; however, it is challenging to efficiently include it in an experiment management system. The engineer needs to be able to easily insert his knowledge into the experiment management system to make it re-usable during later experiments. In practice, simple spreadsheet and word processing tools are mostly applied. As a consequence, the re-use of experiment results and relevant information mainly depends on personal experience.

In order to strive for more substantial analysis, a wider range of information needs to be incorporated. At the same time, the complexity and the manual effort for the engineer need to remain limited. In synthesis, the objective needs to be the conduction of more experiments with profound analysis in less time. As a consequence, the use of sophisticated knowledge management tools should be envisaged.

The application: PV testing platform at Fraunhofer IPA

The testing and demonstration platform for wafer handling experiments at Fraunhofer IPA (see Fig. 1) is applied to evaluate and optimize handling equipments like grippers as well as their configurations in the context of industrial and research projects. In addition, the platform is used to test innovative wafer types, e.g. thin wafers, under a variety of production conditions. Investigating the influence and interference of single production and handling steps on the wafer is the focus of this investigation [3], which results in complex experiment processing and data analysis requirements.

A large amount of different data items and experience knowledge is available at this laboratory environment (see Fig. 2). All these data items are relevant to plan experiments and for analyzing their results.

As is the case in other production environments, a high number of static information is available regarding the testing platform. Equipment and components have specifications, manuals and operational guidelines, which exist in one form of written documents or are available on web pages. Other static information may include the specifications of tested wafers, which are available in the form of Excel tables.

In addition, experiment settings such as the number of runs and machine recipes are available through the line control system. Online machine data such as sensor data and event notifications can be gathered from the equipment and can be used for analysis of the experiment results (see Fig. 3).

The most important – but often not stored and analyzed – information is available from human personnel. This could include a simple comment on the wafer properties or a more detailed description of an event occurring during an experiment run as well as information about potential root causes for test results.

In addition, test reports of former experiments contain highly valuable information. In practice, this information is kept only as the personal experience of the engineer and not often systematically re-used.

Requirements towards system-based knowledge management

In order to perform knowledge management for photovoltaic testing and demonstration platforms or for similar manufacturing environments, requirements can be defined both towards the automation of the experiments as well as towards the knowledge management system working over it. The user requirements towards the automation of the PV test platform are:

UR1 The automation system shall be able to track the execution of an experiment ('run') and which experiment parameters have been used.

UR2 The automation system shall be able to track process and measurement signals and shall link these to individual experiment runs.

UR3 The automation system shall be able to track recipe parameters given to the individual laboratory equipments for each individual experiment run.

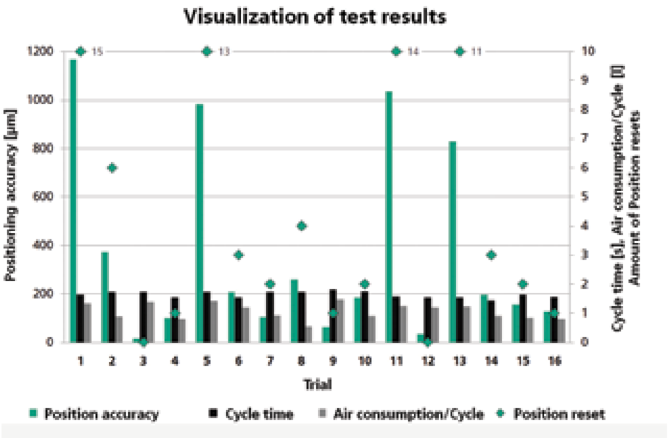


Figure 3. Visualizations of test results for wafer testing.

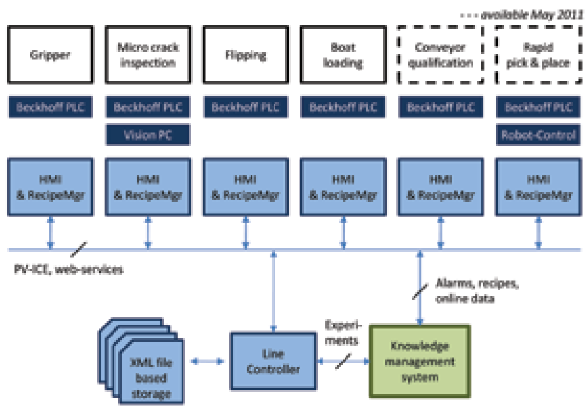


Figure 4. ICT landscape for PV testing line.

UR4 The automation system shall be able to track important alarms and events arising while performing individual experiment runs and shall allow the use of consistent time stamps throughout all equipments.

UR5 Ideally, requirements UR1-4 should be achieved without the need of costly, customized software or demanding further human input.

The user requirements for the knowledge management system working on top of the automation system are:

UR100 The knowledge management system (KMS) shall conceptualize experiments and individual runs and shall describe experiment parameters in detail.

UR101 The KMS shall be able to incorporate and track user comments at any time and shall relate them to experiment runs and/or laboratory equipments.

UR102 The KMS shall provide a structured way to acquire human observations as well as the settings of important manually controlled parameters for individual experiment runs.

UR103 The KMS shall maintain all equipment and product (wafer) specifications and shall make single specification information available to analyses and reporting.

UR104 The KMS shall allow integrating existing factory data bases (e.g. SQL data bases) and expose their data contents towards correlation, integrative analyses and reports.

UR105 The KMS shall allow dealings with human readable documents (PDF, Word and Excel documents) and expose their contents towards full-text search, analyses and reports.

UR106 The KMS shall allow browsing the contained knowledge and specifications at each equipment's HMI (human machine interface).

UR107 The KMS shall be scalable and shall avoid costly customizations when being introduced at a company.

ICT landscape of the PV testing line

In order to fulfill the above requirements and to support the processing of a high number of experiment runs with different recipes, a dedicated ICT landscape has been developed at Fraunhofer IPA (see Fig. 4).

Equipment level

A key element of the ICT landscape is the 'HMI & RecipeMgr', which replaces conventional human machine interface (HMI) solutions with an extensible, plug-in based adaptor framework. This .NET based framework runs directly on the Beckhoff PLCs and interacts deeply with the executed PLC programs. A HMI plug-in imports the Beckhoff HMI project definition and allows executing the Beckhoff HMI panels within the integrated solution, while maintaining common look-and-feel and benefitting from advanced .NET screen rendering (e.g. for high-speed trend graphs).

At the same time, the RecipeMgr plug-in reads and interprets the variable definitions inside the Beckhoff PLC and makes them available for recipe upload and report download. Using a point-and-click approach, the plug-in defines different recipe and report templates, which allows reporting different aspects of the process execution in great detail, while keeping message sizes small. By identifying only eight control variables, the plug-in permits the remote control execution of the equipment including automatic capturing of reports. The plug-in allows reading XML recipes and writing XML reports directly at the equipment; it enables standalone execution of laboratory equipment. Further on, the plug-ins enable online connection to supervisory systems by realizing standard SEMI PV-2 [4] and easy-to-use web-service interfaces.

Further plug-ins are interfacing with cameras, industrial vision software and robot controls, which capture screen recordings and browse the internet –all integrating into a common look-and-feel user-interface, which can be adopted to different company designs and styles.

By reading existing HMI definitions and by accessing PLC variable declarations, the HMI & RecipeMgr realizes the user-requirement UR5, as no costly proprietary implementation effort is needed. The RecipeMgr plug-in realizes the user requirements UR1-UR4 and makes the information, which is needed for later knowledge management, available to various host systems.

Supervisory level

The second cornerstone in the ICT landscape is the 'line controller,' which implements supervisory control functions for the PV testing line and small manufacturing lines without the need for costly customization. The line controller interfaces via SEMI PV-2 or web services with the RecipeMgr plug-ins of each piece of equipment and takes advantage of the herein defined recipe and report templates. For maintaining recipe settings and for storing reports, the line controller relies on the storage of individual XML and CSV (Excel) files, which seems a very basic approach but avoids costly customization and allows the re-use of the files within a large multiplicity of computer programs. Hence, this approach is optimally suited for the application within the rapidly changing laboratory environment. All recipe and report functions are available through drag-and-drop operations, which implement an easy-to-learn, but efficient user interface. By providing a two-dimensional grid of recipe settings, the line controller allows the execution of multi-step experiment sequences. This feature enables performance of complex experiments without introducing variances brought in by human operators into the experiment result data. The automatic capture of report files ensures that a maximum of experiment result data is always available for later analysis.

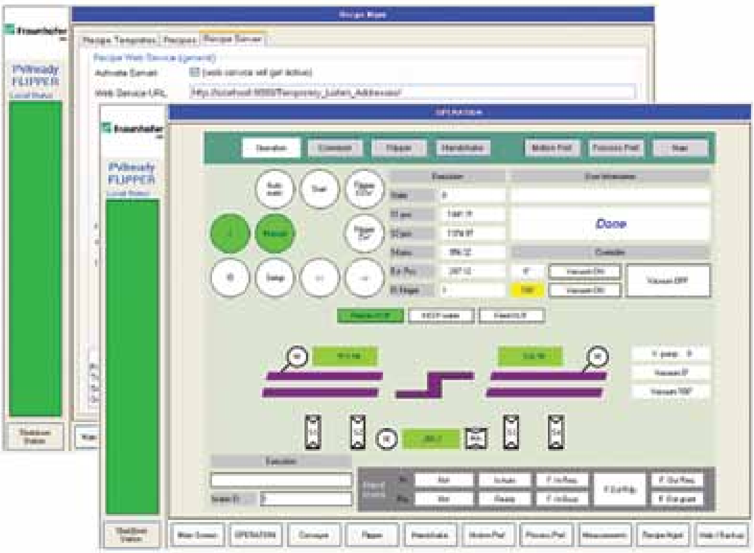
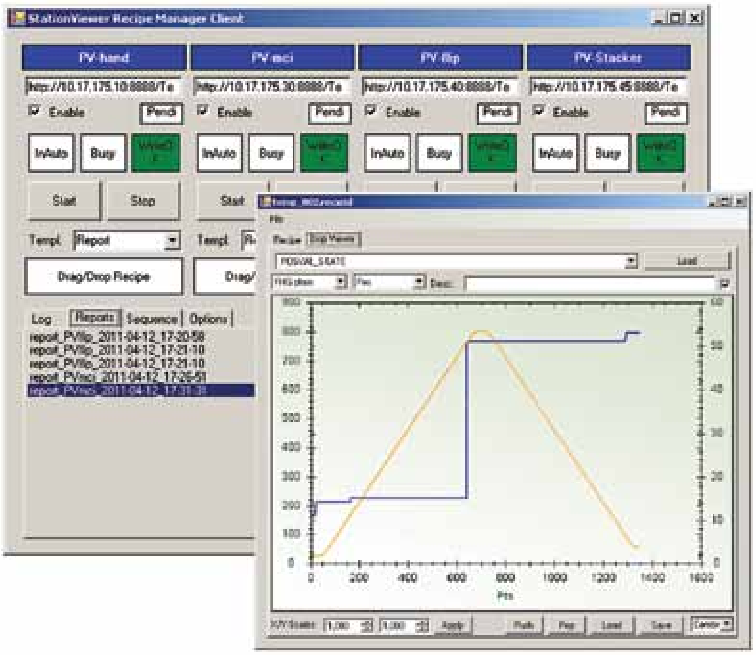


Figure 5. Equipment-level HMI and recipe management.

Conclusion and suggestions for further development

The set of RecipeMgr plug-ins within individual equipment and the line controller supervisory control allows for orchestrated line behaviour and the conductance of even complex experiment scenarios; in this sense, it exposes the same functionalities as equipment controls and manufacturing execution systems in conventional production shop floors. Despite these proven capabilities of the system, there are still important links missing for an effective knowledge management for the management of experiments. More



http://10.17.175.10:8888/Te
http://10.17.175.30:8888/Te
http://10.17.175.40:8888/Te
http://10.17.175.45:8888/Te

Templ. Report

report_PVflip_2011-04-12_17-20-58
report_PVflip_2011-04-12_17-21-10
report_PVflip_2011-04-12_17-21-10
report_PVmci_2011-04-12_17-26-51
report_PVmci_2011-04-12_17-31-31

Figure 6. Supervisory-level line controller and recipe management.

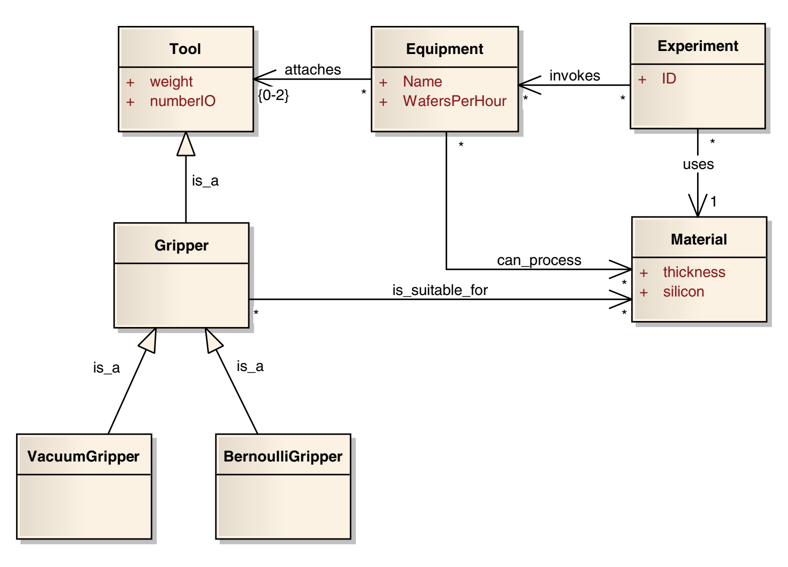


Figure 7. Exemplary ontology for the PV testing line.

precisely, it is not known to the system which exact equipment and material combinations were used when conducting the experiments, what the intention of the planning engineers was (design of experiments) and what observations were made by human personnel.

This gap shall be filled by introducing a knowledge management system, which is online coupled with the manufacturing system of the photovoltaic testing line.

Semantic technologies and knowledge management systems

Knowledge management can be accomplished by a large variety of approaches; in the last year, it has been widely acknowledged that ontology-based knowledge management systems can be used effectively, when the context of the KMS can be kept constrained and well-defined. Based on this philosophy, later used extensively by linguistics, ontology is now becoming an ICT approach for organizing data.

Ontology as a method of structuring information

According to Gruber [5], an ontology is a "formal, explicit specification of a shared conceptualization". Conceptualization is performed in order to decompose the knowledge about a specific domain (the context) in well-defined and non-overlapping terms. It is formal in order to be used by technical systems, it is explicit in order to avoid inconsistencies and it is shared commonly among a group of people in order to be used by all of them.

Aside from this theoretical definition, ontology can be seen as a carefully chosen dictionary of 'concepts' on a specific domain, which describes not only the concepts but also their meaning, and uses different relations in order to interlink them. This can attach knowledge items to the different concepts and perform analysis and reasoning along the different relations. An exemplary ontology is depicted in Fig. 7.

The widely known unified modelling language (UML) syntax is used to graphically describe this ontology. Concepts of the ontology are expressed as classes; the relations between concepts are expressed as associations. Concept definitions may have attribute declarations, which are inherited to sub-concepts.

In this small ontology, 'experiments' are defined, which are restricted to use one wafer type: 'material'. The experiments are indentified by an attribute 'ID'. For performing experiments, 'equipments' are invoked by the experiment, which are described by the attributes 'name' and 'WafersPerHour'. Every equipment declares to 'can_process' a range of materials. The materials are described by 'thickness' and 'silicon type'.

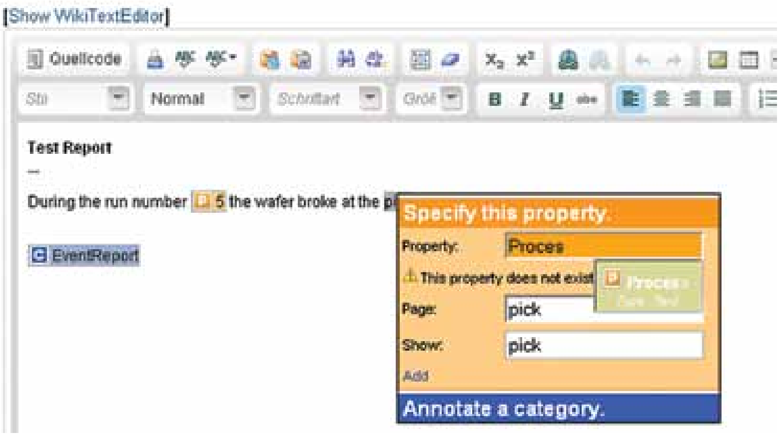
Ontologies are perfectly suited for classifications. In this small ontology, a classification is done towards the ranges of tools for the PV testing line. A 'gripper' is a certain 'tool', which means that every gripper can be treated as a tool, sharing the same attributes. 'VacuumGripper' and 'BernoulliGripper' are both specializations of the concept gripper. When reasoning, the ontology will conclude that when a certain material 'is_suitable_for' the concept gripper, it will be automatically suitable for all VacuumGrippers and BernoulliGrippers.

Rules can be stated towards ontologies; they can be used to create 'virtual' relations and attributes by concluding on knowledge, which is already contained in the ontology. For instance, the weight of a wafer can be approximated by its thickness and side lengths, using some specific mass density. A gripper can describe that it can handle wafers up to a certain weight and maximum dimensions.

During analysis, these 'virtual' relations and attributes will be treated exactly the same as the direct ones. This means a 'query' can be stated, detailing which grippers were already used for a certain experiment and which grippers will be additionally suitable for performing this experiment.

Ontology-based knowledge management systems

Referring back to knowledge management systems, which are now supposed to be ontology-based, only very fundamental concepts will be expressed by UML or further specification languages. The users of a KMS will require an adequate tool for expressing knowledge in human readable form but, at the same time, should be able to express relations to other concepts and set attributes as above. One way of achieving this is through ontology-based Wikis (so called semantic Wikis). Regarding content management



Test Report

During the run number 5 the wafer broke at the p

EventReport

Specify this property.

Property: Proces

This property does not exist

Page: pick

Show: pick

Annotate a category.

Figure 8. Exemplary annotation of rich text in Semantic Media Wiki+[6].

Figure 9. Unique features of the realized knowledge management system.

systems, these Wikis are becoming very user-friendly ways of expressing contents by editing text pages and using special annotations to link to graphics, make lists or captions. In this manner, Wiki pages are already a form of knowledge inside a KMS, as pages have captions and its subsections also have captions. Linking between different pages is already supported.

Moving on to ontology-based Wikis, these Wikis attempt to gather semantic knowledge (relations and attributes) from the users. This can be achieved in two ways:

- A 'standard form' section is displayed whenever the user creates a new Wiki page based on an ontology concept. By filling out this standard form, the user can quickly elaborate important relations and attributes for this sub-concept. After filling it out, the user can proceed to the 'free format' section of the Wiki page and can add descriptions, specification, experiences as with any other Wiki system.
- A 'semantic annotation palette' is provided to mark some special semantic attributes, while writing free format Wiki text. This is as easy as marking text with the mouse cursor, going to the 'semantic annotation palette' and selecting, so that this marking sets a specific semantic attribute for the edited page (see Fig. 8).

In either approach, additional knowledge might be added to the Wiki page by adding files and documents in proprietary format (such as PDF documents, Excel tables or Word documents).

Proposition towards a system-based knowledge management system

Fraunhofer IPA is currently integrating a state-of-the-art semantic Wiki system

Intranet-based environment	The semantic Wiki system will run on an internal web-server within the protected intranet of a company and can be used through web-browsers. This will make it possible for any personnel (engineers and students) to use and contribute to the system, even directly on the equipment HMI (see UR106).
Standard forms feature	The system allows providing standard forms to be filled out for every Wiki page. This feature will drastically increase experiment quality. The content of the standard forms will be directly available for analyses, interactive querying and reporting (see UR102).
Free format user comments	A 'semantic annotation palette' will allow easy addition of user comments in free format. This will enable users to freely describe observations. Photos, drawings, tables and sound files can be used to contribute to these observations (see UR101).
Document management	The system will allow attaching any kind of documents and specifications to each Wiki page. Therefore, the system can act as single source of information (see UR103).
Full-text search capabilities	Some semantic middlewares are integrating text-mining tools into the environment, such as [7]. This allows doing a full-text search on documents indexed by the systems. Important terms can be provided by using auto-completion features. Classification of documents can be automated (see UR105).
Connection to data bases	Due to their import capabilities, nearly every semantic middleware can import data from conventional SQL data bases. Furthermore, some middleware allow the online-integration of data base entries [8,9]. Using that feature, during querying and analysis, the middleware will not only search the own data bases but also the online integrated databases for applicable knowledge. This unique feature allows integrating and unifying an landscape of data bases, which evolved over time such as in manufacturing environments (see UR104).
Online connection to PV equipment	As described, data from experiment runs will end up automatically within the system as applicable knowledge and can be directly used for analyses and interactive querying (see UR100, UR102).
Interactive querying	The system supports the generation of analyses and queries by means of a point-and-click feature. Queries can be created using lists of already available concepts, relations and attributes of the stored knowledge. These queries can be stored afterwards and made available as regular Wiki pages using this mechanism, every user can utilize a set of highly specialized analyses.
Plug-ins for analysis	The semantic Wiki systems provide the possibility to create ones own plug-ins for displaying content within the system. This will ultimately lead to the capability to apply statistical functions (e.g. from SPC) directly within the analysis workflow of the system.
Scalability and cost-effectiveness	The chosen commercial product is relatively low-cost; the deployment on web-servers allows for scalability (see UR107).

Table 1. Unique features to be integrated into proposed knowledge management system.

within the existing ICT landscape of the PV testing line. The objective is to create and demonstrate an easy-to-apply knowledge management system for manufacturing environments in laboratory or even on an industrial scale. The novelty will lie on the capability of the system to integrate data online from shopfloor automation level, recipe data and report data together with conventional sources of knowledge like wiki pages, various documentations and feedback from human personnel.

The ICT landscape of the PV testing line is already realizing the user requirements of UR1-4, as described above. Together with the unique approach of RecipeMgr and line controller, it will collect all sensible data, such as tracking of experiment parameters, recipe settings and sensor measurements, for almost no additional effort in customization and costs. User requirement UR5 is therefore fulfilled.

The chosen approach allows integrating a set of unique features, as seen in Table 1.

Summary

During the course of this paper an approach for a semantic-based knowledge management concept was presented by using a photovoltaic wafer testing and demonstration platform. The main objective is to improve the quality and efficiency of automatic execution and analysis of experiments. Using this automation and knowledge management system, the range of data considered for the experiment management is expanded and the complexity of the operation as well as the required manual effort is reduced. Based on the defined ontology, the gathered knowledge can be more easily interconnected and re-used.

As a consequence, an automation and knowledge management system with integration of online machine data was outlined, which was built onto the existing ICT landscape of the PV test platform with minimal effort. Various unstructured documents, operator feedback and expert knowledge are now recognized, stored and linked in a more efficient manner than before. The presented concepts are not only suitable and beneficial for test and staging environments, but can in future also be applied in small manufacturing lines.

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