Use Case Study

Collaborative knowledge management for manufacturing recipes

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Dr. Dirk Ortloff, Dr. Jens Popp

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Thin-film fabrication processes for semiconductors, MEMS, etc., use a broad spectrum of different process technologies and a diverse mix of used materials. The details of the manufacturing recipes represent an important body of knowledge. Unlike in microelectronics, the MEMS fabrication process is, in most cases, application-specific, and therefore an integral part of the application design. The high amount of different step variants, the long chains of steps required for a complete manufacturing flow, the knowledge of the individual steps, the interactions between used manufacturing steps, and the dos and don'ts of chaining them together are the secret sauce for manufacturing success and the competitive edge. Discovering the correct combination of process steps, materials, and process parameters usually requires many expensive and time-consuming experiments. But the multitude of manufacturing steps used in product manufacturing is only a very small fraction of the recipes existing in a company. The plethora of processing steps used only once in an R&D institute or university requires even more careful management.

This use case study presents a project with a research institute applying a specialized software system to perform holistic Research Data Management [**Wisconsin** 2021]. It supports the MEMS device and process designers in managing their process knowledge, especially their detailed recipe knowledge. They use the software system to assemble and verify their new or amended fabrication processes in a virtual fabrication environment, thus reducing the number of real-world experiments to a minimum.

Who is the customer?

The customer of this use case study is an applied research institute working in several technology areas like, semiconductors and other nano-technologies. Their aim is to bridge the gap between basic research in universities and the implementation of the new technologies in industry. Due to the breadth of research topics and applied technologies, managing and sharing the knowledge of the manufacturing recipes is a major concern. Initial attempts using spreadsheets and documents stored on an centralized server were not overly successful because finding an appropriate and up-to-date recipe swiftly was still complicated and time consuming. Therefore they reached out to potential software suppliers to evaluate different software solutions for recipe knowledge management.

The starting position

Designing MEMS, NEMS, and other high-tech devices necessitates assembling specific combinations of process steps, materials, and process parameters. This assembly task can be time-consuming because even minor changes to single process parameters can have a significant impact on the three-dimensional shape. Furthermore, the properties of the produced microstructure can vary significantly. Researchers must consider many complex interdependencies and constraints between process steps during development. Detecting such constraints usually requires a slew of costly and time-consuming experiments. Another critical problem in this context was that in most cases only the successful recipes are kept. Data linked to “failures” was often discarded, not properly archived and most times “forgotten”. This practice causes that only one engineer or a small group of engineers rather than the company gained knowledge from the “failed” experiments. Therefore, developing process flows for MEMS and other nano-devices and verifying the output response became at least as costly as developing the actual structure of a device. The bottom line, in the organization of this use case study was that process engineers had little to no support from any Computer Aided Engineering (CAE) [Wikipedia 2021a] resources for performing process development tasks. The management of manufacturing recipe knowledge and the compilation of process flows in the form of runcards / travelers was based on Excel sheets or documents that could be reused virtually only by copy, paste & change.

Disadvantages of this knowledge management approach

The presented starting point for knowledge management of this use case study is still quite common and has some disadvantages which will be presented here in general terms.

The first of these is that the development and tracking of recipe changes are not transparent. Therefore, it is often unclear whether the latest and best version of a recipe gets used or whether there is an existing latest or nearest best reference version of process step recipe. Using outdated process step recipes causes suboptimal results. That sometimes required relearning previous mistakes and, in the spirit of Lean Six Sigma, resulted in waste and project delays.

Another disadvantage of this knowledge management approach is that consistent variation of a step recipe within a longer manufacturing flow is an error-prone process. Because the length of complex manufacturing flows can easily exceed several hundred steps, and the same step may be used in more than a handful of instances, manually and consistently modifying all occurrences is often difficult and a source of error. Such an inconsistent change can lead to the misproduction of an entire lot rendering it or an experimental design to being inconclusive.

Informal recipe knowledge management also has the unwanted effect that knowledge gained from experiments usually exists only in the minds of engineers and perhaps in lessons learned reports. These informal reports and the fact that it is difficult to formalize the knowledge gained makes knowledge sharing very time-consuming and not very comprehensive. That leads, more often than is acceptable, engineers repeating the same “errors” as their colleagues did some time ago.

The project goal

The main objective of the project was to streamline knowledge capture and sharing. The customer desired a software solution to provide the capabilities to capture and apply formalized manufacturing knowledge for virtual recipe/sequence verification. Furthermore, the project intended to reduce the human error rate in adapting reused process step recipes. Another project goal was to avoid reinventing the wheel. By making manufacturing recipes more accessible and also by avoiding the use of obsolete process steps or at least making the use transparent.

Quick wins and long-term goals

The first step was that the customer had to compile lists of the most frequently used process steps and the most current manufacturing processes. The documentation available for this were documents and run sheets. They were collected and subjected to analysis. This analysis then identified all parameters, the necessary units, and materials.

In parallel, an instance of the XperiDesk Process Development Execution System (PDES) [Wikipedia 2020b] was set up as an on-premise installation. An initial set of test users got configured. The system serves as a central component of the development environment and functions as a comprehensive knowledge base. The detailed technology knowledge required for all aspects of the physical design flow gets stored in it. A relatively high degree of formalization is necessary to be able to use the fabrication knowledge for design automation and verification. Formalization is enabled by an extensible parameter and unit management. That ensures that all parameters are kept consistent in the system while maintaining maximum flexibility. The units and numerical parameters can be linked using conversion formulas that trace the numerical parameters back to a (set of) SI units. Thus, the system can always convert and compare numerical parameter values, regardless of the unit used. For more complex or dynamic parameters, the assignment (and integrated calculation) of calculation models is possible making dependent parameters calculable from other parameters. The management of process steps and materials is also greatly simplified by object-oriented inheritance to allow the inheritance of properties through the definition of abstract classes (e.g., metals, semiconductors). This capability enables an incremental and collaborative design strategy. In the first design iteration, a manufacturing process may contain only abstract process steps or modules such as deposition or etch that outline the manufacturing process. This principle process can now be assigned to individual experts who then elaborate on the abstract parts of the manufacturing process and exchange the abstract steps with concrete manufacturing recipes.

The freshly installed system already contained a predefined unit database. After the completion of the initial collection of customer-specific recipes, etc., in step one, the configuration of the specific units, parameters, materials, and process steps got started. During this task, the users observed that the inheritance hierarchy and the copying capabilities of the system allowed for an increasingly rapid configuration of new materials and steps. As a result, the initial filling of the knowledge base could be completed well before the planned end date and within a few days.

The next step was to configure the collected manufacturing processes in the XperiDesk system. For this, the necessary steps / sub-processes can be inserted one by one from the step/flow database into a new production process using Drag&Drop. After this, the users can adapt the detailed parameterization of individual steps. Because the system allows the modular structuring of the sequences from reusable sub-sequences, it was once again possible to configure them ever more quickly. Based on these configured processes, consistent run cards could now be generated at the push of a button, or electronic tracking&tracing like with ELN- [**Wikipedia** 2021b], LIMS- [**Wikipedia** 2021c] or MES-System [**Wikipedia** 2020a] could be performed in the laboratory.

In the second phase of the project, the XperiDesk system was to support the virtual verification of newly assembled or adapted production sequences. For this purpose, the system offers, according to the representation in Figure 1, a verification process divided into three stages, where the first two stages are optional. Each additional stage provides more accuracy but is also more time-consuming and costly.

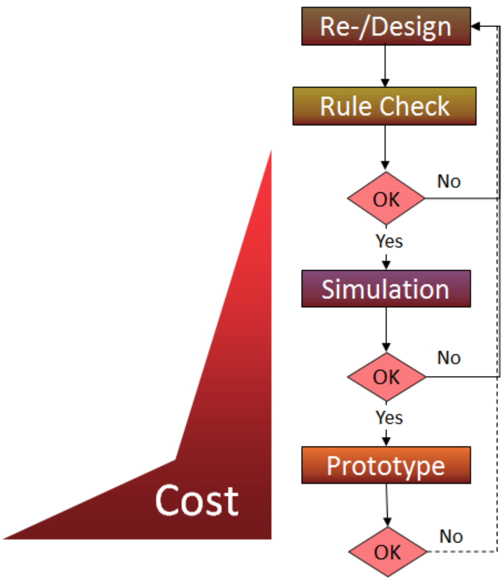

Figure 1: Verification process with three steps and the corresponding costs

The first stage performs a virtual check of a manufacturing process flow for producibility and feasibility. It uses a rule-based consistency check with user-defined consistency rules assignable to individual process steps. These can be used, for example, to define exclusion criteria such as, after this step, the processing temperature must not be higher than X unless material Y has been completely removed. This is the demand for context based recipe resolution when material contexts change or get removed. Thus, learned abstract process knowledge is transformable into machine-processable knowledge.

The second virtual verification stage validates the results of the process using commercial Technology Computer-Aided Design (TCAD) tools [**Wikipedia** 2020c]. In this process, the simulation interface of the environment automatically generates simulation input files by parameterizing a simulation model from the knowledge base with the current parameters from the process steps for each step. In doing so, the models define an input snippet with placeholders for the current process step parameters for a given simulator. The abstraction provided by the models efficiently decouples simulation knowledge from technology knowledge, providing a convenient way to enable virtual experiments for verification and optimization for technology experts without simulation knowledge. The same mechanism can also be used, for example, to calculate the costs of a production process. Here, the costs are to be understood in the broadest sense, so also, for example, the CO2 emissions.

The third and final verification stage of an initial development iteration is a prototype run in the laboratory or fabrication line. The environment supports this stage with an experiment tracking module, in the sense of ELN, LIMS, or MES-Systems, that enables fine-grained control of this verification stage. The whole verification flow supports various development iteration loops from initial prototype loops over Qualifications Runs to Stabilization loops. The Stabilization Stage is applicable to monitor the mass production yield and create the final conclusion for the experiment with the golden recipe setting in use. These data records can be stored in XperiDesk for future experiment reference.

In this customer project, only the rule-based consistency check was used initially in the second phase, followed directly by prototype production. The process steps in the XperiDesk knowledge base got augmented with generic rules (e.g., each deposition process requires a cleaning step directly before it) to facilitate the consistency check. Subsequently, interviews with the experts of the individual process steps were conducted, delivering specific knowledge regarding dependencies and avoidance scenarios (non-functioning step/parameter combinations). These were then formulated in rule sets and attached to the corresponding process steps (classes). Again, the power of inheritance became apparent, as rules such as “cleaning-before-deposition” only need to be stored once in the class “deposition”, thus securing all steps below (but additionally allowing that more specific rules get inserted at lower levels). Because the process engineers can develop and store these rules themselves formalizing their newly gained experience, the XperiDesk system learned more and more manufacturing knowledge over time.

The basic setup meant that the XperiDesk system contained a representative amount of customer-specific manufacturing knowledge. To initiate and support the setting of the software productive, a change management and organizational development project was launched. That effort involved intensive user training to create buy-in and establish the added value of the new structures and the newly gained overview. The essential goal was to ensure that, despite the necessary changes in work methodology, researchers’ lives would become more efficient and effective in the long run. In addition, mental hurdles were removed through initial quick wins and the block of manufacturing knowledge already in the system. Regular question-and-answer sessions, monitoring the usage for a sustainable transition of the work environment to the new tool, support for the client in operating the platform, and ongoing post-qualification of (new) employees rounded out the implementation.

These measures were an essential part of this effective digitization measure in the research and development of the use case partner.

Added value for employees

The added value for the employees resulted from a variety of simplifications in their daily work. The most important improvements were:

- Access to information and manufacturing knowledge generated by colleagues, about 30 engineers, was greatly simplified and significantly accelerated. Especially in cases where colleagues are not available promptly.
- The generation of current and the reuse of historical runcards got greatly simplified. Because all sequences are easy to find, copy and modify in the software, prototype manufacturing got started much earlier.
- Novel sequences of process steps can be checked for manufacturability easily and automatically.
- The version management integrated into XperiDesk for all entities prevents unwanted side effects caused by changes (no automatic feed-forward) and allows easy detection of the use of obsolete versions. It thus enables full transparency concerning the history.

Added value for the institute

In addition to the added value for the employees, great added values resulted for the implementing institute. Here is the list of the most substantial improvements:

- a 25% increase in the effectiveness and efficiency of research&development projects. Several improvements collectively led to these efficiency gains. The majority resulted from avoiding lengthy searches for the most current version of manufacturing recipes. Before using the XperiDesk system, people in charge of the individual steps got contacted for reassurance concerning the version quite often. Waiting for an answer often led to corresponding delays. With the introduction of XperiDesk, these delays got eliminated.
- The introduction of the comprehensive data management of the XperiDesk system and the new workflows also closed the infrastructural gaps in the area of research data management [**Wisconsin** 2021] and the implementation of the FAIR principles [**Initiative** 2021].
- a significant reduction in machine failures, because inconsistencies in production processes and the associated contamination of machines/chambers can be avoided utilizing the rule check.
- considerably reduced loss of knowledge in the event of employee fluctuation.
- the versioning of the entities allows the automatic creation of an audit trail so that the fulfillment of the documentation requirements according to FDA CFR21.11 [**FDA** 2019] is supported.

Summary

Process modularization supported by XperiDesk enables efficient reuse of process step knowledge. The process engineers can use process steps and process modules directly from the knowledge base and combine them to create new manufacturing processes. Process parameters can be individually adapted to the specific requirements of the manufacturing process. Possible dependencies between the individual steps and modules get handled by special compatibility rules, which are used in the consistency check. The ability of the XperiDesk environment to handle abstract building blocks such as process step classes enables an incremental and collaborative design strategy. The inheritance model ensures that consistency checking and process simulation are available at all levels of abstraction. It was proven that a structured knowledge management with CAE / PDES can significantly improve research efficiency. By focusing engineers on creative and not administrative tasks also an increase in work satisfaction can be monitored.

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