INTERNATIONAL DESIGN CONFERENCE - DESIGN 2014
Dubrovnik - Croatia, May 19 - 22, 2014.

TOWARDS A PRODUCTION SYSTEM SPECIFICATION TECHNIQUE FOR FUNCTIONALLY GRADED COMPONENTS

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Keywords: specification technique, manufacturing process planning, hierarchical process chain synthetisation, model-based optimisation, functionally graded components

1. Introduction

Functional gradation denotes a continuous and reproducible distribution of properties over at least one spatial dimension of a component. This distribution is essential for the customisation of the component with regard to the later intended application. The improved material utilisation also enables light weight design constructions and simplifies the recycling by using only single material components. Hence, it provides a resource-conserving alternative for modern composite materials [Biermann et al. 2012].

Fields of application for functionally graded components can be found for example in the automotive industry. For instance car interior door panels are usually made of plastic materials that are supposed to absorb the impact energy of a lateral crash to a defined extent. The overall objective in this case is of course the security of the passengers. Therefore it is never allowed that the resulting deformation behaviour of the interior door panel leads to an injury of the car's passengers. To achieve such a desired behaviour it is necessary to assign exactly defined material properties to local regions of the door panel. The utilisation of functional gradation (e.g. the hardness) for interior door panels can considerably extend the functionality of those components. Then the interior door panel, which had formerly only a supporting and decorative function, becomes an important element of the passive car safety [Petersen et al. 2013].

The production of functionally graded components certainly requires complex thermo-mechanically coupled and directly connected manufacturing process chains. A lot of engineering methods exist on how to design and set-up an isolated manufacturing process step to achieve a well-defined distribution of properties. However the holistic design of connected process chains is much more difficult. For that purpose in section two a planning framework that is being developed to synthesise a manufacturing process chain with optimised process parameters for a desired component will be described. During the continuous planning process within the framework numerous information are generated and consolidated. Information like the material, the gradation or the reason for auxiliary processes as well as the optimised process parameters for each step of the best process chain according to the specific planning objective and many more. All these information are very important for the elaboration of a real production system that manufactures the desired component. But how can the information be passed on to the further design phases – outside the planning framework?

Therefore, section three describes a production system specification technique for functionally graded components. The specification technique enables the visualisation of the resulting process chain that includes all relevant information in a descriptive manner and offers an interface for the specified manufacturing process chain to the widely-used Microsoft Visio tool. The import function allows the utilisation of the process chain along the further design phases. Section four then summarises the contribution and identifies the research challenges of the future.

2. Computer-aided planning framework

Thermo-mechanically coupled and directly connected manufacturing process chains are characterised by strong interdependencies between the process steps themselves as well as between the process steps and the realisable component properties. All these interdependencies have to be considered during the planning and optimisation of manufacturing process chains for the production of functionally graded components [Biermann et al. 2012]. Hence, a computer-aided planning framework is being developed. This framework integrates all the required methods, surrogate models for the processes as well as the knowledge obtained, for example, by laboratory experiments along the planning process. This planning process is thereby continuously supported by the three modules *Component Description*, *Expert System* and *Modelling and Process Chain Optimisation.*

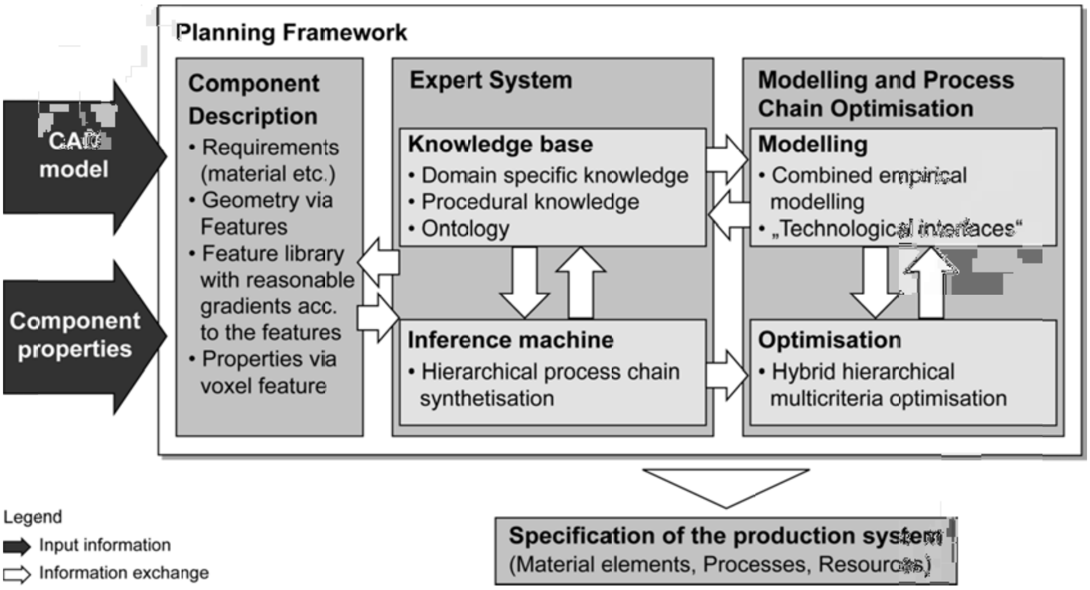

Figure 1. Architecture of the proposed planning framework (acc. to [Gausemeier et al. 2010], [Biermann et al. 2013])

Figure 1 shows the architecture of the planning framework with the required input information and the information exchange between the three modules. The input information is provided by the CAD model of the desired component, the intended properties and the additional requirements (the material etc.). Based on this information, the *Component Description* as the first module enables the properties to be specified at the inner points of the component model (cf. [Biermann et al. 2009]). Subsequently the *Expert System* synthesises a set of several alternative manufacturing process chains to produce the component, whereby the third module optimises the process parameters of each manufacturing process chain and identifies the best process chain for the given planning objective. Finally, the resulting process chain is described by means of a production system specification technique within the last step of the planning process [Gausemeier et al. 2013].

2.1 Feature-based component description

Functionally graded components are characterised by their geometry and the distribution of properties over their volume. The integration of this distribution into the CAD model of the component for the further planning steps is therefore the purpose of the framework's first module. A CAD model of a complex component nowadays contains a hierarchy of geometric features (like cuboids or cylinders). All these features will be extracted after the import of the model and allow the framework to consider the geometry of the component for a pre-selection of reasonable gradients in accordance to the features. A pre-selected generic gradient shows thereby a suitable and producible distribution of the desired graded property from the minimum to the maximum value and is encoded by a colour scale. All these gradients are presented in a so called feature library and simplify the description of the desired gradient by letting the engineer only define the parameters of the corresponding mathematical expression, which increase the description efficiency. After the description, the former generic feature of the library becomes a gradient feature and the application-specific gradient is presented by a voxel-based representation (cf. [Bauer et al. 2011]).

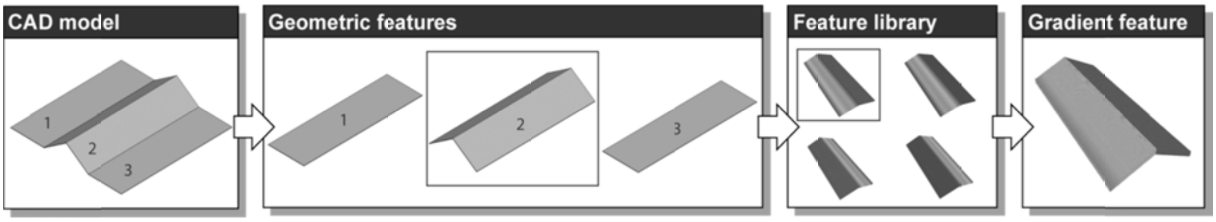

Figure 2. Example definition of a pre-selected gradient (framed) for the geometric feature "angle section" (feature 2, framed)

The description process is summarised in figure 2 which shows an example definition of a pre-selected gradient out of the feature library for a geometric feature. A more detailed explanation of the feature-based component description can be found in [Bauer et al. 2011] or [Biermann et al. 2013].
A further objective of the module is the retrieval of requirements for producing components according to the component description.
For the production system specification technique, the following component characteristics are the most important input information that are provided by the first module of the framework:

- Component and production requirements, like the material, the roughness or the dimensional accuracy
- Geometry of the component given by the hierarchy of geometric features
- Distribution of graded properties over the volume of the component facilitated by the gradient features with the application-specific gradients

2.2 Hierarchical process chain synthetisation

The *Expert System* within the framework automatically synthesises several alternative manufacturing process chains for the production of functionally graded components according to the component's description. Whereas there are a lot of computer systems for the planning of process or operation sequences related to one resource (often milling or turning operations for the shape creation, e.g. [Feng et al. 2005]), we focus the complete manufacturing process chain with all required process steps to produce the component with its desired properties. However, the current planning framework does not provide any numerical controlled (NC) code like other systems do (c.f. [Opas and Mäntylä 1994]). The process chain synthetisation process works in a hierarchical manner and is supported by two steps: the *Core Process Selection* and the *Process Chain Synthetisation*.
At first, all the component properties encoded in the enhanced CAD model of the component's description are translated into discrete component requirements, for example by obtaining the property values at characteristic regions of the feature. Besides the distribution of graded properties, the material and all the other component and production requirements (e.g. dimensional accuracy of +/- 2 µm) contribute to the requirements profile of the component as product attributes (cf. figure 3), which is illustrated by means of a radar chart profile [Fallböhmer 2000]. This profile provides the input information for the *Expert System* [Biermann et al. 2013].
The *Core Process Selection* (according to [Ashby 2007]) marks the first synthetisation step of the *Expert System* and results in the core process for the manufacturing of the component. For that purpose, all the manufacturing process steps available in the knowledge base are structured according to each product attribute of the requirements profile by means of so called selection diagrams. These diagrams consist of tables in which all the manufacturing processes are displayed in the rows and their ability range for the current product attribute is displayed over the columns, while the user-defined

range for this attribute is also marked. Based on these selection diagrams a process profile in the style of the requirement profile is established for every manufacturing process that complies with all the product requirements in the defined range. These process profiles illustrate the fulfilment of the component requirements by the given manufacturing process in a descriptive way (cf. Figure 3) and are therefore displayed to the engineer to explain the *Core Process Selection*. Afterwards, the process step with the highest fulfilment of the product attributes according to the requirements profile is selected to be the core process and the unfulfilled requirements constitute the main input for the *Process Chain Synthetisation* as new requirements profile [Petersen and Gausemeier 2013].

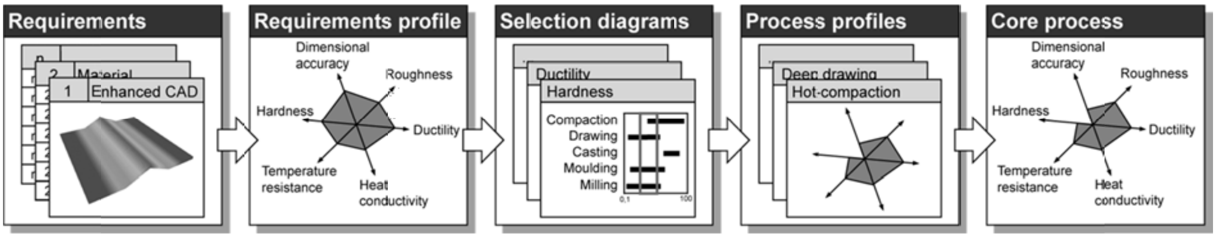

Figure 3. Schematical overview of the *Core Process Selection* to produce polymer composites with a defined hardness distribution as functional gradation

The *Process Chain Synthetisation* is an extension of the process selection method according to [Ashby 2007] and starts only if the *Core Process Selection* ends up with some unfulfilled requirements. This step of the *Expert System* tries to reduce the unfulfilled requirements to a minimum by creating several alternative manufacturing process chains. For the generation of the process chains, the *Expert System* restarts the *Core Process Selection* in a loop, in which the unfulfilled requirements of each concluded iteration loop provide the input information for the next iteration. These loope continue until no further process steps can be found to reduce the open requirements of the current requirements profile.

After every loop, a pairwise evaluation with the new selected process step and the already connected manufacturing processes is performed to ensure the compatibility of the synthesised process chain. If there is only one incompatible process step in the process chain, a new alternative chain will be started without this step, but with an own unfulfilled requirement profile. This new process chain will also be considered during the following iteration loops, so new selected process steps will be integrated in every suitable process chain. The result of the hierarchical process chain synthetisation is therefore a set of several alternative manufacturing process chains for the production of the components according to the component description [Biermann et al. 2013].

The output information of the *Expert System* as listed below constitute the main input information for the production system specification technique:

- Alternative manufacturing process chains, each with
    - Process steps and their characteristics
    - Connection between the process steps
    - Rules that have lead to auxiliary processes (if any)
    - Degree of overall fulfilment according to the requirements profile

2.3 Hybrid hierarchical multicriteria process chain optimisation

The individual process steps are represented by empirical surrogate models. They form the foundation for a hierarchical process chain optimisation by fulfilling an important requirement. During the hierarchical optimisation, a large number of possible process parameter vectors have to be evaluated. While empirical surrogate models can provide that many evaluation results within a few seconds, FE simulations may require too much computational efforts. For this reason empirical models are better suited for an application in the process chain optimisation. They can be fitted based on a small number of real experiments and can predict the resulting functional gradation of the considered properties for all parameter settings. For functionally graded components, models from the Design and Analysis of Computer Experiments (DACE) [Sacks et al. 1989] have proven to be an excellent choice as they are able to describe highly non-linear relationships. Originally, these models were developed for

deterministic computer experiments. However, Biermann et al. showed the applicability of DACE models also for noisy data. Examples of the individual adaptation of these models can be found in [Hess et al. 2013]. In addition, simulated data from computer experiments of the considered processes can be included in the model. This allows a combined empirical model to be applied, which provides an even better prediction quality, in particular with respect to the resulting property distributions [Wagner et al. 2010].
The individual process steps are linked by the so called *Technological Interfaces*. These interfaces are responses of a process that are passed on to a subsequent process as an input parameter. Figure 4 exemplarily shows these process links in a process chain for manufacturing polymer composites. The output of each model contains the resulting component characteristics. In this case, the material temperature TMat acts as Technological Interface. In the first process step, a desired temperature gradation is introduced by a certain parameter setting of heating time tH and heating temperature TH. When the component is passed on to the subsequent compression moulding process, the initial material temperature is an input parameter. Since the compression moulding process is the last process in the process chain, its parameters must be optimised to produce the desired functionally graded properties. Since these properties are often in conflict with each other, multi-criteria optimisation techniques can be employed in order to evaluate the potential of a process. The final objective value for the optimisation approach is obtained by transforming the final component properties using the desirability function of Harrington [Harrington 1965]. This transformation has two important advantages. On the one hand, it allows a better comparison of the different objectives in multi-objective optimisation. On the other hand, a characteristic value describing the ability of the process chain to provide the specified property distribution can directly be assessed.

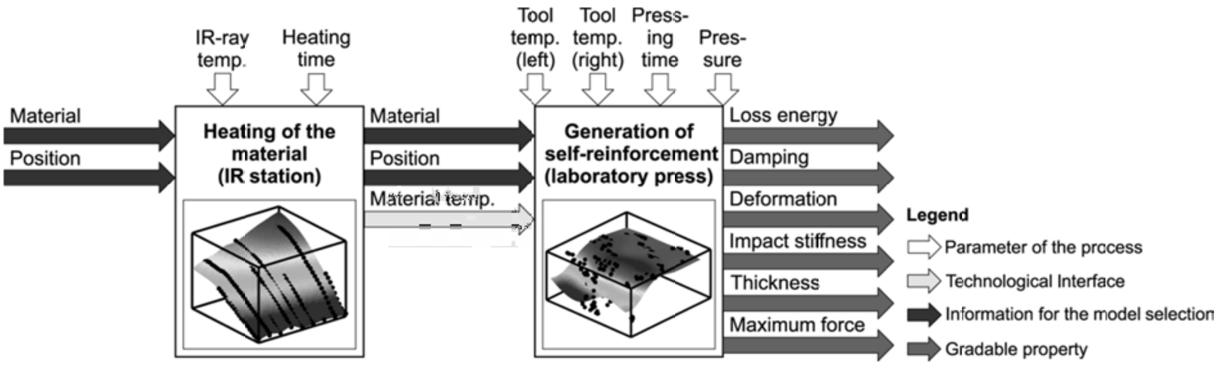

Figure 4. Exemplary process chain for functionally graded polymer composites

Because of the strong interdependencies and an increasing problem dimension, standard optimisation algorithms may fail in the simultaneous optimisation procedure for all the process parameters. Therefore, a concept for the hierarchical multi-objective optimisation of process chains for functionally graded components has been developed [Reyez-Perez et al. 2009]. Starting with the last process in a possible manufacturing process chain, the corresponding empirical model is optimised by means of evolutionary optimisation algorithms. Thus, the parameter setting for the best match with respect to the desired and the predicted properties regarding the specification and desirability functions is obtained. The optimal parameter setting also includes the desired values for the *Technological Interfaces* in the previous processes. If the proposed value for these interfaces cannot be produced in the subsequent process within the allowed tolerances, the process chain is disregarded. In case of a feasible result, the previous processes are optimised in the same manner. This procedure is continued until all processes have been optimised to achieve the best match with the desired specification. The resulting process chain is stored. The results of this procedure are optimised process parameters and an evaluation of the match with the specification of the graded properties for all possible process chain alternatives.
The third module of the planning framework provides the production system specification technique with the following input information:

- Best process chain identified by means of the optimisation, with

- Optimised set-up of the process parameters
- Predicted distribution of graded properties
- Match of the desired and the predicted property distributions

3. Production system specification technique

The objective of the production system specification technique is the collection of all the information generated by the planning framework and required for the elaboration towards a real production system for manufacturing functionally graded components. In order to not overstrain the engineer with all these information at once, a Level-of-Detail (LoD, cf. [Nischwitz and Haberäcker 2004]) concept consisting of two layers is used here for the representation of the information.

3.1 Visualisation

The visualisation as part of the specification technique is based on a process sequence and a resource diagram in accordance to Gausemeier et al. [Gausemeier et al. 2011]. The process sequence illustrates the sequential arrangements of the manufacturing process steps which have to be executed in order to produce the desired component. The input and output object of every manufacturing process chain is always at least one material element. In the context of functionally graded components, material elements are raw materials, auxiliary materials or final components. The resource diagram consists of all the resources (equipment and tools) which are necessary to execute the manufacturing process steps of the process sequence in a logical order [Gausemeier et al. 2010]. The complete process sequence with the corresponding resource diagram for manufacturing polymer composite can be found in [Biermann et al. 2009].

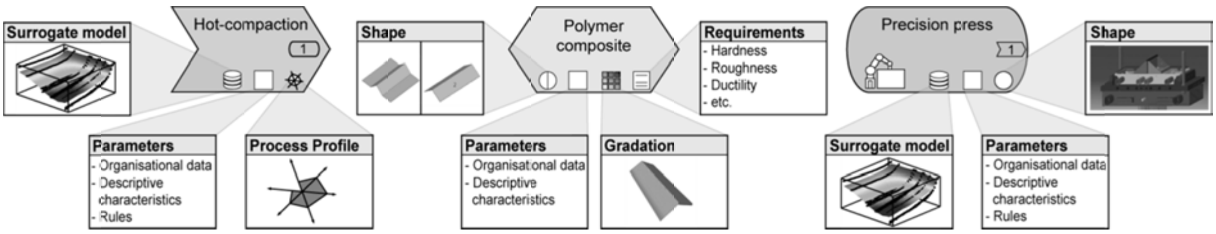

Figure 5. Basic elements of the production system specification technique (*management layer*) with opened sub elements (*detail layer*) and their information

The visualisation is based on a Level-of-Detail concept with two layers within the planning framework as well as the intended Microsoft Visio Add-In for a didactic reduction of the presented information. The architecture consists of a *management layer* and a *detail layer*. Figure 5 shows the three basic elements of the specification technique as shown on the *management layer* with their sub elements as part of the *detail layer*. The *management layer* illustrates only the basic elements of a process sequence or a resource diagram, but without any opened sub element. Furthermore the connection between the elements is constituted by lines and arrows (cf. [Biermann et al. 2009]). If the engineer selects a pictogram on the surface of an element, the *detail layer* is activated. This layer consists of all the information which have been generated during the planning process within the framework (cf. section 2) and, after being activated, selects all the information according to the pictogram. The possible presentation of these information differs a lot and depends on the type of information.

3.2 Data models and structure

For an efficient use of all information within the production system specification technique for functionally graded components, new data models for the three basic elements material, process and resource have been developed in accordance to [Rehage et al. 2013]. These data models are also used by the knowledge base of the planning framework to store the elements, because the main information about a process or a resource – except the process parameter values – are provided by the *Expert System* and are therefore already available in the knowledge base.

Figure 6 gives an overview about the data models for the parameters of the three basic elements exemplified by the car interior door panel, whereby only a part of the parameters or attributes respectively is displayed here. All the attributes within the different sets of a data model (e.g. organisational data oder descriptive characteristics) have a hierarchical structure and are represented by a tree of conjunctions (AND-function, ∧) and disjunctions (OR-function, ∨). An exception is provided by the rules of a data model. These rules have no hierarchy and are only allowed in the data model of a process or a resource element. Every rule has been executed during the synthetisation of the process chain and explain the creation of the process chain. They are added to the data models, so the engineer can retrace the synthetisation step later. An example for a rule is "in case of the hardness as the gradient property and a maximum hardness value of 600 HV, a pre-heating process to heat up the component to 160 °C for 5 seconds must be added before the moulding process".

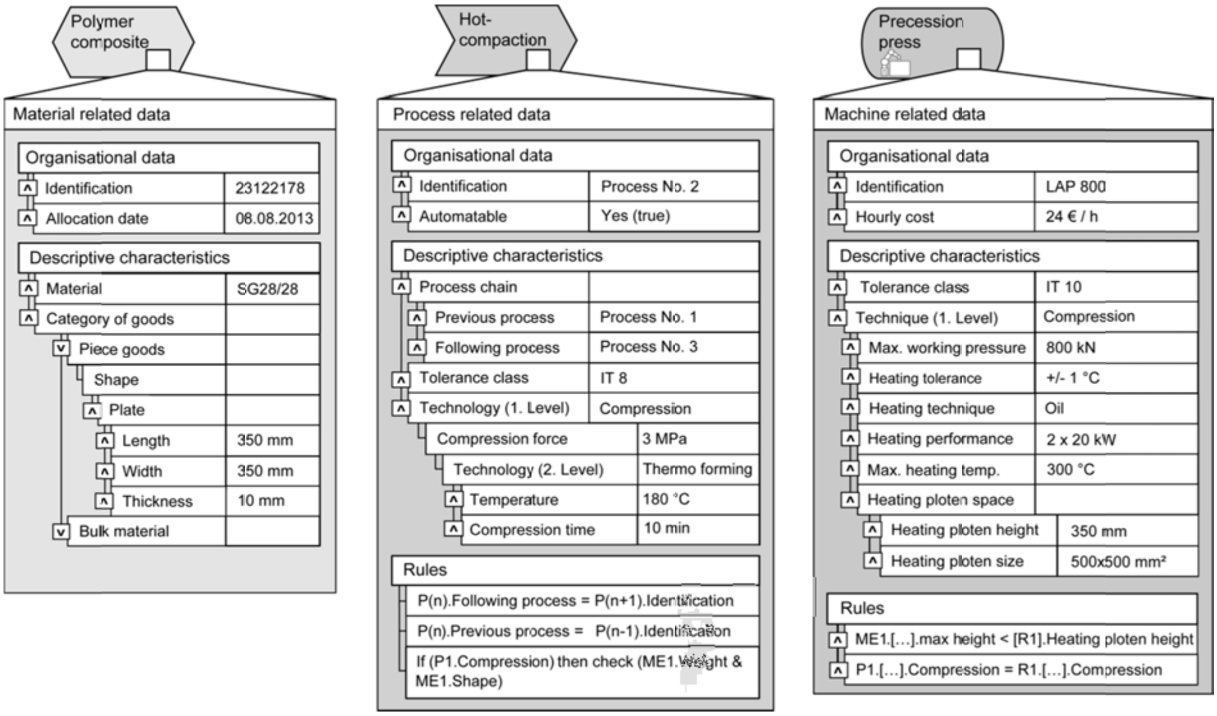

Figure 6. Data models for the parameters of the three basic elements of the production system specification technique exemplified by the car interior door panel

For the sub element "Requirements", a table with all requirements in the first column and the user-defined value in the second column is utilised as data structure and every external data resource like an image of the CAD model or the data file of a surrogate model is integrated into the corresponding data model of the element by a file link. This link is represented as a checksum consisting of the filename and the current timestamp to avoid assignment collisions if the engineer names two files by the same file name. Hence, if two elements are using the same external resource, the corresponding file links of both data models are identical. In case of a surrogate model of a process, there is always a resource with the same file link, because every surrogate model has been fitted by experimental data from real experiments and is therefore directly connected with this resource. Accordingly, if a surrogate model is utilised to optimise the parameters of a process, the process is linked to the resource of the surrogate model, because they are using the same link.

3.3 Import function for Microsoft Visio

The import function for Microsoft Visio allows the utilisation of the best process chain along the further design phases, because Microsoft Visio is widely spread and easy to use. This import function consists of a data exchange interface between the planning framework and Microsoft Visio as well as an Add-In for Visio, which is under development at the moment.

The interface between both tools is defined by a procedure model and a file format based on the Extensible Markup Language (XML). The procedure model consists of the three steps – *File Creation*, *File Transportation* and *File Import*. XML has been chosen as file format, because it is very flexible and large parts of the planning framework's knowledge base have already been set up with XML files. Figure 7 gives an overview of the interface between the framework and Microsoft Visio.

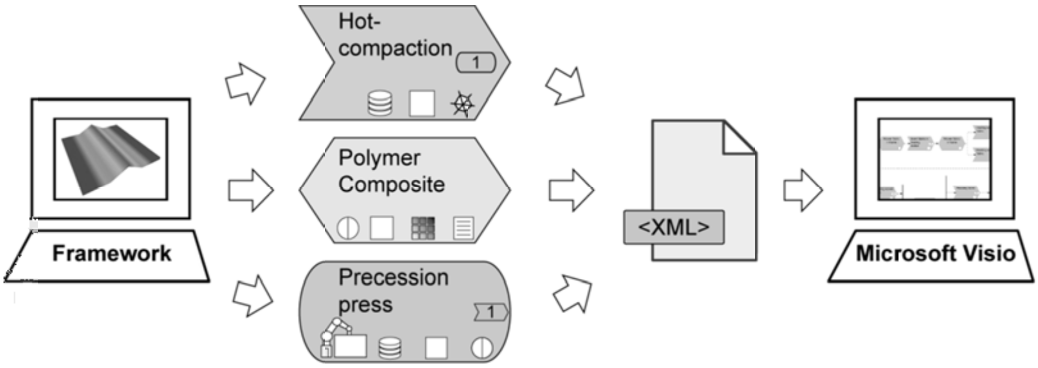

Figure 7. Interface between the planning framework and Microsoft Visio

File Creation means the consolidation of all the information generated during the planning process and their integration into only one XML file. An exception are the photos and surrogate models, these files are stored separately in the same folder as the XML file and linked to the data models. The *File Creation* step is conducted by the planning framework in a fully automated manner as opposed to the *File Transportation*. The transportation between both tools is only necessary if Microsoft Visio runs on another computer and has to be done by the engineer himself. The *File Import* as last step of the procedure model reads the XML file, creates the structure of the process sequence as well as the resource diagram, establishes the links between all the various elements and fills the *detail layer* with the information. All the elements of the *management layer* are represented by standardised shapes in Visio, so the engineer is able to work with the elements, e.g. for changing the order of the process steps within the manufacturing process chain. This *File Import* step is supposed to be performed by the Microsoft Visio Add-In which is being developed.

4. Conclusion and outlook

Components with functional graded properties based on thermo-mechanically coupled processes offer a new and sustainable approach for customisable smart products of the future. Hence, a planning framework for the computer-aided planning and optimisation of those components as well as a production system specification technique which provides all needed information for the elaboration of the production system in a descriptive manner have been presented. Furthermore the prototypical implementation of the specification technique within Microsoft Visio has been demonstrated.

Future work includes the enhancement of the planning framework by novel methods and knowledge to analyse and evaluate the cost-effectiveness, uncertainty, robustness and sustainability of the synthesised manufacturing process chains. All these information are important to rank the process chains according to a specific planning objective. In addition, new visualisation concepts for an intuitive assessment of the uncertainty and robustness of the process chains by the engineer will be developed. Afterwards, a multi-criteria decision support that handles the highly diverse and dynamic characteristics of the decision criteria for selecting the best process chain alternative will be implemented. A general proof of concept for this idea based on the Analytic Hierarchy Process (AHP, cf. [Saaty and Vargas 2012]) can be found in [Petersen et al. 2013].

The enhancement of the knowledge base with additional materials, features, suitable gradations, manufacturing process steps, interdependencies and surrogate models as well as the adjustment of the ontology are further development steps. According to all these new information, the specification technique must also be adapted. The rules of the *Expert System* and the ontology have to be expanded to realise the synthetisation of more complex manufacturing process chains as well as their pairwise evaluation.

Acknowledgement

The work of this contribution is based on investigations of the subproject D5 (TP D5) “Synthesis and multi-objective model-based optimisation of process chains for manufacturing components with functionally graded properties” as part of the Collaborative Transregional Research Centre 30 (CRC Transregio 30), which is kindly supported by the German Research Foundation (DFG).

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