COMPUTER-AIDED DESIGN & APPLICATIONS, 2018
VOL. 15, NO. 5, 619–630
https://doi.org/10.1080/16864360.2018.1441228

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3D CAD modeling of deep drawing tools based on a new graphical language

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ABSTRACT
Increasing diversity of types and decreasing batch sizes along with a growing complexity of products manufactured by forming technology result in new challenges for developers and designers. The construction of a full parametric model of a deep drawing tool in a 3D CAD system is usually considered time-consuming and associated with high cost, and thus discourages many designers. In order to render this type of modeling easier and faultless, a new method for the model-driven design of deep drawing tools is developed. For this purpose the analysis of fully parametric 3D CAD models of deep drawing tools is necessary. This analyzing contributes to the newly developed graphical domain-specific language, which makes the modeling of deep drawing tools more flexible and time-efficient.

KEYWORDS
parametric modeling; graphical domain-specific language; metal forming

1. Introduction

The use of CAD technology is currently state-of-the-art in technical product development. The main purpose of CAD is to support the designer in the development process. 3D modeling is represented in the following product development and design stages: product layout, product preparation, creation of a complete product model such as computer-aided simulations and animations. Consequently, the use of 3D CAD systems allows the creation of complete digital product models and as a result an earlier detection and prevention of functional and manufacturing problems [6]. This leads to several optimization cycles in a product development process and to shorter development times [4]. CAD technology is also used in sheet metal forming during product development phases. Fig. 1 depicts the process chain for the development of a sheet metal component.

The first step of the process chain includes the styling and design of the part. Here, the early part data are dealing less with feasibility and functionality than with aesthetics and fluid mechanics. The relevant construction data of the part are derived and passed on to the method planning department. During method planning the forming processes and the sequence of operations for the manufacturing of components are defined. Subsequently, the design and development of deep drawing tools for forming operations take place. In this step, the use of 3D CAD systems plays an important role, since the complete deep drawing tool is first modelled as a 3D CAD model. After virtual tool development the deep drawing tools are manufactured. During the try-out operations the deep drawing tools are reworked until the desired quality has been achieved. Only after this step can the production of the real component out of a sheet metal in the press plant begin [20].

Nowadays, the development and design of deep drawing tools in a 3D CAD system are state-of-the-art. These systems allow for the creation, addition and expansion of virtual deep drawing tools [7, 25]. In addition to geometry data, the 3D CAD models could also include technological and functional information as well as information about design and manufacturing process [9].

In order to standardize and automate the product development and design process by means of a 3D CAD system, the product developer could integrate different parameters in a 3D CAD model. Using these parameters, the properties of a 3D CAD model can be varied and thus new modified variant constructions can be generated and used for further investigations [8]. However, a fully parametric 3D CAD model requires accurate planning and modeling of parameters and their relations, between individual components as well as between assemblies. Additionally, increasing component complexity results in a high complexity of parametric 3D CAD models

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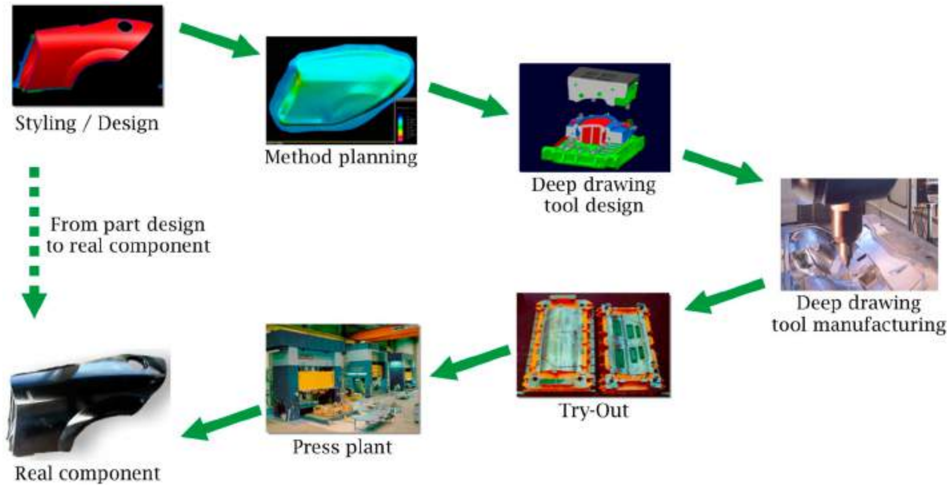

Figure 1. Process chain for the production of a car body component out of sheet metal.

and this is what keeps many engineers from using this procedure.

Recent scientific studies deal with simplification of the modeling and planning of deep drawing tools. Naranje and Kumar designed a knowledge based system which simplifies the modeling of deep drawing die. This system supports designer by selection of major components of a deep drawing die [15]. Kim et al. developed an automated design system of die components using 3D CAD library. This 3D CAD library includes only standard components for modeling of a die [11]. Rao et al. developed a low cost knowledge base system for design of deep drawing tools. Based on input data this system can generate the design parameters of deep drawing process [21]. Potocnik et al. designed a parameter-based 3D CAD model of the stamping die using CATIA V5 PLM. They called this CAD model intelligent system for the automatic calculation of stamping parameters [19]. Thereby the publication describes the structure of the developed parameter-based model but not the necessary effort for the changing of the internal relations between the parameters by system user. None of the above studies has dealt with the simplification of fully parametric modeling of deep drawing tools. Due to the increasingly complex forming technologies and thus forming tools, it is necessary to ensure the flexibility of the forming tools. This can be achieved by simplifying the parametric design using the new graphical domain-specific language.

Currently, suitable methods and support tools for a simple and transparent modeling of parametric relations in a 3D CAD model do not exist. In order to simplify this modeling, a new graphical domain-specific language for the design of parametrical deep drawing tools is developed. The CAD models described in this new language can be generated using model transformation in a 3D CAD system. Thus, the designer is equipped with a tool for the non-geometrical design of 3D CAD models of deep drawing tools. In particular, the parametric relations can be modeled simpler and faultlessly using graphical modeling instead of geometrical design.

Domain-specific languages (DSL) are formal languages that are tailored for the use of a specific domain. In the form of textual languages (e.g. Modelica) they are widely used to model artefacts (objects, facts, functions, behaviors) of the specific domain. Graphical languages also exist, with the most widely used being Unified Modeling Language (UML) for the domain of Software Engineering and Systems Modeling Language (SysML) for the domain of Systems Engineering.

While textual languages are usually described by grammars, and it is also possible to specify graphical languages by graph grammars, the latter are usually modelled by defining a meta-model for the abstract syntax of the language. UML and SysML meta-modeling allows specification and extension, so that new DSL can be defined on top of the existing languages.

Graphical domain-specific languages (GDSL) have already been introduced to the domain of mechanical construction: Au and Yuen developed a GDSL for the modeling of sculpted objects. Although these objects are completely defined by their geometric representation, the user works with abstract features and their relations [5]. The early stages of the construction process were targeted by Andersson, who developed a modeling tool for the concept phase to create geometric and non-geometric models [3].

Wölkl and Shea showed the utility of several SysML diagrams after examining the use of SysML for concept modeling in mechanical construction [26]. Peak and Zingel applied SysML in the early design phase to generate

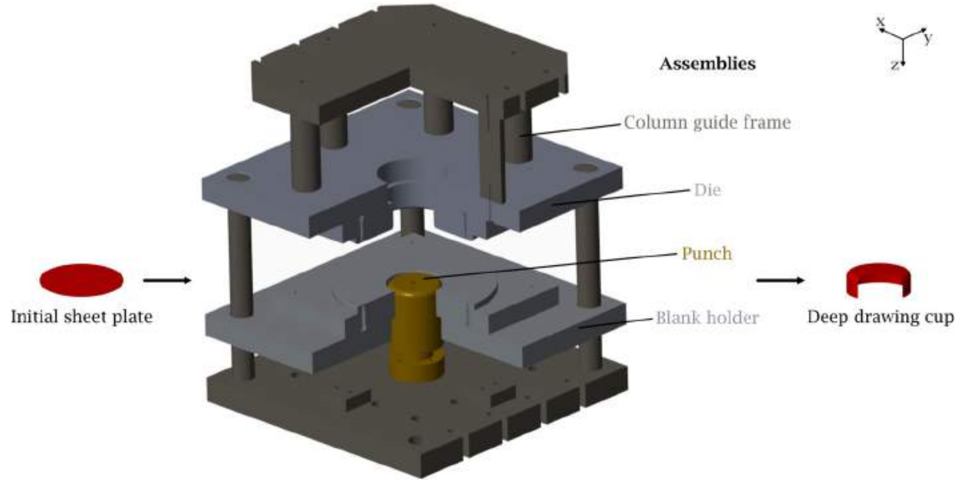

Figure 2. 3D CAD model of single-acting deep drawing tool.

a simulation model [17], [18]. Albers and Zingel implemented SysML based functional modeling techniques in the product development process of mechatronic systems [1].

These industrial and research projects highlight the potential of SysML for the domain of parametric mechanical construction. But while Model-Based Systems Engineering (MBSE) is increasingly applied, there is still no widespread use of MBSE approaches throughout the domain. Therefore, several surveys have investigated the low acceptance of modeling techniques in engineering [2], [10]. The main challenge seems to be the steep learning curve of SysML, particularly the application of concepts that do not exist in mechanical construction like inheritance (derived from UML). Mechanical engineers are not used to SysML models that differ considerably from CAD models.

Albers and Zingel specifically surveyed the usage of diagram types and found out that only 48% of the participants had knowledge of Constraint (i.e. Parametric) Diagrams and as little as 4% found them to be "crucial" for modeling [2]. This essentially proves that Parametric Diagrams are just too complex for the reality of mechanical engineering. Polled for improvement recommendations, the surveyed suggested increasing the usability of existing modeling software tools instead of the SysML language itself, which was also one of the recommendations by Bone and Cloutier [10].

2. Construction parametric 3D CAD model of a deep drawing tool

At the beginning of this chapter the construction of a deep drawing tool for rotationally symmetrical components is illustrated and explained. Following, the parameterization of these tools takes place, based on the tools structure. Due to the complexity of the parametric 3D CAD model of the deep drawing tool the following discussion only concentrates on one assembly.

2.1. Design of a single-acting deep drawing tool

The task of a deep drawing tool is to transfer punch geometry to the workpiece considering the material flow. The deep drawing tool is installed in the forming machine, which provides energy for forming operations. The mounting space of the forming machine is imported for the design of the deep drawing tool. Generally, forming machines are divided into single-, double- and triple-acting machines by their principle of operation. As a consequence, deep drawing tools are also classified as single-, double- and triple-acting tools [16].

This paper focuses on a single-acting deep drawing tool for rotationally symmetrical parts. Fig. 2 depicts a 3D CAD model of a single-acting deep drawing tool, which allows manufacturing of round cups with flat bottom out of initial sheet plate. This deep drawing tool consists of four assemblies: punch, die, blank holder and column guide frame assembly. The punch and the die are components used for the forming of workpieces. Here, the cavity of the die provides the counterpart of the punch. The blank holder is used to control the material flow and to prevent wrinkles and cracks caused by the force applied. The tasks of the column guide frame are fixing the whole tool in the forming machine as well as guiding the die and blank holder assemblies [12].

At the beginning of the deep drawing process an initial sheet plate is centered on the blank holder. In the next step the die assembly moves down and the sheet plate is jammed between blank holder and die assemblies. The continued translational movement of the die assembly

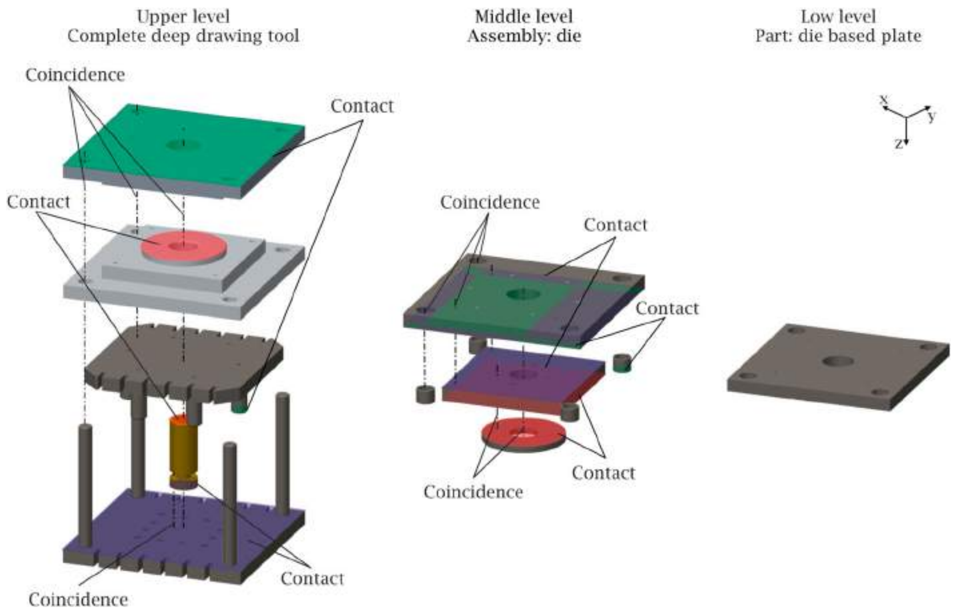

Figure 3. Structure of deep drawing tool divided into three levels.

moves the blank holder down so that the sheet plate is pushed over the punch and the cup is formed.

2.2. Method for the parametric modeling of a deep drawing tool

Parametric or parametric-associative modeling by means of a 3D CAD system is a history-based design of a 3D CAD model. The aim of a parametric model is the quick and consistent realization of model adjustment by varying the input parameters. An important aspect in this is to determine the input parameters and their relations with the other model elements before modeling. A subsequent modification of the parameters and relations leads to increasing modeling effort [22].

Modeling and parameterization of the 3D CAD model described in section 2.1 are done in the 3D CAD program CATIA V5. The parameterization of the 3D CAD model should be solution-oriented and have a clear and flexible relational structure.

In a deep-drawing tool for rotationally symmetric components the requirements of the forming operation primarily depend on the punch and the die geometry. Thus, the punch diameter, punch height, punch edge radius and die edge radius are defined as input parameters. After determining these input parameters, the structure of parameterization in the 3D CAD model should be specified. Based on the structure of the deep drawing tool depicted in Fig. 3, three construction levels can be derived. The upper level of the model represents the complete deep drawing tool with its conditions between the individual assemblies. The conditions in CATIA V5 are divided in surface conditions, congruence as well as offsets and allow the adjustment of single components or assemblies in a 3D CAD model. The center level contains an assembly with geometrical conditions between the individual components. The low level represents an individual component of the assembly. Based on these three levels, the relation flow between individual components can be designed differently. It is possible to save the relations in the upper level or in the levels in which they are active.

The advantage of the relations in the top level is the fast access to the individual relations. However, in this case CATIA saves the created relations in the model in sequence, so that the structure of the relations becomes increasingly confusing with growing model complexity. An allocation of relations on all model levels reduces the complexity of the relational structure by targeted data distribution which improves the clarity of the model. Thus, the model is also flexible enough to carry out changes or subsequent modifications since the relations can be located quickly.

After the determination of the defining input parameters and the location of the relations in the model, the structure of the relation flow can be specified. As a result of the model size, the user has a lot of possibilities to create relations between the parameters. However, it is recommended to configure a structured flow between individual relations to control the overview and the complexity of data. In addition, the aspect of flexibility should be observed during the modification.

In this study, two possibilities to design the relation flow in a parametric 3D CAD model of deep drawing

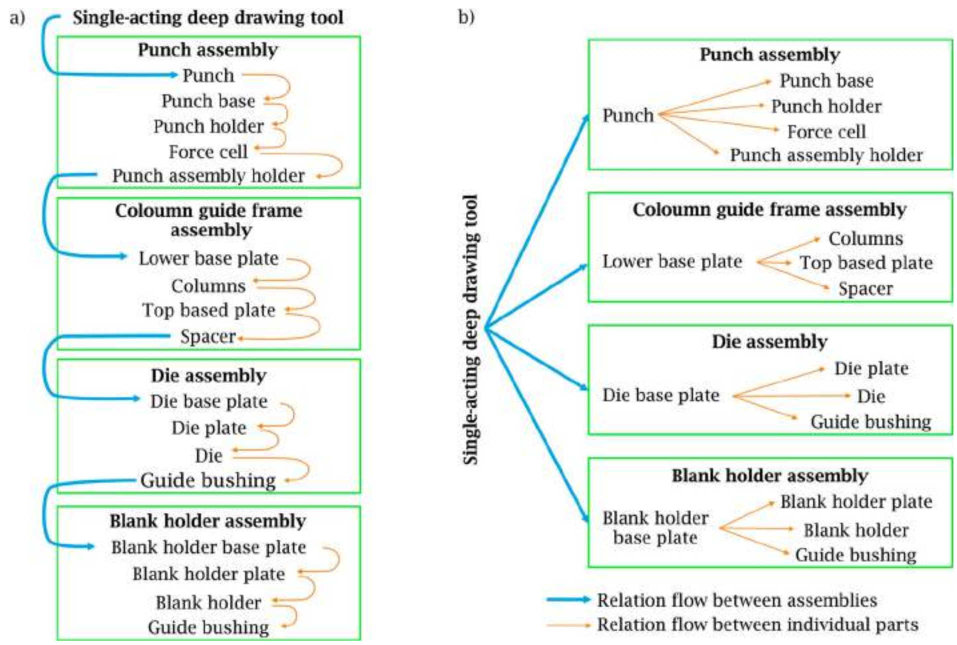

Figure 4. a) Linear relation flow and b) parallel relation flow for a parametric 3D CAD model of a deep drawing tool.

tools are developed and investigated. The first one is to configure the relation flow in a strictly linear path depicted in Fig. 4 (a). In this variant, the logical relationship between many elements should be determined. Further, model flexibility as to subsequent changes is very limited since the design elements are all interrelated. The second variant with parallel relation flow is illustrated in Fig. 4 (b). In this case, most elements are independent of each other. In comparison to the first variant, the second provides much more flexibility for subsequent modifications of the individual components since dependencies between the individual components are minimized. For this variant, a part of the assembly should be chosen to provide the relation flow from input parameters to other assembly components.

In order to enable an overview of the relation flow and also the logical relations between individual parts, both above-mentioned variants for configuring the relation flow for the single-acting deep drawing tool are mixed. The structure of the desired relation flow is depicted in Fig. 5 (a). As already mentioned, the punch parameters are defined as input parameters in the model so that the relation flow starts at the punch. Between the individual assemblies a linear relation flow is desired starting at the punch. In the individual assemblies a parallel relation flow should be achieved starting at the part connected with the punch.

Fig. 5 (b) depicts the configuration of the resulting relations in a fully parametrical 3D CAD model of a single-acting deep drawing tool. Compared to the targeted relational structure of Fig. 5 a) the factual structure has more relations and seems more complex. The additional logical relations result from the model parameterization and are therefore mainly used for reducing the modeling effort as well as for a better overview of the model structure. For example, the sizing of the blank holder assembly is completely created by the relations with the die assembly, because the design structure of these two assemblies is identical.

2.3. Parametric modeling of the punch assembly

In this study the complexity of the parametric model structure of a complete single-acting deep drawing tool is illustrated by means of the punch assembly due to the large model scope. Fig. 6 (a) depicts the individual components of the punch assembly as well as the relation flow and the boundaries between these components.

Since the punch is the significant component of the deep drawing tool and thus of the parametric design, the geometric parameters of the punch should directly be linked to the input parameters as well as to each other by relations. Fig. 6 (b) depicts the complete relation flow between the individual elements of the punch assembly. Here, the actual punch diameter corresponds to the input parameter named diameter. The description of the counterbore hole, the distance between dowel hole and center axis as well as the pin diameter depend on the actual punch diameter. In order to create relations between the punch diameter and the description of the counterbore hole, a hole table is generated. This table includes the design data of the three threads M10, M20 and M30 such

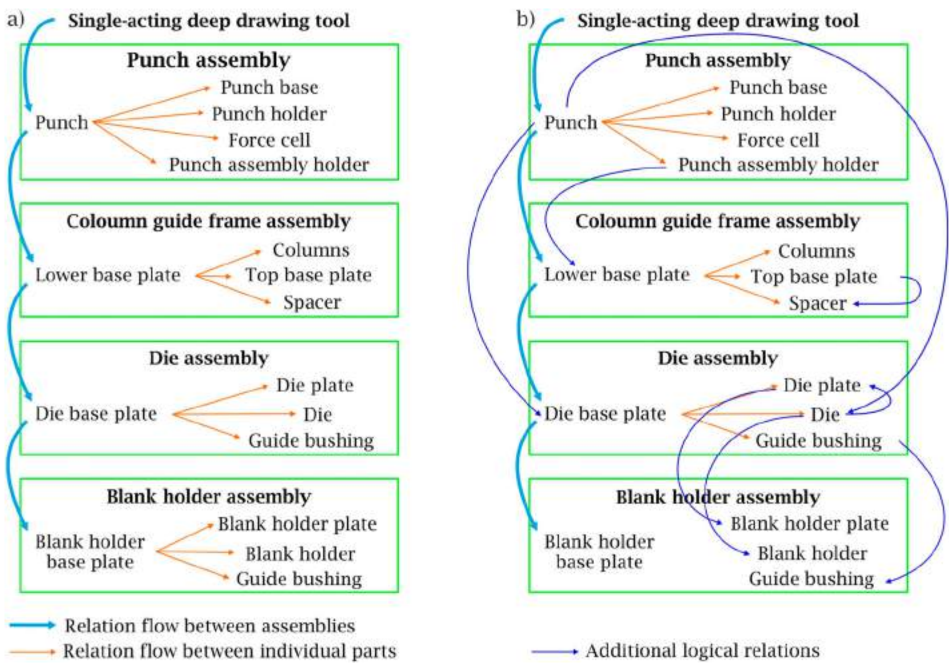

Figure 5. a) Desired relation flow and b) resulting relation flow in a fully parametric 3D CAD model of a single-acting deep drawing tool.

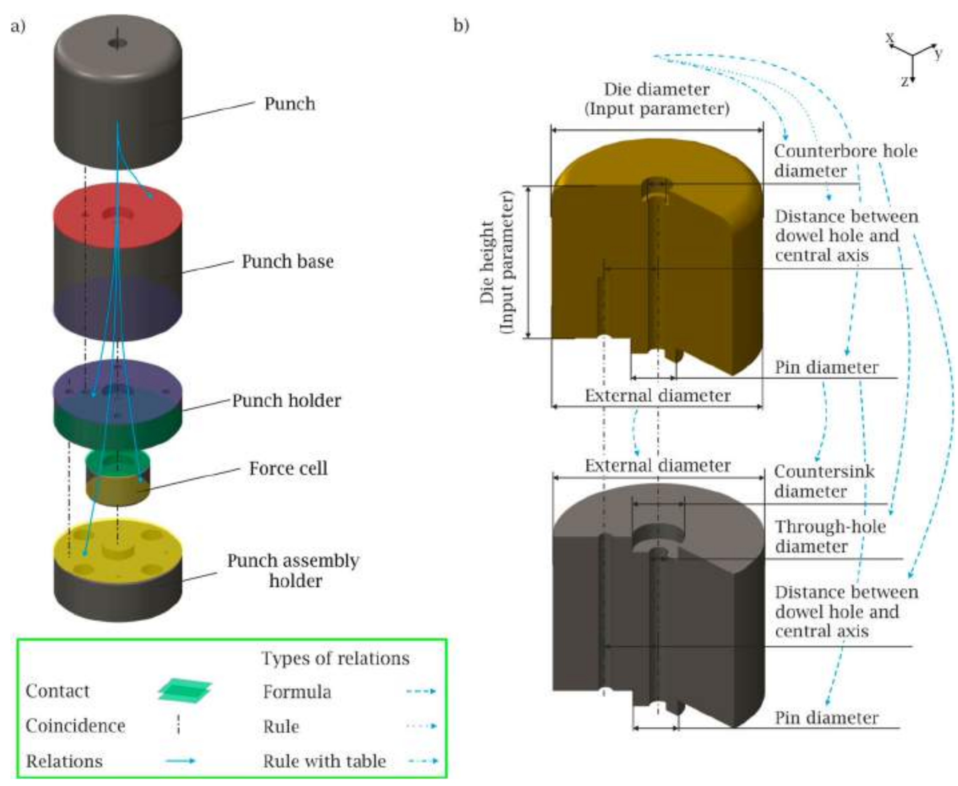

Figure 6. a) Individual components of the punch assembly, b) relations flow and boundaries between punch and punch base.

as drill diameter, counterbore diameter and counterbore depth. In order to define these design data based on the punch diameter, a rule with the if-else-relation is created in CATIA. By means of this rule, the design data of a thread are assigned to the range of the diameter value.

After the parameterization of the counterbore hole, the pin diameter is defined as a quarter of the punch diameter. Such simple relations are defined by a formula created and saved in the formula editor of CATIA. The distance between dowel hole and central axis is also

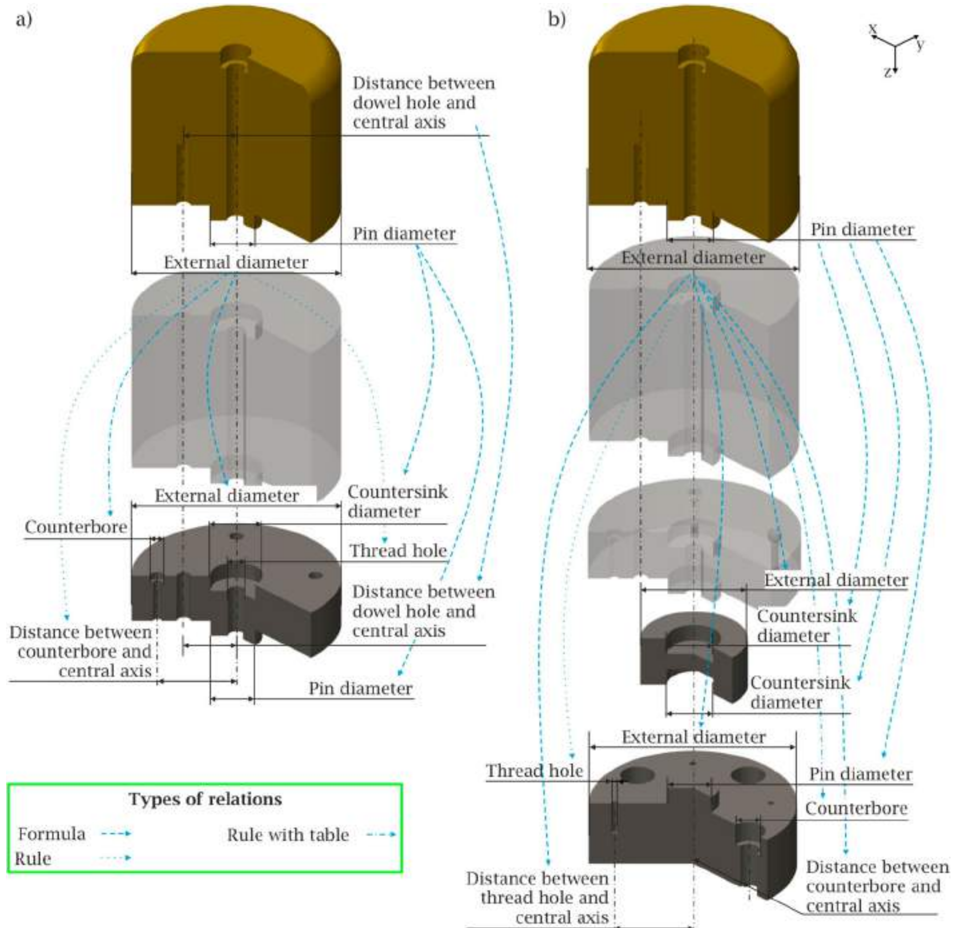

Figure 7. a) Relations between punch and punch holder b) relations between punch and load cell as well as between punch and punch assembly holder.

described by a formula and amounts to half of the punch diameter. Thus, the risk of the dowel hole being positioned outside the punch or inside the pin is eliminated.

The described relations allow for an automatic adjustment of the counterbore hole, of the distance between dowel hole and central axis as well as of the pin diameter by changing the input parameter punch diameter.

The punch base is positioned below the punch. The geometrical parameters of the punch base are depicted in Fig. 6 (b). The punch base represents the extension of the punch, which is connected by a counterbore crew and is adjusted by a dowel with the punch. Thus, the parameters of the punch base are connected with the corresponding parameters of the punch by simple formulas. The height of punch base, countersink and pin was kept constant for model simplification.

Punch and punch base are fixed to the punch holder by a centrally positioned screw. Thus, the next step is the creation of the relations between the punch and the punch holder pictured in Fig. 7 (a). Also, in this case the relations between identical parameters, such as pin diameter, external diameter and the distance between dowel hole and central axis, are equated by simple formulas. In the parameterization of the thread hole for the attachment of punch and punch base the nominal thread of the hole is defined in a rule depending on the punch diameter to M10, M20 or M30. For the creation and parameterization of a thread hole in CATIA V5 a rule is sufficient. The use of a table is not necessary since the parameters of a thread hole already exist in CATIA V5.

Firstly, the counterbore holes of the punch holder serve to position and fix punch, punch base and punch holder on the load cell. The punch holder is connected to the punch assembly holder by counterbore holes. The parameterization of these counterbore holes is similar to the counterbore hole of the punch and is performed by means of a table and a rule. Due to the lack of space, the dimensions of the counterbore holes are defined for three screw sizes M4, M6 and M10 depending on the punch diameter. The distance between the counterbore holes and the central axis is defined by a formula as ¾ of the punch diameter. Thus, the counterbore holes are exactly

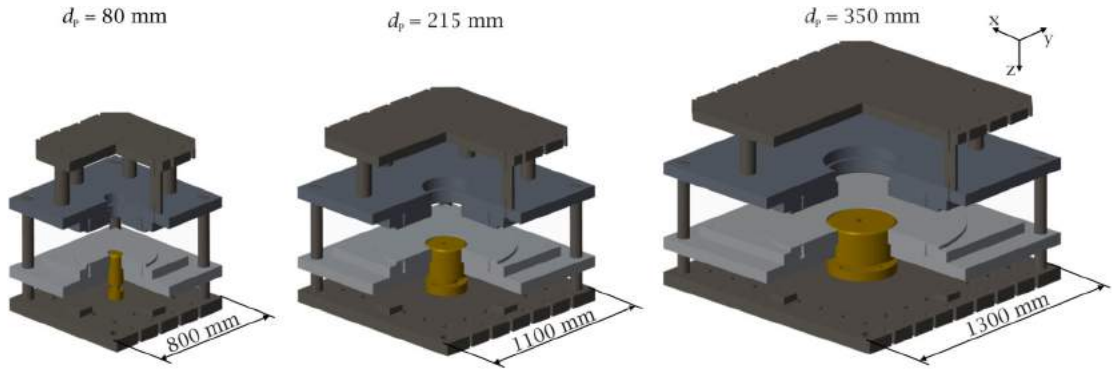

Figure 8. Model adaptation by varying the punch diameter d_P.

positioned between dowel hole and external edge of the punch holder independent of the punch diameter.

As noted above, a load cell is positioned between punch holder and punch assembly holder for force absorption. The simplified view of the load cell is depicted in Fig. 7 (b). The parameterization of the load cell depends on the punch parameters. Due to the simplified design the load cell is connected to the punch parameters only via formulas.

The last part of the punch assembly is the punch assembly holder, fixing the whole punch assembly to the lower base plate of the column guide frame assembly. The relations flow between punch and punch assembly holder is shown in Fig. 7 (b). The identical parameters of both components such as external and pin diameter are linked via simple formulas. The threaded bores are used to connect the punch holder with the punch assembly holder. The distance between the thread bores and the central axis is defined by a formula as ¾ of the punch diameter. Furthermore, the thread bores are dimensioned by a rule depending on the punch diameter for three screw sizes M4, M6 and M10 according to the counterbore holes of the punch holder. The counterbore holes for fixing the whole assembly to the lower base plate are parameterized similar to the already described counterbore holes via a table and a rule. The used dimensioning allows for three screw sizes M12, M14 and M18, depending on the punch diameter.

2.4. Results of parameter-based modeling

Identical to the parameterization of the punch assembly, the whole 3D CAD model of the single-acting deep drawing tools is structured via the relation flow defined in section 2.2. Fig. 8 depicts three models which are generated from the parameter-based 3D CAD model of the deep drawing tool based on the variation of the punch diameter d_p in CATIA V5. Due to structural and functional constraints, three sizes of the column guide frame are defined in the model depending on the punch diameter.

Despite systematic problem solving for the parameterization of 3D CAD models of deep drawing tools, the complete parameter-associative structure of a model proved to be very complex and time-consuming. A lot of relations such as formulas, rules and tables render the structure of parametric 3D CAD models unclear and confusing. In order to provide an overview of the relations, they were noted in the requirement lists of the deep drawing tools. Thus, the lists of requirements form the basis for the new graphical modeling language for the domain of deep drawing tools.

3. Graphical modeling language for deep drawing tools

A main component of the new method to design deep drawing tools is the graphical modeling of the structure of CAD models. The structure consists of the hierarchical setup of the model, which is the composition of products from assemblies, parts and properties (properties being components of their respective elements), on the one hand and the dependencies between elements, properties and parameters on the other hand.

To simplify, relations can be divided into two broad categories: outer relations describe semantic dependencies between parts and inner relations describe actual specific dependencies between properties. Outer relations are only expressed in natural language, explicitly not directly formulaic. The relation between punch and punch holder in the above example is an outer relation "is fixed to". The specific meaning of an outer relation is then detailed by a number of inner relations; see Fig. 7 (b). An outer relation therefore consists of (by composition) several inner relations that are the actual formulas, tables, etc.

The structure as described before can be modeled apart from geometric characteristics. Existing CAD

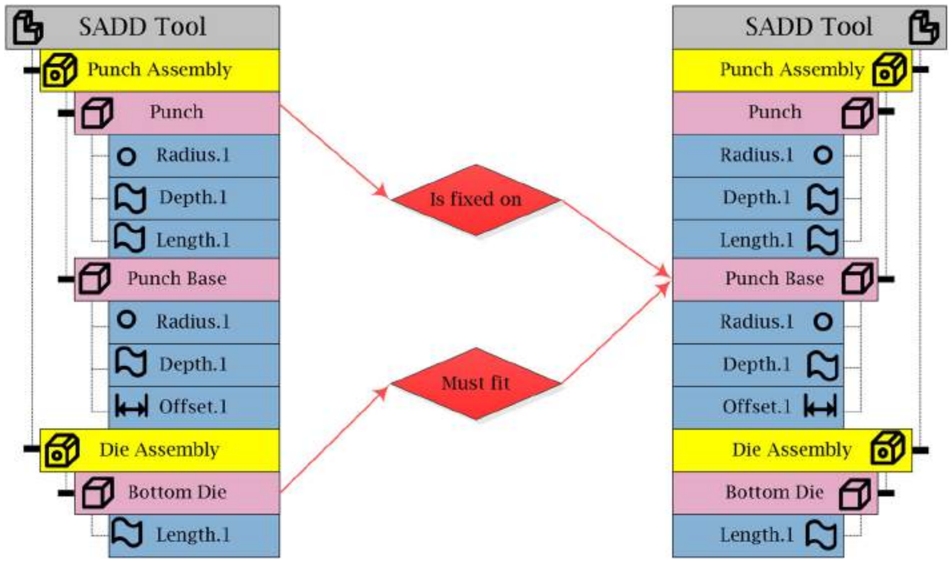

Figure 9. Dual tree view snippet of a single-acting deep drawing tool.

software only rudimentarily supports this type of modeling since it is focused on the 3D view. Graphical modeling is advisable, since visual links between model elements can be intuitively grasped and easily created. The graphical language has to be easy to handle, so that it appeals to a broad section of engineers.

Systems Modeling Language (SysML) is a powerful and widely used modeling language for engineering domains. While mainly used in Systems Engineering, it also has been applied in mechanical construction, particularly in the early phases of the construction process. That means that software tools and exchange formats exist, so that SysML models can be integrated into tool chains. Block Definition Diagrams, Internal Block Diagrams and Parametric Diagrams are the main diagram types that are eligible for the modeling of parametric relations with SysML. Studies, surveys and personal examinations have shown that these diagram forms, particularly Parametric Diagrams are unsuitable for this domain with regard to usability [23].

CAD designers without prior knowledge of SysML will disregard it as unusable, so it is necessary to develop a new graphical domain-specific language (GDSL) that is tailored for parametric CAD modeling. The GDSL is still based on SysML to preserve the advantage of interoperability as mentioned above. The main components of the new GDSL are a meta-model for deep drawing tools and two new diagram types [24]. The diagrams are developed with a focus on interactivity in order to simplify the visualization and modification of models.

A Dual Tree View in Fig. 9 shows the hierarchical composition of a 3D CAD model in mirrored tree visualization. The newly created space between the trees is used for the clear drawing of parameter dependencies through lines. This gives a prominent role to the hierarchical structure which is visualized by established schemes while having a focus on the central relations. Relations and their lines can be drawn with short lines without overlap and with minimal crossings, which are the notable criteria for a clear presentation.

The interaction approach for the Dual Tree View is based on the showing and hiding of model elements, which enables the presentation of precisely the needed information at the right time to the right user. The diagram offers filters and intuitive tree interactions (expand, collapse) and expands these by relation-specific interactions: Relations can be expanded and the trees can automatically be moved relative to one another to improve the drawing (with regard to short lines etc.).

Therefore, the Dual Tree View is well suited to show and modify the hierarchical structure and outer relations of a model. Inner relations can be visualized in the second new diagram type, a parameter map shown in Fig. 10. These are inspired by mind map visualizations and again put the relations in the center of attention. The properties and parameters connected by the relations are grouped around the relation symbols at top and bottom. The hierarchical structure is still visible with a smart symbol design. The interaction approach in this diagram is focused on the drawing of new lines and relations.

The new diagram types combine into a graphical language that is created from the ground up with readability in mind. Entities and their connections can be modelled as vertices and edges and thus form graphs. The field of Graph Drawing is concerned with the adequate and aesthetic visualization of these structures. The development

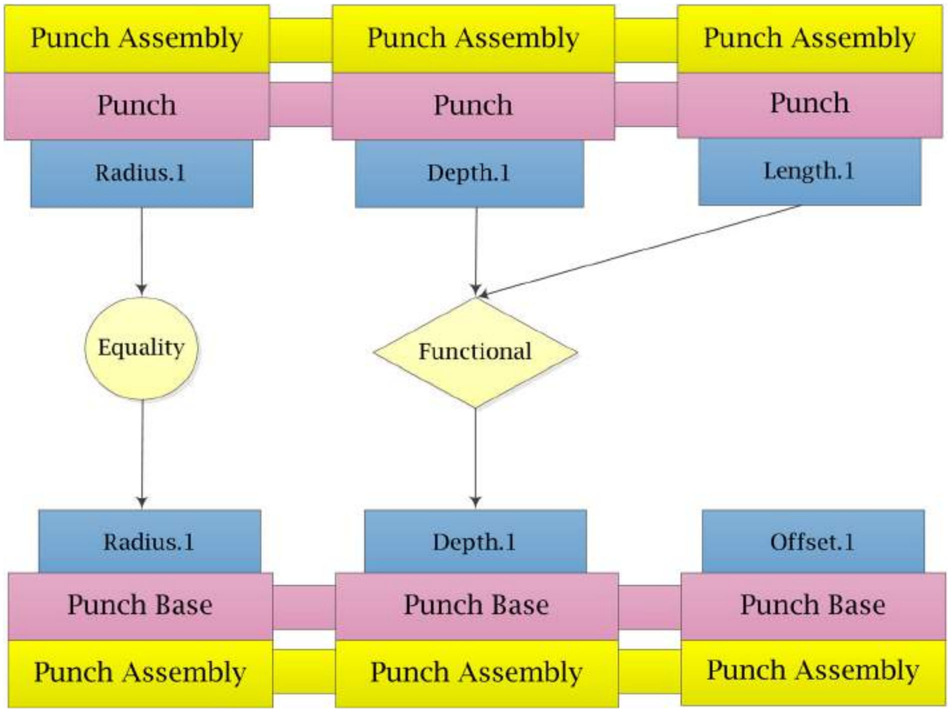

Figure 10. Parameter map of inner relations.

of the new graphical language follows studies on important criteria for the understanding and usability of different graph drawings [23]. Interactions were added onto the visualization following typical UI design paradigms.

While in [13] only the visualization of parameter and dependency information is realized by graphical language diagrams, the latest work covers implemented editors to create and modify models in a software prototype [14]. The presented work is to be understood as a proposal for the new method in model-driven design and the implementation serves as a demonstrator for the possibilities in its application. Limiting the domain to specifically deep drawing tools allowed for a smaller meta-model and thus faster and easier modeling both in SysML and in the new GDSL. The prototype was tested on a small scale and early results show good readability and thus usability of the new diagrams and their interactions. Integration into existing tools or tool chains would further improve the design process.

Designing a new 3D CAD model can start from an existing CAD model, a SysML model or only from the meta-model (effectively a blank slate). The main structure, consisting of hierarchical composition and relations, is created graphically and dialog-based. Then, designed models can be used in other tools. Export and transformation mechanisms to SysML and CAD formats were implemented prototypically. An exemplary process would be to transfer the model to CAD software to fill out the actual geometric information of the model.

4. Summary and conclusions

The aim of this paper is to show and explain the structure complexity of a parameter-associative 3D CAD model of a deep drawing tool. Furthermore, in order to facilitate the mapping of the product logic and the design expertise of a parameter-associative 3D CAD model, a new graphical modeling language for the domain of deep drawing tools is developed and introduced in this paper. Using this new graphical language, the parameters and their relations can be quickly and easily defined or changed, thus the modeling of parametric CAD models can be made more flexible, transparent and time-efficient.

The next step in developing the new graphical modeling language for the domain of deep drawing tools is the increase in tool complexity as well as the inclusion of the tool environment in form of initial sheet plate parameters and forming machines.

Acknowledgements

The authors thank the German Research Foundation (DFG) for the financial support of the research project “Method for the Model-Driven Design of Deep Drawing Tools” (project numbers BE 1691/164-1 and PL 706/1-1).

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