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A SPREADSHEET-DRIVEN CAD MODEL FOR CONFIGURING CULTIVATORS

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Abstract: *Parametric and chronology-based CAD system are still predominantly in use in mechanical engineering. Although this modelling principle simplifies the creation of changeable part and assembly models, there is only little scientific literature dealing with the implementation of advanced parameter control concepts. In this article, the authors discuss the externalization of the parameter control in commercial spreadsheet software as tool for product configuration. On the example of a cultivator, formal knowledge engineering, parameter planning, implementation of the parameter control and the spreadsheet-driven CAD models, and the user interface design are demonstrated.*

Key Words: ***Design Automation, Knowledge-Based Engineering, Spreadsheet-Driven Design, Computer-Aided Design, Solution Space Modelling***

1. INTRODUCTION

Parametric computer-aided design (CAD) systems are still predominantly in use in mechanical engineering. Many of them include methods and functionalities to embed engineering knowledge and design intent. Examples are mathematical and logical constraints, design rules, and reasoning up to knowledge-based CAD configuration (Poot et al., 2020; Gembarski, 2018; Amadori et al., 2012). An associated benefit with such design automation is reduction of error rate and time required for modelling tasks as well as the optimization of downstream development processes (Kuegler et al., 2023; Verhagen et al., 2012).

It is essential to establish a suitable control and rebuild concept of the model when creating knowledge-based CAD models, as they encompass multiple interlinked geometric features and domain knowledge artefacts. In this context, the capabilities enabled by parametric modelling also present challenges: Since each feature and sketch requires specific dimensions, a medium complex CAD part model can easily contain over a hundred parameters. A well-structured model setup with hierarchies of parameters is imperative as components become more complex and assemblies contain many parts. When parameters are limited, related, or used as references, they create dependency chains that should stay unidirectional (Tang et al., 2023; Li et al., 2018; Frank et al., 2014; Hoffmann & Kim, 2001).

Although parametric modelling simplifies the creation of changeable part and assembly models, there is only little scientific literature dealing with the implementation of advanced parameter control concepts.

In this article, the authors discuss the externalization of the parameter control in commercial spreadsheet software as entry in knowledge-based product modelling and design automation. On the example of a cultivator, formal knowledge engineering, parameter planning, implementation of the parameter control and the spreadsheet-driven CAD models, and the user interface design are demonstrated.

2. THEORETICAL BACKGROUND

A foundational concept for design automation and knowledge-based design is solution space modelling. The solution space is the set of all feasible variants of a product (or product-service system) which meets a set or multiple sets of requirements (Gembarski, 2020; Lindemann & Ponn, 2008).

Depending on the purpose, different models of the design solution space found their way into application. To those belong, e.g., variant trees and variant bill-of-materials, rule-based configurators and abstractions of product models which use constraint programming (Felfernig et al., 2014; Jiao et al., 2007; Pahl et al., 2007).

Parametric CAD systems have also the possibility to represent design solution spaces when the geometric model is enriched with design intent. This knowledge-based CAD combines the abilities of a full geometric representation of parts and assemblies with all attached features and properties, such as model-based definition and evaluation of tolerances and material, with the capability to reason about the design context (Ortner-Pichler & Landschützer, 2022; Hirz et al., 2013; VDI2209:2009).

Today's CAD systems provide a range of options for creating knowledge-based product models (Fig. 1). By establishing logical and mathematical constraints between parameters, it is possible to differentiate between leading and driven parameters. As a result, the designer must also carefully plan the configuration concept and parameterization of the component (Aranburu et al., 2022; Camba et al., 2016).

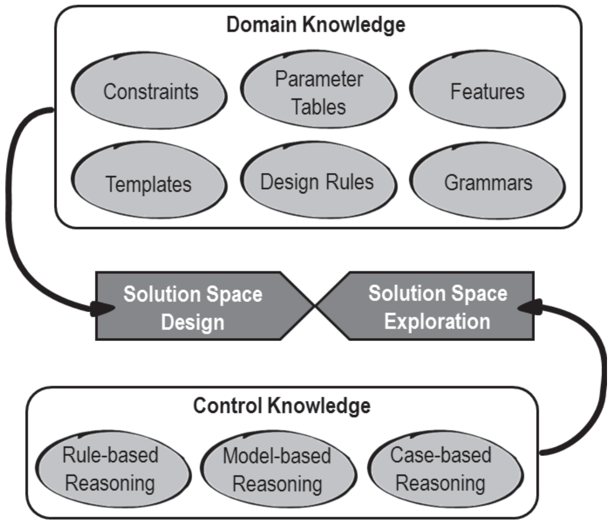

Fig. 1. *Knowledge modelling in Knowledge-based design and engineering (Gembarski, 2018)*

Users can define additional parameters for length or angular dimensions and stresses, forces, or moments of inertia. This feature allows extensive mathematical formulas to be integrated directly into the CAD model for tasks such as dimensioning and proof calculation, which streamlines the design workflow (Raffaeli & Germani, 2010).

In part families, parameter tables represent the instantiation of geometry with dimensions and other parameters in a single table row. This streamlines the data model of, e.g., machine elements and allows for easy size-switching (Gembarski, 2018).

Features describe semantic objects representing geometric elements, e.g. a drill hole, enhanced with behaviour and process data (VDI2209:2009). Templates aggregate multiple features and rigid geometry in a reusable, updatable building block in a virtual prototype. Especially geometric templates provide variable geometry and configuration parameters which then can be derived into the referencing components. Such a template can be used as a starting point for detailed design respectively. In the same manner, CAD models can be linked to skeletons that define the positioning of components and features and their geometric characteristics. (Li et al., 2018; Cox, 2000).

Additionally, many CAD systems allow the definition of design rules in the sense of if-then-else statements. These can be used to, e.g., link the suppression state of features or components to parameters (Grković et al., 2020; Myung & Han, 2001).

Grammars can be seen as graph languages that distinctly use rules. They represent geometry, either as an abstract graph or as real 2D or 3D geometry. Applying the synthesis algorithms now involves searching for specific structures in the geometry representation and replacing them with structures defined in the rule. In this manner, a vast number of design options can be established and quickly explored (McKay et al., 2012; Hoisl & Shea, 2011).

When the abovementioned methods are considered as domain knowledge to model the solution space, its exploration is based on control knowledge. Three basic concepts are rule-based, model-based and case-based reasoning. The first relies on rules as described above, the second uses an abstract or analytical model to get from requirements to product variant and the third uses a database of previously solved design problems and evaluates their similarity and thus applicability to the present one (Gembarski, 2018, Felfernig et al., 2014).

Linking domain and control knowledge can lead to externalizing parameter control of the CAD model. A straightforward and readily available method in a CAD system is to integrate a spreadsheet. This provides additional mathematical and statistical capabilities beyond the CAD system, e.g., by integrating lookup tables to efficiently select standard parts based on geometric or load information (Gembarski, 2018; Peng & Ridgway, 1993).

3. RESEARCH OBJECTIVES AND METHOD

The body of literature concerning knowledge-based design is large but only little case studies report in detail about the knowledge-bases and the implementation in CAD (Kuegler et al., 2023; Plappert et al., 2020; Verhagen et al., 2012). Focusing on parameter control, parameter trees, parameter plans, and constraint networks are positioned as planning aids to define and manage the dependencies between parameters (Tang et al., 2023; Marchenko et al., 2011; Hoffmann & Kim, 2001). Furthermore, KBE system development methodologies are applied for planning knowledge-based CAD models (Torres et al., 2010; Skarka, 2007).

Many of these concepts need external software or force the development of case-specific tools within the CAD environment. As described above, many CAD systems offer the integration or linking of spreadsheets into part and assembly models. Tools such as MS Excel are well-known to many engineers and still a standard tool for analytical calculations. The question arises of how such spreadsheet applications can contribute to parameter control in knowledge-based CAD models?

To explore this and develop a showcase following a learning-by-building approach, the subsequent modelling study of a cultivator uses the MOKA approach (Stokes, 2001) with a focus on informal modelling (sub. sect. 4.1), formal modelling (sub. sect. 4.2), and packaging (sub. sect. 4.3). The evaluation of the implemented CAD configurator is divided into three parts (sect. 5):

- Passing parameters to the CAD system: Notation, implementation, directionality, and updatability.
- Structuring parameters in the spreadsheet: Worksheet organisation, parameter constraining, and lookup.
- User Interface design: Input controls, user feedback, conditional formatting, and interactive graphical elements.

4. CASE: CULTIVATOR

A cultivator (Fig. 2) is an agricultural implement that is used for non-turning soil cultivation. The purpose of this implement is to loosen the soil, crumble it, control weeds and incorporate crop residues and fertilizer. This wide range of applications also results in a variety of design solutions for this implement. A cultivator usually consists of a frame that can be attached to the tractor using a standardized rear three-point linkage according to DIN ISO 730. The cultivator tines or sweeps and an optional trailing roller are attached to this frame. The roller is used to improve the soil structure and ensure reconsolidation of the soil after cultivation. The rear three-point linkage has four different sizes, which depend on the tractor power and differ in width, height and diameter of the fastening bolts (Abbaspour-Gilandeh et al, 2020; Fennimore et al., 2014).

Fig. 2. *Cultivator*

The shares come in a variety of geometries which depend on the respective application. Narrow tines are designed to generate a low tractive force requirement for deep loosening of the soil. Wide sweeps are designed to cut weeds across the entire working width. Another rule is that the deeper the cultivation, the less mixing of the soil should take place. The cultivator shares and their mounts must be protected against possible overloading, e.g. by large stones in the ground. The simplest option is a shear bolt, which must be replaced after the safety device has been triggered. The second variant is a spring assembly. Here, the tine is folded away against a spring, which ensures that the tine springs back into its original position. This safety device is ideal for soils with many stones (Tekeste et al., 2019; Owsiak, 1999).

4.1. Knowledge Engineering

The tractive power of a tractor is calculated from the engine power, minus the power for locomotion (incl. overcoming inclines) and the power losses. The working width of the cultivator should be designed for the selected tractor based on its available tractive power.

The tractive power is calculated according to Soucek & Pippig (1990) as follows:

$$N_Z = N_e - (N_R + N_S + N_V) \qquad (1)$$

where N_Z is the draw hook power, N_e is the effective motor power, N_r is the power for self-movement, N_s is the slip power loss and N_v is the engine power loss.

The tractive force requirement F_z and the tractive power P_z for a cultivator can be calculated as follows (Soucek & Pippig, 1990):

$$F_Z = b \cdot t \cdot (k + e \cdot v_f^2) \text{ in kN} \qquad (2)$$

$$P_Z = F_Z \cdot v \text{ in kW} \qquad (3)$$

where b is the working width, t is the working depth, k is the specific soil resistance, e is the dynamic tension constant and v is the working speed.

The specific soil resistance k depends on the soil type and the so-called soil index (Tab. 1) which is a comparative value for soil evaluation, whereby a soil with an index of 50 provides a yield of around 50 % of the yield of an ideal field with soil index 100.

Table 1. *Soil Indices*

sand	0-10
sandy clay	11-30
heavy to clay loam	31-50
clay, partly with loess layer	51-70
clay with loess layers	71-90
loess	91-100

If the soil index is expanded with additional parameters such as slope inclination and shading, the field number is obtained. However, only the soil index is relevant for the configuration of the cultivator.

The dynamic tension constant e is related to the geometry of the shares and is a comparative measure to express the resistance of the share to advance and the draft force in a reference soil (Abbaspour-Gilandeh et al, 2020; Novák et al., 2014).

The working speed should be constant for the calculation and is 7 km/h. This is in the optimum range for the function of modern cultivator shares. For cultivators with a roller, the calculated tractive power is increased by 20 %. The possible working width of the cultivator should be determined by entering the available tractor power, selecting a share and specifying the soil index. The pattern how the single tools are mounted to the cultivator follows a symmetry rule and a defined wedge-shaped distribution over the single bars to guarantee homogeneous cultivation results and minimize wear (Kalinin et al., 2019; Owsiak, 1999).

In addition, the power requirement of a cultivator tine should be used to select a sufficiently dimensioned square profile. For this purpose, the torsional moment on the profile caused by the load on the cultivator tines needs to be considered. The calculation is according to usual steel construction procedures and includes force calculation, area moment of inertia for the necessary profile dimensions, strength calculation of the bars and the weld seams (Wittel et al., 2013; Klebanov et al., 2007, Spotts et al., 2004).

4.2. Spreadsheet Design

The Excel table contains several worksheets. The first is reserved for transferring parameters to the CAD system. It usually needs to follow a certain notation of columns, in the case of Inventor this is first parameter name, then value, then unit, followed by comment. All other columns are ignored by the transfer to the CAD system and can be used for, e.g., information purposes.

The second worksheet contains a graphical user interface for the entries (Fig. 3). All fields in which the user is required to make an entry are highlighted in green. To the right of the input field, the GUI provides information or results from plausibility checks and calculations to support the user.

Since the future location of the cultivator is a decisive configuration parameter, a procedure is needed to reason from location to its soil index. Public geo-information services provide such data, in this case the Lower Saxony Soil Information System was chosen since it is available for automatic processing. A python script was built to obtain two maps, one with raster data and a second with the arable land coloured according to the soil index, based on a town name or coordinates. Both maps are then superimposed and saved as an image. In addition, the value for the soil index in the centre of the map is retrieved and saved as a text file. The numerical value and the image are then passed to the first block of the GUI worksheet. Furthermore, the user is asked to enter information about their tractor, such as the tractor's engine power in horsepower and its weight. This data is used later to calculate the maximum possible working width. The user is also shown the category of the three-point linkage on the tractor, which results according to the standard depending on the power.

The second GUI block deals with the actual configuration of the cultivator. The first step is to find out how many stones the farmer expects to find in his fields. Based on this information, the CAD model is used to select whether the shares are to be equipped with a spring-loaded stone safety device or only with a mechanical shear bolt safety device. In the next query, the farmer can use a drop-down menu to select the working depth.

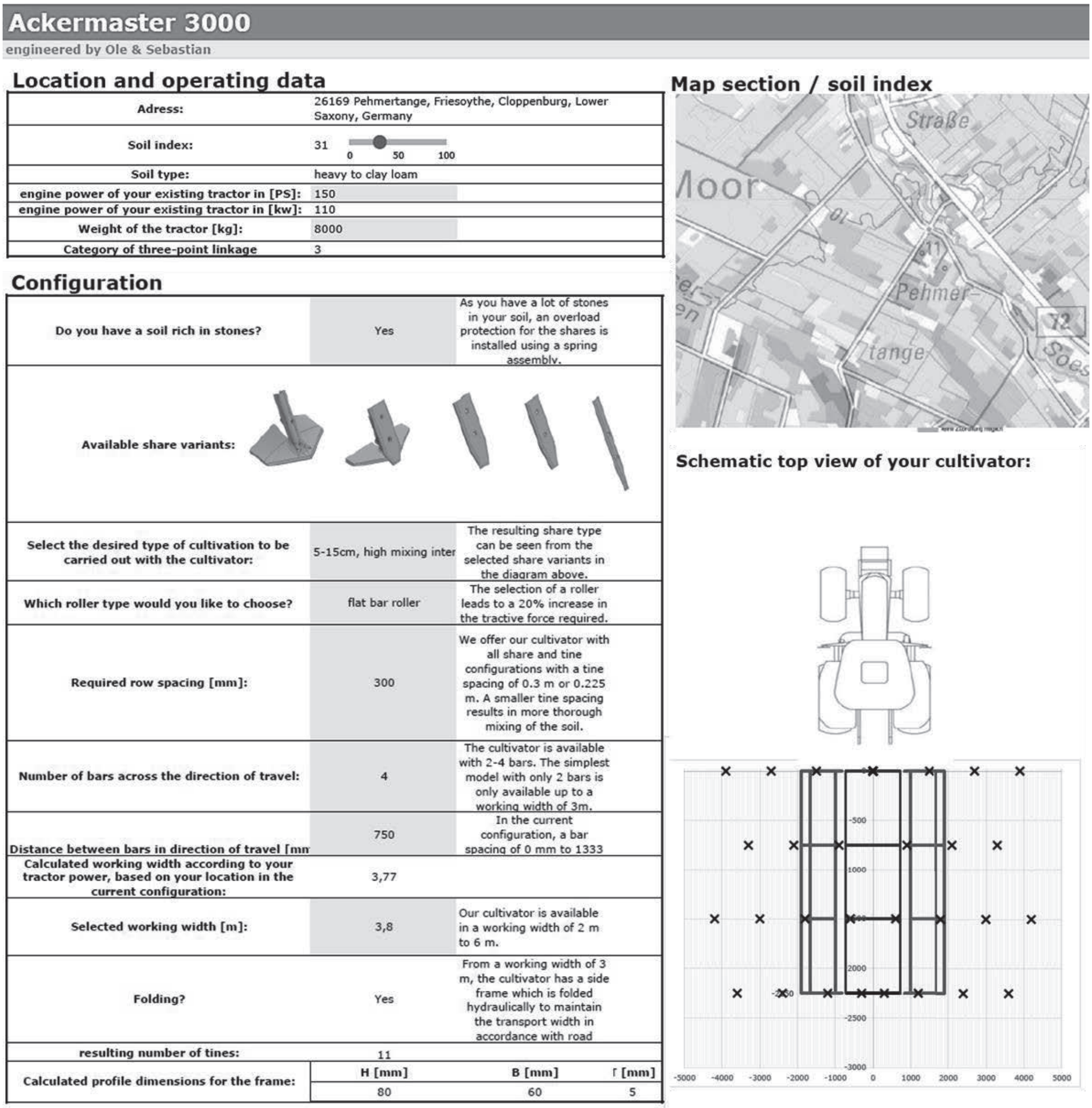

Fig. 3. *Configurator user interface*

This information is important for the tool selection and for the calculation of the tractive force and the resulting maximum working width. The user can then choose whether he wants a trailing roller to re-compact the soil but is also informed that this leads to an increased tractive force requirement. The next input is the desired line spacing, which can be 22.5 or 30 cm. The number of bars can be two, three or four. The distance between the beams can also be selected. A valid range is calculated specifically for the configuration. This is limited by the maximum length of the attachment and factors such as the choice of the tine holder and the number of bars.

Based on the previously entered power and the weight of the tractor, a tractive power for use in the field is calculated in the "Power calculation" worksheet. In addition, a tractive power requirement for a share is calculated on this worksheet by defining the desired form of cultivation. This can now be used to calculate a possible number of shares and a maximum possible working width for the selected tractor can be output by the arrangement of these defined in the "Tines" folder. In addition, a rough calculation for the dimensions of the steel construction profiles is carried out in this worksheet. It is determined how many tines sit on a profile and thus generate a bending moment. This can now be compared with a list of torsional moments of resistance and the correct profile is selected.

The calculation of the tine position is particularly important for the product configuration. These are carried out in the "Tines" worksheet. The distance between the tines is determined by the line spacing and must be adhered to. At the same time, the tines must be arranged on the various beams in such a way that they are symmetrical for the sake of simplicity and there is no overlap with components of the frame, the folding, and the roller or with the tines themselves. The arrangement must also function with different numbers of beams and also in the folded state.

The position and the number of tines required are returned. This is implemented using a dynamic reference table. As some positions would lead to overlaps due to frame or folding mechanism components, affected positions are determined manually in certain configurations. If a working width of over 3 m is selected, a folding mechanism must be provided for the cultivator to comply with traffic regulations.

The GUI also contains a diagram for the configuration preview which is also calculated in the “Tines” worksheet. The diagram realizes an adaptive overview sketch, which shows the beams, struts and tines in top view.

4.3. CAD Implementation

The configurator is linked to Inventor via a control component in the sense of a skeleton. What makes it distinctive is that it does not contain any geometry but only the embedded spreadsheet and the linked parameters. To be able to access the parameters in other components or assemblies, this control component is derived or linked in an assembly. The parameters are therefore always passed on unidirectional.

The cultivator can be divided into several main components. These are placed in the top-level assembly. These include the components of the main frame, the side frame assemblies, the roller and the tines. Additional attachments, such as the hydraulic cylinders, are also located here. The CAD model is adapted via iLogic. For many sub-assemblies, a second variant is not simply shown or hidden, but adapted and the parameters of the individual parts are changed. This reduces the number of files. The iLogic code is distributed across the different files because many assemblies and components have to be changed depending on the parameters transferred from the skeleton. The folding of the cultivator is incorporated into the CAD model as design view. This allows possible overlaps to be corrected and the dimensions to be determined in the folded state.

The main frame consists of a configurable number of beams (2 to 4), struts that run from front to rear and the mounting triangle. The cross strut of the attachment triangle always runs from the upper attachment point of the triangle to the last bar. If a working width of over 3 m is selected, and a folding mechanism must be provided. This means that the pivot points for the side frame, hydraulic cylinders and mounts for these on the main frame are also activated. Depending on the line spacing, the beams are designed with a projection in the middle so that there is space for a tine. The two side frames are mirrored and designed similarly to the main frame. They also consist of a configurable number of beams and, depending on the width, two or three struts. As with the main frame, the middle bars are designed with or without an inward projection, depending on the line spacing.

The tine assembly consists of two different versions of the holder and five different components for the shares. Different tool shapes enable different forms of processing. The mounting is designed with either a shear bolt or a spring lock. All tools are compatible with both mountings. For each tine assembly, coordinates for positioning are transferred from Excel.

The rear frame holds the roller and also adapts to the cultivator configuration. Without folding, the rear frame is just as wide as the main frame and has mounting points for two hydraulic cylinders, which can be used to adjust the roller position. If there is a folding mechanism, there are two rear frames. These are approximately half as wide as the overall working width and, like the side frames, are mirrored. They are then also attached to the side frames and fold accordingly. In this case, one hydraulic cylinder is used on the inside and one coupling rod on the outside for each side frame.

The rear frame accommodates the roller, which can be designed as a bar roller or a U-profile roller. The length or number of profiles automatically adapts to the rear frame width.

Fig. 4 shows configurations of the cultivator with different tools, working widths, roller types, and mounting assemblies.

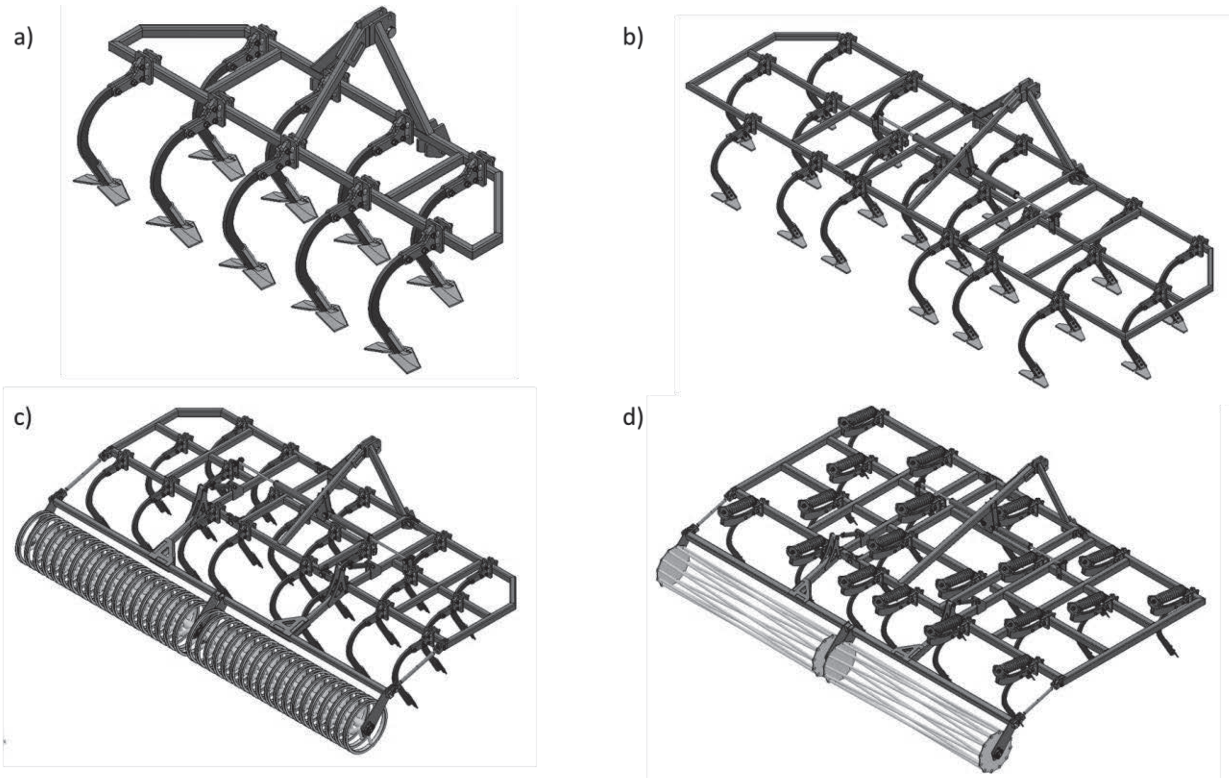

Fig. 4. *Example configurations a) Narrow cultivator with stiff wing sweeps b) Foldable cultivator with stiff sweeps c) Foldable cultivator with stiff shares and follow-up disc roller d) Foldable cultivator with spring-mounted tines and flat bar roller*

5. ASSESSMENT AND DISCUSSION

Three fields of action were defined to the assessment of the study: (1) Passing parameters to the CAD system, (2) structuring parameters in the spreadsheet, and (3) user interface design.

Concerning the first, the notation of parameters follows strictly the convention name, value, unit, and comment as described above. The spreadsheet can be integrated in two ways. Embedding includes the Excel file into the CAD model itself as a third-party component so that it is accessible only through editing the CAD file. The second way is linking which creates a relation to a distinct location in the file system. The parameters from the spreadsheet are introduced as external reference parameters in Inventor and thus write-protected. The only way to update them is through the spreadsheet itself. When new parameters are added to the spreadsheet, they are available in the CAD model after saving the spreadsheet. When parameters are deleted, they are labelled as disconnected in the parameter list of the CAD model. This has the advantage that if such a parameter is still used in equations of, e.g., dimensions, they are still consistent and can be traced. After all instances of the parameter are substituted, the parameter can be deleted manually from the list.

Regarding the structuring, the only requirement is that the parameter list for the export to the CAD system is situated on the first worksheet. From there, every location in the spreadsheet, independently from being on the same worksheet or a different one can be included in equations and relations. Parameter constraining is possible by many commands like analytical functions, decision structures, lookups, and dynamic reference tables. Especially the vertical lookup function enables the efficient integration of choosing standard parts based on, e.g., draft calculations. In such a way, simple rule-based and model-based reasoning is available. Possible extensions to case-based reasoning are imaginable since the basic setup of finding a solution in dependence on a problem statement can also be prepared as a lookup. Nonetheless, the evaluation of similarity measures is an open point. Also excluded from the study but basically interesting for creating additional functionality and reasoning is the integration of macros and the Excel internal solver, e.g., for applying linear optimization.

The user interface design has different levels. Integrating simple visual feedback for the user about incorrect entries or violated restrictions is possible using conditional formatting functions. For the dynamic output of messages a rich set of text operations is available. As input controls beside the cells themselves, different control elements are available in the development tools. In such a way, dropdown lists can be implemented that return their selection into a cell as index number which can be processed further by a vertical lookup. Another way of introducing dropdown lists without the development tools is the application of the data validation methods. To integrate visual feedback on the design, the diagram function of Excel offers plenty of possibilities. In the case study it was used to visualize the frame design and the attachment points of the share tools on it by abstracting the vertex positions to data points and let the diagram generate the lines between them. This is an acceptable solution for any design which is representable in 2D like in the study. More sophisticated approaches for visual feedback would again include macros, e.g., for exchanging pictures or picture elements as layers depending on the user inputs known from simple sales configurators. A full visualization of the 3D model in the spreadsheet in the sense of a preview seems obsolete with respect to the CAD model behind it.

The implemented knowledge-based CAD configurator successfully modelled the solution space of the cultivator. To solely rely on hand-on tools like the CAD system itself and a spreadsheet application yet could build a comprehensive and to a certain degree interactive system.

The cultivator has to be understood as a placeholder for assemblies that contain both composition and design degrees of freedom. The first means that components are exchanged with others while the second refers to variable shapes and dimensions of the components. Adequate modelling of the latter is particularly important when multiple intertwined parameters or constraints like in the case of the positioning of the shares need to be evaluated.

6. SUMMARY AND OUTLOOK

Advanced parameter control is essential for creating knowledge-based CAD models that can be easily linked to configurators. Spreadsheet-driven design is such a tool which relates analytical modelling, lookup tables, basic model-based reasoning and elementary user interface design. In the reported modelling study for the cultivator, all of these elements could be demonstrated and showcase the potential of linking simple computer-aided tools that most engineers are used to working within an engineering environment.

A detailed comparison of such a solution space model with commercial configuration software, either in-CAD or as external shell, is an obvious next step. The definition of benchmarking configuration problems would be beneficial here to compare the available functionalities and implementation effort in a structured way.

Besides the tool support, the “magic” behind the parameter control is still an abstracted model of the solution space of the respecting design artefact. In the case of the cultivator, the idea of using the address to get the soil indices makes the configuration more robust since it relies on operationalized data. Such data-based configuration is not only interesting for product-related offerings but also for new, sustainable business models which aim no longer exclusively at selling products, but rather at their optimal use and maximum efficiency (Chen et al., 2022; Wang et al., 2022; Gembarski, 2020). Thinking of the example of the cultivator further, a use-oriented product-service system could be designed with data about location, use frequency and a short-term booking system that allows to station a cultivator within a group of farms and share it across them. Product configuration would thus be enhanced with other classic problems like the facility location problem and the rostering problem. This again opens the research avenue the extend product configuration from single customer touch pints to the operation of such (smart) product-service systems.

7. REFERENCES

Abbaspour-Gilandeh, Y., Fazeli, M., Roshanianfard, A., Hernández-Hernández, J.L., Fuentes Penna, A., & Herrera-Miranda, I. (2020). Effect of different working and tool parameters on performance of several types of cultivators. *Agriculture*, 10 (5), 145. DOI: 10.3390/agriculture10050145

Amadori, K., Tarkian, M., Ölvander, J. & Krus, M. (2012) Flexible and robust CAD models for design automation. *Advanced Engineering Informatics*. 26 (2), 180-195. DOI: 10.1016/j.aei.2012.01.004

Aranburu, A., Cotillas, J., Justel, D., Contero, M., & Camba, J.D. (2022). How does the modelling strategy influence design optimization and the automatic generation of parametric geometry variations?. *Computer-Aided Design*, 151, 103364. DOI: 10.1016/j.cad.2022.103364

Camba, J. D., Contero, M., & Company, P. (2016). Parametric CAD modelling: An analysis of strategies for design reusability. *Computer-Aided Design*, 74, 18-31. DOI: 10.1016/j.cad.2016.01.003

Chen, Z., Zhou, T., Ming, X., Zhang, X., & Miao, R. (2022). Configuration optimization of service solution for smart product service system under hybrid uncertain environments. *Advanced Engineering Informatics*, 52, 101632. DOI: 10.1016/j.aei.2022.101632

Cox, J.J. (2000). “Product Templates” A Parametric Approach to Mass Customization. *CAD Tools and Algorithms for Product Design*, 3-15. DOI: 10.1007/978-3-662-04123-9_1

Fennimore, S.A., Smith, R.F., Tourte, L., LeStrange, M., & Rachuy, J.S. (2014). Evaluation and economics of a rotating cultivator in bok choy, celery, lettuce, and radicchio. *Weed Technology*, 28 (1), 176-188. DOI: 10.1614/WT-D-13-00051.1

Felfernig, A., Hotz, L., Bagley, C., & Tiihonen, J. (2014). *Knowledge-based configuration: From research to business cases*. Waltham, Morgan Kaufmann.

Frank, G., Entner, D., Prante, T., Khachatouri, V., & Schwarz, M. (2014). Towards a generic framework of engineering design automation for creating complex CAD models. *International Journal on Advances in Systems and Measurements*, 7 (1), 179-192.

Gembarski, P.C., & Lachmayer, R. (2017). Mass customization und product-service-systems: Vergleich der Unternehmenstypen und der Entwicklungs-umgebungen. In *Smart Service Engineering: Konzepte und Anwendungsszenarien für die digitale Transformation*, pp. 214-232. DOI: 10.1007/978-3-658-16262-7_10

Gembarski, P.C. (2018). *Komplexitätsmanagement mittels wissensbasiertem CAD: Ein Ansatz zum unternehmenstypologischen Management konstruktiver Lösungsräume.* Garbsen, TEWISS.

Gembarski, P.C. (2020). The meaning of solution space modelling and knowledge-based product configurators for smart service systems. In: Świątek, J., Borzemski, L., Wilimowska, Z. (eds) Information Systems Architecture and Technology: Proceedings of 40th Anniversary International Conference on Information Systems Architecture and Technology – ISAT 2019. Advances in Intelligent Systems and Computing, vol 1051. Springer, Cham. DOI: 10.1007/978-3-030-30440-9_4

Grković, V., Kolarevic, M., Petrović, A., & Bjelić, M. (2020). CAD configurator for automatic configuration of modular strongrooms. In *Proceedings of the 9th International Conference on Mass Customization and Personalization-Community of Europe (MCE-CE 2020)*, University of Novi Sad-Faculty of Technical Sciences: Novi Sad, Serbia, pp. 85–92.

Hirz, M., Dietrich, W., Gfrerrer, A., & Lang, J. (2013). *Integrated computer-aided design in automotive development*. Berlin, Heidelberg, Springer. DOI: 10.1007/978-3-642-11940-8

Hoffmann, C.M., & Kim, K.J. (2001). Towards valid parametric CAD models. *Computer-Aided Design*, 33 (1), 81-90. DOI: 10.1016/S0010-4485(00)00073-7

Hoisl, F., & Shea, K. (2011). An interactive, visual approach to developing and applying parametric three-dimensional spatial grammars. *AI EDAM*, 25 (4), 333-356. DOI: 10.1017/S0890060411000205

Jiao, J., Simpson, T. W., & Siddique, Z. (2007). Product family design and platform-based product development: a state-of-the-art review. *Journal of intelligent Manufacturing*, 18, 5-29. DOI: 10.1007/s10845-007-0003-2

Kalinin, A. B., Teplinsky, I. Z., Ustroev, A. A., & Kudryavtsev, P. P. (2019). Selection and substantiation of cultivator adjustment parameters for differential soil treatment on potato based on the rheology state of soil horizons. In *IOP Conference Series: Materials Science and Engineering (Vol. 516, No. 1, p. 012025)*. IOP Publishing. DOI: 10.1088/1757-899X/516/1/012025

Klebanov, B. M., Barlam, D. M., & Nystrom, F. E. (2007). *Machine elements: life and design*. CRC Press.

Kuegler, P., Dworschak, F., Schleich, B., & Wartzack, S. (2023). The evolution of knowledge-based engineering from a design research perspective: Literature review 2012–2021. *Advanced Engineering Informatics*. 55, 101892. DOI: 10.1016/j.aei.2023.101892

Li, H., Gembarski, P.C., & Lachmayer, R. (2018). Template-based design for design co-creation. In *Proceedings of the fifth international conference on design creativity (ICDC 2018)*, University of Bath, Bath, UK, pp. 387-394.

Lindemann, U., & Ponn, J. (2008). *Konzeptentwicklung und Gestaltung technischer Produkte*. Heidelberg: Springer. DOI: 10.1007/978-3-642-20580-4

Marchenko, M., Behrens, B.A., Wrobel, G., Scheffler, R., & Pleßow, M. (2011). A new method of visualization and documentation of parametric information of 3D CAD models. *Computer-Aided Design and Applications*, 8(3), 435-448. DOI: 10.3722/cadaps.2011.435-448

McKay, A., Chase, S., Shea, K., & Chau, H. H. (2012). Spatial grammar implementation: From theory to useable software. *AI EDAM*, 26 (2), 143-159. DOI: 10.1017/S0890060412000042

Myung, S., & Han, S. (2001). Knowledge-based parametric design of mechanical products based on configuration design method. *Expert Systems with applications*, 21 (2), 99-107. DOI: 10.1016/S0957-4174(01)00030-6

Novák, P., Chyba, J., Kumhála, F., & Procházka, P. (2014). Measurement of stubble cultivator draught force under different soil conditions. *Agronomy Research* 12 (1), 135–142.

Ortner-Pichler, A., & Landschützer, C. (2022). Integration of parametric modelling in web-based knowledge-based engineering applications. *Advanced Engineering Informatics*, 51, 101492. DOI: 10.1016/j.aei.2021.101492

Owsiak, Z. (1999). Wear of spring tine cultivator points in sandy loam and light clay soils in southern Poland. *Soil and Tillage Research*, 50 (3-4), 333-340. DOI: 10.1016/S0167-1987(99)00019-7

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. H. (2007). *Engineering design: a systematic approach*. London: Springer.

Peng, C., & Ridgway, K. (1993). Integration of CAD/CAM and spreadsheet data processing. *Integrated Manufacturing Systems*, 4 (4), 29-36. DOI: 10.1108/09576069310044646

Plappert, S., Gembarski, P.C., Lachmayer, R. (2020). The Use of Knowledge-Based Engineering Systems and Artificial Intelligence in Product Development: A Snapshot. In: Świątek, J., Borzemski, L., Wilimowska, Z. (eds) Information Systems Architecture and Technology: Proceedings of 40th Anniversary International Conference on Information Systems Architecture and Technology – ISAT 2019. Advances in Intelligent Systems and Computing, vol 1051. Springer, Cham. DOI: 10.1007/978-3-030-30604-5_6

Poot, L.P., Wehlin, C., Tarkian, M., & Ölvander, J. (2020). Integrating sales and design: applying CAD configurators in the product development process. In: *Proceedings of the Design Society: DESIGN Conference*. 1, 345-354. DOI: 10.1017/dsd.2020.129

Raffaeli, R., & Germani, M. (2010). Knowledge-based approach to flexible part design. *Journal of Engineering Design*, 21 (1), 7-29. DOI: 10.1080/09544820802086996

Skarka, W. (2007). Application of MOKA methodology in generative model creation using CATIA. *Engineering Applications of Artificial Intelligence*, 20 (5), 677-690. DOI: 10.1016/j.engappai.2006.11.019

Soucek, R., & Pippig, G. (1990) *Maschinen und Geräte für Bodenbearbeitung, Düngung und Aussaat*. Berlin, Verlag Technik.

Spotts, M. F., Shoup, T. E., Hornberger, L. E., & Kazmer, D. O. (2004). *Design of machine elements*. Lonon, Pearson.

Stokes, M. (2001). *Managing engineering knowledge: MOKA: methodology for knowledge based engineering applications*. London, Professional Engineering Publishing.

Tang, Z., Zou, Q., & Gao, S. (2023). A decision-support method for multi-parameter editing of parametric CAD models. *Advanced Engineering Informatics*, 56, 101997. DOI: 10.1016/j.aei.2023.101997

Tekeste, M. Z., Balvanz, L. R., Hatfield, J. L., & Ghorbani, S. (2019). Discrete element modeling of cultivator sweep-to-soil interaction: Worn and hardened edges effects on soil-tool forces and soil flow. *Journal of terramechanics*, 82, 1-11. DOI: 10.1016/j.jterra.2018.11.001

Torres, V. H., Ríos, J., Vizán, A., & Pérez, J. M. (2010). Integration of design tools and knowledge capture into a CAD system: a case study. *Concurrent Engineering*, 18 (4), 311-324. DOI: 10.1177/1063293X10389788

Verein Deutscher Ingenieure. (2009) VDI 2209:2009. *3D product modelling - Technical and organizational requirements - Procedures, tools, and applications - Cost-effective practical use.* Berlin, Beuth.

Verhagen, W.J., Bermell-Garcia, P., Van Dijk, R.E., & Curran, R. (2012). A critical review of Knowledge-Based Engineering: An identification of research challenges. *Advanced Engineering Informatics*, 26 (1), 5-15. DOI: 10.1016/j.aei.2011.06.004

Wang, Z., Chen, C. H., Zheng, P., Li, X., & Song, W. (2022). A hypergraph-based approach for context-aware smart product-service system configuration. *Computers & Industrial Engineering*, 163, 107816. DOI: 10.1016/j.cie.2021.107816

Wittel, H., Jannasch, D., Voßiek, J., & Spura, C. (2013). *Roloff/Matek Maschinenelemente*. Wiesbaden: Springer Vieweg. DOI: 10.1007/978-3-658-02327-0

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