The reconfiguration of tool parameters in clay extruder

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Reconfigurable manufacturing systems (RMS), which have emerged with mass customization in the industry, allow the tool or system parameters to be adjusted in a controlled manner to produce customized products. Although the reconfigurable manufacturing systems have been applied in building and construction for waste, time, and cost reduction in producing specific mold forms at a prototype level, their utilization in additive manufacturing (extrusion) has not been explored. This paper presents, initial steps of ongoing research on the development of reconfigurable tools and workflow by transforming the tool's rigid parts with controlled parametric movable parts. The clay extruder tool used in crafts is transformed into a reconfigurable extruder tool that allows making customized forms. In the experimental setup, die combinations and tool head rotations are examined with the proposed Extrusion-based Making Grammar (EbMG). Produced forms illustrate the variations of the design space in relation to the rule sets. Here, a rule-based approach is found to be efficient for controlling the making parameters. This study explored the potentials of transforming a rigid craft tool into a customizable tool that allow the generation of product variation. It presents the preliminary stage of transforming craft tools into further digital craft tools.

Keywords: *Hands-on making, craft, reconfigurable tools, extrusion, tool making*

1 INTRODUCTION

Customization strategies have already been integrated into the architecture, engineering, and construction (AEC) industry in terms of housing (Matsumura et al. 2019), urban spaces (Verebes 2015), and building components (Tu and Wei 2013). It has recently expanded to the area of the design and development of on-demand or bespoke tools which produce a specific family of products by implementing the strategies of flexible and reconfigurable manufacturing systems (FMS and RMS). These systems are employed to respond to the user demands in terms of product variation in the industry. The reconfigurable manufacturing systems have been applied in building and construction for waste, time, and cost reduction in producing specific mold forms (Khabazi and Budig 2016; Raun and Kirkegaard 2015) at a prototype level. However, their utilization in additive manufacturing i.e., extrusion has not been explored. Yet, the integration of customization strategies into craft practices in terms of tool development is overlooked. The customization of craft tools is a promising area of research that enables in-situ fabrication by transforming manual rigid tools into reconfigurable mechanisms.

This study aims to parameterize the craft tool use to control the making process and produce customized designs. As a case study, a manual clay extruder is analyzed to determine the part-function relations and control the variation in outputs using Extrusion-based Making Grammar (EbMG). We utilized experimentation and a rule-based method to discover and define the parameters of the die-tool head component as the first phase of this study. The outputs produced with combinations of tool parts and functions extend the defined solution space of the rigid tool.

2 BACKGROUND

The idea of mass customization is to provide an increased variability with the flexible and reconfigurable manufacturing systems (FMS and RMS) at an affordable cost unlike crafts (Piller 2013). The RMS can respond promptly to the changes in the market, but in a defined design space (Bortolini, Galizia, and Mora 2018). The FMS can adapt to any changes in the production workflow in the long run, because of the use of digital fabrication tools such as CNC, robotic arm, and 3D printers. Digital fabrication tools offer a certain degree of flexibility in terms of variation. However, the FMS has a higher investment cost compared to the RMS, which uses the combinatorial logic of assembly (Koren 2006). Moreover, digital fabrication tools have limitations such as file-to-factory production, single tool operation, limited bed size, limited manipulation of tool parameters and parts (Koren 2006; Oxman 2007; Peek and Moyer 2017). Having been low-cost and easy-to-operate, reconfigurable tooling strategies can be employed to transform craft tools. It enables the manufacturing of a family of products rather than one-off and unique products with available tools and techniques (Oral and Colakoglu 2020). By using changing or moving parts with manual, machine or robot control, reconfigurable tools allow experimentation with the material, resulting in novel production workflows (Asut, Eigenraam, and Christidi 2018; Raun and Kirkegaard 2015; Tessmann and Mehdizadeh 2019).

In the literature, the customization of tools mainly relies on the moveable mechanisms which enable the variation of building components. These mechanisms are designed by parameterization and reconfiguration of existing tool parts and functions (Oral and Colakoglu 2020). Pin-based tooling, parts-based molds, polymer, and fabric-formed molds are developed to reduce lead-time, cost, and waste in producing differentiated units out of one mechanism. In pin-based molds, double-curved surface geometry is controlled via pins moving on Z-axis (Kelkar, Nagi, and Koc 2005; Schipper et al. 2014). Parts-based molds consist of moveable planar parts to change the size or form of the components (Khabazi and Budig 2016; Shaffer 2017). The variation can also be produced by flexible materials like elastic fabrics and polymers controlled by moveable mechanical parts (Khan 2008; Tessmann and Mehdizadeh 2019). Changes in the orientation of tool parts directly affect the overall size and form in a defined solution space.

In crafts, every product needs individualized production as a result of lacking control defined as “the risk in making” (Pye 1968). Craft practices mainly rely on tacit knowledge gained through hands-on making with material and the tool. The function of the tool is derived from the affordances of its parts and the expertise of the craftsman. Considering the hidden knowledge in crafts, it is important to parametrize the making process. The rule-based approach is a widely used method to decipher existing designs (Duarte 2005; Colakoğlu 2005) and recently the fabrication processes (MacLachlan and Jowers 2016). Formalizing the manual-making processes can enhance creativity through shape computations (Knight 2018), resulting in the emergence of outputs. Tool reconfigurations leading to emergent use of the tool can be explored with a grammar based on combinations of tool subparts and functions rather than shape computation. A making grammar can be generated by focusing on not the outputs, but on the process of forming the material with the tool. A manual tool can be parametrized to be controlled and reconfigured to generate variation as in the parametric model. Especially for non-expert designers and multi-operators, visually described rules can create a medium to formalize the making process and facilitate the execution of the grammar.

3 METHODOLOGY

The methodology of this paper consists of the experimental method to decipher the use of the craft tool and the rule-based method to explicitly define the tool use. In the first stage, a set of experiments are conducted with the die-tool head component to explore the reconfiguration scenarios hidden in tool use. Die combinations, tool head rotation, and die change operations, which are embedded in tool affordances. are discovered in this phase. The Extrusion-based Making Grammar (EbMG) is generated by adding the discovered functions to the rigid tool ruleset. In this study, die combinations and tool head rotations are examined and variable forms are physically produced with the tool and playdough material. The outputs of this study are the novel use of the craft tool with the reconfiguration of tool parameters unveiled through hands-on experimentation and variable extruded units with differentiated surface patterns. The physical outputs are discussed regarding the effect of die shapes and rule combinations on the surface and the boundary of extruded forms.

The following questions will be examined in this study.

RQ1: Which parameters of extrusion as a hands-on making process can be identified in the context of reconfigurable tools?

RQ2: How the parameters can accommodate product variation from the reconfiguration of the tool head and die parts?

RQ1 will be explored by conducting experiments to discover moveable, changeable, and combinable parts of the manual extruder. RQ2 will be discussed through the physical outputs produced with the Extrusion-based Making Grammar.

4 RECONFIGURING THE PARAMETERS OF THE EXTRUSION

4.1 Parameterizing the Making Process

The manual clay extruder is chosen as a craft tool to be examined. It is used in workshops to produce coils out of soft materials such as clay, polymer clay, and playdough. It is selected for its adaptability to 1:1 scale being able to produce extruded building units and components. The sub-parts of the extruder are the tool head holding the polygonal metal dies, the pressing disk controlled by the rotation of the screw, handle, and the tube for the material (Figure 1).

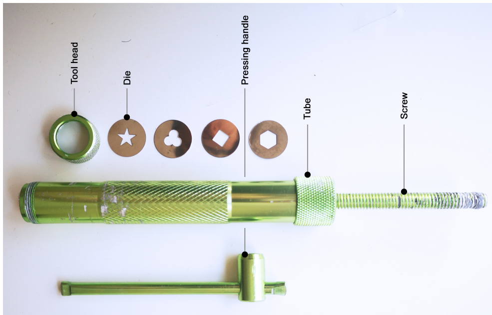


Figure 1
The sub-parts of the craft tool.

In the conventional use of the tool, first, the soft material is put in the tube and the die is placed into the tool head. When the handle is rotated, the disk pushes the clay down through the die to make the material dislodged. The output is a straight extrusion that is built layer by layer. It is cut to the defined length by a wire.

The Extrusion-based Making Grammar (EbMG) consists of pre-press, press, and post-press operations, which are represented as a visual grammar to be applied easily (Figure 2). In the pre-press, the die is placed, combined with other dies, or omitted from the tool head (1a,2a, and 2b). In the extrusion phase,

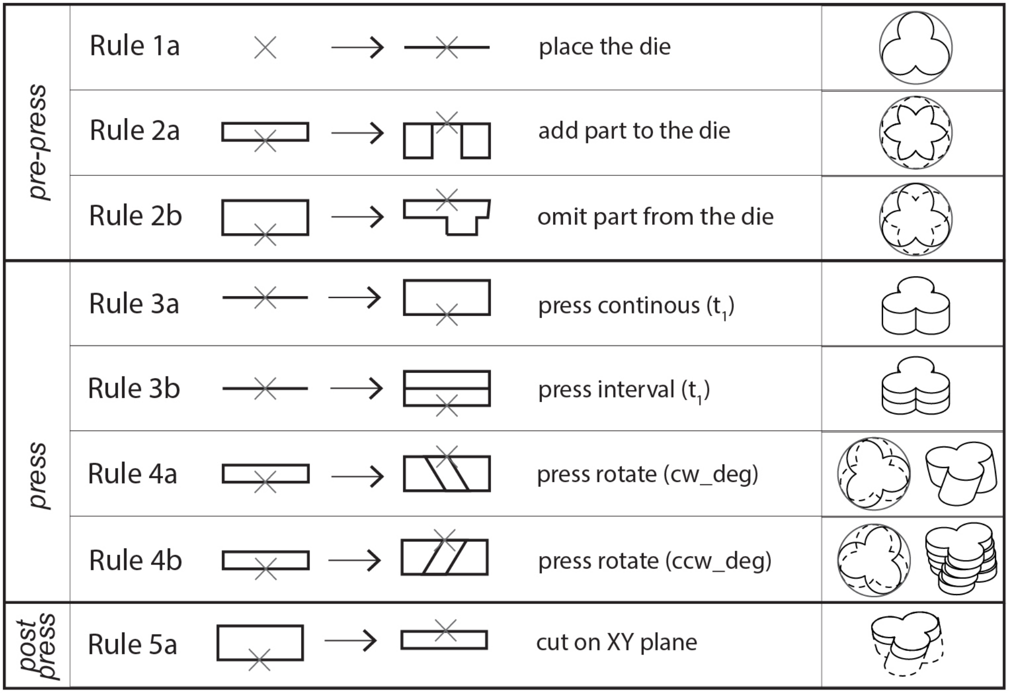


Figure 2
Extrusion-based making grammar (EbMG).

two types of pressing are shown with continuous and stepped surface qualities. The single rotation of the screw determines the extruded layer height represented with t1 (3a and 3b). The tool head rotating in CW and CCW directions and variable angles can be combined with continuous and interval pressing. The post-press operations are limited to separating the extruded form from the material by cutting (5a).

In the ruleset application, two operators are needed for controlling the rotation of the screw and tool head synchronously, especially in combined operations. Thus, the grammar guides both the experimental process and the operators who apply the ruleset, resulting in a controlled making process even with hands.

4.2 The Experimental Setup

As a first phase of analyzing the part-function relation, several experiments are conducted with the die-tool head component. In the experimental setup, the tool is operated manually, and playdough is used as a material. Dies found in the toolset are concave and convex polygons cut from thin metal plates. A concave chamfered pentagon is 3D printed and added to the existing toolset to explore the die customization. The pitch of the screw defines the height of the extruded layer in one revolution of the screw. The extruded forms are generated with 4 revolutions of the screw.

In the preliminary experiments, it is discovered that the rigid die-tool head component can be reconfigured in terms of die combinations, tool head rotation, and die change (Figure 3), which are not available in conventional tool use. While die combinations generate emergent surface patterns on extruded forms, tool head rotation forms twist extrusions. Die change during the extrusion process creates tapered extrusions. Due to the small effect of die change operations on this scale, it is out of the scope of this paper.

Figure 3
The die-tool head component reconfigurations.

In the experiments, tool head and die parts were examined in terms of moveable, changeable, and combinable features to create variation by reconfiguring tool parts. In the first experiment, selected concave and convex dies are combined in specific orientations and stuck to the tool head with clay. In the second experiment, the nuts-like tool head is utilized for rotating the dies during the extrusion.

4.2.1 Experiment 1: The Die Combinations. Following the extracting and discovering of the die-tool head component parameters and functions in the first experiment, a set of forms is produced by reconfiguring dies in a controlled way (Figure 4). By using rectangular and three-circle dies, the straight extrusion is obtained and cut with the wire in defined length (1a and 2a). Then, selected convex and concave dies are superimposed in different angles to examine the effect on extruded forms. The combination of the star polygon with the circular polygon generates again star shape extrusions with chamfered edges due to the similar die gap (3a). The combination of the hexagon and chamfered pentagon creates grooves only at the side of the form due to the die shift during extrusion as an emergent behavior (4a). The three-circle and star-shaped dies form again modified star extrusions with linear grooves (5a). Circular and half-circular dies are useful for scaling down the extruded forms by reducing the size of the die gap (7a and 9a). The combination of identical dies also creates variation by superimposing them in different angles (6a, 8a, and 10a). Two star-shaped dies are combined in 50 and 18 degrees of relative orientation forming a decagram (6a and 8a). The extruded forms of these combinations have variable lengths of corners.

The placement of the dies in relation to each other is visually shown in the EbMG to be able to repeat the process. The non-symmetric dies create curved extrusions by bending the output (9a). The longer the extrusion, the more the bending occurs, which can be corrected by hand during the process. The sharp-edged polygons like stars tend to have deformations on edges compared to chamfered polygons such as the three-circle die. The variation of outputs is increased with the number of die combinations.

4.2.2 Experiment 2: The Tool Head Rotation. The second experiment focuses on die rotation to discover the potentials of the die-tool head component. The rectangular and three-circle dies are used by utilizing the rotational ability of the tool head shown in Figure 5. Following the straight extrusions, twist extrusions with different surface properties are produced by manipulating the pressing, rotation angles, and die combination parameters. By sticking the material to the pressing disk, a continuous extruded form is obtained without the need for rotating the tool head (3a). Due to the changes in pressure applied to the material, the sections of the extruded form oscillate between larger to smaller. The rotation of the tool head can also generate this form by fixing the die to the tool head (5a). The frequency of twisted edges is lowered in this sample compared to Figure 5.3a. The variable rotation angles can be used also in the same extrusion process (7a and 8a). The synchronization between rotation and press creates twist extrusions (5a and 6a). When the press and rotation operations are applied consecutively, multi-step extrusions are produced with sliced appearance due to the displacement of the die deforming the surface (4a

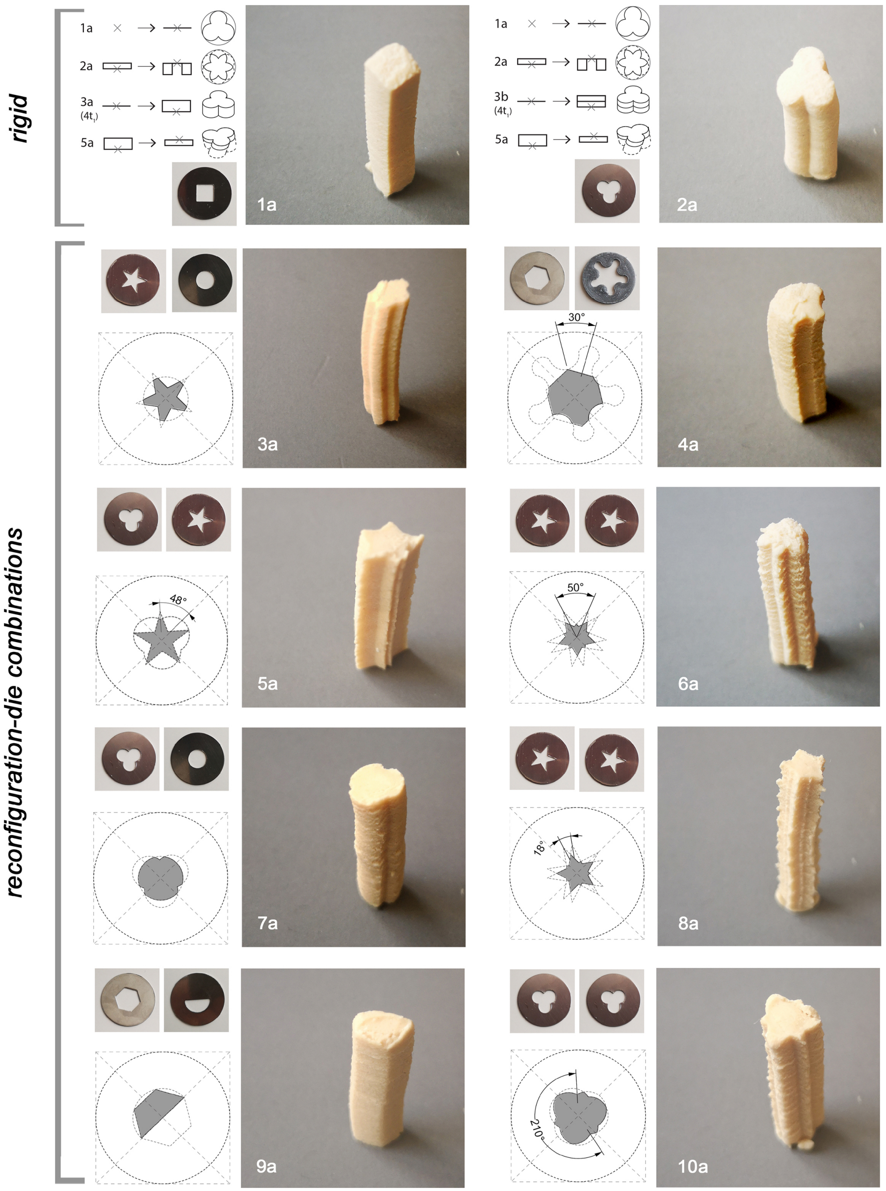
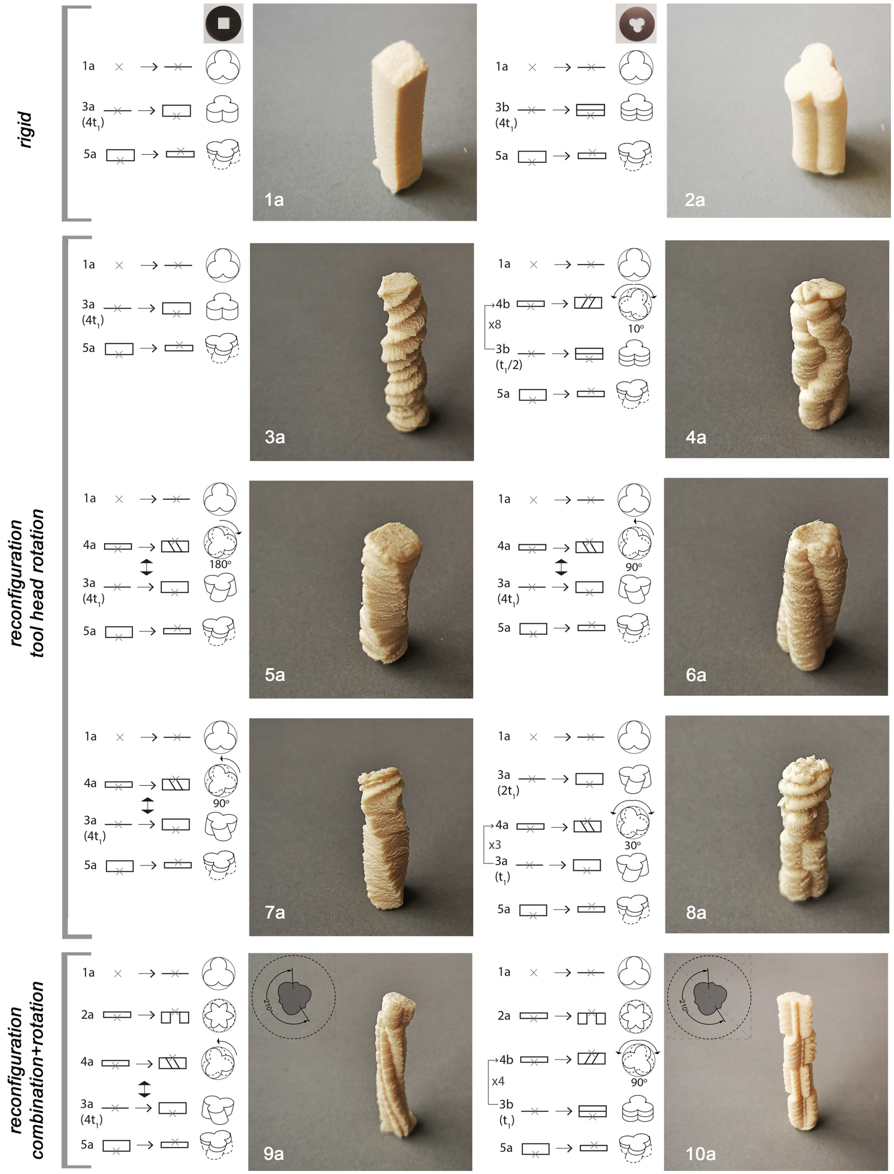


Figure 4
The product
variation obtained
by die
combinations.

Figure 5
The product variation obtained by the rotation of the single and combined dies.



and 8a). The combination and rotation of dies also generate variation both in the section and the surface. As shown in Figure 5.9a, continuous press with 360 degrees of tool head rotation introduces variable grooves on the surface. The multi-step extrusion with equal press duration creates equally distributed partitioning on the form (10a).

The tool use is visually represented to coordinate synchronous operations during the making. Interval extrusion operation with rotation is represented by extruded form with horizontal lines, while continuous extrusion operation with rotation by extruded form with no lines. Degrees shows the approximate angles of rotation due to manual making. The special condition as emergent behavior in which material is stuck to the pressing disk is shown in Figure 5.3a. The rules and their combinations can be increased by using different polygonal dies and rotation-press sequences.

5 RESULTS AND DISCUSSION

The produced forms are straight, twist, and multi-step extrusions with variable surface patterns. These forms can be modeled by lofting the series of orthogonal sections with bending deformations. Considering the dimensions of the hand-held tool, the produced forms can be used in the early design and prototyping phase to experiment and define the tolerances of extrusion in terms of material properties, die shape and dimensions, haptic feedback, and pressing force.

The findings of the experiments are related to the effect of die shapes and combinations on surfaces and the boundary of extruded forms. The layer height is calculated as 3 mm in square die and 2,22 mm in there-circle die related to the die gap area. A larger die gap area results in smaller extruded material. To achieve the same height in different dies, the number of screw revolutions should be increased. Surface deformations are high in extrusions with concave polygons compared to convex ones due to the sharp edges. Circular and half-circular dies are useful in reducing the width of the components. However, the extruded form is bent in the non-symmetrical polygons such as half-circle bend due to the unequal pressing applied to the material. The bending also increases when the number of operations and height of the extruded forms rise. The rotation of the tool head and different angular superimposition of the concave polygons creates variable grooves on surfaces. These grooves are effective in enlarging the surface area and creating visually appealing patterns.

Considering the intricate surface details of the outputs, problems are encountered in the production of these surfaces with rigid or reconfigurable molds. Two or more mold parts with smaller surface protrusions are required to produce such detailed surface elements in CNC molding with high cost and waste. When liquid material is poured into the mold, the material can be stuck in small protrusions. In reconfigurable molding, part-based or flexible material molds must be used to produce 3-dimensional forms rather than pin-based tooling. In the literature, part-based molds produce different sizes of the same unit, whereas, in polymer and fabric-formed molds, intricate surfaces with certain precision are difficult to produce since the fabric behavior is inconsistent.

The extruder has the same advantages of additive manufacturing technique as low waste and producing complex surface details. In addition, the extruder has a 2-dimensional die cost, which is very low compared to the multi-part and complex molds used in rigid and reconfigurable molding. In addition, diversity can be increased with modifiable die designs and combinations. Although the forms are directly produced with the reconfigurable extruder in this study, the extruder with a circular die can be utilized to extrude coils of discrete tool paths as in the 3D clay printer. The robotic arm, which is one of the digital fabrication tools, can perform customized production workflows through different end effectors. The reconfigurable extruder can be integrated into robotic production as in clay printing, but this time the nozzle is changeable and combinable owing to the dies. New 3D printed pentagonal die can generate interlocking units with protruding parts fitting to each unit by eliminating additional joints.

6 CONCLUSION

This study aimed to decode the parameters of a craft tool use to control and reconfigure the tool parts for producing customized units as initial steps of the ongoing research. A manual clay extruder was examined to define part-function relations that can be changeable, moveable, or combinable by following the reconfiguration methods in the industry. The methodology based on experimentation and a rule-based approach is found to be effective to parametrize the intuitive making process to further control the workflow. The novel part-function relations are discovered which is not included in the conventional use of the rigid tool such as die combinations, tool head rotation, and die change. Variable dies and part-function combinations are examined by benefitting the combinatorial logic in terms of reconfigurable tooling.

The series of experiments shows the product variation generated by the minimum number of the dies. The use of a 3D printed die as an extension of the toolset shows the CAD/CAM tools can also be convenient to enhance available tools to generate new forms. The diversity is achieved in terms of surface variations compared to the rigid tool as a result of the numerical explorations with the material. The resulting die shapes and operations are represented visually for the use of non-expert designers and multi-operator applying the ruleset. The limitation of this study is related to the experimental setup. Playdough is used as a material in the experiments in which clay, polymer, and air-drying clay can be examined further.

Future studies will be focused on:

- Controlling the tool with motors to improve the accuracy and precision in produced components.
- Developing an interface to control and simulate the tool use.
- Using different materials in experiments to evaluate the effect on the forms.

Unveiling tool parameters and define them explicitly enables the design and development of novel tools and procedures derived from available tools, materials, and techniques. Furthermore, for each rigid affordance of tool parts, variable affordances emerge from experimenting with them. Parameterizing and controlling the manual tools enable producing diversity in components. Using manual tools as an input for developing customized tools provides a gradual improvement in craft practices as a result of integrating computational thinking into making processes.

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