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The Digital Tool Development by Formalizing the Making with Manual Clay Extruder

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Abstract. This paper aims to illuminate ways in which digital tools can be used to translate tacit knowledge to further analyze and evaluate the hands-on making processes with craft tools. The research methodology reviews and analyses the making grammar studies and digital tools developed by makers to suggest a procedure for parametrization and digitalization of craft processes. As a case study, the extrusion process conducted with a manual clay extruder (MCE) is examined and a parametric model derived from physical making is generated in Rhinoceros Grasshopper environment. The correlation between the physical and digital medium is measured with photogrammetry and written scripts by comparing produced forms. The developed parametric model is found to be useful in enhancing the maker's knowledge through correlating the parameters of making and evaluating the process as an extension of the maker's toolset. The parametric model can be further used to fabricate the digitalized versions of hand-made artifacts with digital fabrication tools and communicate the making knowledge through virtual guilds.

Keywords: rule-based design, clay extruder, digital tools, Grasshopper, maker culture, grammars
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1 INTRODUCTION

Recent studies on co-design environments, open-source design, and maker culture have made the designers revisit the very intuitive and personal making processes in crafts [24, 28, 30]. To be able to benefit the potential of crafts, hybrid ways of making have been suggested for the designer-makers who are not solely working with computers but also are keen on the material processes of artifacts [5, 47]. Moreover, digital interfaces and models support the maker to explore the solution space and manipulate the variables of designs through decoding the tacit knowledge of making [22, 28]. This digitalization process of crafts results in the generation and distribution of collective knowledge throughout digital communities named virtual guilds [6, 17]. Making craft knowledge open-source, unlike the traditional craft practices enables the knowledge transfer between communities by preventing the craft itself from being diminished [6].

It is an open discussion on what kind of knowledge can be generated by translating a physical making process into the digital medium as a way of extending the knowledge of the maker with the capacity of digital tools. In that regard, the tacit knowledge generated through making should be explicitly defined by parametrization. Parametrization is defined as translating the design and making conditions into variables and functions affecting the output rather than directly modelling the output itself. Thus, the whole process can be explored and manipulated by receiving direct feedback from the model. Several studies are conducted to explicitly define the hands-on making [16, 19, 46], and fabrication processes [26, 36] and to generate making grammars as translations of the maker's actions. However, the studies on formalizing making processes through grammar focused on precisely controlling the process rather than suggesting ways to parameterize and translate the performance of making to the digital medium. While the increased number of craftsmen and makers have integrated digital tools into their making processes [9, 18, 24] as well as clay processes [4, 34, 39], the studies focused on the parametric model development for making with craft tools are quite limited.

This paper aims to illuminate ways in which digital tools can be used to translate tacit knowledge into parameters and rules to further analyze and evaluate hands-on making processes in the digital medium. As a case study of the procedure, the extrusion process with a manual hand-held clay extruder (MCE) is examined and a parametric model of the process is generated in Rhinoceros Grasshopper. The correlation between the physical and digital medium is measured by translating the physical outputs into the digital medium by using the photogrammetry method and comparing them with their simulations regarding the parameters of the extrusion time, the dies, and forming rulesets. The significance of this study is to offer a parametrization and digitalization approach for making processes with craft tools as performances rather than the parametrization of the sole geometries. The developed parametric model was found to be useful in enhancing the maker's knowledge through correlating the parameters of making and evaluating the process as an extension of the maker's toolset.

2 STATE-OF-THE-ART: DIGITALIZING THE MAKING WITH MANUAL TOOLS

In craft practice, defined mechanical actions are iteratively applied to recreate the object [28]. Skill that is learnt-by-doing [1, 28] is the most prominent aspect of the craft in which material, tool, and technique are improvised through trial and error. The craft ethos benefiting from the personal experience of the one-self is extensively adopted by maker and crafter movements as a part of the do-it-yourself culture [15]. More emphasis is put on the making as a way of generating new knowledge through interaction with the material and tool. A new actor named designer-maker has emerged who is keener on the materials, processes, and life-cycle itself rather than solely being in the digital medium [25].

With the pervasion of the virtual guilds and co-design platforms, the articulation of the intuitive making processes becomes important as a way of communicating the tacit knowledge. To ensure the communication between mediums and makers, the making process should be carried out with certain rules for the object to be measurable, and thus, it can be simulated in the digital medium. Parameterization of the performance conducted with either hands or tools is the prominent aspect of the digitalization of crafts. In this way, the knowledge of making, which is analogous to the maker, can be articulated and shared by embracing the digital in crafts [7]. In this hybrid ground, craftsmen, makers, and researcher-practitioners have integrated digital tools into their making processes such as glass casting [18], woodblock printmaking [9], clay printing [34, 39], and slip-casting [29]. New tools have also been developed by non-expert makers with the use of digital tools supporting the physical making processes [18, 28, 33]. The digitalized artifacts were produced with digital fabrication tools owing to the digitalization of the tacit knowledge produced through making with hands and tools [30]. Integrating digital tools into crafts supports creative thinking by stimulation, communication, and manipulation of visual concepts [45]. The designer can now modify and adapt the digital tool in the same way that tools are manipulated in craft practices thanks to open-source coding and software [24]. Based on these studies, it is obvious that digital tools such as parametric models and simulations can enhance the maker's skillset as an extension of hands and tools by probing the object in making.

The first question arises of how we can transfer a very intuitive making process into the digital medium. The rule-based methods such as shape and making grammar are widely used methods to formalize the designs and processes. With these methods, existing designs and processes can be encoded [10, 43] and new styles can be generated through a rule set derived from existing designs [12, 23, 41]. While designing with shape grammars is defined as "doing and seeing", designing with making grammars is described as "doing and sensing" by which things are produced as a result of craft performances of hands or machines [19, 21]. The studies of making grammar have focused on the materialization of the designs through a set of instructions [42]. Following this argument, several hands-on making processes have been formalized to explicitly manipulate the material and discover emergent forms [16, 20, 26] and systematize the assembly process of building components related to the material and connection detail as a method of mass customization [20, 23, 36, 37]. However, the examined studies are limited to the partial visualization of the performance of manual making, or automating the manufacturing and assembly processes rather than modifying or developing digital tools and processes derived from the making with manual tools. The extraction of parameters related to tool parts and making rules can provide the ability to modify the even duration of actions performed by the maker. Parametrization methods can be categorized as constructive or deformative methods in which developing a model from scratch or modifying an existing geometry, respectively [2]. Since the parametrization studies focused on the modelling of the form itself in engineering, a more inclusive methodology is needed for the manual making process consisting of intuitive decision-making. Having a set of parts that can be fixed, changeable, and moveable, the manual craft tools can provide unique making procedures affected by maker's ability, material and the medium. The translation of manual tools into digital medium can further enable the development and the use of these tools even by non-expert makers to search the tool-based solution space, develop new parts, integrate them into the new workflows and compare the hand-made forms with the simulations to evaluate the intuitive making processes.

The second question emerges of how we can evaluate the hand-made forms in which quality assurance is calculated by hand and defined by tool affordances. Pye [33] emphasizes that the quality of crafts should not be taken for granted, which is at risk during the making, depending on the judgment, dexterity, and care of the craftsman. Mason [27] asserts that the quality of crafted objects increases as the judgment level of the maker advances. The quality of the hand-made object can be assessed concerning the designer's intention [33]. Thus, the quality in crafts is defined as the correlation between what is intended and made rather than targeting precision of the outputs as in engineering. In the parameterization and digitalization processes in crafts, the assessment of the process is related to the correlation of the parameters. The digital models are not the same as scientific models as Pye stated that "the quality of craft is relative and not predetermined" [33]. They are specific to the medium consisting of the maker, tools, and materials. Thus, the formal analysis of physically and digitally produced forms is conducted by comparing the distance between a set of points projected onto the digital and scanned model named as the total surface displacement value [48, 49]. Considering the performance of the making which is specific to the maker and medium, the quality of crafted objects should be measured by combining quantitative analysis and qualitative observations.

3 RESEARCH METHODOLOGY

This paper aims to transform the hands-on and intuitive making process into a computable and explicitly defined process by parameterizing and digitalizing it. According to the literature review, the main questions to be answered in this paper are explained below.

RQ1: How is the physical making process translated to the digital medium?

RQ2: What is the correlation between physically and digitally produced outputs to assess the parametric model of the manual extrusion process?

To determine the methodology of this paper, the literature studies are reviewed and analyzed considering formalization techniques in rule-based design as shape, and making grammar [8, 21, 26, 36] as well as the methods for comparing digital and physical mediums [13, 31, 48, 49]. For the parameterizing process, hands-on experiments are conducted to discover and extend the tool affordances by using the making grammar approach and for the digitalization of the making process, the photogrammetry approach is employed and visual scripts are generated in the Rhinoceros Grasshopper environment. Then, the parametric model is developed based on the physical making process. The mixed-method combining qualitative and quantitive data is used to assess the parametric model to compare physically and digitally produced outputs.

3.1 The Parametrization of the Making Process with Craft Tools

The extrusion is an additive manufacturing process in which paste-based material is deposited layer by layer through a nozzle or die to produce a solid form. There are many variants of the manual extrusion mechanisms that produce forms at different scales from bricks to jewelry (Figure 1). Although a straight extrusion is generally produced with these tools, various cross-sectional dies are developed and unexpected deformation of forms such as bending, and swelling are integrated into the design process at the workshops in a creative way as in the studies of Anton Alvarez [3] and Stein and Swaine [40]. The manual clay extruder (MCE) is used in workshops to produce extruded forms out of soft materials such as clay, polymer clay, and playdough. The sub-parts of the MCE are a handle, a pressing mechanism, a tube for filling the material, changeable dies, and a tool head for fixing the die to the bottom of the extruder. In the conventional tool use, the MCE presses a clay body through a die via hand.

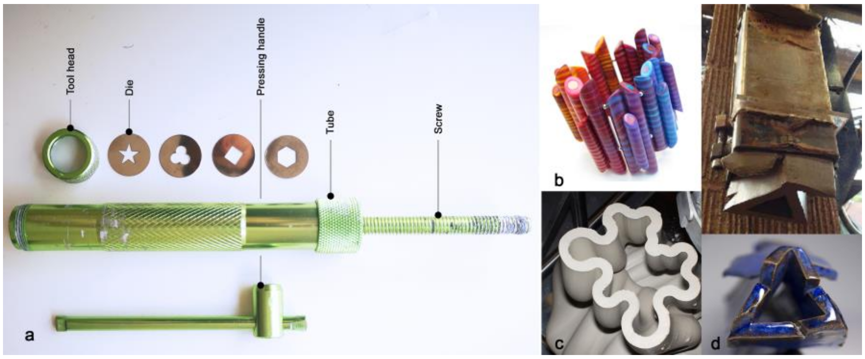

Figure 1: (a) The sub-parts of the manual clay extruder (MCE), (b) Jewellery examples produced with the tool [50], (c) Deformed forms [3], (d) Large scale application of the tool, and the produced brick [40].

3.1.1 The extrusion-based making grammar (EbMG)

The parameters and rules are determined following the hands-on experiments with the tool. The fixed parts are determined as the pitch of the screw (t) equal to one revolution. The moveable and changeable parts are dies (cross-sections), rotating tool head (XY plane), cutting wire (height), and base (surface). The ruleset of the extrusion-based making grammar (EbMG) is divided into three consecutive stages such as pre-press, press, and post-press (Figure 2). The rules are not replacing but transforming the previous extruded layers as a part of the developed method for formalizing the making. The process starts with placing the die inside the tool head, which is at the bottom of the extruder (Rule 1a) as a pre-press operation. The two dies can be combined, or the die parts can be omitted to form new cross-sections (Rule 2a, 2b). In the press phase, two pressing options can be applied such as continuous or interval force (Rule 3a, 3b), and equal or non-equal force (Rule 5a). The form shaped by the extruder is affected by the duration of the press being continuous or interval, the angle and direction of the tool head rotation (Rule 4a, 4b), and its combinations. The extruded form can be slightly bent or deformed (Rule 5a), which can be manipulated by hand to keep the precision of the form (Rule 6a) as a part of the post-pressing operations. In that phase, the die can be changed (Rule 7a) or again modified by altering the base surface other than the planar surface (Rule 6b). Then, the extruded form is cut to separate it from the loaded material, which can be linear or diagonal (Rule 8a and 8b) according to the position of the cutter.

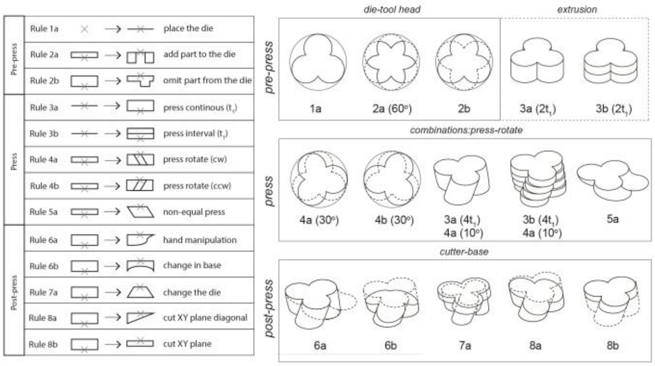

Figure 2: The rules of the tool use and its visual representation for a 3-circle die.

3.1.2 The parametric model derived from the EbMG

The parametric model of the EbMG is developed in the Rhinoceros Grasshopper by translating the hands-on making process into the digital medium. The parametric model consisting of pre-press, press, and post-press operations is shown in Figure 3. Parameters of the model; die cross-section, die combinations, hollow die thickness, layer height produced per unit time, cutting height, and tool head rotation angle.

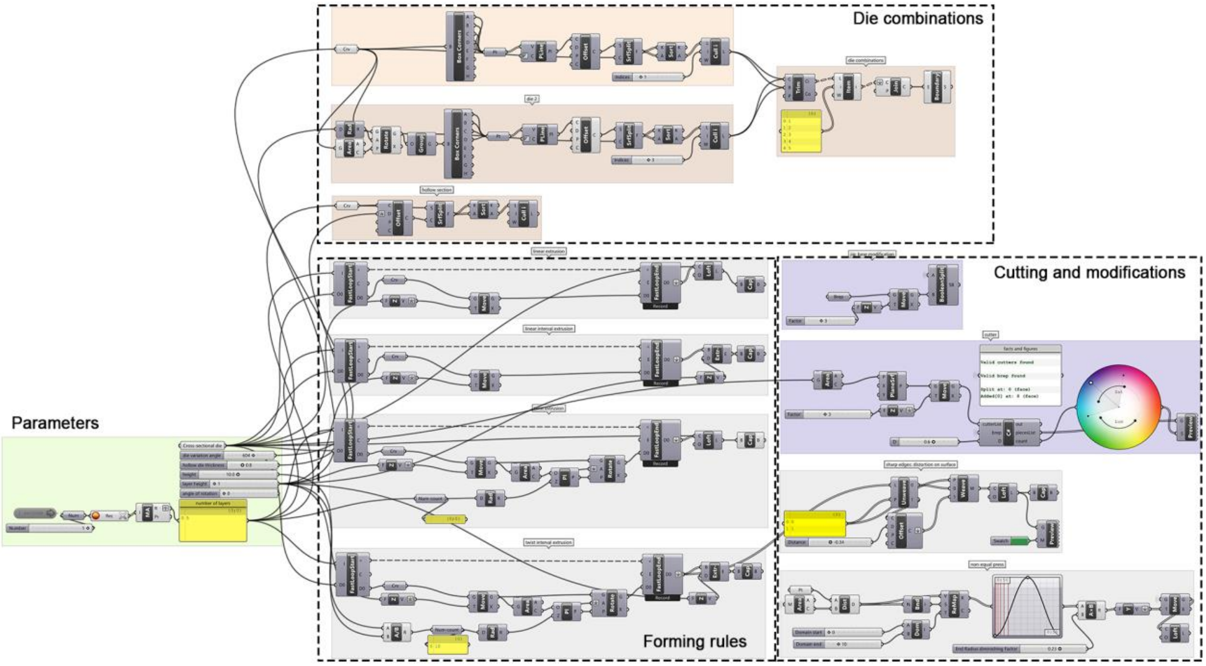

Figure 3: The parametric model based on extrusion-based making grammar.

In the pre-press phase, die combinations can be simulated with the intersection of the polygonal curves as dies. After the die selection, the additive forming process is generated in loops in which the material printed per second is added to the previous one by extruding a curve. If the die within the tool head is fixed while pressing, linear and stepped linear extrusions are obtained. If the die is rotating while pressing twist and multi-step extrusions are obtained depending on the rotation of the die such as continuously or in intervals. After the *BRep* model is obtained by extruding the polygonal curves sequentially, modifications such as cutting and forming are applied to the output by *splitting* the cutting surface out of the *BRep* model with the written script in C#. The deformation of the extruded form due to the sharped edges of dies is represented as deformations of the *BRep's* edges by remapping the surface points according to *Sin* and *Cos* functions. Many forms based on the combinations of the ruleset can be obtained by the parametric model as a result of transferring the physical making process to the digital medium. By using the parametric model, several die geometries, and their combinations, forming rulesets, cutting, and shaping operations can be simulated to foresee the possible forms generated through the MCE.

3.2 The Evaluation of the Parametric Model

In the preliminary experiments, polymer clay, air-drying clay, and play dough were tested by producing the samples at different heights and the relationship between the produced forms and the properties of materials was observed [32]. The final setup is carried out with polymer clay, as it showed the surface details better and did not deteriorate over time. Three rule sets namely straight, twist and multi-step extrusion are applied for each die. The applied rulesets focus on the pressing part of the grammar. Therefore, post-pressing operations such as cutting and base-forming are excluded from the final experiment to focus on the formative operations conducted by the tool itself. Square, 3-circle, and star-shaped dies are chosen because the other dies in the toolset are comprised of the circle or its combinations. Since these dies are limited in producing diversity, the use of more facet dies is preferred in the final experiment. The selection of rotation angles is determined by the easiness to follow the marking on the tool head with the eye.

Figure 4: Forms produced by the extrusion-based making grammar in the physical medium.

Systematic experiments are conducted within the above setup. In this setup, 12 outputs of 24 mm in height are produced with square, 3-circle, and star-shaped die by the MCE (Figure 4). In the straight extrusion rule set, the form is directly determined by the die shape, since any other manipulations were not applied to the form (Figure 4a). The length of the form depends on the number of rotations of the handle (t). t is equal to 360°, which defines the height of the printed material. In the twist extrusion rule set, the form is determined by the parallel processing of pressing and rotation of the tool head-die. Thus, the printed layer is twisting in line with the rotation angle and direction in every pressing (Figure 4b). In multi-step extrusion, the form is again generated by the application of rotation and pressing operations, not in parallel but consecutively. Thus, the form seems separately extruded layers with a deformed parting line (Figure 4c).

The comparison workflow for the outputs produced with the parametric model and physical grammar is shown in Figure 5. The outputs produced in the physical medium are digitalized with the photogrammetry and the successfully generated mesh models (M_1, M_2, etc.) are imported into Rhinoceros software. In parallel, the outputs as mesh models (Sim_1, Sim_2, etc.) are generated by the same rulesets in the Rhinoceros Grasshopper software with the parametric model of the EbMG.

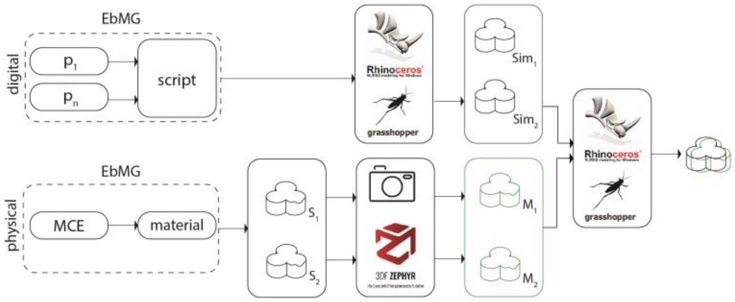

Figure 5: The flowchart showing the evaluation of the samples.

Following the making of the forms in the physical medium, the photogrammetry method is employed, which is frequently used in the digitalization and analysis of outputs produced with the experimental method [11, 14, 44, 49] to digitalize them. This method is based on taking overlapping photos at certain angles by rotating around 360° of the output and generating a 3D model via image processing software. Since the applied photogrammetry methods have been developed for bigger and undetailed forms, a photogrammetry workflow named the Relational Positioning Method (RPM) is developed based on the aerial photography technique and adapted for processing the small-scale, detailed, white, and symmetrical forms. In the RPM, the sharp edges of the outputs are painted with variable-colored pencils, and found objects are placed as control points around the outputs to help the software successfully calibrate the photos by 3DF Zephyr Aerial software. Then, 360 photos taken at angles of 1° that show all the details are processed in 5 stages in the 3DF Zephyr Aerial to obtain both a mesh-based 3D model and a rendered image containing the surface texture of the physical object. The calibration of the captured photos is done by detecting camera properties and the photos are processed with the relatively positioned surrounding objects defined as control points. If the image diagnostic process is successful, the Sparse and Dense Point Cloud are produced respectively as a high-detailed mesh model. The model is selectively cleaned with the editing tools from the surrounding objects.

The produced forms are compared by the visual code written in Rhinoceros Grasshopper (Figure 6). An average surface deviation value is obtained as a result of the calculation of distances between the points on surfaces of the mesh models.

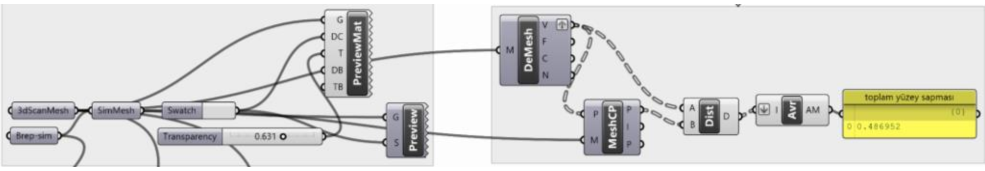

Figure 6: The script to compare the outputs produced digitally and physically.

4 RESULTS AND DISCUSSION

The produced forms have variable surface patterns as grooves related to the die forms and rule sets. The data obtained by the Relational Positioning Method vary within a certain range, between 0,53 and 4,26 mm depending on the different dies, rulesets, and maker's ability. In previous studies, it has been stated that if the deviation values are within a certain range, it is an acceptable indicator of accuracy [38, 49]. The consistency in the obtained values shows that the developed RPM is successful in the digitalization and comparative analysis of the small-scale forms.

Sample name	Rulesets	Die geometry and gap area (mm²)	Time (sec)	Rotation angle (°)	Total surface displ. (mm)
(a)	Straight extrusion	Square: 36	32		0,74
(b)	Twist extrusion	Square: 36	34,4	45	0,48
(c)	Multi-step extrusion	Square: 36	48	90	7,33
(d)	Straight extrusion	3-circle: 50,8	44		0,28
(e)	Twist extrusion	3-circle: 50,8	47,2	60	0,52
(f)	Multi-step extrusion	3-circle: 50,8	66	15	7,05
(g)	Straight extrusion	Star: 30	26,6		0,55
(h)	Twist extrusion	Star: 30	28,7	15	0,57
(i)	Multi-step extrusion	Star: 30	39,6	15	7,73

Table 1: The comparison of the outputs.

In line with the obtained data, the correlation between the die geometries, extrusion time, and rulesets of the EbMG has been analyzed and discussed to determine the new knowledge generated by the translation of the physical making process to the digital medium. Table 1 shows the values obtained by comparing the outputs produced in two mediums. The found relations are explained below.

- The die gap affects the printed material per second.
- Concave polygonal dies tend to create more displacements on surfaces.
- The multi-step extrusion results in more displacements on surfaces due to the difficulty in incrementally rotating the tool head.
- Softer the material, easier to apply the ruleset.

The quantitative data obtained by the parametric model and qualitative data based on the maker's observations are evaluated to answer the research questions.

4.1 How is the Physical Making Process Translated to the Digital Medium?

The translation of the physical making into the digital model is related to the sequence of operations related to the degree-of-the-freedom (DOF), changeability, and adaptability of the tool parts. Since the making process with the manual clay extruder includes repetitive actions such as the movement of the tool parts pushing the disk and rotating the tool head, these operations are translated to the digital medium by using loops. The changeability and combinability of dies are modelled as the intersection of the polygonal curves. The movement of the pressing disk is modelled by incrementally extruding a polygon dependent on the time variable. All these parameters and functions are coordinated in the model to automate various forms and explore the design space.

The outcomes show how knowledge is gained through translations between mediums. The translation of physical making procedures into digital models extends the knowledge of the maker by exposing the relations between parameters of tools and hands. The parametric model of the making process has helped reveal tacit knowledge that is intuitive during the making process of the outputs produced through rulesets. This new knowledge is related to the tool parts, material, and ruleset that are coordinating the making process. This type of knowledge is difficult to describe, such as the relationship between the die gap and the printed material per unit time, the effect of die geometry on the outputs, and the relationship between deviation values and the haptic sense of the maker. Moreover, the tool-based solution space can be explored digitally by using the parametric model. From this point of view, the parametric model can be used as a digital tool that is open to continuous improvement as it can be reprogrammed in line with the changes in the tool and process.

4.2 What is the Correlation Between Physically and Digitally Produced Outputs to Assess the Parametric Model of the Manual Extrusion Process?

The outputs are evaluated by comparing the data related to deviation values, extrusion time, die geometries and gaps, and rulesets to discover new relations between parameters. The outputs are analyzed and results are obtained related to extrusion time and die geometries. The dies used during extrusion can be sorted from large to small die gaps as 3-circle, square, and star. As a result of the evaluation, there is an inverse proportionality between the area of the die gap and the material printed per unit time (Figure 7a). The layer height of the printed material per second is calculated as 3 mm in a square, 2.22 mm in a 3-circle, and 3.6 mm in a star die. Therefore, more time is required to produce the same height outputs with dies having a larger gap. To achieve the same height in different die geometries, the number of screw turns should be increased. When the ratio between the die gap and the extrusion time is evaluated, the time required to press 1 mm^2 material is calculated as 0.98 seconds on average. This value is integrated into the parametric model as printing layer time.

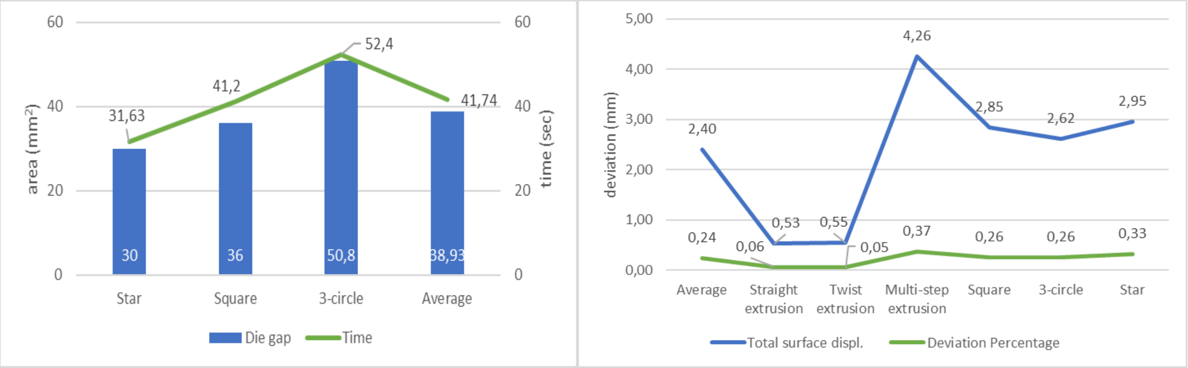

Figure 7: The relationship between the die gap area and the printed material per second. The comparison of die geometries.

When we compare the die geometries, the 3-circle die, in which the die gap is larger than the other dies, generates less total surface displacement value than the others. According to the data obtained from the outputs, we can say that larger, curved, and less grooved die geometries give more accurate results (Figure 7b). According to the total surface displacement values, it has been determined that the rulesets of straight and twist extrusions give closer values to each other, while the ruleset of multi-step extrusions results in more displacements of surface geometry. This shows the difficulties in the application of interval operations such as press-stop-rotate by hands due to the deviations of the rotation angles and material deformation. Moreover, square and 3-circle die geometries give accurate results compared to star dies having sharp edges. Thus, if accurate forms are aimed to produce by the maker, more chamfered dies and continuous pressing functions should be used. These deviation values are also integrated into the parametric model as coefficients.

5 CONCLUSION

The procedure presented in this paper is an example of how a craft practitioner attempts to discover ways of translating manual-making processes into a new form of craft that is digitally modeled to be able to be shared, discovered, and evaluated. The procedure is developed and tested through the extrusion with a craft tool for analyzing hands-on making, increasing the tool-based solution space, and assessing the correlation between intended and made forms. This study shows the developed parametric model is found to be useful in creating the cycle of making, measuring-comparing, and remaking accordingly, which is carried out in both physical and digital mediums. Although the digitalization of crafts is argued by several researchers and practitioners due to the removal of the human hand from the process and the lack of originality of the artifact, the translation of the physical making processes into the digital medium as a hybrid process enhances the skill development, especially in non-expert makers and prevent the disappearance of the craft knowledge [35].

The limitation of this study is related to the experimental setup consisting of the tool parts, rulesets, and medium. Different die geometries and post-pressing operations of the grammar can be examined in future studies. The coefficients may change due to the different setups and the maker's ability. Thus, the tool-based parametric model is peculiar to the maker. For future studies, the procedure can be applied to analyze and evaluate other craft tools used by makers such as clay forming, embossing, and carving tools "by extending the tool affordance by starting with the known tools and techniques" [31]. The procedure can be applied to different settings to parameterize and digitalize the manual making processes for both exploring the design space and developing the digital model of the tool-based making process. The models and digitalized artifacts can be further transferred to the computer-aided fabrication tools by means of extending the design domain from manual tools to machines. Using computational thinking and digital tools to record and analyze the forms created by hand and manual tools can enable self-learning processes even by a non-expert maker.

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