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A METHOD TO CHART THE STRUCTURE OF DESIGNERS' CLAY MODELING PROCESSES

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1. Introduction

Physical modelling methods are often used in the early phases of shape design, in spite of the rapid development of CAD software [Lennings 2000]. Apparently, in these phases, designers often prefer physical modelling over virtual tools. As industrial designers are responsible for the appearance of the product, they need to be fully engaged in the creative process of form-giving, where tactile exploration and hands-on interaction between designers and the material they are shaping, is extremely essential [Fjeld 2002, Scali 2002]. Nevertheless, computer tools offer a functionality which is difficult to achieve using media such as sketches, cardboard or clay. It is therefore very important to investigate how designers can benefit best from physical modelling *and* CAD [Sener 2002].
The goal of this research is to gain insight in the structure and to identify possible patterns of physical modelling methods during shape ideation. Our research focuses on clay modelling. Clay models can both be automatically milled from CAD models, and be hand modelled by designers. Therefore clay is appropriate for integration of physical and virtual shape modelling methods. Several "Digital Clay" systems exist, but are limited. Schweikardt (2000) describes a system that derives 3D models from architectural sketches. Industrial designers, however, must also be able to develop free forms. A virtual rake was investigated by Kanai (1996). Jung (2005) proposes a virtual spray tool and observed some physical modelling methods. However, we found few studies on clay modelling. To investigate clay modelling processes we have developed a method to observe actual processes, to capture the data and to analyze the acquired information. This research method provides both qualitative and quantitative data on clay modelling. The analysis should reveal the designers' performed clay modelling approaches, and their advantages and disadvantages. The next section describes the research method. Section 3 will explain the coding and interpretation of the data. Finally, conclusions are presented in section 4.

2. The research method

The method that we developed to investigate the structure of clay modelling processes contains conduction of an experimental design process, coding of experiment data, and interpretation of the coded data. During the experiment, a subject has to model some objects in clay. The subject's activities are video recorded. From the video recordings it is inventoried what the test subject does from moment to moment. In particular the activities that cause a modification of shape are observed, including preparing activities (like positioning the object) and finishing activities. The activities are assigned to categories, and patterns are identified. Patterns are aggregated into sequences and parts, and frequencies and durations are determined. The following paragraphs introduce a test case to present the method.

2.1 The experimental design process

During the experiment, the subject had to perform three assignments: firstly, recreate an existing soap box in clay, then enlarge the clay model and finally adapt its top to fit a new, oval soap bar, see Figure 1. Roughly, the durations of these assignments were 13, 6 and 6 minutes, respectively.

Figure 1. Results of assignments: Soap box in clay, enlarged box, and box with rounded top

2.2 Identifying activities

We started the analysis by identifying activities. The following categories were distinguished:

- shape *modification* (or modification, for short)
- *preparation* for a modification
- *postprocessing* after a modification
- *examination* of the object
- *other activity*, unrelated to a modification.

Shape *modifications* are activities during which the shape of the clay model changes, such as adding material, or deforming. Some *preparation* may be necessary, e.g. grabbing a tool. Some *postprocessing* may follow, e.g. to lift a stick that was used to make an impression. *Examining* occurs when the subject watches the clay object for evaluation, or to plan the next step. All remaining activities are characterized as *other activities*. They are not directly related to a shape modification.

The first step of coding the data is identifying activities and determining their start times. The start time of an activity is measured in seconds, from the moment the modelling process began. Next, the activity details are coded. These details concern the following data items (see Table 1):

- operand – object or part to which the activity applies
- region of interest - the area of the object that is affected by the activity
- tool - the tool used; fingers or hands will also be considered as 'tools'
- execution details - necessary details about the way an activity is performed.
- comment - Anything that is important but does not belong to one of the data categories above.

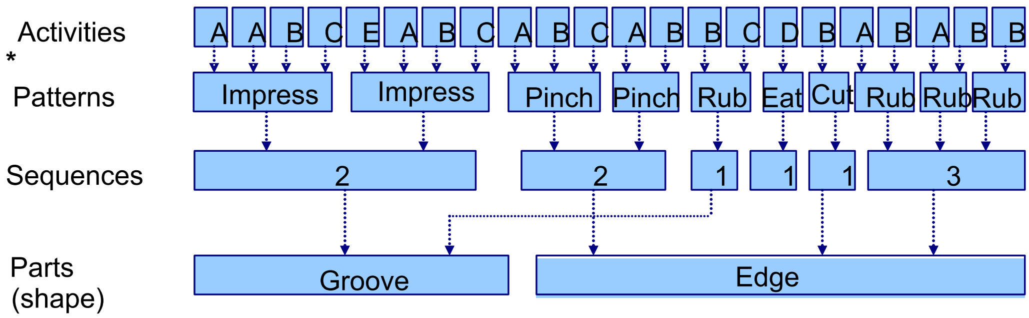
Table 1. The data items characterizing an activity, and some activities filled out as examples

Detail level	Start time (s)	Activity set	Activity	Operand	Region of interest	Tool	Execution details	Comment
1	733.6	Kneading						
2	753.6	Grooving	Positioning	tool				
4	755.6		Impressing	top face	lengthwise axis	stick	with both hands	
4	756.0		Positioning	tool	crosswise axis	stick		along carve
3	756.6		Impressing	top face	crosswise axis	stick	with both hands	

The method allows to code the data with different levels of detail. Detail level 1 shows sets of activities and their start time. At detail level 2, each individual activity is coded, together with its start time and with the operand, if applicable. The region of interest and the used tool, if applicable, are added at detail level 3. Finally, applicable execution details are filled out at detail level 4. A comment can be filled out if necessary, at any detail level.

2.3 Finding patterns

When the activities are identified, grouping into patterns can begin. A pattern contains one shape modification activity and all activities that support that modification activity. Next, repetitions of the same types of patterns are grouped into sequences. Following aggregation steps are based on the intention of the subjects' activities. Sequences of activities are aggregated into a part when they are performed to achieve a specific shape element. Then all the parts that collectively define a complete, individual shape are combined. Figure 2 shows the different steps in the aggregation process. The next sections will discuss each step in detail.



* A = preparation, B = shape modification C = post processing D = other activity E = examination

Figure 2. Aggregation from observed activities into shape parts

A pattern contains one shape modification activity and all related preparations, postprocessings and examinations. As an example, we show a pattern in which a groove is made in the top face of a box:

- positioning box *(preparation)*
- positioning stick *(preparation)*
- impressing stick *(modification)*
- pulling out stick *(postprocessing)*

The identification of patterns is achieved by the following steps:

1. Mark activities that modify shape as *modifications*.
2. Mark each examining-activity as *examining*.
3. Check which activities belong to a modification as *preparation* or as *postprocessing*.
4. Mark remaining activities as *other activity*.
5. Aggregate subsequent *preparation*, *modification* and *postprocessing* activities into a pattern. Also, aggregate subsequent *other activities* into patterns. Assign each *examining* activity to an existing patterns if there is an indication that it belongs to it.
6. Number and name the generated patterns.

2.4 Aggregating patterns into sequences

When subsequent patterns contain the same type of shape modification activity they can be aggregated into sequences. Differences may occur in the number of preparations and postprocessings. Multiple sequences of the same pattern type may occur, with each sequence having its own number of patterns. An example of a sequence is the repeated impressing of a stick to form grooves.

Sequences are aggregated as follows:

1. Mark subsequent, similar patterns as a sequence. If no subsequent, similar patterns are found, the sequence consists of a single pattern.
2. Include preparations that are done once, before the first pattern.
3. Include the postprocessings that are done once, after the last pattern.
4. Include patterns that do not contain a modification.

5. Number and name the found sequences.
6. Describe the activities that occur in a typical pattern, and the number of patterns.
7. Describe special preparations, postprocessings or other activities.

2.5 Mapping sequences to shape parts

To get more insight into the shape modelling process, we need to be able to express the sequences in terms of intended shape. Parts can be used, for example, to investigate whether multiple sequences contain the same shape intent. Shape intent is more or less implicit during clay modelling. What can be seen is how the subject manipulates the clay, not the shape the subject has in mind. The shape intent is often not visible before the subject finished the modelling. And even the result need not exactly be what the subject initially had in mind. Physical model and mental image can develop hand in hand. Here is a difference compared to CAD. When the subject wants a basic shape to start with, that shape should be explicitly specified. In clay modelling one can start with an arbitrary lump of clay, but in CAD one starts with a block, a sphere, or any other well defined shape. Recent research has found relations between the shape elements a subject works on and the parameters that can describe the resulting modifications [Dumitrescu 2004]. Once these parameters are known, it may be possible to define some clay modelling operations in such a way that they can be performed in CAD at one hand, but at the other hand still with some of the flexibility with which they can be performed in clay.

3. Results obtained using the method

3.1 Identifie activities

The method described was applied for the analysis of a session of the soap box experiment. Assignment 1 took 13 minutes, assignments 2 and 3 each ca. 6 minutes, and 6 minutes were spent on instructions and preparations before and between the assignments. The identification of activities resulted in a table (like Table 1) with 660 lines. 622 of these lines are of detail level 3 or 4.

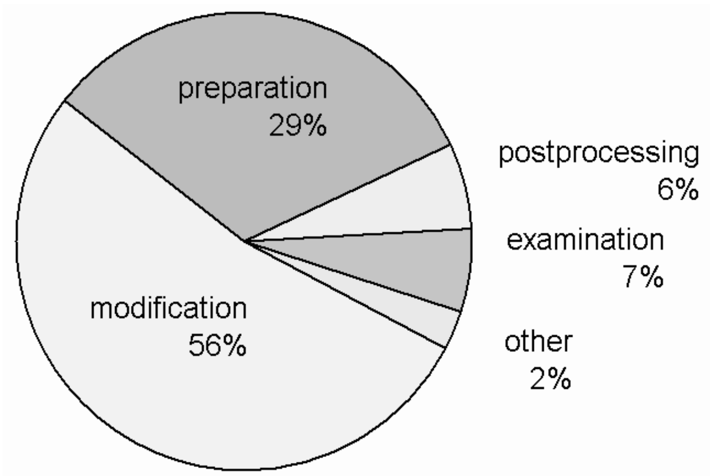


Figure 3. Time division over the different activity categories

Categorization of these activities is presented in Figure 3. Most time was spent on shape modifications. Preparations also took a considerable part of the time, but far less time was spent on Postprocessing, Examination, and Other activities. Preparations mainly concerned positioning an object or a tool. Modifications were made by 15 different types of activities. Figure 4 shows them all. Most time was spent on pressing, rubbing, impressing, and hitting.

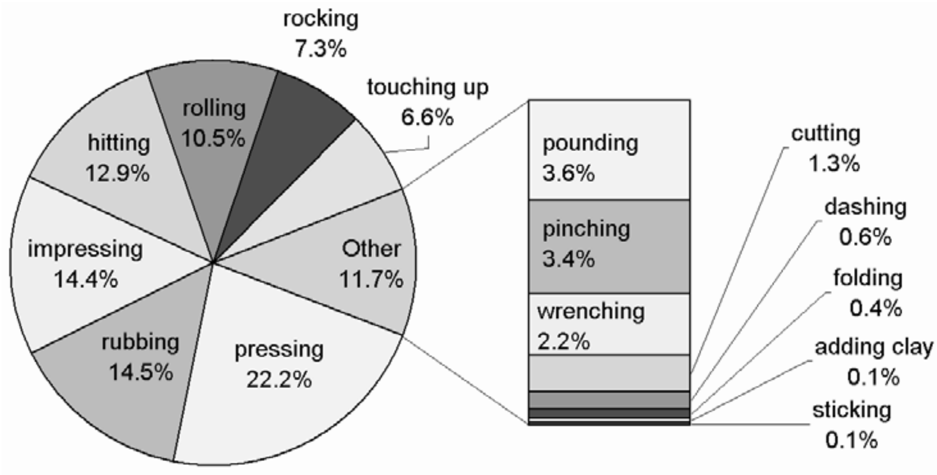


Figure 4. Time division of modifications

Rocking and rolling were relatively slow activities. The most frequent activities were hitting (76 times), pressing (65), and rubbing (37). The quickest activities were pounding (31 times in 8s), hitting (76 times in 28 s) and pinching (16 times in 7 s). Few modifications had a duration of more then one second. These were rocking, rolling and cutting. A typical modification activity took 0.71 +/- 0.15 s on average. The coded data also tell us how activities were performed and which objects or regions were involved.

Most modifications were done by hand. A tool was used in only 34 of the 547 modifications (about 6%). The operand was a clay object in 80% of the cases, and a tool in 15%. The remaining 5%, the operand was the subject's hand or finger. When a region of interest was specified, it was a face or two opposing faces in more than a half of the cases (104 out of 200 times). Other regions of interest were edge, groove, carve, ribbon or other area's (36, 17, 12, 9 and 22 times respectively).

Table 2. Patterns and their frequencies

Patterns	Frequency	Patterns	Frequency	Patterns (without a modification activity)	Frequency
Pressing	65	Pinching	16	Examining	5
Rubbing	37	Wrenching	5	Grasping	4
Impressing	34	Cutting	2	Taking	3
Hitting faces	76	Dashing	2	Putting away	1
Rolling	9	Folding	1	Shifting his position	1
Rocking	6	Adding clay	1		
Touching up	19	Sticking	1		
Pounding	31				

3.2 Patterns

A number of 319 patterns was recognized. Patterns vary in complexity. Some patterns consist of a single modification activity. There are also complex patterns, containing a modification that is preceded with several preparations and examinations and followed by postprocessing activities. Table 2 lists all types of patterns. Only 14 patterns did not contain a modification activity. They are listed in a separate column in the table.

3.3 Sequences

Aggregation of patterns produced 84 types of sequences. Table 3 shows the most frequent types. For example, two sequences of type 'pinching' were found. One contains 14 pinching patterns, the other contains two. Only 27 sequences consisted of a single pattern. As much as 93 % of the analyzed activities appeared to be spent on repeated patterns.

Table 3. Sequences, their frequencies and the number of patterns they contain

Sequence type	Frequency	Nr. of patterns in the respective sequences
Hitting	12	1, 26, 7, 1, 11, 2, 4, 1, 9, 4, 7, 3
Impressing	4	9, 11, 4, 10
Pinching	2	14, 2
Pounding	8	10, 7, 1, 2, 1, 3, 5, 2
Pressing	22	2, 2, 1, 1, 1, 2, 2, 1, 1, 9, 2, 4, 2, 7, 5, 4, 2, 3, 2, 7, 3, 1
Rubbing	13	4, 1, 1, 3, 10, 7, 1, 1, 3, 1, 1, 2, 2, 7
Touching up	11	1, 1, 2, 1, 1, 1, 1, 1, 1, 5, 4

The aggregation of patterns into sequences resulted in a more global overview of the process. The sequence plots could be divided into groups of 2 - 5 different sequence types. These groups are referred to as parts. Figure 5 shows two parts. In part I, the 'impressing' sequence goes on for half a minute. Part III, at the other hand, shows very quick changes of sequences.

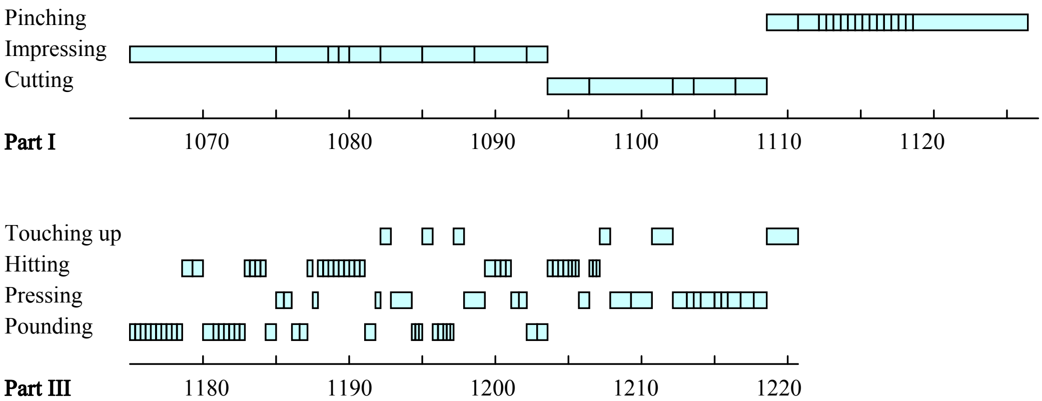


Figure 5. Two of the recognized parts (times in seconds)

After the sequences were identified, data were compared to find the similarity of patterns within a sequence, and the similarity between different sequences of the same type. Finally, the video recordings were revisited to see how the shape of the object developed during each part. In part I the test subject starts with measuring the soap box that has to be enlarged (t=1061.9), then cuts off the right volume of extra clay (t=1094.0), adds it to the soap box to be enlarged, and starts kneading. The result is a lump of clay that has the right volume, but not yet a specific shape (t=1141,4). In part II the lump of clay is converted into a block-like shape (t=1174.6) which is elaborated in part III into a neat box with flat sides (t=1208.2). Also in part III the edges are rounded (t=1220.7). So far the subject only used his hands and the table top. In part IV, the subject grabs a stick (t=1362.1) and adds grooves to the box, finishing at t= 1400.0. Table 4 summarizes the shape elements that are a result of the above mentioned parts. Indeed the parts help to find shape development steps, however part I does not deliver a specific shape, only the requested volume. And part III can be split up into two shape development steps.

Table 4. Shape elements delivered by parts of assignment 2

Part	Delivered shape element	Delivery time (seconds after start)
I	Right volume of clay	1141.4
II	Base of the shape	1174.6
III	Flat sided box Rounded edges	1208.2 1220.7
IV	Grooves	1400.0

4. Conclusions

We have developed a method that provides an overview of and insight into the designers shape modification activities. The observed data include activity sets, durations, repetitions, etc. The method was applied to a test case, to investigate whether the method could gather appropriate data, and whether the data analysis could deliver meaningful results. During the experiment, a test subject was modelling in clay to generate three variants of a soap box. Analysis of the data showed that the method can indeed deliver useful information about the shape modification activities of the test subject.

The data analysis resulted in overviews of performed activities. These overviews include detailed activity tables, enabling the description of activities as short as a tenth of a second. At a less detailed level, activities are grouped and presented as patterns. Most of the patterns appear to be performed in sequences of subsequent repetitions, called sequences. Further aggregation results in the presentation of parts. The parts can be used as indications for the steps in development of the shape.

The first application of the method was mainly meant to verify whether the method can work, if the afore mentioned data categories can be unveiled, and if possible improvements in the method are required. The retrieved data itself is not more or not less than the result of one simple test. Bearing this in mind, we have presented the data and mention some interesting results, however, without claiming generalisibility.

More than half of the claying time was spent on modifications. Also preparations took a large part of the time (29%). Examinations were often done during other activities. The remaining time was spent on postprocessings (6%), examinations (7%) and other activities (2%). The mean duration of an activity was less than a second. 15 different types of modifications were identified, from which pressing, rubbing, impressing and hitting had the longest total durations. Tools were used for only 34 out of 547 modifications. In more than 50% of the cases, two opposing faces were concerned at a modification. Most patterns occurred in repetition sequences. Time diagrams of the sequences show that the modelling process can be divided into parts in which 2 to 5 pattern types occur. These parts often deliver a particular shape element, e.g. in assignment 2 the right volume of clay, the base of the shape, flat sides, rounded edges, and grooves, respectively.

With the method described, data can be retrieved about which activities designers perform when they physically model a shape. Gathering these data may be a goal in itself, for getting more insight in the modelling process. However, the data can also be necessary for further studies on modelling, such as:

1. Comparing different modelling methods for the same intended shape;
2. Comparing clay modelling methods to CAD modelling methods;
3. Improving integration of clay modelling and CAD modelling;
4. Proposing CAD methods that connect to the physical skills of designers;
5. Evaluation of applied modelling methods;
6. Developing a system that advises on methods that can be used in complex modelling cases;
7. Studying the different modelling styles of designers
8. Investigating whether typical modelling methods exist for particular shape types;
9. Finding out in which parameters designers think when they want to modify a shape

The framework in which this study was started, is the need for better control over shape parameters, as expressed by designers [Wiegers 2001]. The main goal is to identify the parameters that designers want to vary. A result from the research can be a CAD function that connects to the designers' natural way of shape modelling [Dumitrescu 2002]. Another type of support is to enable designers to switch from modelling in clay to CAD and back. They can then select the most appropriate method for each type of shape modification [Vergeest 2004].

Further research is being undertaken to enhance the method in such a way, that it will also show the strategies and activities that were applied for each shape intent the designer had in mind. On the long term, the described method can help to develop tools and methods that better exploit the modelling skills and preferences of designers, in stead of forcing them to apply a second choice modelling method.

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