Design Divergence Using the Morphological Chart

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Abstract

This paper investigates the effectiveness of the morphological chart method in design divergence. The literature presents the morphological chart as an engineering design method that does not particularly aim novelty, but instead gathers possible means for fulfilling the independently decomposed sub-functions of a product. On the other hand, implementations of this method in design education has shown that this method offers the possibility of design exploration for groups of interrelated sub-functions. Accordingly, this widens the solution space and encourages designers to think on the consequences of their design decisions while generating ideas, hence allowing situated design divergence to take place. The paper presents the findings of a review carried out on twelve morphological charts completed in groups, containing a total of 686 sub-solution sketches made for a pool of 21 sub-functions. The charts were reviewed as a whole in terms of group performance in idea generation for a decomposed design problem. Then the sub-solution ideas were grouped according to sub-functions and were reviewed in terms of idea content. It was seen that a background preparation with product trials, 3D exploration of product configuration, and experience in using the morphological chart method, affected the number of cells that the participants completed. Besides, several factors were found to influence the ways in which participants filled in the morphological charts. The reviews revealed eleven factors affecting design divergence using the morphological chart method, grouping under the headings of: preparations, group dynamics, boundaries of sub-functions, and interrelations of product components. In addition, thirteen strategies were identified that participants followed for idea generation using the morphological chart method, grouping under the headings of: beginning idea generation, ensuring effective idea generation, exploring ideas, diversifying ideas and representing ideas.

Key words

morphological chart method; design divergence; idea generation; sub-functions; sub-solutions; visual content analysis

1. Introduction

A main objective in design education is supporting prospective designers in developing and mastering skills in carrying out design exploration. The usage of generative methods is an important resource in simulating design situations allowing this process to take place (Daalhuizen, Person and Gattol, 2014; Curry, 2014; Cash, Elias, Dekoninck and Culley, 2012). This paper presents the findings of a study that reviews the outcomes of the implementation of such a method.

Generating alternative design solutions for products with multiple components can present difficulties particularly when components are expected to fulfil coordinated sub-functions within a technical-physical system. Closely related sub-functions of a product may lead to tight boundaries of physical components (e.g. interrelated components with predefined parameters), leaving limited space for design interventions. For such design problems, design exploration may remain limited and variety in idea generation may not be achieved. In this case, methods that ensure design divergence must be chosen. The literature offers many idea generation methods used for widening the solution space for engineering and product design, the morphological chart method being one of them.

Widening of the solution space is about determining the boundaries within which design exploration will take place, such that several and diverse possibilities can be considered. This involves design divergence, which is about generating an extensive range of alternative ideas that will contribute to this exploration. The more informed this process, the more appropriately the boundaries of the solution space will be set, and better this exploration will be grounded. An in-depth analysis of the problem is thus important in preparing for this exploration, as i) it contributes to the designer's understanding of the problem context and components, ii) supports the reasoning behind idea generation, and iii) provides the criteria based on which the outcomes of the design exploration will be evaluated and processed.

This paper presents the findings of a study on the outcomes of the morphological chart method implemented for a short-term educational project on drip filter coffee makers. The project was repeated four years in a row, for a graduate course on design methods, with different sets of students participating in the project each time. The project followed a design process that began with an in-depth analysis of the design problem (drip filter coffee makers), followed by idea generation using the morphological chart method. The outcomes of the method were A1 size charts containing many table cells filled in with freehand sketches. Fundamentally, the method was found to be effective in achieving design divergence. Concentrating on the content of twelve morphological charts prepared by twelve participant groups for drip filter coffee maker components, collected throughout the four years, this paper examines the performances of participants in design divergence in order to identify the factors that contributed to the effective implementation of the method. The charts contained a total of 686 freehand sketches for sub-solutions. A visual content analysis of this data was carried out to reveal the ways in which participants extended and explored the solution space. The research questions were:

- What are the factors affecting participants' performances in design divergence using the morphological chart method?
- What are the strategies that participants followed for idea generation using the morphological chart method?

Within this framework, the paper begins with a literature review on the morphological chart method, its aims and outcomes, the significance of design divergence for idea generation, and the ways in which the method supports it. The paper then describes the study and data analysis procedure. The paper concludes with the presentation of the findings answering the above research questions, and a brief discussion on insights gained on design divergence for a fixed problem.

2. The Morphological Chart Method and Design Divergence

The morphological chart method is based on the General Morphological Analysis (GMA) method developed by Fritz Zwicky, for the investigation of non-quantifiable problem complexes (Ritchey, 2013; Ritchey, 2017). The method is used for breaking down a problem into sub-functions (problem decomposition), generating numerous sub-solutions for these (design divergence), and selecting and combining the suitable sub-solutions into alternative overall solutions (design convergence) (Cross, 2000; Magrab, Gupta, McClusky and Sandborn, 2010; Pahl and Beitz, 1996; Roozenburg and Eekels, 1995; Wright, 1998). This method is recommended for use particularly in idea development stages, where the solution space is extended in search of all possible means that can act as a solution for a sub-function; this includes a search for form, as the name (*morph-*) implies. Richardson, Summers and Mocko (2011) summarise the benefits of the morphological chart method as: enlarging the design space to be explored, generating novel concepts that would otherwise not be considered, and representing a wide range of concepts allowing the unexpected matching of components to be considered.

The morphological chart is a table that lists the sub-functions on the first column, and places numbers in the cells of the heading row to represent sub-solutions (generally around six) (Figure 1). The first step of the method is to determine the sub-functions expected from the final solution to fulfil, which can be done using various methods such as function analysis (Sapuan, 2005; Roozenburg and Eekels, 1995), brainstorming (Yang, 2009), determining product design specifications, and customer requirement analysis (Wright, 1998). It is expected to consider all possible means of fulfilling a sub-function when filling in the morphological chart (Wright, 1998) and this works best when the sub-functions are considered as independent of each other as possible (Cross, 2000; Roozenburg and Eekels, 1995). The sub-functions are expressed in the same level of generality and preferably in abstract terms rather than referring to physical components (Cross, 2000).

	Sub-solution 1	Sub-solution 2	Sub-solution 3	Sub-solution 4	Sub-solution 5	Sub-solution 6
Sub-function 1						
Sub-function 2						
Sub-function 3						
Sub-function 4						
Sub-function 5						
Sub-function 6						
Sub-function 7						
Sub-function 8						

Figure 1. A typical morphological chart representing eight sub-functions and six sub-solutions, yielding a total of 48 cells to be filled in with design ideas.

The next step is to fill in the rows for each sub-function with ideas for sub-solutions. These sub-solutions should offer means to achieve the sub-functions, and therefore represent physical components. Various strategies may be followed in filling in the charts. Hsiao and Huang (2002) apply several shape generation rules to diversify product types, following a certain logic, such as changing the shape of one part and keeping the rest the same, then changing the shape of two parts, and so on. In their experiments, Smith, Richardson, Summers and Mocko (2012) constructed morphological charts with tables in different sizes, variating the numbers for the sub-functions and sub-solutions (*means*). Their evaluations of engineering student performances showed that the final design solutions obtained from charts with a higher number of means and a lesser number of sub-functions gave better results in terms of task management and quality design concepts. Their findings emphasize the benefits of limiting functional decomposition, and rather allowing space for the conduct of idea generation for sub-solutions. As such, the literature recommends a comprehensive list of sub-functions that is not too long (Cross, 2000; Wright, 1998; Roozenburg and Eekels, 1995) and 8 to 12 items seem to be ideal.

The completed chart presents alternative sub-solutions from which to combine, yielding a large number of alternative solutions. This is presented in the literature as a weakness of the method, the disadvantages of which are cited as: difficulties in exploring the large number of concepts, not all combinations of components yielding feasible solutions; and lack of guidelines for determining those components that would be useful (Richardson et al, 2011; Smith et al., 2012). Therefore, the selection of sub-solutions to combine requires effective strategies for evaluating potential sub-solutions (Roozenburg and Eekels, 1995). To prevent the information overflow that this method can create, Lo, Tseng and Chu (2010) suggest using the quality function deployment method (QFD) in advance in order to transfer client requirements into design specifications and then into function modules, and also computer modelling the sub-solutions to be able to assess their feasibility as they are being generated. Mansor, Sapuan, Zainadur, Nuraini and Hambali (2014) suggest first using the theory of inventive problem-solving method (TRIZ) in order to generate solutions, then using the morphological chart as the idea refinement tool, to be able to generate relevant solution principles that are transferrable into specific design features. Van Boeijen, Daalhuizen, Zijlstra and Vander Schoor (2013) suggest grouping sub-functions and rank ordering them; sub-solutions are thus selected according to sub-function groups in order to facilitate the evaluation process. Magrab et al. (2010) suggest rank ordering sub-solutions per row. Pahl and Beitz (1996) suggest using compatibility matrices in order to assess the degree to which two sub-solutions match one another. Mansor et al. (2014) recommend the analytical hierarchy process (AHP) as the concept design selection tool.

The final combinations can be given diverse embodiments (Magrab et al., 2010). Consequently, this also requires effort in revising, interpreting and adapting the selected sub-solutions while synthesizing an overall design solution (Pahl and Beitz, 1996; Roozenburg and Eekels, 1995).

Lo et al. (2010) explain that morphological charts are frequently used for product variant design, the generation of new designs made by changing the parameters of certain features of existing design. Various sources specify that this method does not particularly aim novelty through creative concept generation, but as Cross (2000: 105) remarks, provides “variations on established themes”, and this is an important design activity also forming the basis for creativity that displays itself as the restructuring of prevailing components. Cross (2000) describes the morphological chart method as an opportunity for systematically restructuring components under various combinations and thus extending the solution space for design exploration. The solution space is extended in two aspects: from an analytic perspective by generating alternative sub-solutions for decomposed sub-problems; and from a synthetic perspective by generating alternative combinations of these sub-solutions into overall solutions. Referring to different stages of the design process, the designerly activities required for both tasks are a combination of *divergence* and *convergence*.

Divergence is the initiating phase of the design process where the design problem is broken down into parts for *analysis*. Analysis is about carrying out various activities such as research, technical inquiry and concept search towards extending the solution space for the sub-problems. This phase prepares for the phase of *transformation* where design synthesis takes place; which is followed by the phase of *convergence* where alternatives are evaluated for selection (Jones, 1980). Within this context, Hsiao and Chou (2004) consider the morphological chart as a technique employed in the transformation phase where the problem components are identified as product features, and creative solutions generated for these are combined into alternative designs. In brief, design divergence that the morphological chart method supports, takes place in the analysis phase of the design process, where the design problem is broken down into its components and numerous sub-solutions are generated for these, and then in the synthesis phase where the selected sub-solutions are brought together into alternative overall solutions. This paper is concerned with design divergence taking place in the analysis phase, as this is the stage where an intensive design exploration is required for situated idea generation.

3. The Study

A short-term project on drip filter coffee makers was carried out four years in a row for a graduate course on design methods. The design problem was the renewal of the typical drip filter coffee maker (DFCM from hereon) by making product modifications, and the same project brief was given in each of the four years. The drip filter coffee maker was chosen to be studied as a design problem for its interrelated structure of components. The design process followed was composed of the stages of a) problem analysis, b) idea generation, and c) development of the final design proposal. The problem analysis stage was planned for an in-depth exploration of the design problem, to build the necessary technical and functional background for a grounded design exploration. The implementation of the morphological chart method took place in the idea generation stage, and aimed for an extensive design exploration before moving on to the stage of final design proposal development. As a result, twelve morphological charts were collected over the four years.

The study described in this paper was carried out to investigate the role of the morphological chart method in supporting design divergence for a fixed design problem, and the factors that contributed to the effective implementation of the method. The focus of the study was the contents of the twelve morphological charts. The study involved a two-step review.

- The design process was reviewed for all four years, in order to determine the contribution of the preparations made, to the idea generation stage. The data for this comprised of the project brief and exercise briefs distributed in class to the participants, and the submissions that the participants made (collected digitally).
- Then, the morphological charts, prepared by groups of participants, were reviewed in terms of content and representation, in order to examine the participants' performances in effectively using the method, and identify their idea generation strategies. The data for this included the digital copies of twelve A1 size morphological charts filled in with 686 freehand sketches of ideas for DFCM components.
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3.1 The Participants

Four different sets of graduate students participated in the project in respective years; the total number of participants were 50 (Table 1). Forty-four had background in design-related fields (42 industrial designers, two interior architects). Six were from fields other than design (preschool education, mechanical engineering, industrial engineering, business administration). The participants worked in groups for the tasks carried out in each stage of the process; the final submissions of design proposals were made individually.

Table 1. The participants

Participants (Total: 50)	Female	Male	MSc	PhD	Design background	Non-design background	
2013	05	01	04	02	04	02	06
2014	09	08	11	06	15	02	17
2015	13	06	13	06	19	00	19
2016	03	05	05	03	06	02	08
TOTAL	30	20	33	17	44	06	50

3.2 The Design Process

The project was carried out in four course sessions, each being four hours once a week. The design process followed for the project was the same for all four years (Figure 2).

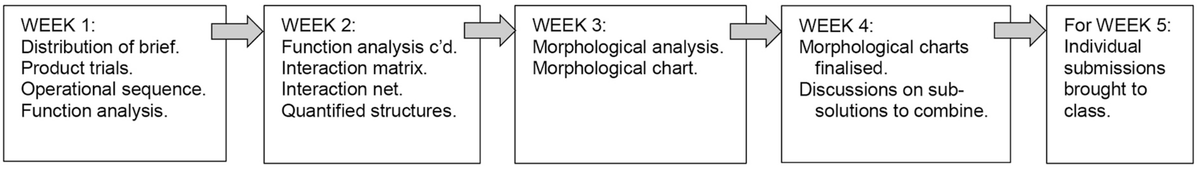

Figure 2. The time plan followed for the DFCM project design process.

i) Product Trials: The process began with trials of various product examples to understand how DFCMs operate. Participants prepared filter coffee for themselves using drip filter coffee makers brought to class. The number of the DFCMs ranged from five to seven per year (Table 2).

Table 2. The drip filter coffee makers used in the project

	Arçelik	Bosch Private Collection	Braun	Ciatronic	Goldfilter	Philips MyAroma	Touchme
							
2013	X		X	X	X	X	
2014	X	X	X	X	X	X	
2015	X	X	X	X	X	X	X
2016		X	X	X	X		X

ii) Operational Sequence: Determining Sequence of Product Operation: Based on product trials, participants prepared an operational sequence chart, which is a flow chart representing the way in which the product operates (Kirwan and Ainsworth, 2005). They were asked to identify the actions that initiate an operation, the chain of operations that follow during functioning, the actualization from the users' part during operations, the results of operational steps and how these impact new ones (Figure 3).

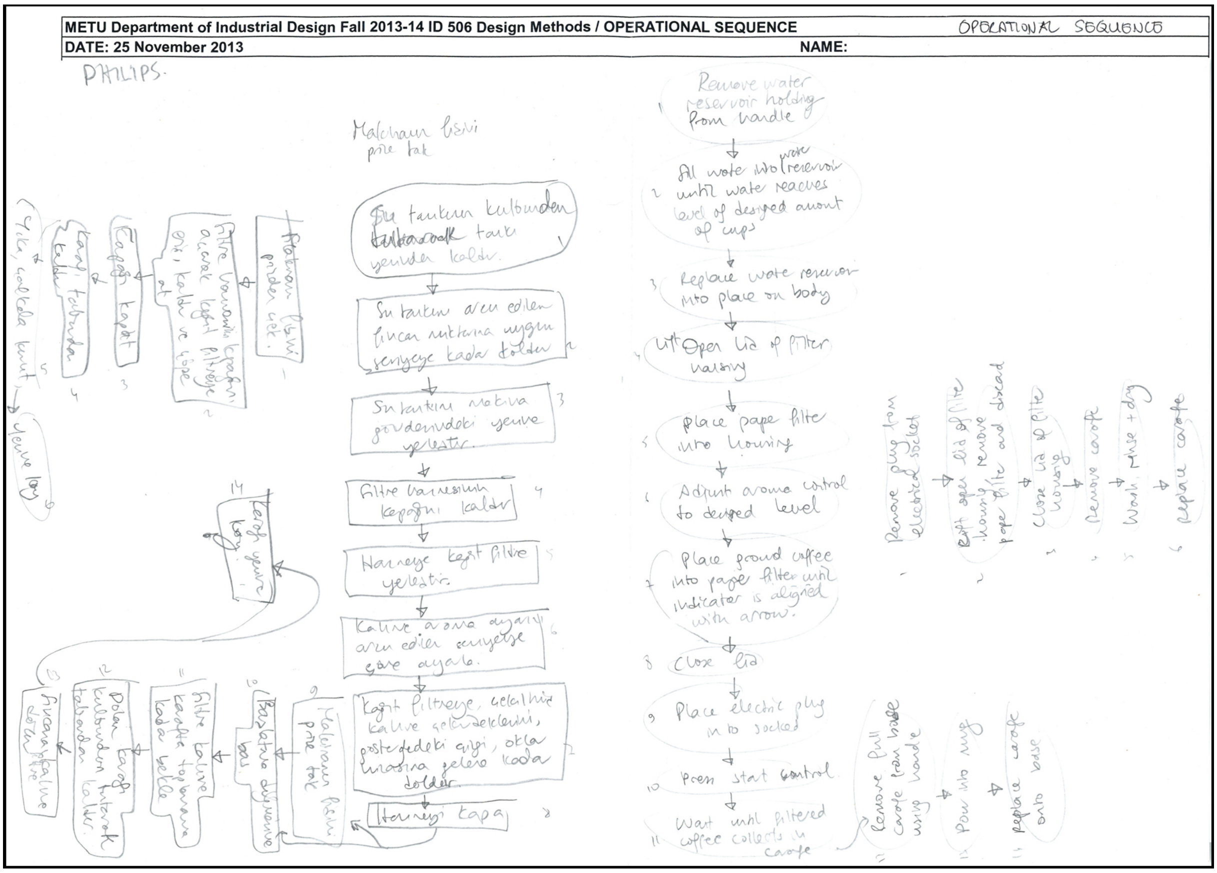

Figure 3. Operational Sequence Chart prepared for the Philips MyAroma DFCM (2013).

iii) Function Analysis: Determining Product Components and Sub-functions: Participants then made a function analysis (Roozenburg and Eekels, 1995; Cross, 2000), also known as problem decomposition (Wright, 1998) or function structure (Pahl and Beitz, 1996) (Figure 4). Function analysis considers the product to be a technical-physical system that is a means for transforming input into output (Wright, 1998; Cross, 2000). In the case of DFCMs, input is energy (electric) and matter (coffee and water), which are converted into output, that is filter coffee. Based on the function analysis of the products, the components were identified and their functions were described. Each component was given a letter and represented in a block diagram showing the interaction between means for sub-functions working together for realising the essential function (Wright, 1998; Cross, 2000), the function that the product must satisfy primarily (Srinivasan, Chakrabarti and Lindemann, 2012; Kitamura and Mizoguchi, 2010).

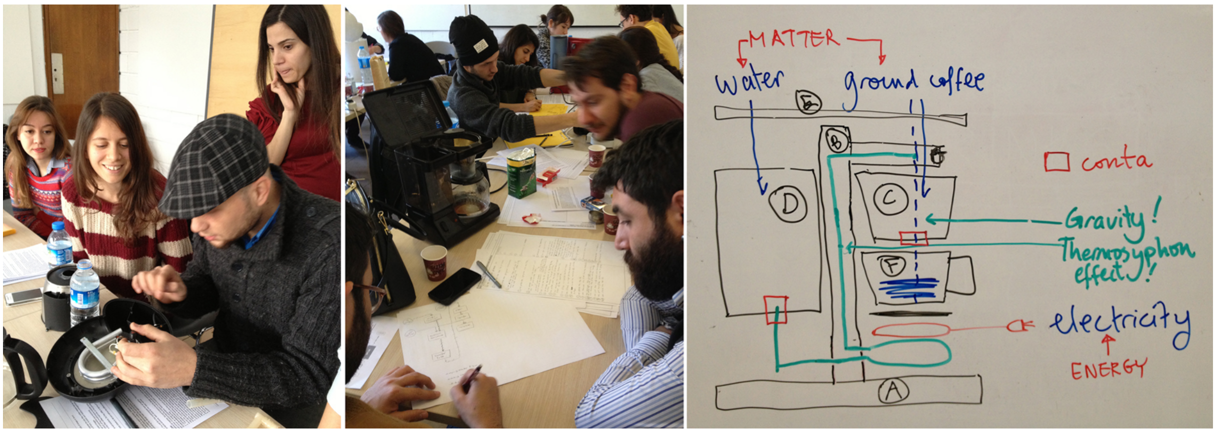

Figure 4. Left: Product disassembly during product trials (2013). Center: Function analysis during product trials (2014). Right: A diagram prepared collectively on white board based on function analysis (2015).

iv) Interaction Matrix and Net: Determining Functional Connections of Components: In the following stage, participants studied the functional relations among the components and their levels of connectedness using the interaction matrix (Jones, 1980). On the intersecting cells of the matrix the links between components were marked as either existing or non-existing depending on the type of connection. The interaction matrices were then converted into interaction nets (Jones, 1980) in the form of a diagram that displayed the direct links between components (Figure 5).

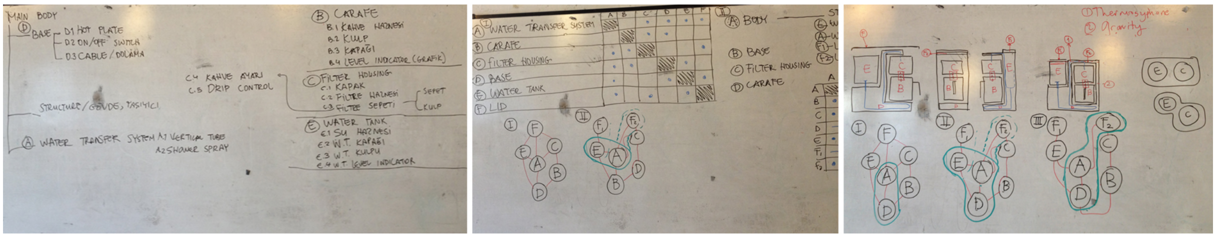

Figure 5. Left: Components and sub-components determined. Center: Interaction matrix and interaction net prepared for the components. Right: Three types of quantified structures identified for the DFCMs studied in class (2016).

This net allowed to determine among the seven DFCMs examined in class, three types of relative arrangements of components, which are variations on component configurations (Tjalve, 1979). The relative arrangement of a product is affected by the working principle based on which it operates (Pahl and Beitz, 1996). The working principles for the DFCM are *thermosyphoning* and *gravity*, around which the components are configured. When the water reservoir is placed in its position, the gasket underneath it opens, allowing water to run into a tube within the product base, placed underneath the hot plate. Between the hot plate and the water tube is positioned a heating coil. When switched on, the coil starts heating the hot plate and the water tube. The heated water rises upwards as a result of the thermosyphoning effect, and moves onto the filter shower head. The water thereon drips onto the ground coffee in the filter basket with the help of gravity, hence giving the product its name. Keeping these common working principles, the DFCMs varied in terms of component configurations.

v) Quantified Structure Analysis: Determining Structural Relations of Components: Participants next explored variations for the component configurations of the DFCM. They were asked to represent the relative arrangements of the DFCM components examined in class as simple diagrams of quantified structure and then generate alternative quantified structures in regard of the working principles (Figure 6, left). This type of diagram shows the configurations of product components and their dimensions (size, volume, distance) in correct proportions (Tjalve, 1979), and is used to search for alternative component configurations.

In the first two years, the exploration for quantified structures was carried out on paper, in two-dimensions (2D). In the following two years, the participants were asked to support their 2D exploration with three-dimensional (3D) representations of the components allowing component manipulation and spatial exploration (Figure 6).

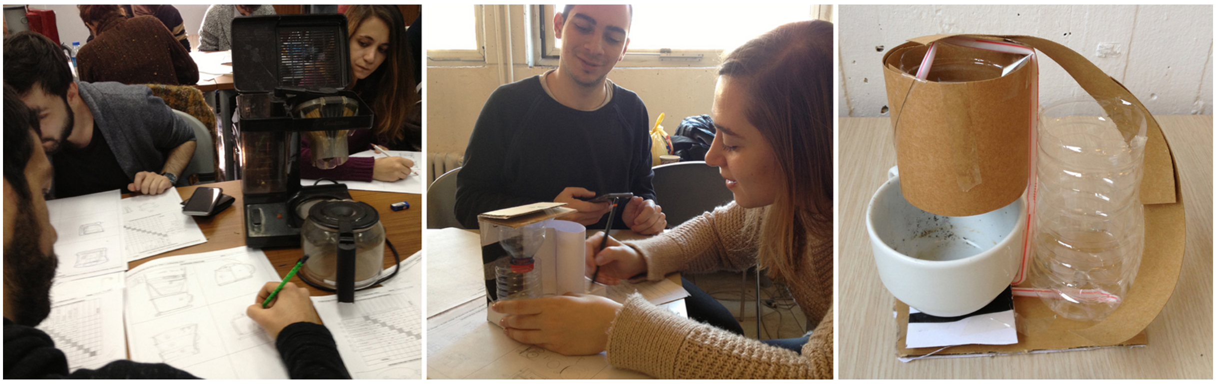

Figure 6. Left: Participants developing quantified structures in 2D (2015). Centre: Participants developing quantified structures in 3D (2016). Right: A 3D quantified structure (2016).

vi) Morphological Analysis: Determining Variations in Product Features: In the next stage, participants carried out a morphological analysis in groups to compare the DFCM components in terms of design features. Groups were handed out envelopes with shuffled images of the sub-components of the DFCMs studied in class. On charts that were distributed, they assembled and pasted these components according to the DFCMs that they belong to (per column) and the sub-functions that they fulfil (per row) (Figure 7, left). Groups then conducted discussions on the completed charts to compare the components and determine whether the designs differ in terms of *form*, *function*, *working principle* or *relative arrangement* (Figure 7, right).

Figure 7. Left: Groups sorting out their shuffled component images (2014). Right: Groups studying their completed charts (2015).

vii) Morphological Chart Method: Design Divergence for Product Sub-solutions: Subsequently, participants carried out idea generation for DFCM components using the morphological chart in groups. The sub-functions that the design solution must perform were determined altogether in a short brainstorming session. Groups itemised the sub-functions on the first column of their charts, and generated alternative sub-solutions that could perform the sub-functions on each row (Figure 8).

Figure 8. Left: Group of four working on their morphological chart (2016). Right: Group of four working on their morphological chart (2015).

The performances of the groups from the first two years of project conduct (2013, 2014) showed that, implementing the morphological chart method for the first time brought its limitations. It took two class sessions for these groups to fill in their charts, and most charts remained incomplete (Figure 9, left). Therefore, in the following two years (2015, 2016), to prepare for this project, a prior morphological chart exercise was conducted for a product of a less complicated component structure, for participants to familiarise with the mechanics of the method and amount of effort required. Thus, during the DFCM project, all participants from these two years had brief experience in using the method. The DFCM morphological charts of these years were prepared more rapidly, and almost all were complete (Figure 9, centre and right).

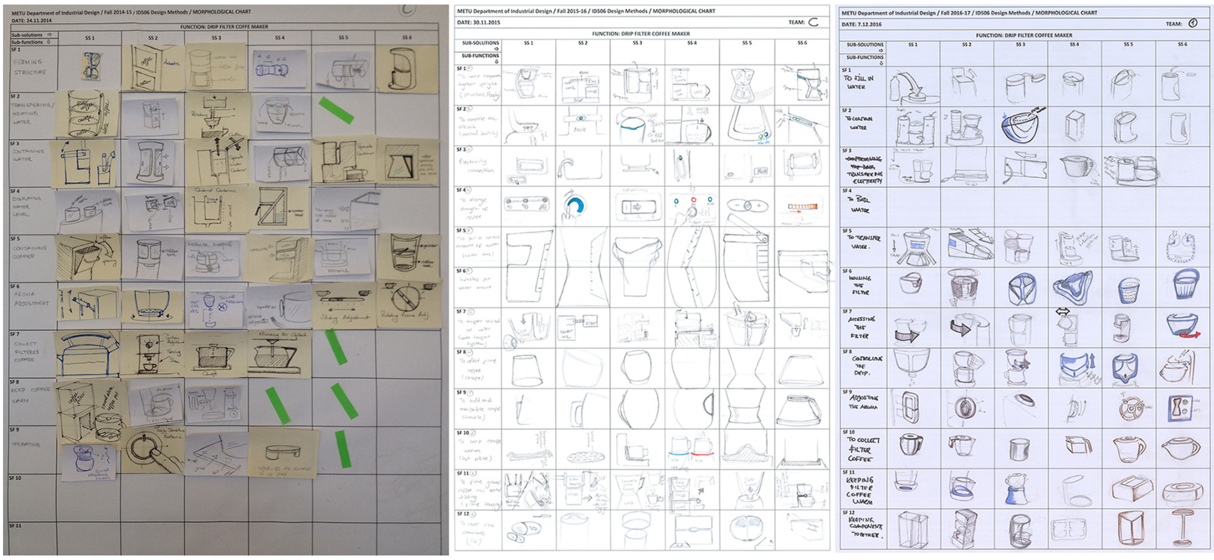

Figure 9. Left: DFCM Morphological chart with empty cells (2014, Gp-D). Center: DFCM Morphological chart filled in entirely (2015, Gp-H). Right: DFCM Morphological chart filled in almost entirely (2016, Gp-K).

viii) Final Design Proposals: When the task was completed, groups examined their charts and decided on the sub-solutions that would work well together in terms of function and attribute. Then, group members individually combined the sub-solutions that they chose from rows, to generate one alternative design proposal on A3 size sheets. These design proposals were the final submissions made for this project.

4. Analysis of the Data

The twelve morphological charts contained a total of 686 freehand sketches for sub-solutions, constituting the data for this study. This data was subjected to visual content analysis. Content analysis is a method that involves the decomposition of meaningful material (including visual and text) into identifiable units and their coding into a hierarchical classification that can then be processed (Krippendorf, 2004). From the classification can be determined patterns, revealing themes that help explain the material (Savin-Baden and Major, 2013). The contents of the DFCM morphological charts were reviewed using both quantitative and qualitative approaches. Two sets of A3 size copies were printed out from the digital copies of the original morphological charts. One set was used for an overall evaluation. The other set was used to cut out and group sub-solution rows for sub-functions. All sheets were displayed on the wall and analysed for visual clues. These clues were identified from the representations of sub-solutions, as drawing elements (Schenk, 2014; Suwa, Purcell and Gero, 1998; McGown, Green and Rodgers, 1998) and as independent units of design ideas (Goldschmidt, 2016; Sun, Xiang, Chai, Wang and Huang, 2014; Yilmaz and Seifert, 2011).

4.1 Quantitative Analysis

For a quantitative analysis, the number of cells on the charts, sub-functions treated, cells that offered sub-solutions for these sub-functions, and groups that addressed these sub-functions were identified and tabulated (Table 3). A total of 21 sub-functions were identified from the pool of sub-functions that groups determined for themselves, with the numbers of sub-functions explored in the charts ranging from 8 to 13 (Table 4). The sub-functions were thematically distributed into four categories, describing the groups of sub-functions that were functionally related. From among these, *sub-functions related to working principles* (water reservoir, filter housing, coffee strength adjustment, drip nozzle and carafe) were explored the most, with 269 cells dedicated to sub-solutions. These sub-functions are those supporting the essential function of the drip filter coffee maker, and include containing water (input), containing ground coffee (input) and containing filter coffee (output). This indicates an interest in the exploration of components that characterise the DFCM, and the central role that these components play in fulfilling its essential function.

The charts were then reviewed according to group performance. Group compositions were revised, revealing that five groups were mixed (A, B, C, K and L), with some participants from non-design backgrounds, and seven groups were formed of designers only (D, E, F, G, H, I and J). Five groups (A, B, C, D and E) from the first two years (2013, 2014), carried out a 2D quantified structure exploration only, and had no prior experience in using the morphological chart method. Seven groups (F, G, H, I, J, K and L) from the final two years (2015, 2016) carried out both 2D and 3D quantified structure explorations, and had experience in using the morphological chart method. In the first two years, the average number of filled-in cells per participant ranged from 7,2 to 11,34, whereas in the final two years, this number ranged from 15 to 24. It is seen that the average numbers of cells filled in per participant have risen in the final two years (Table 4). The groups F, G, H, I and J filled in all their cells, and Group K had only one cell empty out of 66. The charts with the lowest average numbers of full cells per participant were produced by groups A, B, C, E and L. Groups A, B, C and E were from the first two years, with participants using the method for the first time. Besides, groups A, B, C and L had members from non-design backgrounds. From this assessment, it was inferred that having carried out a 3D quantified structure exploration, experience in using the morphological chart method, and group composition, were among factors affecting group performance.

Table 3. The sub-functions explored

		Sub-function	No. of Groups	No. of Sub-solution Cells
Group 1: Sub-functions determining component configuration	**1A**	Structure	10	60
		Relative arrangement	2	12
	1B	Transfer of boiled water from reservoir to filter housing	3	16
		Boiling water	2	8
		Transferring water	8	38
				(134)
Group 2: Sub-functions related to working principles	**2A**	Water reservoir	12	67
	2B	Filter housing	9	50
		Adjustment of coffee strength	10	53
		Drip nozzle	7	34
	2C	Carafe	12	65
				(269)
Group 3: Sub-functions related to operating components	**3A**	On/off switch	9	42
	3B	Cable and cable storage	6	35
	3C	Hot plate	12	59
				(136)
Group 4: Features common to sub-functions	**4A**	Carafe handle	6	36
	4B	Carafe lid	2	12
		Water reservoir lid	2	12
		Filter housing lid	2	10
		Lid for overall DFCM	4	24
		Lid (mixed components)	1	6
	4C	Water level indicator	8	39
		Coffee amount indicator	1	8
				(147)
		TOTAL No. of CELLS		**686**

Table 4. Numerical information on the twelve morphological charts

	2D quantified structure exploration; No morphological chart experience.					**2D and 3D quantified structure exploration; With morphological chart experience.**						
	2013	2014				2015					2016	
	Gp-A	Gp-B	Gp-C	Gp-D	Gp-E	Gp-F	Gp-G	Gp-H	Gp-I	Gp-J	Gp-K	Gp-L
No. of group members (a)	6	4	5	4	4	4	4	4	3	4	4	4
No. of sub-functions (b)	13	8	9	9	10	12	11	12	12	10	11	11
No. of columns for sub-solutions (c)	7	6	6	6	6	6	6	6	6	6	6	6
Total no. of cells in chart (bxc) (d)	91	48	54	54	60	72	66	72	72	60	66	66
No. of filled-in cells (e)	68	36	36	44	41	72	66	72	72	60	65	54
No. of empty cells (d-e) (f)	23	12	18	10	19	0	0	0	0	0	1	12
Ave. no. of cells per participant (d/a) (g)	15,17	12	10,8	13,5	15	18	16,5	18	24	15	16,5	16,5
Ave. no. of filled-in cells per participant (e/a) (h)	11,34	9	7,2	11	10,25	18	16,5	18	24	15	16,25	13,5
Difference (g-h)	3,83	3	3,6	2,5	4,75	0	0	0	0	0	0,25	3

4.2 Qualitative Analysis

The qualitative analysis of the chart contents was carried out in three stages. The charts were first reviewed in whole for *representational quality*. Representational quality was assessed by the ways in which the drawing elements, symbols and annotations were used

(Bar-Eli, 2013), the levels of complexity in which ideas were represented (McGown et al., 1998), and the degree of detailing in the sketches (Tovey, Porter and Newman, 2003). This was done in order to identify the operational strategies of participants in quick sketching for design divergence.

Following, rows of the charts were cut out and those belonging to specific sub-functions were brought together on separate sheets in order to review *the information content of the ideas* generated for each sub-function (Yilmaz, Seifert and Gonzales, 2010; Rodgers, Green and McGowan, 2000; Do, Gross, Neiman and Zimring, 2000). This involved a descriptive assessment of what the design solutions were about and how they offered to fulfil sub-functions, and was made according to the thematic grouping of sub-functions (Table 3). This assessment helped determine the design directions followed, topics and themes addressed, means offered for fulfilling sub-functions, interrelations between components, and interactions between the user and DFCMs. It was seen that the ideas offered design solutions grouped around: component configuration, form (shape, size, amount, texture, material), means (ways in which an operation is carried out), component location (in reference to overall DFCM), and consequences of operations.

The morphological chart contents were reviewed for a third time to understand *how participants actualised design divergence*. For this, the ways in which participants approached the task of filling in the morphological charts (e.g. how they began sketching, continued with idea generation, and completed the charts) were examined. Also, the various design thinking tactics that participants employed for idea generation (e.g. how they increased ideas in number, and diversified them) were studied (Börekçi, 2017). As a result, several factors that affected participants' performance in design divergence, as well as particular strategies that they employed for idea generation, were identified. The following section presents the findings, supported with insights gained from the four years of experience in conducting the project and observations on how participants used the morphological chart method.

5. Factors Involved in Design Divergence Using the Morphological Chart

It was seen that, in the design divergence task of filling in morphological charts, participants displayed performance in terms of the following abilities:

- time keeping (completing the charts within a given timeframe),
- producing quantity (amount of ideas for particular sub-functions),
- producing variety (degree to which ideas were diversified to explore various possible means),
- attaining complexity (extent of information conveyed with an idea),
- attaining creativity (extent to which ideas displayed out-of-the-box thinking).
- achieving idea quality (generating ideas able to address the design problem), and

- achieving representational quality (visually communicating ideas in an effective way).

The performance of participants in displaying these abilities ranged from low to high, depending on certain factors. The factors that affected these abilities were found to be based on preparations undertaken before carrying out the design task, and dynamics of the participant compositions in the groups. How the participants defined sub-functions towards setting their problem boundaries, and to what degree the product components were interrelated were also found to affect performance.

5.1 Preparations

Research on the problem area: Being informed on the problem area through product trials and product analysis contributed to the performance of participants. Participants were ready in terms of technical background, as well as familiar with various precedents.

Experience in using the morphological chart: Having prior experience with the morphological chart seemed to have positive impact on idea generation performances. The general tendency in groups with experience was for participants to work individually on all the cells in an entire row and generate ideas successively (Aspelund, 2010) rather than filling in random cells for whatever idea came first. This suggests that the participants understood the mechanics of the method and made use of it for design divergence.

5.2 Group Dynamics

Setting a common ground: Some groups carried out a short discussion on the possible relative arrangements that could be considered, bringing a holistic (from whole to parts) approach to the design task, also giving direction to the individual efforts of the group members. One group of mixed participants supported their process with collective online search for product examples.

Making strategic decisions: Carrying out discussions at the onset of the method helped groups make strategic decisions, such as how to name the sub-functions, which sub-functions to combine, which ones to consider as independent of others, and which ones to consider in relation to others.

Division of labour: Based on discussions, some groups divided labour. This mostly was about sharing sub-functions among group members. Five groups filled in the cells in a mixed manner; meaning, members freely filled in the cells that were closest to them, with ideas they could think of first for random sub-functions. Therefore, ideas represented in rows were not always indicative of an order of appearance; such that, some ideas were drawn upside down in reference to the chart orientation. These groups were those who used the morphological chart method for the first time.

Six groups distributed the sub-functions among members and worked individually on entire rows. These groups performed well in generating a succession of sketch ideas and completing their shares. One group filled in the charts conjointly; to begin with, each group member filled between 2 to 4 cells in each row, then the group members swapped sub-functions, and filled the remaining 2 to 4 cells in each row. This effort ensured that all the cells were filled.

Thinking on others' ideas: Group members also undertook the filling in of cells that remained empty. Some participants were observed to write over annotations to make them legible, go over sketches that remained weak, and use markers to highlight sketches, on behalf of the group. This helped to complete the charts, gave the charts a group identity, and ensured that group members were familiar with the ideas of others.

Working together versus working away: An initial group discussion and working together helped groups develop strategies in order to proceed with the work. A designer participant in one group was observed to sketch on behalf of a non-designer fellow group member who explained her ideas and gave instructions on how the solution should be represented. Two groups that did not carry out discussions at the beginning worked individually over the chart, and after a certain level of progress, group members preferred to work at separate desks on pieces of paper which they later pasted onto the chart. This indicates a tendency in working in parallel but away from the others and not in collaboration. These groups were those that had the lowest average number of filled-in cells per participant.

5.3 Boundaries of Sub-functions

Level of familiarity with sub-functions: Participants were familiar with the problem situation, and also had studied the product components. This made it easier for them to suggest alternative working principles from similar problem situations and transfer them onto the sub-functions of the DFCM (*e.g. hooks or winding springs for winding the electric cable*).

Degree to which parameters for sub-functions are fixed: Participants mainly generated alternatives in form when the problem boundaries were fixed (*e.g. carafe sits on hot plate*) and parameters known (*e.g. volume of water reservoir is compatible with volume of carafe*). On the other hand, participants generated alternatives in means for fulfilling sub-functions more, when parameters were not rigidly set (*e.g. accessing the filter housing somehow*).

5.4 Interrelations of Product Components

Level of complexity of components: Complicated components were studied more in depth compared to simple components, in terms of relative arrangements of sub-components, working principles, consequences of operation, interaction between other components, and form for functionality.

Level of interaction between components: Participants tended to explore the direct and indirect effects of their design decisions. The interactions of complex components with neighbouring components were explored more, compared to simple components. Participants isolated components totally independent of others such as carafe, or sub-components such as handle, in their form exploration. Less independent components were almost always drawn with neighbouring components.

6. Strategies for Idea Generation Using the Morphological Chart

A significant factor in participant performances in design divergence was the usage of various idea generation strategies. These were the design thinking and idea representation tactics that participants employed for effectively generating and representing ideas. The strategies were determined for beginning idea generation, carrying out effective idea generation, exploring ideas, diversifying ideas, and representing ideas.

6.1 Strategies for Beginning Idea Generation

Naming the sub-function: The way the sub-function was named indicated how groups decided to approach the sub-problem. The general tendency was to use nouns as the names of sub-functions for components that were relatively more independent, with fixed problem boundaries (*e.g. "carafe", "hot plate"*). In this case, form was explored more confidently. On the other hand, sub-functions were described in general terms for components that were more closely related to neighbouring components with problem boundaries not yet fixed (*e.g. "boiling and transferring water"*; *"keeping product components together"*). In this case, working principles and sub-component configurations were explored to begin with.

Finding sources for ideas: Participants used precedents, analogies and transfers as sources supporting idea generation (Figure 10). Participants used sub-solutions offered on precedents, meaning other DFCM examples (*e.g. drip nozzle, electric cable winder, water level indicator*). They used analogies related to form (*e.g. bubbles*), function (*e.g. stove*) or working principles (*e.g. water dispenser*). They also made transfers for sub-solutions from other product categories (*e.g. interfaces from electronics*).

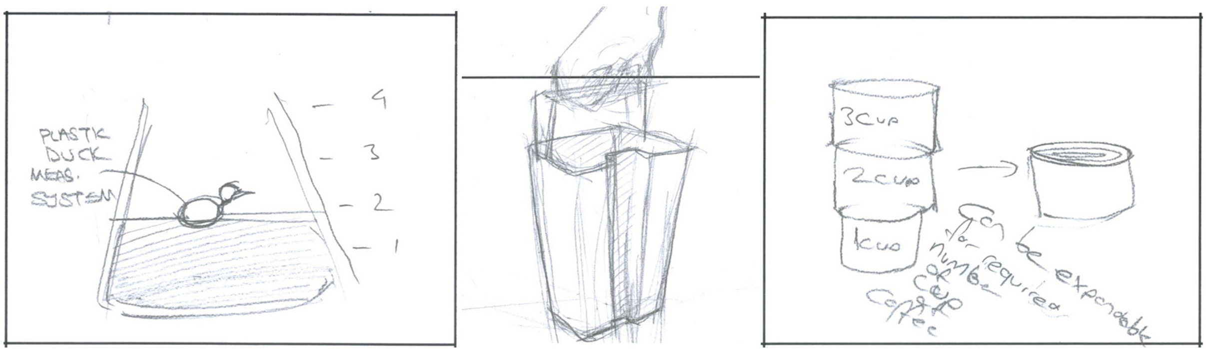

Figure 10. Left: Functional analogy of a rubber duck as level indicator (2015, Gp-J). Center: Handle solution from a precedent examined in class (2015, Gp-I). Right: Transfer of telescopic extension for expanding filter basket (2015, Gp-J).

6.2 Strategies for Effective Idea Generation

Thinking holistically: All groups started generating ideas for "product structure" or "relative arrangements" first, before moving on to other sub-functions. As for sub-functions, groups generally sketched a whole or partial product showing the position of a feature on the DFCM somewhere in the row. This was preceded or followed by close-up sketches of alternative solutions for the particular feature in the other cells. Participants also displayed the need to contextualise their exploration and even when they worked mainly on a particular feature, they still tended to show neighbouring components in their sketches.

Successive thinking: For groups that completed their charts without leaving cells out (F, G, H, I and J), a significant strategy affecting their performance was successive thinking. Once participants in these groups started idea generation, they aimed to complete an entire row (Figure 11). This supported goal-oriented thinking and variation of ideas. These groups were all formed from designer participants.

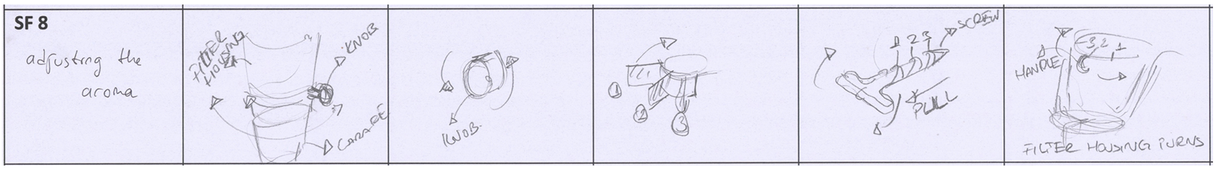

Figure 11. Successive thinking for variations, showing controls for adjusting coffee strength on filter housing as well as on their own (2016, Gp-L).

6.3 Strategies for Exploring Ideas

Exploring form: Form-related explorations were functional as well as aesthetic. One strategy was, deciding on an overall product form that was then broken down into its components, which were then explored (Figure 12, left and centre). Another strategy was exploring forms of components that were determined as most significant (e.g. *carafe*), and building the remaining product components around it. Material properties and surface qualities were also explored as part of form.

Exploring working principles: Explorations of working principles took place for: alternative ways of fulfilling same function; alternative configurations of components (Figure 12, right); and common or shared features in different components. The effects of a new working principle suggested for a sub-function were shown for the particular sub-function for which it was suggested, and also for its neighbouring components.

Exploring common means for realising different sub-functions: Some sub-functions common to multiple components such as controls, handles and lids, were solved in common ways (*e.g. common controls for on-off switches and coffee strength adjustment*; *common handles for carafe and water reservoir*; *common lids for water reservoir and filter housing*). Common means were seen as the feature identifying a product component family.

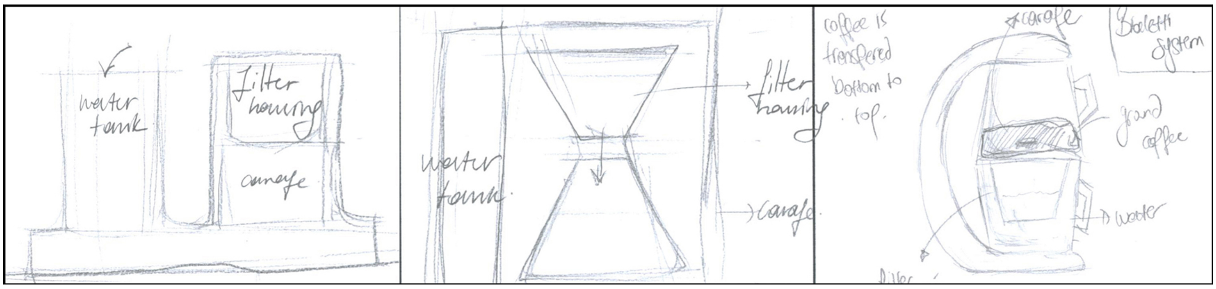

Figure 12. Exploration of form on same row. Left: Dispersed layout of components. Centre: Components divided from a volume by same group member. Right: Components reconfigured by another group member (2015, Gp-I)

6.4 Strategies for Diversifying Ideas

Thinking on consequences: Participants tended to consider the effects of their sub-solutions in terms of output as well as the consequential actions triggered in other components. Therefore, there were sketches showing components in various versions (*e.g. open/closed*) and in various situations (*e.g. before/after*).

Using parallel perspectives: Some sub-functions were explored in multiple rows besides the row dedicated to them; there could be sub-solutions offered for them in rows exploring other sub-functions. This means, participants did not isolate sub-functions and consider them to be entirely independent of others. They had the tendency of thinking on multiple design solutions simultaneously. Therefore, another significant finding was that cells generally contained multiple design solutions.

Shifting perspective: Participants varied their approaches to the sub-functions using certain tactics. These were: combining sub-functions (*e.g. water reservoir and structure*); eliminating sub-functions (*e.g. eliminating water reservoir altogether*); splitting sub-functions (*e.g. making a separable hot plate*); adding new sub-functions to a component (*e.g. funnel integrated lid for pouring in water*); adding new sub-functions as a component (*e.g. coffee bean grinder*); and suggesting alternative means for a sub-function (*e.g. using commercial water bottle instead of including a reservoir*) (Figure 13).

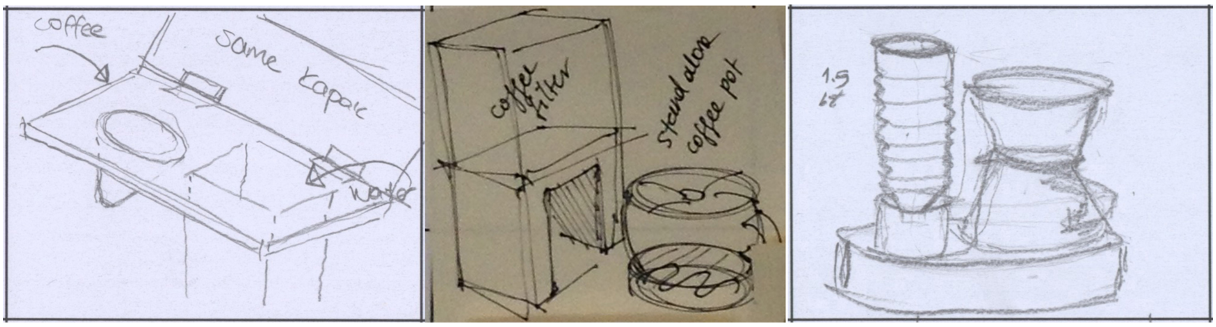

Figure 13. Left: Combined lid (2016, Gp-L). Centre: Split hot plate (2014, Gp-D). Right: Alternative means for the water reservoir (1,5 lt water bottle placed upside down) (2016, Gp-K)

6.5 Strategies for Representing Ideas

Varying drawing elements: The cells contained a variety of sketch types, ranging from simple 2D diagrams to refined 3D sketches. Sketches were supported with annotations, the contents of which relating to: *function, material, effect, component, input* and *output*. Sketches included arrows to point out to features and locations, as well as show directions of movement. Shading and texture were used to give three-dimensionality and depict form of product parts; colour was used to emphasize a detail, show graphical applications or represent various stages on interface displays. User hands were represented to show size, usage and order of operations (Figure 14, left).

Varying focus: Sketches contained a mixture of ideas shown on whole or partial products, or on close-ups of details (Börekçi, 2017). Sketches of whole DFCMs showed overall form, component configurations, alternative working principles and their effect on configuration, and features on a particular component in reference to the remaining of the DFCM. Sketches of partial DFCMs showed components in detail, some with neighbouring components to indicate location or to show how an operation of a component affects the next one. Sketches of isolated components or features were also made. These were generally studies of form, drawings showing how features work (*e.g. moving, rotating, retracting parts; steps of operation*); specific characteristics of the features (*e.g. texture, pattern*); hidden parts or sections; and features of the interface (*e.g. knobs, controls, displays*).

Varying level of sketch detail: The more complicated the components, the more detailed the sketches were (Figure 14, centre). Some cells with detailed sketches included multiple drawings of a component, which could be perspectives, orthographic views and sections. Detailed sketches showed nesting and moving parts in 3D, using sections or drawing open and closed versions of a component. Such sketches also showed the DFCM in different situations (*e.g. with or without a component; during operation; when hot/when cold*). Less complex components were generally mainly explored for form. These sketches remained two-dimensional; some had incomplete contours with missing lines, probably for the purpose of using time economically, or due to the visual information being sufficient (Figure 14, right).

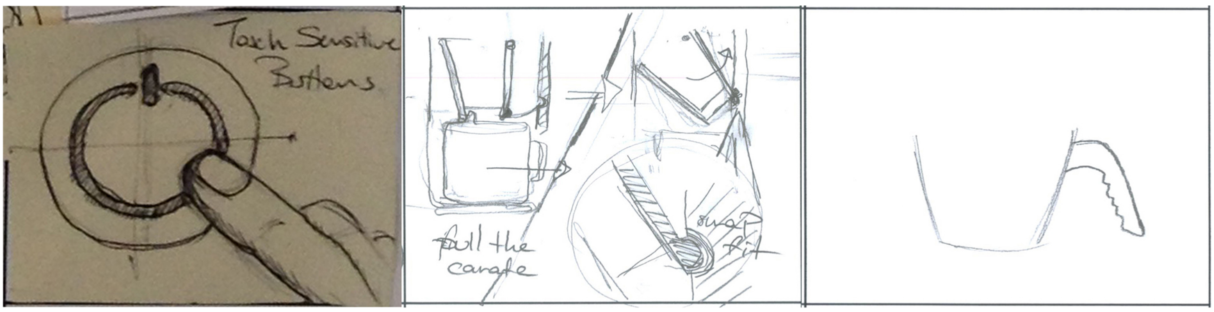

Figure 14. Left: Close-up sketch of a control with user's finger (2014, Gp-D). Centre: Detailed sketch with multiple drawings (2015, Gp-H). Right: Simple and incomplete sketch of a carafe showing handle (2015, Gp-F).

7. Conclusion

This study examined the performances of designers in using the morphological chart method for design divergence in idea generation. It was seen that participants treated the task as an opportunity for holistic and partial design exploration, and not mainly for the revision of possible means for fulfilling individual sub-functions. It is possible to make the following inferences regarding the findings of the study.

- The ways in which participants named sub-functions displayed the ways in which they approached the design problem (problem framing; Schön, 1991; Stompff, Smulders and Henze, 2016; Zahedi and Heaton, 2017), and also manifested variations in their level of abstraction (Teegavarapu, Snider, Summers, Thompson and Grujicic, 2007; Richardson et al., 2011; Smith et al., 2012). Sub-functions with fixed design specifications were named with nouns and explored freely in terms of form (e.g. “hot plate”; “carafe”). Those with parameters less rigidly set were named with functional descriptions, and explored more in depth in terms of means (e.g. “transferring hot water from water container to filter housing”).
- Although they were not guided in doing so, all groups collaboratively developed alternatives for tentative configurations representing the whole product first, and then broke them down for exploration (primary generators; Darke, 1984).
- This consequently allowed groups to set a common ground for design explorations, determine design divergence strategies and divide labour among members.
- When carrying out idea generation for a sub-function row, participants were inclined to think on multiple design features at the same time. Besides, they tended to continue explorations for some design features in other rows of sub-functions, in combination with new ones. They preferred exploring multiple components rather than isolated ones, demonstrating their tendency for thinking in parallel lines of thought (Lawson, 2000).
- Once working on a sub-function, participants tended to individually develop a succession of sub-solutions for completing the entire row at one go (Aspelund, 2010).
- Participants mostly considered components as interdependent and therefore explored the effects of their design decisions on the following steps of operation, related components and outputs.
- It was seen that designer participants were more accustomed to visual thinking with tactics that help explore a design problem, such as diversifying working principles and variating design ideas.
- They were able to use their 2D representation skills to demonstrate the consequences in different situational contexts, showing an ability in thinking in terms of process (*i.e. before, during and after*) and from the point of view of users (*i.e. how to, what if*).

The following direction of research would be to study the activities of design convergence carried out by the participants in the development of the final design proposals. This would require understanding their evaluation and selection processes of sub-solution alternatives to combine into overall design solutions. The main issues of enquiry in this case would be the criteria involved in the course, resolution of conflicts between selected sub-solutions, and decisions related to design embodiment.

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