Volume 20, Number 3, 2018

Global Journal of Engineering Education

Supporting idea generation with design tools: nesting design heuristics within morphological analysis

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ABSTRACT: As some design problems are complex, generating concepts for a complete artefact may be overwhelming for designers, especially for novices. Students often learn to use morphological analysis (MA) to decompose a problem into subcomponents, allowing them to focus on designing for more specific functions. However, generating new ideas for subcomponents remains a challenge for novices. In this study, the authors investigated an educational method combining the morphological analysis approach with a tool designed to facilitate the generation of novel, differing ideas called design heuristics (DH). The results demonstrate that adding design heuristics within morphological analysis supported students in building upon their ideas to generate concepts. These findings contribute to the knowledge about how to facilitate idea generation through supporting tools in design pedagogy and practice.

Keywords: Concept generation, design, morphological analysis, functional decomposition, design heuristics

INTRODUCTION

Designers, from novice to expert, face challenges in generating multiple creative ideas [1-4]. For example, designers have been shown to fixate on an initial idea, and as a result fail to explore broader possibilities [5]. Across expertise levels, it can be daunting to generate alternative ideas without support to facilitate broad exploration of a solution space.

The task of creative idea generation can be especially challenging in the design of complex large-scale products. Because of the many components in complex design, students may struggle to recognise them all, and can struggle to determine on which to focus. Additionally, generating concepts for the entire system at once may require too much cognitive load. To alleviate some of this struggle, morphological analysis has been used in both engineering design education and practice contexts [6-11]. Morphological analysis refers to breaking down the problem by its functional goals and generating ideas for components and creating a variety of combinations from the component ideas generation to develop complete concepts [12-15]. While this tool has been shown to support ideation [16], generating ideas for the subcomponents is unaided, and a tool could both guide students in this task, as well as support a more diverse consideration of possibilities. Thus, the focus of this work was to investigate how design heuristics, an empirically-derived ideation tool, could be combined with a morphological analysis approach to facilitate idea generation for complex design artefacts.

MORPHOLOGICAL ANALYSIS

Morphological analysis involves breaking down a problem into its parts (or subcomponents or subfunctions), generating multiple ideas for each of the subfunctions, and then exploring combinations of the ideas to develop a complete solution or concept (re-composition) [12][13]. For example, the morphological analysis for the design of a bicycle might include subfunctions/subcomponents, such as a way to propel, an energy source and a way for the user to sit. A designer can generate ideas for each of these subfunctions, and then consider multiple different combinations of those ideas to explore many designs for the bicycle. This approach can facilitate the designer in understanding the problem in more detail by breaking down the complexity into more manageable pieces [17-19].

Morphological analysis is acknowledged as beneficial for solving complex problems, where it is difficult to think of all of the parts of the whole at one time [20]. The method is prevalent in numerous engineering design textbooks as an idea generation tool [7-11]. However, studies on the tool are limited. In one study of mechanical engineering students, researchers focused on the identification of which of alternative ways to approach a morphological analysis resulted in more success. The study found that those who generated a higher proportion of ideas for subfunctions than the number of subfunctions produced better ideas than those producing charts with more subfunctions than ideas for subfunctions.

Literature has also described challenges designers face when using morphological analysis to generate ideas. For example, novices may struggle to identify which ideas for subfunctions to put together to suggest a *complete* idea available to combine in the resulting solution ideas [14][15]. Additionally, work with practitioners has shown that without high levels of comfort with morphological analysis, it can be challenging to apply [21][22]. Some of this challenge may arise in generating ideas for each of the subfunctions of the larger complex artefact.

DESIGN HEURISTICS

Design heuristics is an evidence-based tool for encouraging the production of varied concepts during idea generation [23][24]. The design heuristics were empirically derived from the synthesis of outcomes across three studies, including an analysis of award-winning products [25], a case-study of an experienced industrial designer [26], and protocol studies of industrial and engineering designers [27][28]. The design heuristics are presented on a deck of 77 cards, with the front of each card including a heuristic, a written description and an abstract depiction of the heuristic [29]. On the reverse of each card, two product examples are provided in which the specific heuristic is evident.

An example of a design heuristic is *apply an existing mechanism in a new way*. This design heuristic prompts the designer to take an existing product or component and incorporate it to function differently in the final product. For example, in designing a generator, the engineer may take an existing mechanism like a bicycle and apply it as a power source. This one design heuristic can be applied repeatedly to generate other concepts (e.g. using a water bottle to squirt water and turn a wheel). Other design heuristics (e.g. *change direction of access*) can be added and combined (placing the pedals in the air with the rider beneath) to produce a variety of ideas.

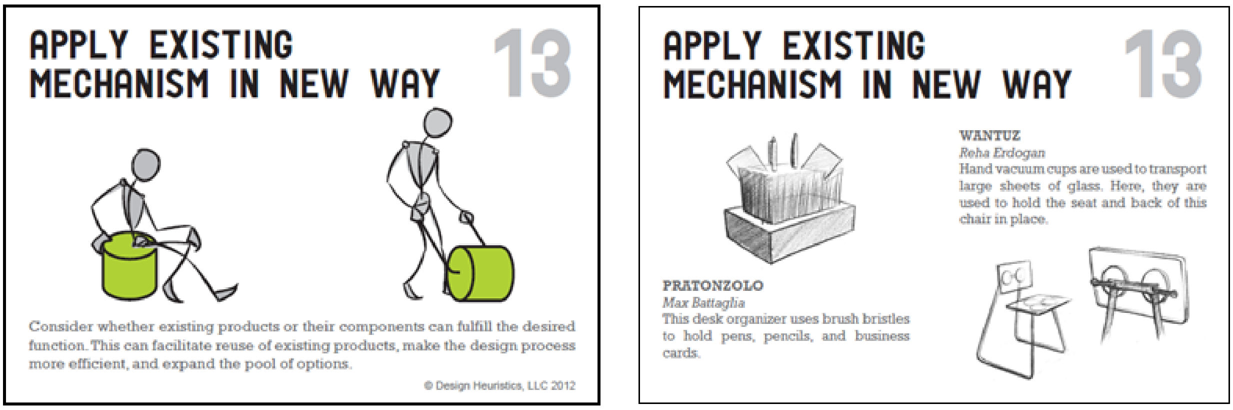


Figure 1: Sample design heuristics card (front and back).

Research has shown various benefits from using the design heuristics [30-37]. In one study comparing ideation tools, practicality ratings for concepts were highest for in outcomes generated by participants who used the design heuristics [6]. In another study, design heuristics use was compared to open idea generation without a tool; resultant concepts were rated as more creative [23]. Further, students have demonstrated that the tool supported idea elaboration [6][30]. These three studies involved student participants, demonstrating support for designers who may have less experience than practitioners. However, even in a practitioner study, design heuristics were shown to have a positive impact on engineering design practitioners' ideation processes, who considered the novel and creative ideas they developed during two ideation sessions with the use of design heuristics [38].

COMPARING IDEATION TOOLS

Some studies have compared morphological analysis and design heuristics to other tools. For example, one study involving 102 entering first year engineering students investigated qualities of ideas generated, including their creativity, elaboration, and practicality when students used one of three different idea generation tool - design heuristics, morphological analysis or individual brainstorming [6]. The three tools showed no differences in rated creativity of ideas; however, the elaboration of concepts was significantly higher with design heuristics and morphological analysis tools than with individual brainstorming, and practicality was significantly better using design heuristics. The findings illustrated differing strengths for ideation tools, and the potential value of exposing beginning designers to multiple tools for idea generation.

While using multiple tools to generate ideas can be beneficial, using these tools in combination may also be beneficial, allowing strengths of tools to support challenges with other tools. For example, one study comparing design outcomes of

83 mechanical engineering seniors found the use of two tools during ideation, morphological analysis and design heuristics, resulted in better quantity, novelty, quality, and variety of ideas than using other pairs of tools for idea generation [39]. Most research focuses on the efficacy of single ideation tools, leaving a lack of understanding of how these tools may interact with one other. While this prior study investigated the use of both tools during ideation, the authors aimed to study the use of the 77 design heuristics ideation cards (tool) to compliment morphological analysis.

In particular, the authors investigated the extent to which the tools could be combined and integrated by using morphological analysis to break down a problem into subfunctions, apply the design heuristics to each subfunction, and then combine various subfunction ideas to form complete concepts. This work furthers scholarly understanding of design tool pairing and integration.

RESEARCH METHODS

This study reports on ideation outcomes as a function of the design heuristic tool used in combination with morphological analysis. The work was guided by the following research questions:

- Are students able to combine morphological analysis and design heuristics together to generate ideas for complex design artifacts?
- What characteristics do ideas have that are generated with morphological analysis and design heuristics in combination?

Participants

Participants were recruited by an email solicitation. Participants included 34 engineering students from a Midwestern University. The gender breakdown consisted of nine female, 22 male and one other. The participant's classification included freshman (3), sophomore (8), junior (8), senior (9), graduate (2) and two students did not indicate. Participants' majors included engineering: mechanical (14), chemical (2), biomedical (1), robotic (1), electrical (3), industrial operations (1), aerospace (1), engineering (undecided) (3); design science (1), biology (1), computer science (1) and one no response. A prerequisite for this study was that participants had prior experience with the design heuristics cards, so that unfamiliarity with the tool was not a barrier to generating ideas.

Data Collection and Analysis

Immediately before the session, each participant was provided a packet containing 12 design heuristics cards (first 12 in deck), concept sheets to record ideas and a post survey handout. Each student was situated at a large desk to allow the spreading out of the DH cards and the participants' generated ideas.

Participants engaged in a 90-minute session, where they were guided through four parts: experiment Part 1, practice, experiment Part 2 and experiment Part 3 (Figure 2).

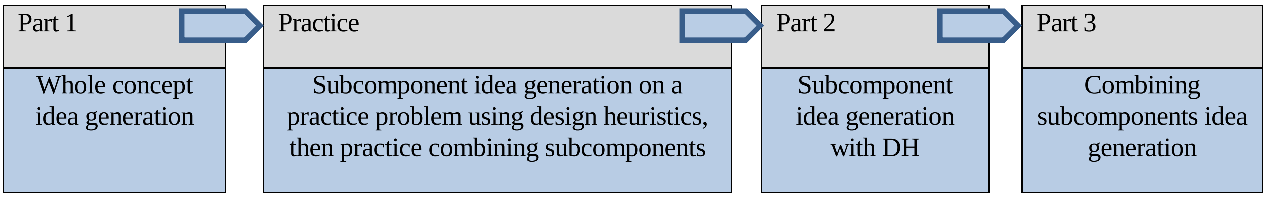


Figure 2: Study structure overview.

In Part 1, participants were given a brief summary of the design heuristics tool and how to use them. Then, participants were asked to first generate whole ideas, and given 12 design heuristics cards to do so, for the following design prompt:

Design a rainwater harvesting system for remote villages to catch and keep rainwater for use in individual homes.

Participants were instructed to sketch up to five ideas (referenced as W1-W5), provide a detailed description of each idea and record which design heuristics card(s) they used. Ten minutes were provided for generating these initial ideas.

The purpose of the rainwater harvester system problem task was to obtain participants' ideas for the *whole concept* (Part 1) to later compare with ideas generated by synthesis of component ideation (created by participants in Part 2) and re-composition (created by participants in Part 3) (morphological analysis and design heuristics combined).

In the practice portion, participants were first given an overview of the first two stages of morphological analysis (functional decomposition and idea generation for each subfunction) and asked to apply this approach with five of their 12 design heuristics cards (for simplicity of the practice) for an unrelated practice task in which they were asked to design ways to dispense salt and pepper (different from their initial task). This problem was already decomposed into subfunctions: pouring mechanism, storage mechanism and stability mechanism. Thus, the practice design task focused on generating ideas for these subcomponents using design heuristics. Participants were asked to draw their ideas, provide a detailed description of each idea and record which design heuristics card(s) they used on a provided idea worksheet. Participants were allocated six minutes for generating ideas.

Next, the participants were introduced to the third stage of morphological analysis - combining ideas for achieving subcomponents into complete concepts. Participants were asked to combine any of their subcomponent ideas from the practice problem to generate one complete concept, which they recorded on a provided concept worksheet with a description of the concept and an indication of which subcomponent ideas they combined.

A brief discussion occurred after the practice session to allow participants to reflect on the approach. The instructor used the following questions as prompts:

- What ideas did you generate for each of the three subfunctions?
- How did using design heuristics impact your ideation process? How did ideating on subcomponents impact your ideation process?
- What questions do you have about using the design heuristics tool in this way?

In Part 2 of the session, the study returned to the rainwater harvester system design problem. Participants were allocated 18 minutes to generate ideas using their 12 design heuristics cards provided for provided problem subfunctions of the design problem: 1) water collection; 2) water purification; and 3) water transportation. Participants sketched and described their ideas on provided worksheets with slots to generate up to five ideas for each of the subfunctions. The subcomponent ideas were titled S1 to S15.

Finally, in Part 3, following the subcomponent idea generation, participants were instructed to combine ideas to generate complete ideas. Participants generated up to five ideas by combining subcomponent ideas and used provided worksheets to sketch and describe their ideas. Participants were also asked to indicate which subcomponent ideas (S1-S15) were used in their complete ideas. Ten minutes were allocated to the combining of ideas. The completed ideas were referenced R1 to R5.

Though the concept sheets had a prerequisite (*up to*) number of ideas, with respect to the number of sheets provided to participants, all participants were informed that more sheets could be requested, if required. Table 1 summarises the session idea generation logistics with respect to the number of sheets and time allocated.

Table 1: Idea generation logistics.

Part of study	Design problem	Supported by	Target number of generated concepts	Time allocated for ideation (minutes)
Part 1: Whole ideas	Rainwater harvest system	12 DH cards	5	10
Part 2: Subcomponent ideas	Rainwater harvest system	12 DH cards with prescribed subfunctions: water collection, water purification, and water transportation	15	20
Part 3: Combining ideas	Rainwater harvest system	Up to 15 subcomponent ideas generated in the previous round	5	10

At the end of the session, participants completed a post-survey with questions on demographic information, evaluations of their ideas, and the level of ease or difficulty experienced using the idea generation tools. The authors also asked open-ended questions to have them explain their answers.

The authors analysed differences between the original whole ideas (Part 1) generated with just the design heuristics to the combined ideas (Part 3). This analysis involved a comparison between the whole ideas (W1-W5) (Part 1) generated by each participant, to the combined ideas (Part 3) generated through the morphological analysis and design heuristics approach (R1-R5). The subcomponent ideas (Part 2) generated were also included in the analysis in order to understand the foundations for the combined ideas (Part 3). The authors also analysed the post-survey for trends in the qualities participants assigned to their ideas.

FINDINGS

Across the 32 participants, 78 *whole ideas* were generated in Part 1, 318 ideas were generated for subfunctions (*subcomponent ideas*) in Part 2, and 93 concepts were generated by combining the subcomponent ideas (*combined ideas*) in Part 3. These data are summarised in Table 2. The practice phase ideas were not included in the findings of this article.

Table 2: Idea generation fluency.

Part	Number of expected concepts	Total number of generated concepts	Max	Min	Mean
Part 1: Whole ideas	5	78	4	1	2
Part 2: Subcomponent ideas	15	318	14	5	10
Part 3: Combined ideas	5	93	5	1	3

In Part 1, whole idea generation, the 32 participants were supported by 12 design heuristics cards each. During this Part 1, 144 design heuristics cards were used to support ideation of 78 generated ideas (Table 3). In Part 2: subcomponent ideas, there were 529 design heuristics cards used to support ideation of 318 generated ideas for the three prescribed subfunctions. Table 4 represents a summary of how many times each of the 12 design heuristics card was used in whole idea generation versus subcomponent idea generation.

Table 3: Design heuristics card use.

Part	Supported by	Number of supports used
Part 1: Whole ideas	12 DH cards	144 Design heuristics cards used
Part 2: Subcomponent ideas	12 DH cards with prescribed subfunctions: 1) water collection, 2) water purification, 3) water transportation	529 Design heuristics cards used
Part 3: Combined ideas	Part 2: Subcomponent ideas	301 Subcomponent ideas used

Table 4: Number of instances where use of each design heuristics card was observed.

Part of study:	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
1: Whole ideas	14	8	15	22	12	5	21	17	12	10	6	2
2: Subcomponent ideas	76	55	60	85	36	25	33	41	47	39	23	9

Ideas Generated with Morphological Analysis and Design Heuristics

The analysis considered each participant's whole ideas (Part 1) compared to their final combined ideas (Part 3). The authors characterised differences among the two idea types and found in most all cases that the participants' combined ideas involved additional relationships and/or configurations than the whole concepts did, as well as the consideration of additional contexts and/or factors (Table 5).

Table 5: Criteria for characterising differences between whole and combined ideas.

Characteristic difference	Meaning/criteria
Additional relationships and/or configurations	Ideas were elaborated (extra detail) in the context of *association between various aspects/features,* which may *affect the configuration or overall layout of the idea*.
Additional contexts and/or factors	Ideas were elaborated with respect to *where it was located* or *situational influences*.

Table 6 represents a summary of characteristic differences for whole and combined ideas. These characteristic differences were determined by using each participant's initial whole idea as a benchmark idea, and analysed further ideas for evidence of elaboration in the context of the characteristic differences. Each participant's subsequent whole ideas and combined ideas were analysed with respect to *additional relationships and/or configurations* and *additional contexts and/or factors*. This analysis evidenced 60% of whole ideas, and 99% of combined ideas, representing additional relationships and/or configurations from participant's respective initial whole idea. In terms of additional contexts and/or factors, the analysis evidenced 49% whole ideas, and 47% of combined ideas, representing such elaboration from participant's respective initial whole idea.

Table 6: Whole to combined idea change through evidence of collaboration.

	% Whole ideas	% Combined ideas
New relationships and/or configurations	60%	99%
Contexts and/or factors	49%	47%

Figure 3 shows an example of one whole idea and three combined ideas generated by Participant 8. The whole idea represents a *tree-like rain collector in which the branches of the tree can effectively collect the rain in limited area, and the water can flow along the branches and get into the tank for storing water at the bottom of the tree*.

The three combined ideas represent evidence of new relationships and/or configurations added, when considering the whole ideas to the combined ideas. An example of how elaboration was added in the context of new configuration, an *adjustable collector to get most rain and a turning tank to purify, and a water wheel to transport water* was added to the combined idea 1.

In the context of combined idea 2, a new relationship was added in the context of the *multiple filters,* where *thinner and thinner filters* were detailed.

In the context of additional contexts and/or factors combined idea 2 was elaborated with respect to where the filter was located*; locate high that water flows down.* Another example of additional contexts and/or factors is represented in combined idea 3 with respect to situational influences, whereby *the tree-like branches allow the water to flow through the stem with purification soil, and store in the ball-like tank.*

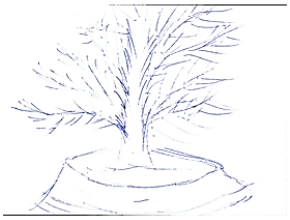
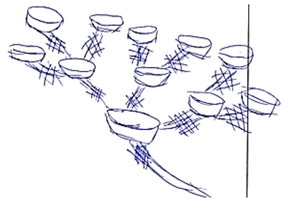
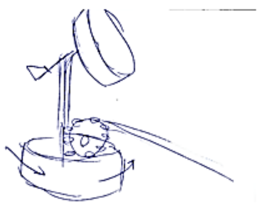
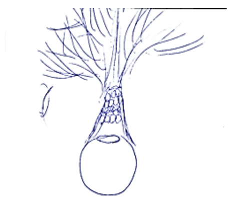
 Whole idea: This is a tree-like rain collector. The branches of the tree can effectively collect the rain in limited area. Moreover, the water can flow along the branch and get into the tank for storing water at the bottom of the tree.	 Combined idea 2: Multiple collectors, thinner and thinner filter, locate high that water flows down.
 Combined idea 1: Adjustable collector to get most rain. Turning tank to purify water wheel to transport water.	 Combined idea 3: Tree-like branches to collect rain, flow through the stem with purification soil, and store in the ball-like tank.

Figure 3: Whole and combined ideas for Participant 8.

To provide further detail on what ideation outcomes looked like when combining morphological analysis and design heuristics, the authors present a case example of Participant 21 in Table 7. Participant 21 initially generated two whole concepts. The first whole concept (W1) was to put bowls in the roof of a house with tubes attached at the end. The tubes would join and fill a big container with water. The bowls were to be made with banana tree leaves, included leaves and bowls to collect water. The participant used four design heuristics to develop it (DH#1, DH#4, DH#8, DH#10).

The leaves were described by the participant as *resistant, mouldable and fittable for making the bowls*, which was inspired by: DH#4 (add to existing product). The collation of the bowl features into the roof of a house with tubes all joined together, was influenced by DH#8 (allow user to assemble) and DH#10 (allow user to reconfigure). The placement of the bowls could have been influenced by DH#1 (add levels), whereby they were located on the roof of a house. The participant did not cite any evidence of heuristic use for the second whole concept (W2), but was described as based on the previous idea (W1), with respect to the *bowl.*

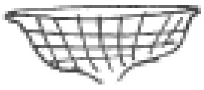
Table 7: Ideation change Participant 21 whole ideas generated.

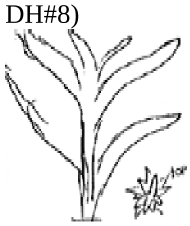
WHOLE IDEAS	
W1 (DH#1, DH#4, DH#8, DH#10)  Bowls in the roof of a house with tubes attached at the end where they join at become one going to a big container; banana tree leaves are resilient, moulded and fitable for making the bowls.	W2 (no heuristics listed)  Based on the previous idea but a big one, several spaced around the village.

Participant 21 generated 10 subcomponent ideas by applying the design heuristics cards with morphological analysis three prescribed subfunctions. Nine of the 10 subcomponent ideas were generated with design heuristics (Table 8).

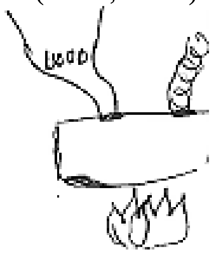
Table 8: Ideation change Participant 21 subcomponent ideas generated.

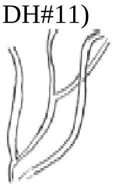
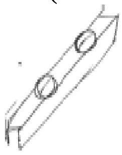
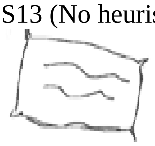
<table>
<tr><th colspan="6">Subcomponent ideas</th></tr>
<tr><td colspan="6">*Note: Student did not record ideas in space for S5, S9, S10, S14, S15</td></tr>
<tr><td colspan="6">Water collection</td></tr>
<tr>
<td>S1 (DH#3, DH#4)

Funnel type made of natural leaves.</td>
<td colspan="2">S2 (DH#3, DH#4)

Box type made of natural leaves.</td>
<td colspan="2">S3 (DH#3)

Cotton or some type of hydroscopic plant to collect and retain water that goes through this plate, like a huge cotton flower.</td>
<td>S4 (DH#2, DH#3, DH#5, DH#7, DH#8)

The structure of a plant to collect water between leaves and goes through little tunnels to storage. Every level can be moved to collect more.</td>
</tr>
<tr><td colspan="6">Water purification</td></tr>
<tr>
<td colspan="3">S6 (DH#1, DH#3, DH#9, DH#10)


Natural rocks to filter water. I do not know their names but are very common in Brazil and South America. Many levels as needed.</td>
<td colspan="2">S7 (DH#3, DH#4, DH#1)

Samambuaia; a natural plant known by its water purification qualitiies, as many as needed.</td>
<td>S8 (DH#4, DH#8)


Decontation (?) system.</td>
</tr>
<tr><td colspan="6">Water transportation</td></tr>
<tr>
<td colspan="3">S11 (DH#3, DH#8, DH#9, DH#10, DH#11)

Tubing system as tree roots upside down.</td>
<td colspan="2">S12 (DH#2, DH#3, DH#6, DH#9)

Dual system where balls (cuba cas) full of water roll until a given destination.</td>
<td>S13 (No heuristics listed)

Big water resistent bag like flour or rice bags or small if for light weight people.</td>
</tr>
</table>

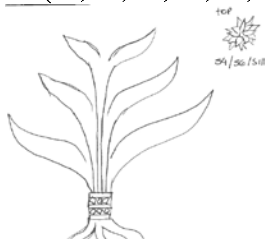
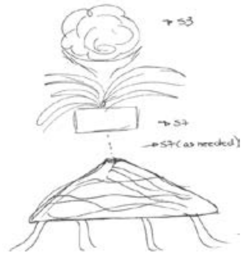
All 10 of the subcomponent concepts were used in the ideation of the two combined ideas (R1 and R2) (Table 9). The two combined ideas represent evidence of new relationships and/or configurations, and additional contexts and/or factors when considering the whole ideas to the combined ideas. R1 represents how elaboration was added in the context of additional relationships and/or configurations; the leaf was elaborated to be a plant configuration, whereby it represents the assembly of many levels of *leaves*.

In addition, the relationship between the leaves was elaborated with a rock filter which accumulates water, and then using tubing to bring the water to user houses. In addition, with respect to additional contexts and/or factors, R1 was elaborated to meet the required quantity based on the context, whereby the leaves have different sizes in each level. In addition, there was an additional situational influence where the leaves rotate along the axis to be in a position that will capture as much water as it can.

In the context of combined idea R2, a new relationship and configuration was added in the context of the hydrofoil plant even plate, which is filtered by *samamboi* storage in a bottom of a sand watch bent to not evaporate, going to a tubing system.

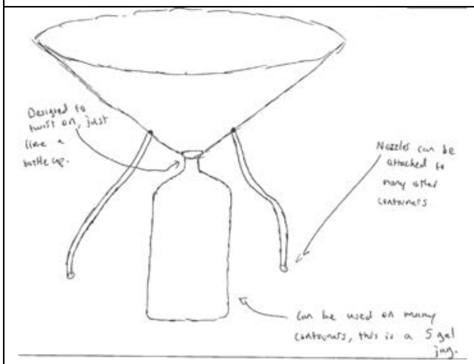
In the context of additional contexts and/or factors, combined idea R2 was elaborated with respect to where it can be placed either on rooftops or ground. In addition, with respect to situational influences the tubing system is placed under sand to prevent water from evaporating.

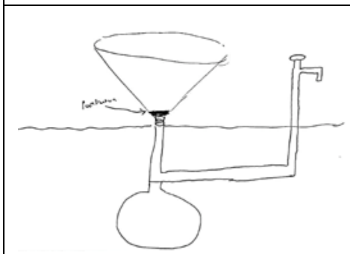
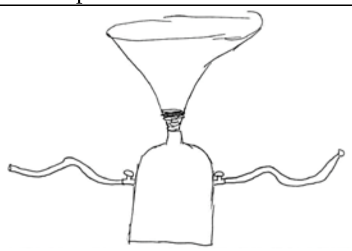
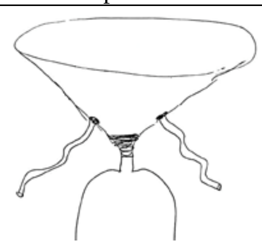
Table 9: Ideation change Participant 21 combined ideas generated.

<table>
<tr><th colspan="2">Combined ideas</th></tr>
<tr><td>R1 (S1, S2, S3, S4, S5, S7, S8, S9, S10)

Using a plant design reproduce it as a product to accumulate water that goes through a rock filter, and then from tubing’s and user houses. This plant can be assembled with as much levels of leaves as it is needed and can be placed on rooftop or floor and the needed quantity. The leaves can rotate along the axis to be in a position that will capture as much water as it can. Also, each leaf has a different size in each level.</td><td>R2 (S1, S3, S4, S7, S8, S9, S12)

The hydrofoil plant even plate, filtered by samamboi storage in a bottom of a sand watch bent to not evaporate, going to a tubing system. Can be placed on rooftops or ground. Looking like a big, big flower.</td></tr>
</table>

As an additional example, the authors present Participant 2’s ideas (Table 10).

Table 10: Whole to combined idea comparison for Participant 2.

<table>
<tr><th colspan="3">Whole idea</th></tr>
<tr><td colspan="3">

The concept is a large, twistable funnel bottle cap. Basically, you twist on this contraption onto the top of a container and it will collect the rainwater in the containers for home use. The contraption also contains hose-like nozzles that will disperse excess water through the pipes into other containers. A filtration system can be implemented as well.</td></tr>
<tr><th colspan="3">Combined ideas</th></tr>
<tr><td>Water collection</td><td>Water purification</td><td>Water transportation</td></tr>
<tr><td>
Funnel system catches the water and filters it, it then gets stored underground and is dispersed above ground through a spout.</td><td>
Water is collected in a jug with the funnel bottle cap system (which contains a filter). Water can then be dispersed with hoses.</td><td>
Funnel system is used to collect the water into a jug. If the jug overflows, hoses on the side of the filter will transport water to other containers.</td></tr>
</table>

Participant 2 initially generated one whole idea, using four design heuristics (DH#1 add levels, DH#4 add to existing product, DH#7 align components along centre, DH#10 allow user to rearrange), which represents *a large, twistable funnel bottle that will collect the rainwater in the containers for home use, via hose-like nozzles that will disperse excess water through the pipes into other containers. A filtration system can be implemented as well.* This initial whole idea was further developed into three combined ideas, which were influenced by the three morphological analysis prescribed subfunctions and design heuristics.

From these three combined ideas it is evident that they each represent elaboration of the whole idea with respect to additional relationships and/or configurations, and additional contexts and/or factors.The three categories of ideas, each focusing on addressing a specific function and elaboration; *collection* via *funnel system catches the water and filters it, it then gets stored underground* (new context) *and is dispersed* (new configuration) *above ground* (new context) *through a spout* (new configuration); *purification* via *water is collected in a jug* (new context) *with the funnel bottle cap system (which contains a filter). Water can then be dispersed with hoses* (new relationship), and *transportation* via *funnel system is used to collect the water into a jug. If the jug overflows, hoses on the side* (new configuration) *of the filter will transport water to other containers* (new context).

Across participants, findings revealed differences in the types of ideas when comparing the whole ideas to the combined ideas in the level of detail included with regards to features of the idea and the context in which the idea would exist. The combined tools were used to decompose ideas (morphological analysis), generate ideas for subcomponents (design heuristics) and recombine subcomponents to whole ideas (morphological analysis).

Student Perceptions

In the post survey, participants indicated the *ease of use* for the two approaches - generating ideas for the whole ideas using the design heuristics, and then decomposing with morphological analysis and generating ideas for subcomponents using the design heuristics and combining these ideas to form new combined ideas. In terms of ease of use, students rated idea generation of the combined ideas as easy (M = 3.8438, SD = 0.9541). Subcomponent idea generation using design heuristics with morphological analysis was rated between easy and easy at times. Whole idea generation was rated as easy at times (M = 3.1875, SD = 0.859) (Table 11).

Table 11: Student perception of ease of use of approaches.

Ease of use	Part 1: Whole ideas	Part 2: Subcomponent ideas	Part 3: Combined ideas
Average	3.19	3.66	3.84
SD	0.86	0.83	0.95

Additionally, the authors compared student's perceptions of creativity and practicality of their ideas. They could select a whole idea from Part 1, a subcomponent idea from Part 2 or a combined idea from Part 3. The majority of students felt their ideas were most creative and practical in Part 3 (Table 12).

Table 12: Whole and combined rainwater ideas rated most creative and most practical concepts by students (n = 32).

Part of study	Most creative idea	Most practical idea
Part 1: Whole ideas	2	1
Part 2: Subcomponent ideas	8	7
Part 3: Combined ideas	19	22

The student perceptions data demonstrated that students felt that they benefited from combining morphological analysis with design heuristics to generate ideas, and that applying these tools together was not difficult to execute.

DISCUSSION

Nesting the use of design heuristics within morphological analysis promoted students' abilities to elaborate on features and consider additional aspects of the context as compared to their initial ideas. While much of the research has considered the use of ideation tools one at a time or using multiple tools independently from one another during ideation phases, this study looked at the integration of two tools with differing advantages. Morphological analysis facilitates the decomposition of complex artefacts into separable functions, and design heuristics facilitates the generation and exploration of multiple, diverse ideas. Both tools also support elaboration on designs, as evidenced for morphological analysis in this study and evidenced in prior work on design heuristics [6][30][40].

Other work also found that the use of these two tools, morphological analysis and design heuristics, by student teams yielded ideas that were considered high quality and creative, and idea sets that were diverse [39]. The work extends this prior work comparing outcomes of pairs of tools during ideation by looking at a structured integration of two tools.

Some ideation tools have been shown to be difficult for novices to learn and implement quickly. For example, TRIZ is an ideation tool that requires extensive training to use as recommended, which includes identifying a contradiction in an existing idea and applying a particular strategy to alleviate that contradiction [41]. Studies have demonstrated uses of TRIZ that do not align with recommendations [42], as well as challenges with using the tool in general [43].

Studies have also shown challenges with using analogical thinking in idea generation, as students struggle to come up with the *right* analogy to use, have difficulty focusing on distant analogies, and cannot translate some analogies to design ideas [44]. Though some tools when used alone have been shown to be challenging, these findings demonstrated that students were able to combine the two tools of morphological analysis and design heuristics within a relatively short period of training and use. Additionally, students reported that combining these tools was relatively easy.

The findings of this work also expand upon the documented uses of the design heuristics tool. Prior work has shown design heuristics can be successfully leveraged by design students and practitioners across multiple disciplines for initial idea generation of whole ideas [27][30][33][34][38]. While much of the research on design heuristics has focused on initial ideation, research has also explored the use of the tool to transforms existing ideas [30][40] and the use of the tool in group idea generation settings [38]. The present study demonstrated that the tool can also be used to develop ideas for subcomponents of larger systems. Utilising multiple design tools in various ways when generating and developing ideas can support broader exploration of a solution space, and research has supported design heuristics as a versatile tool that can be used in various modes of idea generation and development.

Implications for Engineering and Design Education

Design curricula has largely focused on describing one ideation tool at a time, from which students can select one or choose multiple in their ideation processes. A consideration of the strengths of each design tool can support students in leveraging multiple tools together. For example, morphological analysis is often included in engineering design texts and courses [13][20], and as design heuristics has also been broadly used with engineering students and practicing designers, textbooks and curricula could explain how these tools could be leveraged together for complex design scenarios.

Additionally, the findings from this study suggests that thinking about ideation tools in only one way might be a limited perspective. Not only can morphological analysis and design heuristics, and likely other ideation tools as well, be used in combination, but they also may be useful in various formats, such as to transform or develop ideas. Because students in this study had already generated *whole* ideas before using the tools in combination, many of the ideas they developed with the tools in combination built on previous ideas through elaboration of features or consideration of contextual elements. Exploring ideation tools to be leveraged in a variety of ways can further facilitate successful ideation.

Finally, students can benefit from having a collection of ideation strategies in which they are proficient, feel comfortable implementing, and know the strengths and trade-offs of each strategy. That way, when they are in a real design context, they can take advantage of whatever tool or tools align with what is needed at the moment. As ideation tools have some distinct strengths compared to one another, having multiple to guide idea generation and development work can strengthen students' processes and ultimate outcomes.

Limitations

This study was conducted with participants in engineering programmes at one university; as a result, there may be differences in other engineering or design programme contexts. Additionally, the study required participants to have used the design heuristics tool in a past course or workshop. Previous work has shown only a short training time is required for students to learn to use design heuristics. The students in this study completed three phases of idea generation, and the goals for idea generation may have been challenging within the short time allowed. For example, none of the participants generated the total number of requested ideas for Part 1 whole ideas (5) or Part 2 subcomponent ideas (15). Participants may have been fatigued from generating ideas or may not have had enough time to generate the number requested. Breaking the idea generation tasks into separate sessions and allowing longer sessions may increase performance.

Additionally, in the study, participants received the first 12 design heuristics cards from the deck of 77 cards. This smaller quantity of cards prevented participants spending too much time in the short study session examining all 77 cards, but this also may have reduced their options for heuristic selection. The morphological analysis task included pre-defined categories to support participants in the decomposition of functions during the study session. However, some participants may have preferred to identify their own morphological analysis categories. Finally, the study session served to introduce participants to the use of these two tools in combination, but there was no assessment of what they learned through tool use.

CONCLUSIONS

The study demonstrated that students were able to combine morphological analysis and design heuristics successfully to generate what they perceived as creative and practical ideas. First, morphological analysis facilitated decomposing the complex design goal into smaller functional subcomponents. Then, design heuristics were used to support idea generation for multiple parts of the design, which were later recombined into a whole design.

For novice designers, support from tools to assist in dealing with complexity and exploration of solution spaces can make a design task more successful. Design heuristics can be used in a new way than previously documented; specifically, as a tool for idea generation within subcomponent designs. Finally, the two tools together were successfully used by novice students within a short training time. Considering the strengths of multiple ideation tools, they can support idea generation even in complex designs, facilitating the development of multiple ideas in pursuit of a complete design.

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