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A MORPHOLOGICAL DESIGN APPROACH TO USER-EFFICIENT DESIGN

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ABSTRACT
The behaviour of users can have a negative impact on the energy efficiency of products. By using products unnecessarily or inefficiently even a product which has been designed and built with highly efficient technology or materials will still waste energy. This paper follows the work of the authors' to develop a user-efficient design methodology which will allow designers and engineers to create products that will reduce or prevent this energy "inefficiency" of users. The results from a design exercise to create a user-efficient design for a refrigerator are examined, together with the observed behaviours from a user trial. The conclusions from the study have led to the proposed morphological design approach that tackles the energy losses related to use but also addresses the underlying needs of the user.

Keywords: Eco-Design, Morphological Design, Behaviour, Environmental Impact

1 INTRODUCTION
Domestic energy usage of household products has more than doubled since 1970 and by 2010 consumer electronics is predicted to be the biggest single sector of consumer electricity consumption [1]. Research to improve the environmental impacts and energy efficiency of products through engineering technology is a highly researched and highly effective area of work, with many products showing significant improvements in energy efficiency over time.

However a product with good energy efficiency from an engineering technology point of view can have its environmental benefits mitigated by inefficient use and relying on a person's desire to do better will not always affect their behaviour. Changing one or more of a user's beliefs, through improved information, feedback and education may not be sufficient to bring about change in the overall attitude and hence behaviour. This is best summarised by McKenzie-Mohr [2] and other behavioural psychologists who have established that the traditional thinking suggests that changes in behaviour are brought about by increasing the person's knowledge regarding an issue and by then fostering attitudes that support the desired new behaviour. As a result attempts are made to alter behaviour by providing information campaigns and media advertising. Unfortunately, a variety of research studies have shown that enhanced knowledge and a supportive attitude often has little or no impact on the user's long term behaviour.

As a result research is being undertaken to develop ways of improving the energy efficiency of how products are being used, without relying on psychological persuasion of the user. One such approach, user-efficient design, changes the design of the products themselves, locking-in good behaviour into the design stage of the product [3]. A product design led approach [3] [4], such as user-efficient design, would be able, through intelligent design, to deliver a product that could either be only used in an efficient manner, or one that could adapt itself to inefficient use, correcting the user's actions perhaps even without their knowledge. This paper looks at the work that has been done by the authors to develop a methodology for helping engineers and designers to create more user-efficient products and begins with an overview of the research approach taken.

2 RESEARCH APPROACH
The aim of this paper is to describe the testing of a design methodology that will allow designers to create products that are user-efficient in a time efficient and effective manner. With very little research having already been undertaken in this area the authors decided to use an action research approach [5]. The authors would work through this problem, designing new products themselves, critiquing their

efforts and the methods used in order to try and improve the design processes so that it is more appropriate to a user behaviour focus. The research was divided into three broad stages, figure 1, beginning with an exercise to design a refrigerator that tackles the energy losses associated *with use*.

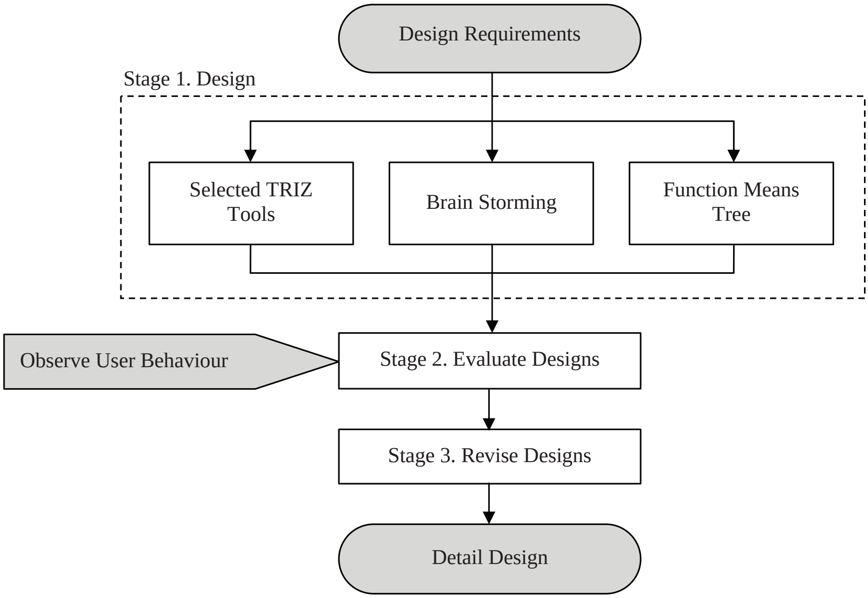

Figure 1. Three stage action research design process

Design requirements are given and a design exercise begins where the authors used primarily three design methods to produce new user-efficient refrigerator concepts. The choice of refrigerator to some extent is arbitrary; however the authors had undertaken some observational studies [6] that would help with the design work. These methods included three selected tools from TRIZ, the Ideal Final Result, Trends of Evolutions and the Contradiction Matrix, as well as two other design tools; Brain Storming and a Function Means Tree [7]. After some possible designs have been generated they are collected together and their effectiveness would then be evaluated against actual behaviours that have been observed and quantified. The designs will then be revised and improved and finally a detailed design stage could begin. The rationale behind doing this process is to generate some understanding on how products should be redesigned to incorporate user-efficient specifications. By following a fairly loose design process such as this and reviewing the implementation and outcomes of every stage it is hoped that new knowledge of how to best design a user-efficient product may be obtained.

3 STAGE 1: DESIGN

As part of stage 1, six design concepts for a new user-efficient refrigerator were created and collected together, figure 2. This exercise was performed with only the author’s personal knowledge and experience of how a refrigerator is used and what constitutes poor use, no additional information was provided. It was decided that detailed information on user behaviour would not be introduced before the design process was underway as too much detailed information may stifle the creative process and may not be necessary since the product in question is well known and used frequently by the authors. Instead detailed behaviour information would be used in stage 2 to assess and evaluate the designs. From this it will be relatively simple to deduce whether this information should have been provided upfront to steer the design process.

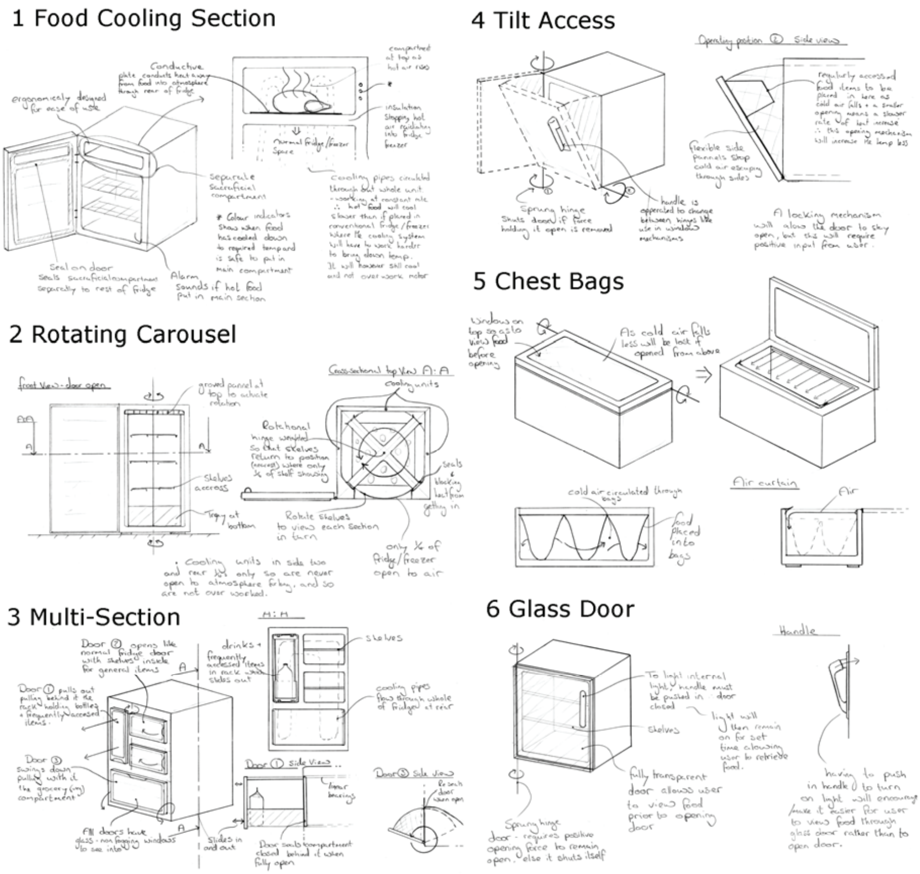

Figure 2. Six design concepts for a user-efficient refrigerator

The initial designs, figure 2, deal with a range of behavioural issues such as putting hot items inside before they have cooled, having a door which opens the whole compartment when only a small part is needed and wasting time searching for items with the door open. Each concept is also deliberately different to broaden the range of solutions and to avoid design variations of a single theme.

Design 1 is fitted with temperature sensors which sound an alarm if hot food is placed in the main cold compartment and provides an insulated area for hot food. Designs 2 and 3 separate the main compartment into different sections so that only a small part is exposed to the warm air of the room once opened. Design 4 alters the hinges on the door of a conventional refrigerator so that in addition to the normal swing door it can also tilt forward. This allows items that are used frequently, such as milk or butter, to be accessed quickly without exposing the whole compartment. Design 5 is a chest style refrigerator and so does not suffer from the same cold air loss issues of the others and is also fitted with bag sections to avoid cross contamination of food and for ease of food removal. The final design 6 has been fitted with a glass door so that users can decide what they wish to remove and can locate it before opening the door in order to reduce the frequency of opening the door.

It became apparent from this exercise that there is a very large range of possible behaviours to design for. Also, there are systems considerations such as; would a modern kitchen be able to afford the space required for a chest style refrigerator. In order to evaluate these designs in terms of which would be the most effective at reducing energy use a study must be made into which behaviours have the worst effects on energy efficiency.

4 OBSERVING AND MEASURING BEHAVIOUR

Stage 2 requires quantifiable data on user actions and behaviours. A process is therefore required to observe and count the occurrence of user's behaviours which in turn needs to be translated into energy impact data. Any design change to the product will also have tradeoffs between the amount of energy saved by the change and the amount of energy taken to implement. Quantifying these behaviours in terms of their energy impacts allows designers and engineers to make design and technology changes to a product and check that the changes will not cause greater environmental impacts than the savings will deliver. This process also allows designers to narrow the range of possible behaviours, in order to focus on only those with a high impact and make the design task more manageable.

Video studies have been used by a number of researchers, albeit in different fashions, to observe and record the behaviours of users [6] [8] [9]. The behaviours witnessed in this study were recorded and, using energy data from the product, an energy impact can be calculated. For example the action of opening the door of a refrigerator will have a direct effect on its energy use. The longer the door is open the warmer the inside will become and subsequently the more electricity is needed to cool it. Data from a study into the energy use of refrigerators [10] shows that opening the door for 5 seconds uses approximately 0.002 kWh. If we assume that this is proportional to the length of time that the door is open, then opening the door for 10 seconds would have double this energy use, 0.004 kWh, and so on. This energy value per second of door opening can now be applied to the observed behaviours in the video studies. Table 1 shows data from a two week video study of a refrigerator in a student house [6] with nine observed behaviours, the frequency of these behaviours during the study, time with the door open and the resulting energy impact. The behaviours have been listed in descending order with the highest total impact at the top.

Table 1. Observed behaviours during a two week video study of a refrigerator, adapted from [6].

Observed Behaviour	Total Time (seconds)	Frequency	Average Time (seconds)	Energy Impact (kWh)
1 Open door to take something out	464	66	7.0	0.186
2 Open door to put something in	289	65	4.4	0.116
3 Open door to look / search / sort inside	229	16	14.3	0.092
4 Leave door open during a task with removed item	169	7	24.1	0.068
5 Leave door open to do something not related to fridge	81	1	81.0	0.032
6 Leave door open to search / sort inside	72	5	14.4	0.029
7 Open door to load shopping / multiple items	20	1	20.0	0.008
8 Leave door open to load shopping / multiple items	7	1	7.0	0.003
9 Leave door open because it's not closed properly	7	1	7.0	0.003

From the ranked observed behaviours of table 1 some interesting insights can be obtained. The total energy impact of these behaviours over a year is approximately 14 kWh or 7% of the energy use for a typical European refrigerator (200 kWh / year). This is in line with the conclusions of [10] which showed energy use relating to the user's actions to be 8% of total energy use of the refrigerator. The users in this study however will not be representative of the user population as a whole, as the findings of refrigerator study [9] showed the behaviours of a young family making breakfast had the door open for 191 seconds, suggesting a possible total energy use of four times that of the users in table 1. Despite the relatively small energy impact of user behaviour in refrigerator use, at the moment [11] (most energy is lost due to poor insulation), useful design insights were still obtained and allowed a trial of the methodology that may be applicable to other consumer products that have high behaviour related impacts such as kettles or a television set.

The users in the study reported here spent a lot of time, approximately 22% of the total time, looking and searching inside the refrigerator without removing anything. This need to look inside and decide what to take out may also explain why it takes 2.6 seconds on average longer to remove something than it does to put it back. An element of discovery and searching is required to establish what is being stored and what is required for a particular meal. If all these seconds of searching could be removed a reduction of 35% in the user related energy impact could be achieved.

5 STAGE 2: DESIGN EVALUATION

The original design concepts of figure 2 can now be evaluated against the ranked behaviours of table 1 in order to establish which designs will be the most effective at addressing the most critical user behaviours. To do this a reinterpretation of some of the classic decision support approaches were used. With this information the design process can then be repeated to improve the original designs and produce a set of designs which perform well at reducing all the behaviours. Table 2 shows the results of this evaluation process, where the behaviours of highest impact are given a greater weighting than those of less significance. The weighting is then multiplied against the concept's potential ability to reduce the impact of this behaviour, ranging from Yes, awarded two points, Partial, awarded a single point and No which is given a negative score of one. If the concept actually made the behaviour impact worse than the current situation it would be given a negative score of 2. For each design concept this score is then summed to give a total and the most suitable design is established.

Table 2. The original design concepts from figure 2 ranked against the observed behaviours from table 1

	Observed Behaviour	Weighting	Design Concept No. (Figure 2) 1	2	3	4	5	6
1	Open door to take something out	9	-1	1	2	2	2	1
2	Open door to put something in	8	-1	1	2	2	2	-1
3	Open door to look / search / sort inside	7	-1	-2	1	-1	1	2
4	Leave door open during a task with removed item	6	-1	2	2	1	2	2
5	Leave door open to do something not related to fridge	5	-1	2	2	1	2	2
6	Leave door open to search / sort inside	4	-1	-1	2	1	1	2
7	Open door to load shopping / multiple items	3	-1	-1	2	-1	2	-1
8	Leave door open to load shopping / multiple items	2	-1	2	2	1	2	2
9	Leave door open because it's not closed properly	1	-1	1	1	-1	1	-1
		Total	-45	23	82	40	78	45

Does the design reduce the impact of this behaviour?

Yes	2	No	-1
Partial	1	Worse	-2

Design 1 fared badly on all of the ranked behaviours because its design changes were aimed at users who put hot food into the fridge. A behaviour which was not observed during the study, since nothing else was changed the design did not improve any of the behaviours. Design 2, the rotating carousel actually made behaviour 3, opening the door to look inside, worse. The carousel may actually make it harder to search inside since only part of the contents is on display at any one time. With only a small section viewable to the user much time might be wasted spinning the carousel unnecessarily rechecking the contents and deciding what to take. All this means the door is likely to be open for longer. The other four designs all did reasonably well with two designs scoring around 80 points out of a maximum of 90. Designs with glass doors automatically did well on a range of behaviours as the glass door allowed the user to perform any searching or decision making without the need to open the door. Also designs which had separate compartments and individual access for each did not expose the whole contents to warm outside air and so reduced the impacts of any behaviour where the door was left open for an extended period of time. The designs must now be improved to reflect the new knowledge learnt from the evaluation.

6 STAGE 3: DESIGN REVISION

Figure 3 shows the six original designs, each with revisions and modifications generated from the lessons leant from the first evaluation process of stage 2. This stage was intended as a quick fix, addressing each of the bad points from the evaluation and as such an in depth design process was not followed.

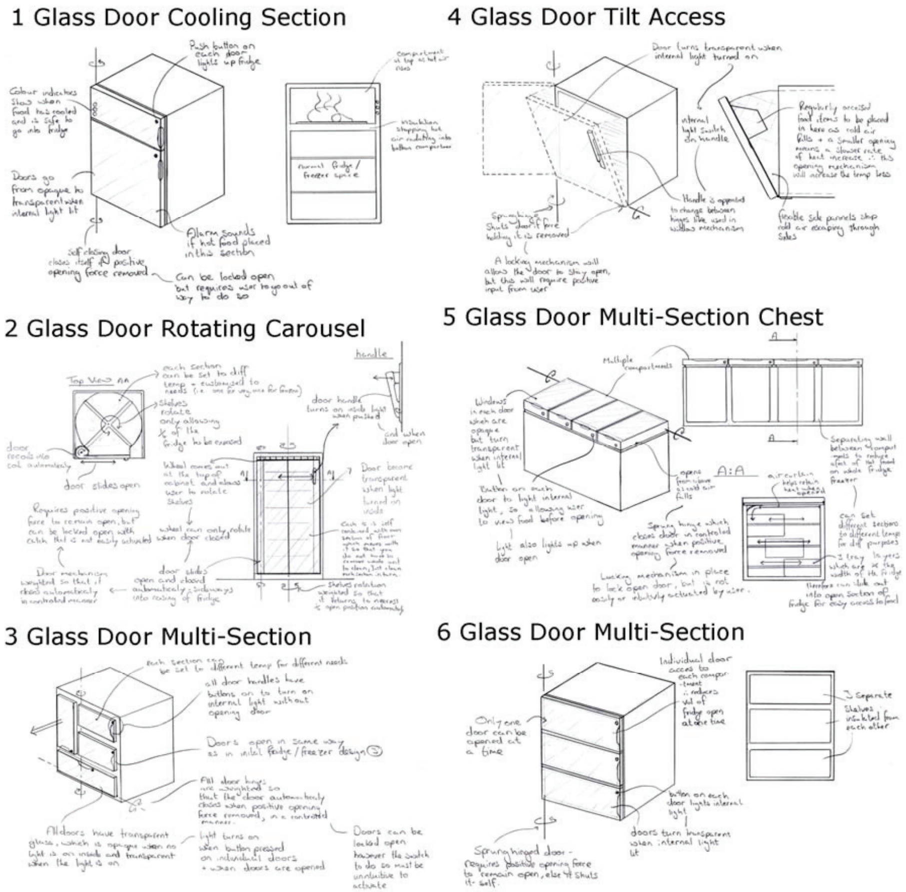

Figure 3. Six revised design concepts for a user-efficient refrigerator

The revised designs clearly showed a lack of original design features from the revision process and revealed that the original six designs could all be improved very quickly and easily if certain features, a glass door, self closing door and multi-section compartments for example, that caused a design to perform well in table 2 were reproduced on every design. This conclusion is confirmed when the new designs are evaluated against the same observed behaviours in table 3. All six designs score above 70 points with four achieving a maximum score of 90. Even design 1, the worst performing design of table 2, is revolutionised with the simple addition of a self closing glass door.

Table 3. The revised design concepts from figure 3 are ranked against the observed behaviours from table 1

	Observed Behaviour	Weighting	Revised Design Concept No. (Figure 3) 1	2	3	4	5	6
1	Open door to take something out	9	1	2	2	2	2	2
2	Open door to put something in	8	1	2	2	1	2	2
3	Open door to look / search / sort inside	7	2	2	2	2	2	2
4	Leave door open during a task with removed item	6	2	2	2	2	2	2
5	Leave door open to do something not related to fridge	5	2	2	2	2	2	2
6	Leave door open to search / sort inside	4	2	2	2	2	2	2
7	Open door to load shopping / multiple items	3	2	2	2	2	2	2
8	Leave door open to load shopping / multiple items	2	2	2	2	2	2	2
9	Leave door open because it's not closed properly	1	2	2	2	2	2	2
		Total	73	90	90	82	90	90

Does the design reduce the impact of this behaviour?				
	Yes	2	No	-1
	Partial	1	Worse	-2

At this stage an interesting observation on the process was made. The original evaluation of the designs and subsequent revision created a situation where a comparison was in fact not being made between the designs as a whole, and the observed behaviours, but particular features of them. For example any design with a glass door or separate compartments would score well on most of the behaviours regardless of how this was implemented or the effectiveness of rest of the design.

The design revision of stage 3 did little to expand the originality of the designs made. However what it did was highlight which specific features from the original designs could be re-used in order to tackle a specific behaviour. Identifying this was a key stepping stone towards this paper's morphological design approach and is an important differentiation from the original unguided design process of stage 1.

7 MORPHOLOGICAL DESIGN

Dismantling the original designs into the features which tackle specific behaviours allows the designer to take the most effective features and transfer them to another design. However, taking this one stage further, with the revised designs from figure 3 it became evident that it was not the feature which was of value to the designer but the function it delivered. For example, the glass door allowed the user to see inside the refrigerator, review the contents and decide what to take without opening the door. However the evaluation process did not take into account the energy impact of these features, such as increased energy use in manufacturing and the thermal effectiveness of the glass. Two identical refrigerators from an American company can be compared to demonstrate this; one with a normal insulated door and the other with a glass door. The difference in energy use between these two products per year is 81 kWh, a 17.5% increase in electricity use [12] due to the glass door and is considerably more than the observed 14 kWh energy impact from the witnessed behaviours. The glass door is however not the only way of achieving this function, there are many ways the refrigerator can be changed so that the user can know or see what is inside without opening the door. Each design feature from the original designs delivers a function which aims to tackle the inefficient behaviours that have been witnessed. These functions can be represented as the functions from a morphological design process.

As Ullman writes in his book on Mechanical Design Processes [13] the desired solution, in the morphological design process, should be broken down into possible functions which meet the requirements of the solution. In this study the observed behaviours provided a list of requirements to be addressed, in addition to the traditional requirements of a refrigerator. The morphological design process is to first identify the required functions. The function must not be solution specific, it is

directed at ‘how’ and not ‘what’ is required. The solution should not be predetermined by the way the function is stated. Secondly, the method aims to help designers to develop as many concepts as possible to meet each function and then finally combine these individual concepts into an overall design that meets all the requirements. Ullman [13] warns that combining the concepts can often generate too many final designs if every combination of function design were to be combined as a feasible solution. It also assumes that each function is independent and that each concept satisfies only one function. Designs should therefore be reviewed as the process progresses to ensure that only the most feasible and desirable of ideas move to a detailed design stage.
Table 4 shows an example selection of three functions, which were identified in the stages 2 and 3 of this refrigerator design study, with the appropriate observed behaviours and a list of possible solution concepts. The solution concepts are physical ways in which the corresponding function can be implemented into the design of a refrigerator. Improving the visibility of the contents of the refrigerator, for example, will reduce the time taken for any of the behaviours where searching or looking inside is required and can be done in a number of different ways; shown as possible the solution concepts.

Table 4. Example functions for the nine observed behaviours and possible solution concepts

Observed Behaviours	Functions	Possible Solution Concepts
1, 3, 6	Improve visibility	Glass / transparent door Video camera feed from inside Computer log of contents
4, 5, 9	Self closing	Spring hinges Chest lid Mechanised door
1, 2, 3, 4, 5, 6, 7, 8, 9	Segmentation	Different sealed sections Separate doors and openings for different areas Separation of items requiring different temperatures Modular design

Table 4 shows three example functions that were used in almost every design in the design revision stage 3. It is clear that some functions are more universal at improving the behaviours, whereas others may be more specific. Splitting the main compartment into smaller sections, through the function of segmentation, is one such example of a function covering a large range of different behaviours. Self-closing reduces the possible damage done by forgetful or wasteful behaviour and therefore improves the energy impact of all nine observed behaviours.
The information from table 4 can be arranged into a user-efficient morphological design chart such as that of table 5. The morphological chart makes it easier for designers to select solution combinations and form final designs. It is laid out with a list of the user behaviours down the left side and the corresponding functions for each alongside. The final series of columns displays the possible solution concepts for each function from which a final design can be created.
Due to the nature of this problem, creating designs to influence behaviour, some functions can influence the behaviour even when not specifically designed to do so. As a result the functions have been colour coded to signify whether they are complete and effective solutions, green, or only partial solutions, in yellow. A partial solution is one that may not address the behaviour directly, but has partial side effects, for example the physical pressure exerted on a user from a spring in a self-closing door may prompt the user to be faster at taking items, behaviour 1, when it was only designed to close the door if they forget to close it, behaviours 4 and 5. This approach therefore combines elements of morphological analysis with at this stage a subjective value analysis.

Table 5 – A graphic representation of the user-efficient morphological approach

Behaviour	Function	Possible Solution Concepts			
1	3	A	B	C	D
	5	X	Y	Z	
	2	H	I	J	K
2	5	X	Y	Z	
	....	...	...	...	...
N	N	N	...	N	

The final design outcome is the red line, highlighting which solution elements have been chosen for this design concept. In this example the new design will tackle behaviour 1 by using function's 3 and 5 and the solution concepts A and Z respectively. Conveniently behaviour 2 is also addressed by function 5 and the same concept Z. Since every design change will have tradeoffs between saved energy from the user and the new energy cost of implementing the new design, using the same solution concept to tackle more than one behaviour may be an effective way of improving this energy balance. The selection process should continue until all the behaviours have been considered in the final design.

8 USER-EFFICIENT MORPHOLOGICAL DESIGN

The original design process, figure 1, set out to use observed user behaviours as a check list to evaluate new product designs, in stage 2, in order to ensure that they were addressing the most important behaviours. The designs were created in stage 1 using three established design methodologies and a good range of feasible solutions were made. However evaluating these new designs against the observed behaviours showed that because there are so many different ways in which a product could be used, it would have been helpful in steering the design process to know what behaviours are important before the design work begins. The research feedback from the authors as they performed the original design process has led to a complete transformation of the design process into that of a morphological approach, figure 4. Firstly a design requirement is created which stipulates that inefficient use is an important factor in the overall energy consumption [11]. After this the morphological design phase begins with the observation of users and a review and analysis of their behaviours. In order to save time or resources the observational study could be done externally to the design team by an ethnographic styled field study with the resulting important behaviours being fed into the design system. However this study and much work by user-centred design organisations such as IDEO [14] and other researchers [15] suggest that it is also of benefit to the design team if they are able to be involved in the process and share some specific examples of the observations during the design process. Observing the behaviours and performing the analysis was in this study done by one of the authors with the act of watching and recording providing a rich source of design inspiration as the behaviours were identified and analysed.

Next the morphological functions are created following the structure of table 4, followed by the solution concepts for each function. Finally the detail design work can begin to assemble the multiple solution concepts into a single end product. This is effectively the end of the design process, a new product or products will have been created that not only address the technical requirements of a refrigerator, but also the user related impacts that so often waste energy unnecessarily. However an interesting opportunity now exists to link this new design back into the design process. By prototyping the new product and trialling it with users, following the 'Design Evaluation' path, it would be possible to observe any new or changed behaviour. These behaviours can be analysed and fed back into the morphological functions acting as a kind of feedback loop and removing the possibility of rebound effects undoing the good work.

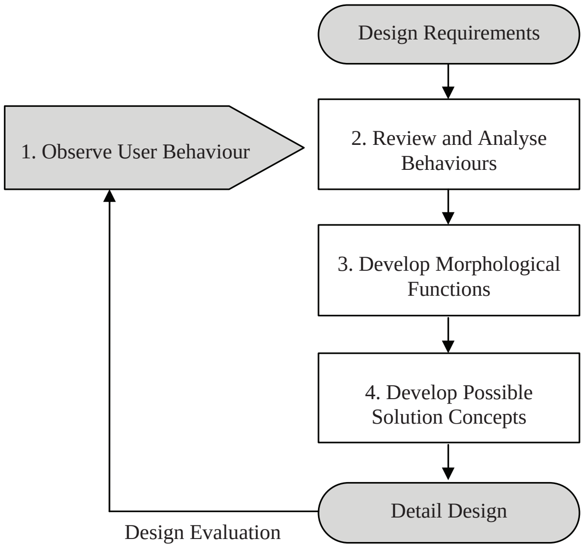

Figure 4. User-Efficient Morphological Design Approach

9 CONCLUSIONS

Energy loss due to user behaviour is an increasing issue as products become more technically efficient. Thus the initial premise to develop and assess the authors' approach was to chose a product that suffered from considerable user inefficiency and redesign it with this particular aspect of energy losses due to use in mind. The design process, set out in the research approach of section 2, gave the authors a guide to follow in which to do this and by reviewing and assessing their progress, improvements and alterations to the process could be made. What has arisen from this action research approach is an enhanced morphological design process that uses actual observed and quantified behaviours of users to guide designers through a traditional morphological design framework that has been combined with a value analysis of the solutions. This user-efficient morphological design approach is more effective because:

- By investigating the users first, products are only selected where the user related energy impact is large enough to justify the redesign work. Overcoming the tradeoffs between the increased energy of manufacture and technical and material efficiency with the benefits of improved user efficiency.
- The most important behaviours are identified early on in the process with quantitative observation based data, steering the designers and the design process.
- Undertaking the observation studies themselves, or in close collaboration with field workers, the design team can gain valuable insights into the latent needs of the users and the subsequent behaviour.
- The morphological functions and charts assist the design team in identifying the most effective solution concepts.
- The 'Design Evaluation' loop provides a good opportunity for confirmation of the success of the changes and an effective preventative check for any negative rebound effects.

Helping designers deal with specific user behaviours that have a particularly adverse effect on energy consumption is an under developed area. Thus the proposed extended morphological approach has grown to address the shortcomings of the original design process to create a process where the behaviour of the user can steer the design team in a targeted manner. Together with the design requirements the morphological approach suggested is likely to provide design rich solutions that focus solely on the highest environmental impacts observed behaviours of the user.

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