

PRIORITISATION METHODOLOGY FOR USER-CENTRED DESIGN OF ENERGY USING DOMESTIC PRODUCT

E.W.A. Elias, E.A. Dekoninck and S.J. Culley

Keywords: energy efficiency, user behaviour, locking in behaviour, domestic products

1. Energy Use and User Behaviour

Energy using products in the home account for over 13% of the UK's domestic electricity use and many of these products have seen considerable electrical efficiency improvements, in 1980 a typical fridge/freezer would use 760 kWh per year compared to an A+ rated fridge/freezer, in 2005, which uses a third of this value at 254 kWh per year (Rüdenauer et al. 2005). Despite these improvements the total consumption of domestic electricity has more than doubled since 1970, with increases in total electricity consumption in every sector of domestic goods. It is expected that similar consumption patterns will be seen across all developed consumer societies.

Energy using products can "experience" energy consumption in two ways, the first is through inefficient use of technology and engineering design. These are the *intrinsic losses* of a product, for example insufficient insulation in a domestic refrigerator accounts for the majority of energy loss, as heat transfer occurs through the insulated walls of the device. This slowly raises the temperature inside the fridge and causes it to activate. These losses are dependant on the engineering design of the device and are locked into the product at the point of design and manufacture. The second set of losses are *user-related losses*, and refer to energy losses caused by inefficient use of a product. The use of a product may be spread over a range of good and bad behaviours. Good behaviour being more energy efficient than bad. Establishing this range is an important step in the determination of user-related losses, Palmborg, in 1986, and Gram-Hansen, in 2003, found that domestic energy use can differ by a factor of two, even when the equipment and appliances are identical. The leaving open of a refrigerator door, for example, can cause large energy losses and is directly related to the user behaviour. Wood et al. (2003) cite studies, in 1978, 1981 and 1996, from the United States, the Netherlands and the UK which estimated that 26 – 36% of in-home energy use is due to the resident's behaviour.

The total energy used by a product consists of the required operational energy (this can be thought of as a theoretical minimum), intrinsic losses and user-related losses. Figure 1 shows the decline in energy use as product efficiency improves over time. Product efficiency is the amount of energy required by a product to carry out a function compared to a theoretical minimum value for that same function (Elias et al. 2007) and hence is a measure of the intrinsic and user-related losses. As efficiency approaches 100% the losses decline to zero and what can be thought of as a theoretical minimum amount of energy required to perform a given function, for that product is reached.

Figure 2 shows how, over the same period of time, the user related losses, as a percentage of the total losses, shown in figure 1, will rise in proportion as the intrinsic losses of the device are reduced with new technology and incremental engineering improvements. For example if a product today had

intrinsic losses of 75% and user related losses of 25% then over time as the technology improves the user losses will rise in significance.

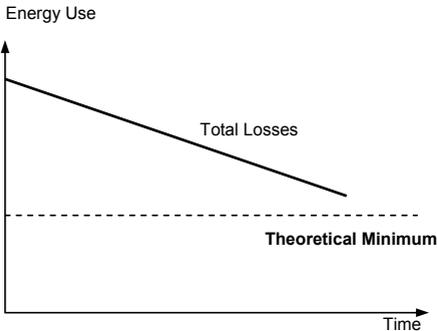


Figure 1. The decline of total product energy losses over time due to improved technical design

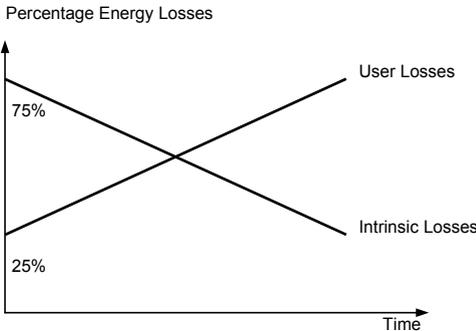


Figure 2. The predicted rise and fall of User and Intrinsic losses over time

Figure 3 shows the steady improvement of energy efficiency, as theorised in figure 1, since 1980. Cold domestic appliances such as fridges and freezers follow a pattern of declining intrinsic losses but an unchanged user related loss. The energy label test for domestic cold appliances, the results of which are the basis for figure 3, is a test in which the door remains closed but the ambient temperature is higher than the average for the UK. As a result of this procedure only the engineering integrity of the device is tested and hence only the intrinsic losses are measured. Comparison tests have shown that the energy label test measures an energy consumption of between 10 - 12% higher than real life use, with door openings at an ambient temperature of 18 - 19°C (MTP 2006), the UK average. Since these tests do not however include factors relating to the user related losses, such as door openings and the temperature recovery from the insertion of warmer food, it could be assumed that, since the design of a refrigerator has not changed significantly since 1980, the user losses may be constant over this time.

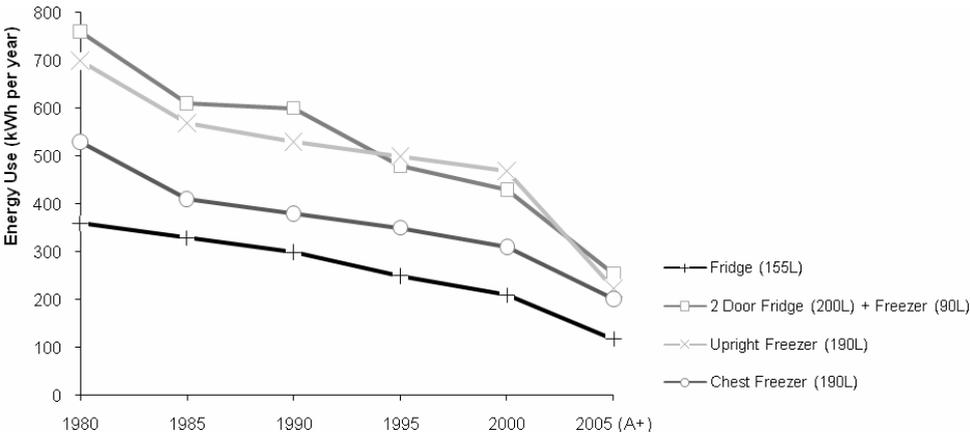


Figure 3. The energy efficiency improvement of cold appliances, adapted from Rüdener et al. 2005 Mennink et al., 1998, carried out a series of tests on a 200 litre refrigerator to determine where the largest sources of energy losses were in the device. The product they tested showed intrinsic losses of

81% (23.3W) due to poor insulation and user related losses of 8% (2.2W), due to door openings, and 11% (3.1W) due to adding food at room temperature each day. As the insulation of such products is improved, the intrinsic losses are reduced, whilst the user related losses remain unchanged and rise in percentage terms of total loss.

The traditional methods of curbing user losses have been predominately in the form of increased consumer education highlighting environmental and energy issues. These methods do perform well but their results are often not sustainable, with large initial savings reducing over time as users revert to old habits. Hayes and Cone, 1977, show this to be the case with a study that they undertook on electricity use in a student housing complex, attempting to change behaviour through education. Initially after energy efficient information was distributed there was a 30% reduction in usage, but in a subsequent week the savings had quickly fallen to 9%.

2. Locking Behaviour through Design

A method is therefore required that would prevent this relapse to an earlier energy inefficient behaviour. One such method can be found in the field of manufacturing changeover design, where the approach of *doing better things rather than doing things better*, McIntosh et al. 1996, guides machine and tooling redesign. Culley et al., in 2003, commented that if a task is made physically simple and straightforward it will be easier to sustain. In this unique 10 year retrospective study, it was shown that it was such design changes that endured and maintained performance. Rather than relying on management discipline alone, or in the case of domestic goods, avoiding a reliance on consumer information and education, physical changes to a device can prevent a return to old working practises and thus *lock-in* the desired behavioural changes. It follows therefore that domestic devices could be redesigned to lock in desired energy efficient behaviour.

But could this good work be mitigated or even reversed due to the rebound effect. The direct effects of which are that a more efficient product would be used more often or for longer, thus reducing and possibly reversing the desired gains. For example a more fuel efficient vehicle may be driven more often or for longer because the user is aware that it is not as damaging to the environment or as expensive to run. In this way the benefits of developing a more fuel efficient vehicle has been mitigated directly by a change in the user's behaviour. The indirect rebound effects are numerous, and considerably harder to mitigate, but a principle factor is that the financial savings generated by improved efficiency of energy using products would translate into a greater spending power of the consumer. Thus the indirect rebound effects would be consumer spending this 'saved' money on more energy using goods and services, such as a larger television, more electronic gadgets or on flights for a foreign holiday, all of which increase the total demand on the planet's resources.

A user-centred design approach has the potential to reduce the direct rebound effects by locking behaviour into an energy efficient pattern. However the indirect effects would be impossible to counteract at the point of product use. Energy efficient products can create a financial saving that may result in a greater freedom to spend, and can only be addressed with consumer education or government policy.

3. Product Assessment

The methodology for product assessment, being developed and explained in this paper, looks at the potential for "behaviour improvement or modification", by comparing good behaviour with bad behaviour, and the impact this has on the user related losses. Drawing parallels with risk analysis Failure Mode Effects Analysis (FMEA) methodologies of "probability" and "seriousness". In an FMEA study of a product or system, the possible modes of failure are identified as well as the possible effects and characteristics of this failure, followed by the severity of failure and the potential causes (Stamatis 2003). With this information to hand it is possible to target the most likely causes of failure and the failures of highest severity, implementing improvements to the system at the design stage focusing on the really important elements. In much the same, way the authors' of this paper hope to achieve reductions in energy losses, through the 'control' or 'influence' of user behaviour, at the

product design stage. To achieve this aim the first step is thus the development of a prioritisation methodology for identifying the probability and seriousness of user-related losses in products.

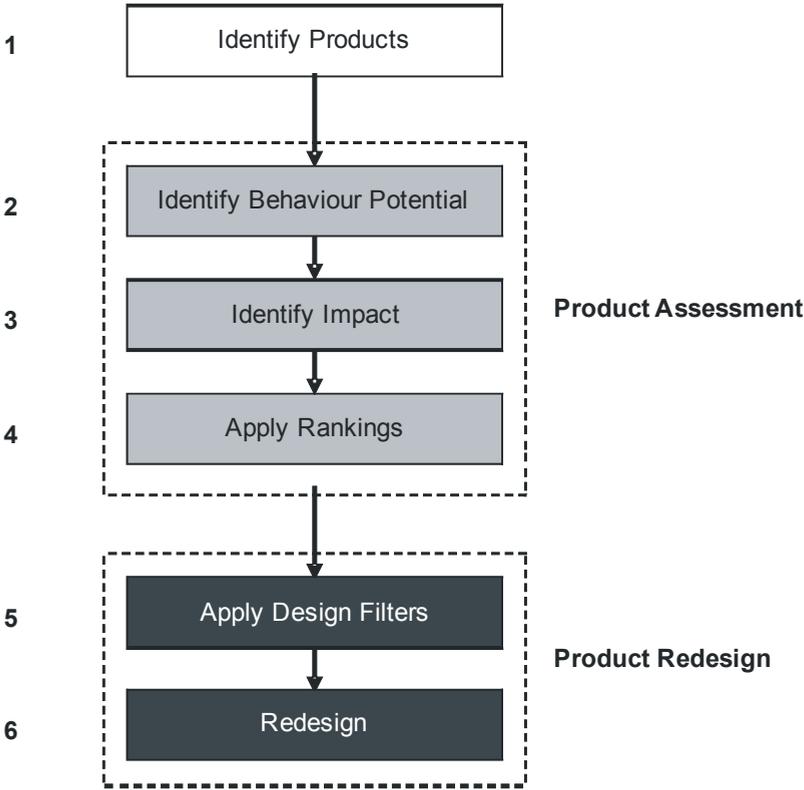


Figure 4. The proposed 6 step methodology for energy efficient redesign product assessment

Figure 4 shows the stages of this 6-step assessment procedure. First the products to be studied are identified, in the case of the example used in this report it is products of a domestic nature. Secondly the possible behaviour scenarios for each product must be established through a combination of user studies and theoretical use scenarios based on the thoughts and personal experiences of the members of the team undergoing the study. These scenarios need to focus on the extremes of behaviour as well as the daily, regular and typical instances of use. Assessing the potential is undertaken by comparing the best, i.e. the benchmark scenario, with the worst case scenarios of use. For example the best use scenario for a television is to have the television only on when it is being watched and to turn it off as soon as the desired programme finished. A bad use scenario would be to leave the television on when no one is watching or listening to it. This may occur when it is being watched from someone's bed late in an evening (scenario A). The watcher falls asleep leaving the television running all night until they wake up the following morning. A possible 8 hours overnight of running time has been wasted. The impact of these behaviours must then be assessed, a small action done with high frequency may be as important as a one-off extreme situation. To establish a quick benchmark for good behaviour for television use the UK national average time of 3:36 hours per person per day can be used. In the example described previously the user who falls asleep, leaving the television on overnight perhaps once a fortnight has increased their daily usage from 3:36 hours to 4:10 hours, an increase of 13.7% due entirely too the user-related losses of a single incident. A modern television is a large user of energy, perhaps using 150W for an LCD screen and up to as much as 400W for a large plasma screen.

Step 4 of the process is to rank the outcomes of steps 2 and 3 in a table, examples of which are shown in figure 5, showing the product name, the theoretical minimum energy required to perform its given function, the intrinsic losses, a user related benchmark and the user-related losses estimated from the use scenarios and behaviour impact.

	Energy Use	Theoretical Minimum	Intrinsic Losses	User Benchmark	User Losses	Percentage Loss
Television	150 W	45 W *	105 W	1 hour	0 W	
(Benchmark)	540 W	162 W	378 W	3:36 hours per day	0 W	
Scenario A	626 W	162 W	378 W	4:10 hours per day	86 W **	13.7%
Refrigerator ***	28.6 W	3.1 W	23.3 W	2.2 W 24 openings a day 5 seconds per opening	0 W	
(Benchmark)	28.6 W	3.1 W	23.3 W	2.2 W (2 minutes open)	0 W	
Scenario B	33 W	3.1 W	23.3 W	6.6 W (6 minutes open)	4.4 W	13.0%

* 45 Watt theoretical minimum is established from a product search of the lowest energy using televisions
 ** 86 Watt User Losses is the total energy increase due to an additional 34 minutes use
 *** The data for the refrigerator is adapted from Mennink et al., 1998

Figure 5. Step 4 of the Prioritisation Methodology, calculating user related losses

The data for scenario A, in figure 5, is based on the television example described previously and the daily use of a refrigerator. Raising the daily use of the television from 3:36 hours to 4:10 entirely through user error causes an additional 86 Watts of electricity to be consumed with no additional benefit, hence an unchanged theoretical minimum and unchanged intrinsic losses. For the refrigerator example of scenario B an additional 4 minutes of opening the refrigerator door per day could be caused through the accumulation of many use scenarios based on careless use, either opening the fridge more often or for longer. Since the same function can be performed for less energy in the benchmark example, the 4 additional minutes is entirely attributed to user losses.

Converting the user losses to a percentage of the energy use gives a useful metric for comparing products, and provides evidence for a ranking of the products in terms of their *potential and impact* as required by step 4 using a simple system of high, medium and low. If there is a large difference between good or normal behaviour and bad behaviour, and that bad behaviour has a large impact, the product would be classed as high, meaning it is a priority for redesign. In the examples shown in figure 5, both these products would be classes as high.

To demonstrate this process on a larger scale, figure 6 shows a list of domestic products which each have been given a rating based on a subjective assessment of the possible difference between good and bad behaviour and the likely impact of this bad behaviour. A further stage of the authors’ work will be to make this process less subjective by collating data such as that presented in figure 5 and the use of previously recorded observational video data for scenario development. The purpose of the 6-step methodology, figure 4, is to determine which products most require a user-centred redesign but Figure 6 shows a majority of products in the high and medium categories and so does little to help narrow the field of potential products. The primary reason for so many high ratings is the lack of an automatic off-switch on the devices. If for example any energy using product was accidentally left on it could use electricity continuously until it was turned off by the user. This raises the possibility of the device having unusually high user-related losses when compared to its normal use.

Cold	Brown	Cooking	Wet	Misc
H Fridge	H TV	H Cooking Hobs	H Washing Machine	H Hair + Beauty
H Fridge Freezer	H Games Consol	H Oven	H Tumble Dryer	H Toys
H Upright Freezer	M DVD Player	H Grill	H Washer Dryer	H DIY Tools
H Chest Freezer	M VCR	H Microwave	H Dishwasher	L Garden
M Mini Fridge	M Set-Top Box	M Toaster	M Iron	M Vacuum Cleaner
M Wine Cooler	M Radio	H Kettle	H Electric Shower	
M Cooling Drawer	M Hi-Fi	M Sandwich Maker		
H Ice Maker	M Computer / Laptop	M Grilling Machine		
L Water Cooler	M Printer	L Blender		
	M Scanner	L Mixer		
	M Fax Machine	L Whisk		
	L Telephone	M Coffee Machine		
	M Phone Charger	L Deep Fat Fryer		
		L Slow Cooker		
		M Cooker hood		
		L Rice Cooker		
		L Bread Maker		
				KEY
				H High
				M Medium
				L Low

Figure 6. A list of domestic products categorised in terms of high, medium and low potential and impact.

Cold	Brown	Cooking	Wet	Misc
H Fridge	M TV	H Cooking Hobs	H Washing Machine	L Hair + Beauty
H Fridge Freezer	M Games Consol	H Oven	H Tumble Dryer	L Toys
H Upright Freezer	L DVD Player	H Grill	H Washer Dryer	L DIY Tools
H Chest Freezer	L VCR	H Microwave	H Dishwasher	L Garden
M Mini Fridge	L Set-Top Box	M Toaster	L Iron	L Vacuum Cleaner
M Wine Cooler	L Radio	H Kettle	H Electric Shower	
M Cooling Drawer	L Hi-Fi	L Sandwich Maker		
H Ice Maker	M Computer / Laptop	L Grilling Machine		
L Water Cooler	L Printer	L Blender		
	L Scanner	L Mixer		
	L Fax Machine	L Whisk		
	L Telephone	L Coffee Machine		
	L Phone Charger	L Deep Fat Fryer		
		L Slow Cooker		
		M Cooker hood		
		L Rice Cooker		
		L Bread Maker		
				KEY
				H High
				M Medium
				L Low

Figure 7. Revised potential and impact assessment after the first design filter has been applied

The methodology could be stopped at this stage with a list of products in terms of their user-related losses, as shown in figure 5, and based on the use scenarios devised in steps 2 and 3, a plan of action to tackle them could be generated. However it is also possible continue into the realm of product redesign by treating this list of products as a group with shared bad behaviours. The next stage of this methodology is therefore to apply design filters which would tackle the largest group of shared bad behaviours. Based on shared bad behaviour a simple design alteration can have considerable impact on

a wide number of products and may create a greater energy saving than focusing on a single end product.

The first filter to be applied is a simple design alteration that may reduce both the potential and impact of these devices. In this case the first filter would be the introduction of an automatic “switch off” or “switch to standby” function if the product has not been used for a determined length of time. Preventing the worst case user scenario of devices being left on accidentally for long periods of time. The length of time before switch off would need to be established case by case with a detailed user study and may give options for the user to disable the function if necessary, although the default should always be enabled.

It may be hard to determine whether some products have been left on unintentionally or are still being used. The television, for example, could have a system which switches to standby if no buttons have been pressed or the remote has not been moved for a period of say 4 hours. This envelope of 4 hours would allow films to be watched but would prevent the set being left on over night. The potential impact from the use of this first design filter and revised assessment can be seen in figure 7 and highlights the effectiveness that a simple design rule could have in reducing the potential for energy waste and its impact of many products. In figure 7 cooling, heating and washing remain as the major energy use activities where unique behaviour still has a considerable effect.

This application of design filters could be repeated until only the products with unique behaviour situations remain. A second potential design filter to be applied to the products in figure 7 could be for the products to be “self adjusting”. The fridge could automatically try to self close the door when it had been left open, correcting a potentially bad behaviour situation avoiding the penalty of increased energy use. Some refrigerators currently available on the market aim to bring prolonged door openings to the attention of the user with the sounding of an alarm. User studies would need to be carried out to find the effectiveness of this approach of “telling the user off” for potentially doing something bad rather than a more convenient device which actually took action to correct the situation and tried to close it itself without the need for the user to be involved. This product design concept of adjusting to the user’s actions makes the product energy efficient despite bad behaviour and independent of user attitudes and desires.

4. Conclusions

User behaviour is a considerable cause of energy loss in energy using products and is set to rise in significance as the intrinsic losses of products are improved over time. This paper presents a method for calculating the user-related losses in terms of behaviour potential and behaviour impact, identifying their significance when compared to the usual intrinsic losses associated with engineering and technical inefficiency of any device. The products under investigation can be ranked and prioritised in terms of percentage user losses so that the most urgent redesign candidates are presented. This method, when applied to a range of products, also draws similarities between products delivering a design strategy based on shared user behaviours.

The final aim of this raised awareness of the increasing impact of user behaviour, improving the efficiency of the product is to lock-in good behaviour at the design stage of product development for both shared and unique user behaviours.

References

- S. J. Culley, G. W. Owen, A. R. Mileham, R. I. McIntosh, Sustaining Changeover Improvement, Department of Mechanical Engineering, University of Bath, UK, 2003.*
- E. W. A. Elias, E. A. Dekoninck, S. J. Culley, The Potential for Domestic Energy Savings through Assessing User Behaviour and Changes in Design, 5th International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, 2007.*
- S.C. Hayes, J.D. Cone, Reducing residential electricity energy use: payments, information, and feedback, Journal of Applied Behavior Analysis 10, 1977, 425–435.*
- Gram-Hansen, K., Domestic electricity consumption—consumers and appliances. Paper, Nordic Conference on Environmental Social Sciences (NESS), 2003.*

- R. McIntosh, S. Culley, G. Gest, T Mileham, G. Owen, *An assessment of the role of design in the improvement of changeover performance*, *International Journal of Operations and Production Management*, Vol. 16, No. 9, 1996, pp. 5-22. University Press, 0144-3577
- B. D. Mennink, D. M. Berchowitz, *Development of an improved stirling cooler for vacuum super insulated fridges with thermal store and photovoltaic power source for industrialized and developing countries*, *Innovatiebureau Mennink*, 7201 AE Zutphen, The Netherlands, 1998.
- MTP, BNC11: *Domestic refrigerator test standard vs. real-use energy consumption*. <http://www.mtprog.com>, 2006.
- Palmborg, C., *Social habits and energy consuming behaviour in single-family houses*. Swedish Council for Building Research, Stockholm Olsson, 1986.
- I. Rüdenauer, C. O. Gensch, *Environmental and economic evaluation of the accelerated replacement of domestic appliances, Case study refrigerators and freezers*, *European Committee of Manufacturers of Domestic Equipment (CECED)*, Institute of Applied Energy, Feiburg, Germany, 2005.
- D. C. Stamatis, *Failure Mode and Effect Analysis: FMEA from Theory to Execution, Second Edition*, ASQ Press, 2003, ISBN 0873895983
- G. Wood, M. Newborough, *Dynamic energy-consumption indicators for domestic appliances: environment, behaviour and design*, *School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, Scotland, UK*, 2003.

Edward Elias MEng
Postgraduate
University of Bath Department of Mechanical Engineering
University of Bath,
BATH,
UK,
BA2 7AY
Tel.: 01225 385138
Email: E.W.A.Elias@bath.ac.uk