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Assessing the 'Design Exclusion' of Heating Controls at a Low-Cost, Low-Carbon Housing Development

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Abstract

Space heating accounts for almost 60% of the energy delivered to the domestic sector, and housing accounts for nearly 27% of total UK carbon emissions. A study was conducted at Elmswell 'Three Gardens' Housing Development in Suffolk to investigate the influence of heating control design on energy consumption. The degree of 'user exclusion' was calculated using a tool developed by the Engineering Design Centre at the University of Cambridge. It was found that the current design placed unreasonable demands on the capabilities of at least 9.3% of the UK population, particularly in terms of 'vision', 'thinking' and 'dexterity'. The tool does not account for level of numeracy and literacy therefore the authors feel the true exclusion may be higher. The controlled monitoring of heating consumption in two houses suggests that a simpler and more inclusive design may lead to savings in the region of 20% at Elmswell.

Keywords: controls; energy consumption; heating; design exclusion

1. Introduction

In November 2008 the Climate Change Act became law in the UK setting a target of an 80% reduction of CO2 emissions, from 1990 levels, by 2050 (DEFRA 2009). Domestic housing accounts for 27% of UK carbon emissions, with energy consumption still rising (Lomas et al. 2009, Boardman 2007a, Sustainable Development Commission 2006). Of this, space heating accounts for up to 60% of the energy consumption within the 25 million existing homes in the UK (Utley & Shorrock 2008). As the vast majority of these homes will still be in use in 2050 the refurbishment of existing housing is needed to improve energy efficiency and reduce their energy demand (Lomas et al. 2009, Boardman 2007b).

The energy consumed by space heating is dependent upon four factors; the time the space is heated for, the temperature setting of the thermostat, the outside temperature and the performance of the building fabric (Lomas et al. 2009, MacKay 2009). The Home Energy Survey conducted by the CaRB consortium states that “a one per cent rise in temperature setting is estimated to cause a 1.55 per cent rise in CO2 emissions” (Lomas et al. 2009).

One methodology considering both the social and environmental impacts of a building is Post-occupancy Evaluation (PoE) which aims to ascertain whether the building performs as intended and how people use the building (Cohen et al. 2001). PoE typically includes questioning the occupants or users of the building and monitoring the buildings energy use taking a holistic approach which is more appropriate to the current sustainable development paradigm. Predominantly occupant satisfaction depends on noise, perceived control of the environment and thermal comfort of users (Bordass & Leaman 2001). The Post-occupancy review of buildings and their engineering (Probe) studies conducted from 1995-2002 shows a consistent decline in the amount of control building occupants perceived they had over their environment, which contributes to their dissatisfaction (Bordass & Leaman 2001).

Furthermore they argue “Simpler systems with usable controls and interfaces for occupants can give better results in terms of user satisfaction than more elaborate (and often more energy-consuming) systems with control interfaces which are poor in function, location, clarity and responsiveness, or even absent” (Bordass & Leaman 2001). This sentiment is echoed by Richard Miller of the Innovation Platform for Low Impact Buildings and the UK Government’s Market Transformation Programme who concur that one of the best ways of reducing domestic energy consumption is encouraging proper use of heating controls by the users (Lomas et al. 2009).

This leads to the conclusion that making control systems simpler could potentially save energy and include more users. By calculating the ‘design exclusion’ of control systems the number of people who can not use the current system and the reasons for this can be understood. Once the reasons for this exclusion are understood it may be possible to improve the usability of these controls, making them more inclusive and potentially reducing household energy consumption. Specifically this study will examine the heating control system currently available at the Elmswell ‘Three Gardens’ Housing Development using the Exclusion Calculator developed by the

Engineering Design Centre at the University of Cambridge. This study will make recommendations as to how the system may be improved to include more users and estimate how much energy could be saved through improved use of the control system.

2. Context of Study - Elmswell 'Three Gardens' Housing Development

Elmswell 'Three Gardens' Housing is a 26 house development in Suffolk which Buro Happold has been involved in throughout the design process. The Sustainable and Alternative Technology department of Buro Happold aimed to make Elmswell a model of sustainable housing development, ensuring the site is extremely energy efficient by implementing a variety of low and zero carbon technologies and using an innovative building fabric. These technologies include rainwater recycling, the use of a biomass boiler for district heating and a south facing orientation to maximise solar gain. The building fabric uses a timber frame with Hemcrete® insulation and lime render giving a combined low U value of 0.25 W/m^2/K.

The development consists of 4 one bedroom, 13 two bedroom and 9 three bedroom dwellings. Currently a Post-occupancy Evaluation to assess the success of the development by monitoring the energy performance on site is being conducted. All 26 dwellings are monitored on a monthly basis with four dwellings being studied in more detail. At each of the four dwellings studied in detail the consumption of electricity (from the grid), heat (from a combination of gas and biomass boilers) and water (from the main supply) has been monitored since 2008. This is alongside bespoke measurements which include monitoring in-situ fabric performance, internal air quality, external conditions and use of thermal imaging.

[Figure 1. Overview of sustainable features of the site]

Based on nine months available data from thirteen fully occupied buildings the data from Elmswell shows overall heat consumption accounts for two thirds of the energy consumed in the dwellings. The total average energy consumed at the development was 224.7kWh/m^2/year. This is split between heating consumption of 144.5kWh/m^2/year and electricity consumption at 80.2kWh/m^2/year. Average consumption for space heating was 78.7kWh/m^2/year and for hot water was 24.8kWh/m^2/year, which is now approaching the design prediction of 57kWh/m^2/year for space heating and 30kWh/m^2/year for hot water. Compared to a 1940's 3 bedroom semi-detached house MacKay (2009) calculated consumed approximately 185kWh/m^2/year in space heating before an energy efficiency refurbishment and approximately 62.5kWh/m^2/year afterwards. Furthermore, turning the thermostat down from 20^{o}C to 17^{o}C reduced heating consumption by approximately 30% (MacKay, 2009).

3. Controls Available at Elmswell

Within each dwelling there is a range of environmental controls, consisting of a thermostat to control temperature, thermostatic radiator valves (TRVs) on all radiators, light switches, automated window controls and plug sockets. The light switches, automated window controls and plug sockets are principally on/off switches. Realistically there is little scope for improvement here because the capability demands are less with an on/off switch in comparison with those required to operate the thermostat.

The majority of products have the biggest environmental impact in the use phase of the life-cycle (Lewis & Gertsakis, 2001). The use phase of products can account for up to 40% of the CO_2 emissions annually in the EU (Kronenberg, 2007). This is especially true for the thermostat due to the large environmental impact of heating the home (Wever et al., 2008, Lockton et al., 2008) and as a result attention will be paid primarily to the design and functionality of the thermostat. Detailed measurements and photographs of the thermostat are shown below.

[Figure 2. Front elevation of the current thermostat, including measurements]

[Figures 3a. & 3b. Photographs of the current interface illustrating the dexterity requirements]

4. Method - Design Exclusion Calculation

The majority of assessment methods fall into two categories: those which include users and those that do not. Although methods involving user participation, such as user observation, interviews or focus groups, can prove expensive and time consuming they are seen to be more realistic (Cardoso et al., 2004). Methods that do not involve users such as simulation, task analysis and self-observation can also prove useful to gain insight into problems at specific stages of the interaction (Cardoso et al., 2004). The Exclusion Calculator, developed by the Engineering Design Centre at the University of Cambridge, falls into the second category of assessment methods and can estimate the number of people currently excluded by the product. The tool considers how demanding each task is using a Likert scale from low to high demand for each of the sensory, cognitive and motor capabilities (Goodman & Waller, 2007). These results are then compared to the number of people who would find the task impossible according to the data from Grundy et al. (1999) giving an overall percentage of the population excluded by the given requirements. The tool was published in the Inclusive Design Toolkit and is publicly available at http://www.inclusivedesigntoolkit.com.

In order to calculate the number of people excluded by the current system at Elmswell a Hierarchical Task Analysis (HTA) was produced to establish the tasks required to operate the system, illustrating the tasks required to achieve the goal of heating the home. HTA is well established and has been a central method in ergonomics research for the past four decades (Stanton, 2006). The process works by breaking down a task into its individual parts and identifying which parts of the task may result in errors.

The HTA (shown in appendix 1.) revealed that many of the individual tasks were physically similar (e.g. pushing a button) but that the complexity of the system lay in the cognitive element of the task. The plans on the HTA illustrate the process required to complete the tasks and achieve the goal of heating the home. The visual representation of these cognitive processes exposes their complexity but aids understanding of how the system is operated.

To carry out this calculation the capability demands of the thermostat needed to be established and a suitable demand level set. The exclusion calculator requires the analyst to choose between generic demands, such as reading text and recognising a person and set the level of the demand. In some cases the level of demand is difficult to judge however demands can be set along the scale between two demand examples. For example the dexterity demands of opening the control panel door are felt to be between picking up a safety pin and using a pen. The calculation is based on a subjective analysis of the capability demands of using the thermostat which may cause variable results and induce errors, experience of the analyst is therefore critically important. Table 1 details the options selected for the demand type and the justification for the level of demand set in this study. A further source of potential error is that the calculation is based upon population data from 1997, although the data may be over ten years old the study was extremely comprehensive.

[Table 1. Assessment of the capability demands of the thermostat]

5. Results of the Exclusion Calculation

The thermostat currently excludes approximately 9.3% of the UK population (data from 1997 population figures). This is broken down by the type of requirement as follows:

Vision requirements excluded 1 525 000 people
Hearing requirements excluded 0 people
Thinking requirements excluded 2 070 000 people
Dexterity requirements excluded 1 670 000 people
Reach and Stretch requirements excluded 318 000 people
Locomotion requirements excluded 895 000 people

Total exclusion = 4 327 000 people

[Figure 4. Graph of results from the Exclusion Calculation]

6. Discussion of Exclusion Calculation Results

The three areas found to be excluding the largest number of people are 'vision', 'dexterity' and 'thinking' requirements. Future design effort should concentrate on trying to reduce the requirements in these areas.

The 'locomotion' and 'reach & stretch' requirements depend upon where the product is located within the home rather than on the product itself. Advice on the appropriate placement of the thermostat can be found in BS8300:2009 however any design modifications to the interface would not reduce these demands.

Hearing requirements do not exclude or include anyone as no audio feedback is provided. This feedback may prove useful to some users. The use of indirect feedback in reducing energy consumption has be linked to savings of around 10% (Wilhite and Ling, 1995 cited in Darby, 2008) through improved billing while direct feedback resulted in potentially greater reductions of up to 15% (Darby, 2008). At present direct feedback is primarily provided in numerical form although recent studies cited in Darby (2008) by Lockwood and Murray (2005) and Martinez and Geltz (2005) have experimented with the use of colour and size of graphics. Feedback could also inform the user of their consumption habits or to confirm the current setting of the thermostat. Feedback could help improve user confidence in the system, encouraging its adjustment as appropriate.

However feedback is not the only method of influencing behaviour, there are variety of approaches according to Wever et al. (2008) and Lockton et al. (2008). Both papers suggest methods such as mistake proofing systems, constraining the functions available to users and systems which automatically adapt to the use context as ways of influencing user behaviour. Wever et al. (2008) conclude that the more intrusive the approach, the greater the sustainability improvement achieved. Further research into this area will be required if an attempt at influencing user behaviour is to be made.

There are two dexterity requirements to be addressed: the opening of the control panel door and the pressing of the buttons. Opening the control panel door (shown in figure 3a.) is the more exclusive of the two actions as it requires substantial grip strength from one or both hands, a potentially painful but essential step for the user. For a user with arthritis this could be particularly painful yet it is a critical step in the programming of the thermostat. The recesses currently provided are shallow and could be improved upon. The force required to open the door should be reduced or removed with the use of a sliding door.

Pushing the buttons (shown in figure 3b.) does not require a significant level of force and therefore does not have high dexterity demands. However from a visual perspective the buttons could be improved in terms of their size, labelling and visual contrast with the other components of the interface. Increasing the size of the buttons could reduce the dexterity requirements, and simultaneously improving the labelling of the buttons could reduce the cognitive work load. To further reduce the vision requirements a tactile element could be introduced to the controls in the form of embossed lettering.

The area of the digital interface accounts for less than ten per cent of the whole interface which for such a critical part of the interface is extremely small. Furthermore the size of the digital display text is particularly small and places a large visual demand on the user. The size of the lettering outside the digital interface is small and its labelling could be improved. The volume of information provided in such a small space may also lead to confusion amongst users and the contrast between the lettering and the background could be improved.

With regards to reducing the thinking requirements of the system it is not necessarily the number of tasks required that proves difficult but the complexity of the overall task, its repetitive nature and the lack of flexibility within the system. When a mistake is made there is no facility to go back a stage, resulting in frustration for the user. The system also requires an understanding of temperature scale and its units of measurement which some users may struggle with due to its somewhat abstract nature.

According to Organisation for Economic Co-operation and Development (OECD, 2000) report, “approximately 20% of the adult UK population has difficulties with basic reading and maths” implying this alone could exclude around 9million adults over 16 years old, using 1997 population figures. These people would not perhaps be classed as having a disability and consequently would not be counted under the Disability in Great Britain survey (Grundy et al., 1999) upon which the results of the exclusion calculation are based. Combining this with the results of the exclusion calculation could potentially take the number of people excluded by the system to 29% of the UK population.

Considering the improvements discussed in this section sketches have been produced to illustrate these points:

[Figure 5. Concept interface taking into consideration the need for larger screen and buttons and improved labelling]

[Figure 6. Concept interface taking into consideration the provision of audio feedback and improved navigation as well as previous improvements]

[Figure 7. Illustration of how dexterity demands of the door could be reduced]

These could potentially form the basis for prototypes which may be tested in future research to establish whether the improvements reduce energy consumption. The type of information displayed on the screen has not been considered at this stage however this will form the basis of further work. In summary the sketches illustrate the provision of:

- Audio feedback
- Larger buttons
- An easier to use door
- A larger screen
- Improved tactility and
- A back button

7. Potential Energy Savings

To put the suggested system improvements in context one house was heated to 21^{o}C constantly and another heated at a variety of temperatures to approximate a typical working week. During the week at 6am the temperature was set to 17.5^{o}C increasing to 21^{o}C at 8am until 7pm. From 7pm to 10.50pm the temperature increased to 22^{o}C before dropping down to 17^{o}C overnight. At the weekend the dwelling was heated to 21^{o}C from 6am until 10pm and then lowered to 17^{o}C overnight. This was thought to mimic the difference between the default settings and being able to use the controls to heat the home appropriately.

The dwellings were both three bedroom houses of identical layout however one was end of terrace and the other was mid-terrace. This may have an impact on the results as the mid-terrace would realistically need less heat due to gains from either side. Initially both houses were set to run at the identical heating profiles for a period of 33 days. At the end of this period consumption was found to be within ±5% of each other.

The house that was set constantly to 21^{o}C was found to have consumed 308 kWh during the subsequent 35 day monitoring period. The house with the varying temperatures consumed 255kWh in the same period. This is a consumption reduction of 53kWh or a saving of around 17%. This is equivalent approximately to running the average desktop computer for 26.5 days continuously, a 40W beside lamp for 53 days or a mobile phone charger constantly for well over a year.

The monitoring period of 35 days ran throughout April and into the first week of May therefore this is by no means the maximum energy saving, as April is not the coldest of months. Considering relevant degree day data from CIBSE Guide A (Chartered Institution of Building Services Engineers, 2006) heating demand is approximately two thirds of the maximum in April, with January requiring the most heating days. Consequently it can be assumed that maximum energy savings could be in the region of one third greater during the coldest months. Further research to establish the maximum savings that could be achieved in reality with a more inclusive solution is required.

8. Conclusions

The current thermostat design placed unreasonable demands on the capabilities of at least 9.3% of the UK population, particularly in terms of 'vision', 'thinking' and 'dexterity'. However due to the understanding required in terms of numeracy and literacy, the true exclusion could be as high as 30%. The three most demanding capabilities should be reduced to make the largest reduction in numbers of people excluded.

When trying to improve the thermostat there are two potential areas to focus on: the physical interface and the digital interface. These physical changes would be cost effective, easy to implement and test on users but most importantly could include more users. The digital interface of the thermostat is more complicated in its nature and therefore reducing this could greatly improve its usability. Increasing the size and contrast of the digital display could reduce the visual demands considerably and the layout of this could also be improved. This improvement could reduce the dependence of the interface on numbers and could help include more of the 20% of the UK population that struggle with numeracy and literacy. Incorporating feedback as discussed earlier may prove beneficial to users and potentially influence their behaviour.

The authors believe simpler and more inclusive controls would include more users and may reduce energy demand. A combination of improvements to both the physical and digital interfaces would result in the best solution from both environmental and inclusive perspectives. If the heating controls were more inclusive then they would be easier to use for the majority of users. In turn this could reduce the energy consumption within the home by around 20%. Prototypes of both the physical and digital interfaces should be developed and tested in future research.

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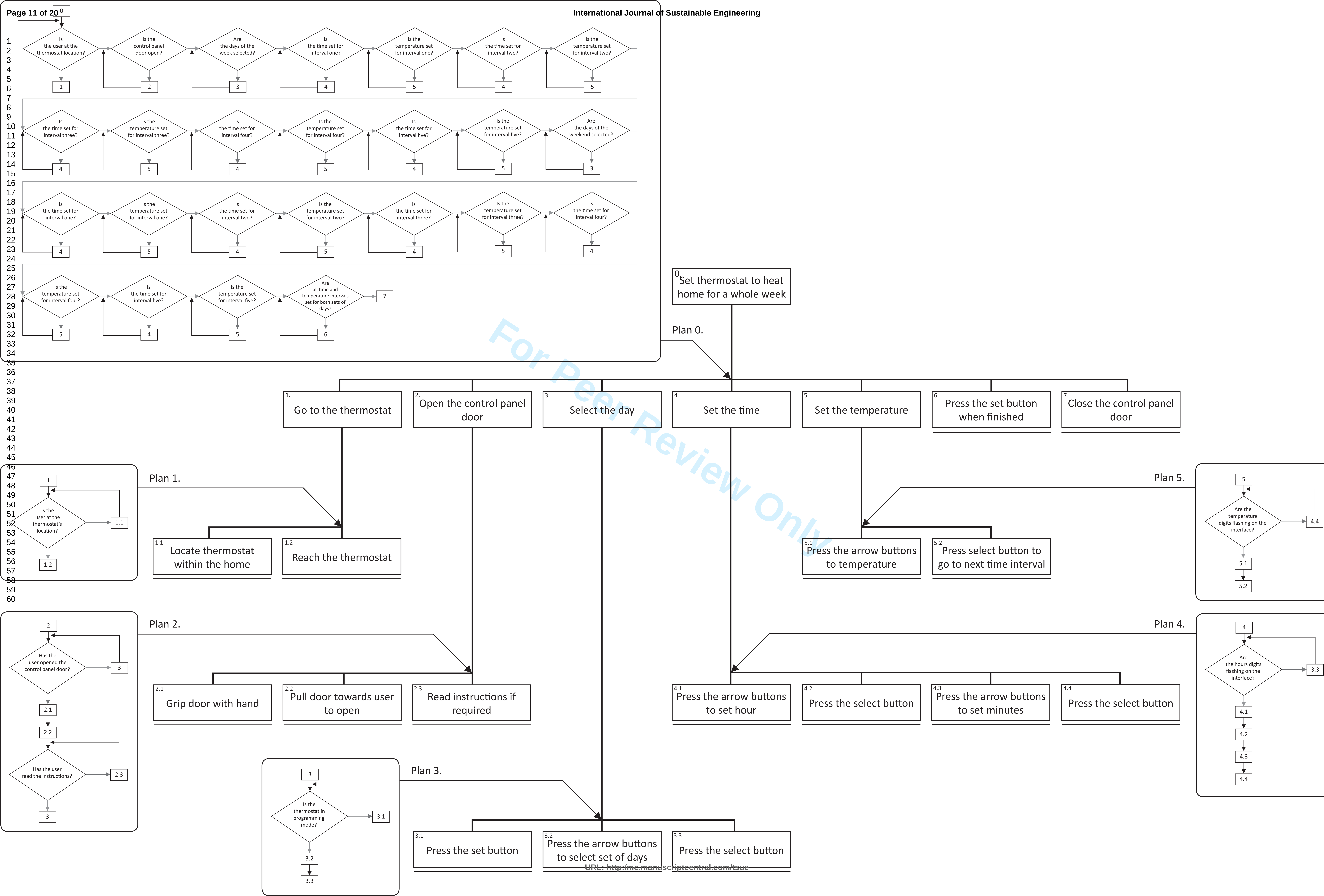
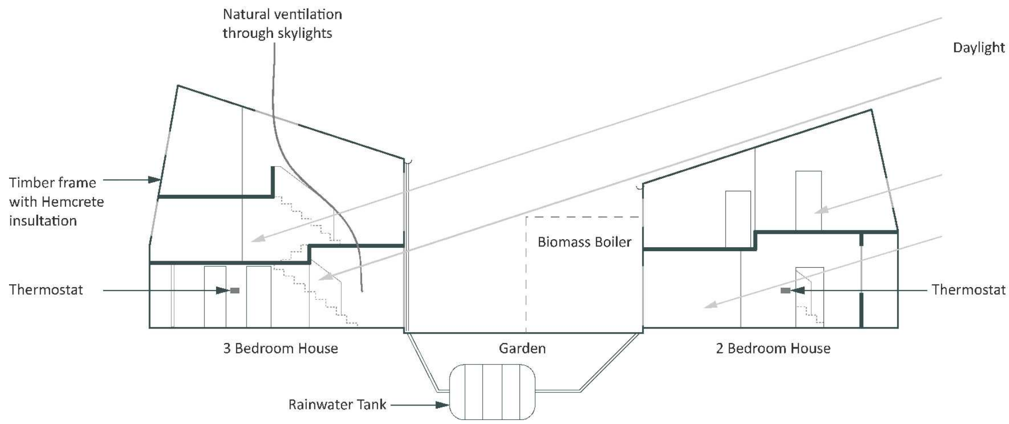
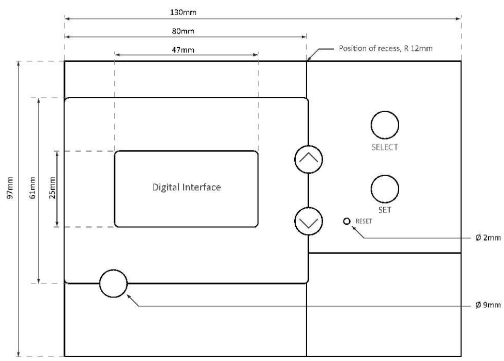

0. Set thermostat to heat home for a whole week
Plan 0.
1. Go to the thermostat
2. Open the control panel door
3. Select the day
4. Set the time
5. Set the temperature
6. Press the set button when finished
7. Close the control panel door
Plan 1.
1.1 Locate thermostat within the home
1.2 Reach the thermostat
Is the user at the thermostat's location?
Plan 2.
2.1 Grip door with hand
2.2 Pull door towards user to open
2.3 Read instructions if required
Has the user opened the control panel door?
Has the user read the instructions?
Plan 3.
3.1 Press the set button
3.2 Press the arrow buttons to select set of days
3.3 Press the select button
Is the thermostat in programming mode?
Plan 4.
4.1 Press the arrow buttons to set hour
4.2 Press the select button
4.3 Press the arrow buttons to set minutes
4.4 Press the select button
Are the hours digits flashing on the interface?
Plan 5.
5.1 Press the arrow buttons to temperature
5.2 Press select button to go to next time interval
Are the temperature digits flashing on the interface?
Is the user at the thermostat location?
Is the control panel door open?
Are the days of the week selected?
Is the time set for interval one?
Is the temperature set for interval one?
Is the time set for interval two?
Is the temperature set for interval two?
Is the time set for interval three?
Is the temperature set for interval three?
Is the time set for interval four?
Is the temperature set for interval four?
Is the time set for interval five?
Is the temperature set for interval five?
Are the days of the weekend selected?
Are all time and temperature intervals set for both sets of days?

Table 1. Assessment of the capability demands of the thermostat

Type of requirement	Demand type	Demand level	Reasoning behind choice
Vision	Reading text at various distances	Read ordinary newsprint	Small instruction text inside door and small size of text on digital interface
Hearing	None	None	The system has no audio feedback
Thinking	Think clearly without muddling thoughts Do something without forgetting what the task was whilst in the middle of it Tell the time of day without any confusion Count well enough to handle money Remember a message and pass it on correctly	Not applicable	The thought process primarily has to deal with sequences and number and these phrases were judged most relevant to the scales available
Dexterity	Performing fine-finger manipulation with either left or right hand	Between pick up a safety pin and use a pen	To open the control panel door the top and bottom of the door must be gripped then pulled to open and pushed to close
Reach & Stretch	Reaching one arm out for a long period	Reach one arm out in front (for long periods)	Controls are manually operated and situated in front of the user
Locomotion	Walking various distances on level ground	Below walk 50m without stopping	Transfer to control system is likely to be less that 50m

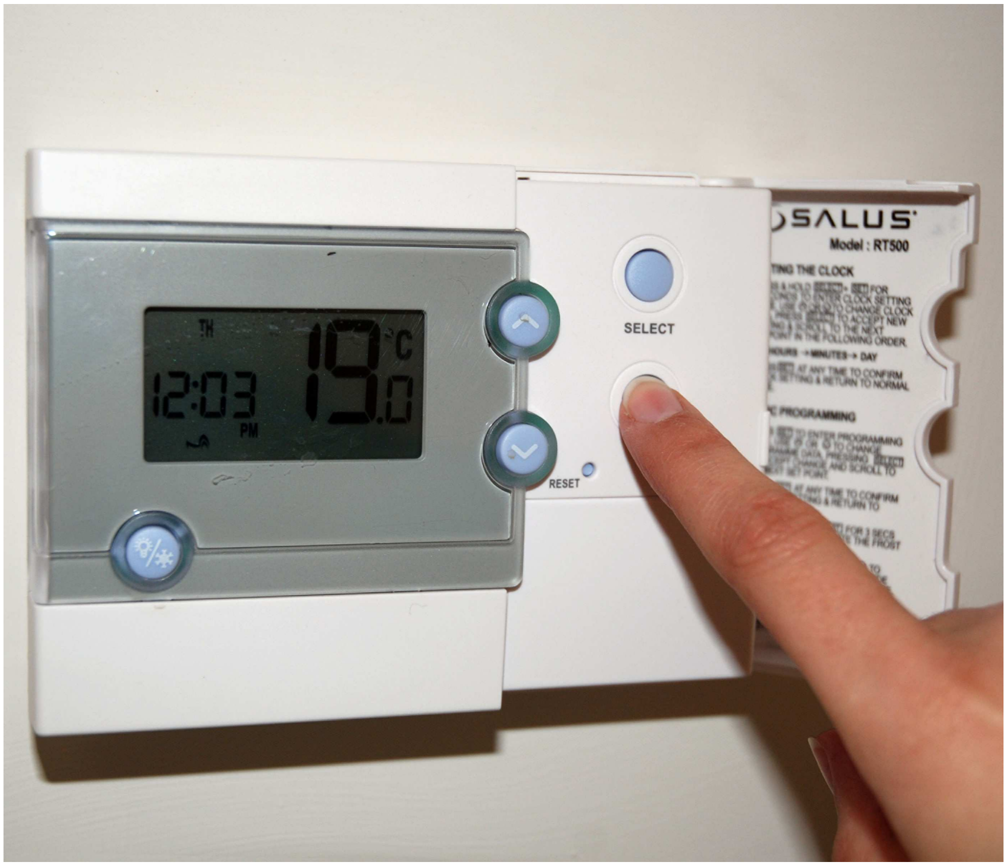


222x92mm (600 x 600 DPI)



327x219mm (600 x 600 DPI)

236x202mm (300 x 300 DPI)



236x202mm (300 x 300 DPI)

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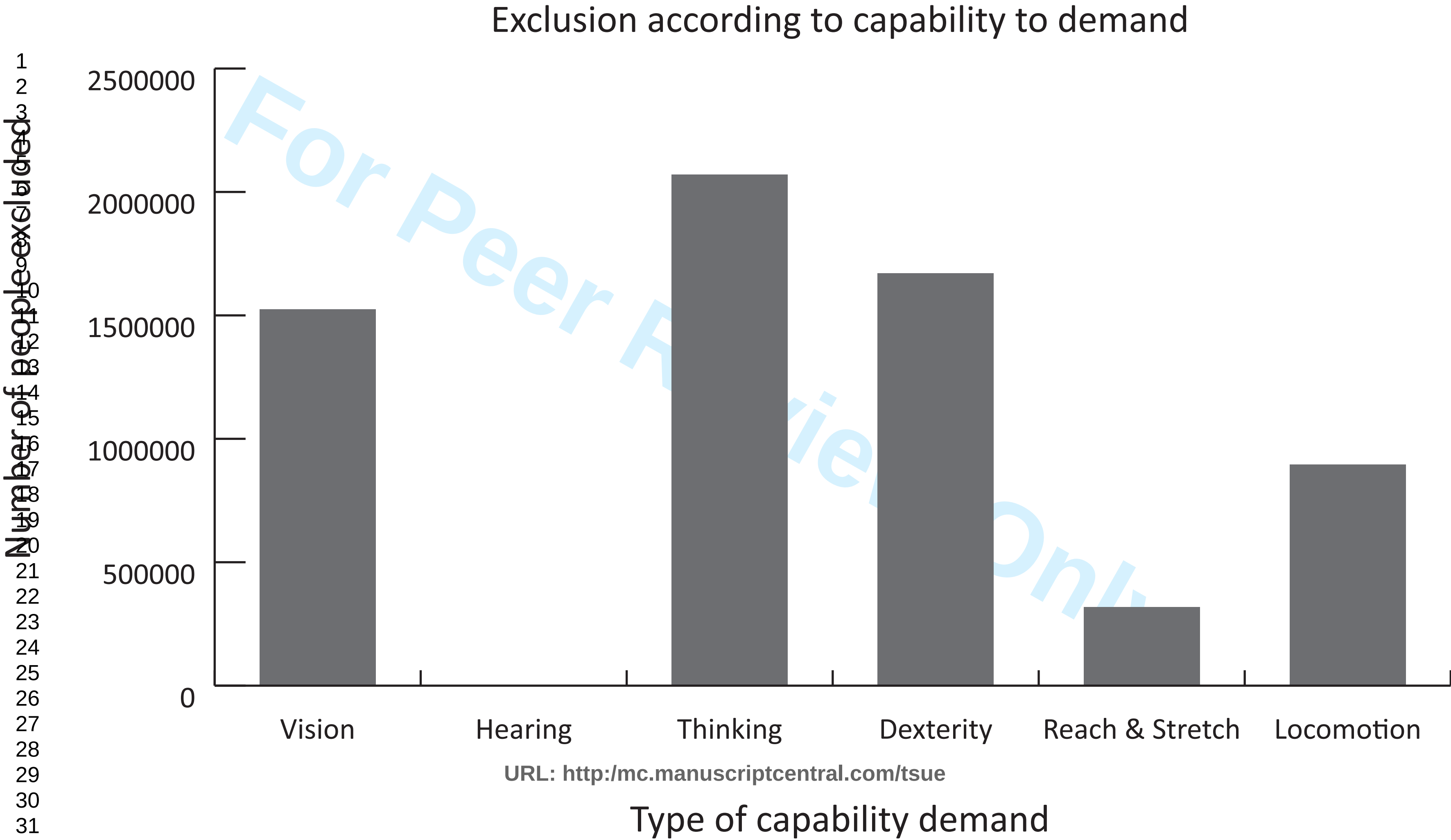
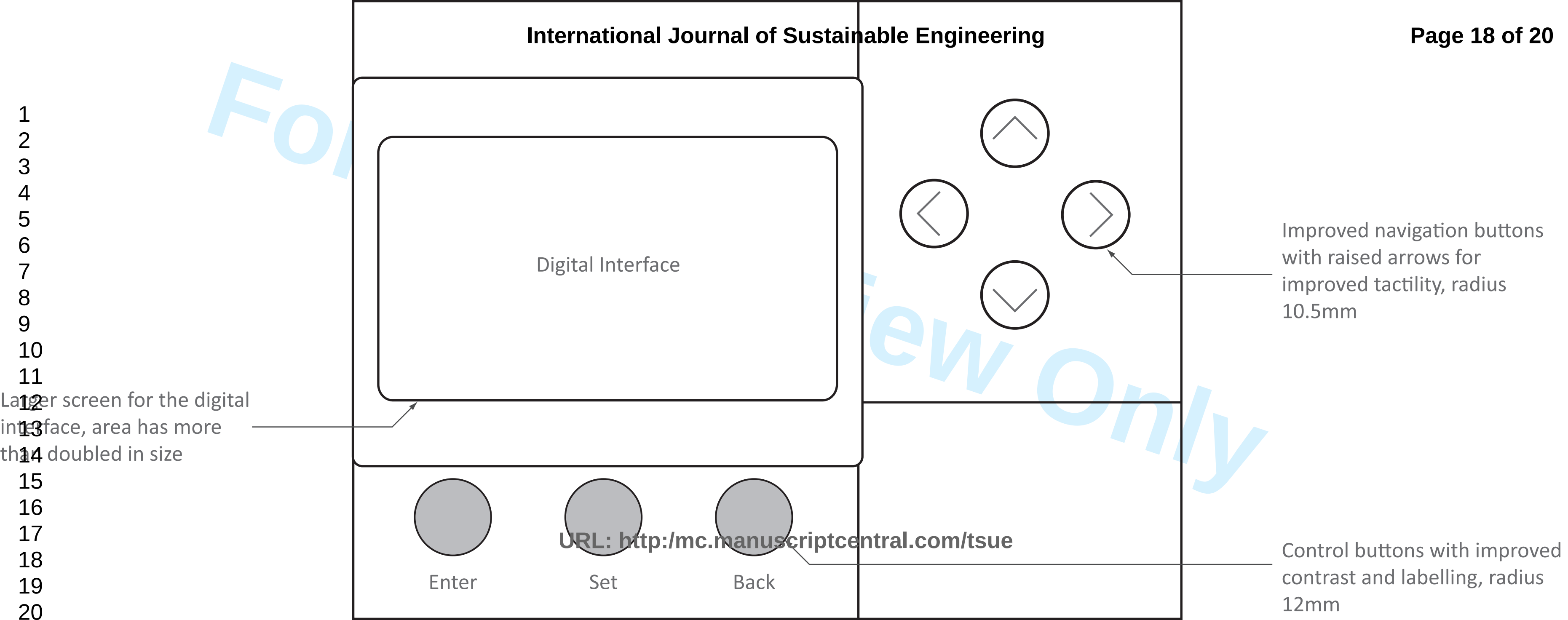
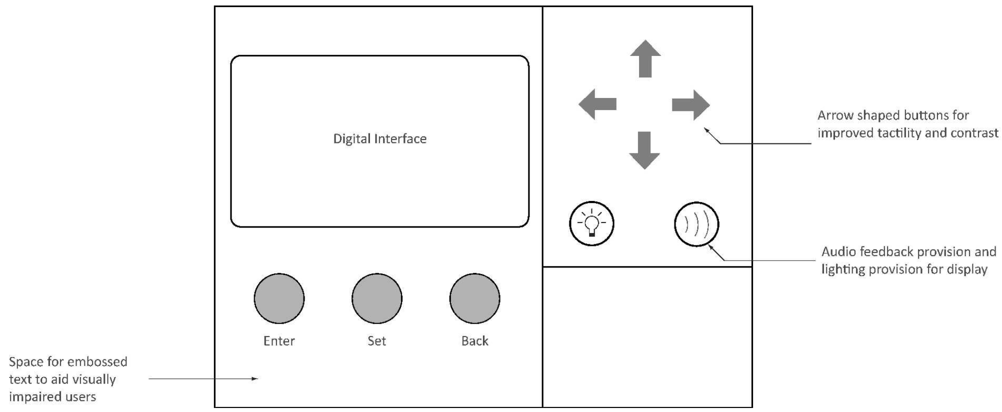
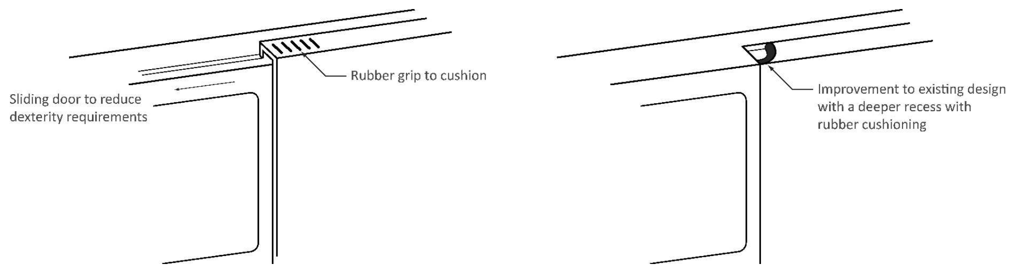



Digital Interface
Enter
Set
Back
Larger screen for the digital interface, area has more than doubled in size
Improved navigation buttons with raised arrows for improved tactility, radius 10.5mm
Control buttons with improved contrast and labelling, radius 12mm



241x97mm (600 x 600 DPI)



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