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HOUSE: Building energy efficiency understanding through an enabled boundary object

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ABSTRACT

We report the results of an empirical study on an enabled application's ability to act as a boundary object and build understanding of energy efficiency solutions. Combining digital and tangible technology with radio-frequency identification (RFID) tags, we have created an interactive, digitally enabled device and application called HOUSE (Home User and Stakeholder Environment). The HOUSE tool and application have been designed and developed to support interaction and collaboration in the exploration of domestic energy efficiency solutions.

HOUSE allows users to associate information with physical representations, and to explore this information through manipulation of enabled objects. The interactive application consists of a 24:1 scale representation of an archetypal UK home and thirteen model energy efficiency interventions integrated with a digital application. Each energy efficiency intervention is enabled with RFID tagging and detection, to allow participants to physically interact with the HOUSE application. The app detects when a model energy efficiency intervention is placed in the model HOUSE. Participants then receive real-time feedback on their energy efficiency selection and the implication of their retrofit decisions.

We explore the role of HOUSE acting as a boundary object, in facilitating the transfer of knowledge across domains. The application was evaluated in academic non-expert and industry (expert) stakeholder workshops. Results showed there is a self-reported increase in collaboration and consensus amongst non-experts (Group A) using the HOUSE interactive application. There is also a self-reported difference in the decision-making process surrounding retrofit selection for experts (Group D) using the HOUSE interactive application. Moreover, there is evidence from experts to conclude that the HOUSE can assist in transmitting findings in meaningful ways to non-experts in the field.

KEYWORDS Boundary Object, Energy Efficiency, Exploratory Study, Tangible User Interface.

INTRODUCTION

The decision-making process surrounding domestic energy use and retrofit is complex, dynamic, multidimensional and involves multiple stakeholders and information asymmetry. However how to enable the transfer of knowledge between stakeholders has received little attention. As a society, we are facing complex challenges such as climate change, energy transition and adaption that require large numbers of multidisciplinary stakeholders to interact and quickly navigate elaborate data sets. Stakeholders need to rapidly access a wide range of scenarios, build understanding and decide on an appropriate set of actions.

New technologies have made it possible to create new ways for stakeholders to interact. Innovations allow us to enable objects with digital information and allow us to interact with this information through tactile interaction with radio-frequency identification (RFID) enabled (tangible) media. Enabled media can be combined with technologies to provide instantaneous feedback on a wide range of different scenarios.

Despite wide-ranging policies for encouraging and supporting energy efficiency, there remains a persistent gap between the technological and economic potential and actual market behaviour (Jaffe & Stavins 1994). Two of the most crucial retrofit decision-making barriers identified are firstly the ‘cognitive burden’ regarding the difficulty of taking complex and permanent decisions (Phillips 2012) and secondly the ‘hassle factor’, i.e. the anticipation of the inconvenience provided by the retrofit operations (Roy et al. 2007). It is widely accepted that interventions to reduce the energy efficiency gap need to address these and other behavioural factors (Whitmarsh 2009). This article introduces a combined physical and digital application to assist stakeholders’ decision-making process in selecting retrofit technologies. To do this, we have developed the HOUSE (HOme User and Stakeholder Environment) tool which provides a tangible representation of an average UK home and allows stakeholders to interact with energy efficiency interventions.

TANGIBLE BOUNDARY OBJECTS

The exchanges of knowledge between organisations and stakeholders throughout the retrofit process take place along multidisciplinary boundaries between specialist and non-specialist, as shown in Figure 1a. A boundary object can link retrofit stakeholders together via ‘collaboration on a common task' (Star & Griesemer 1989).

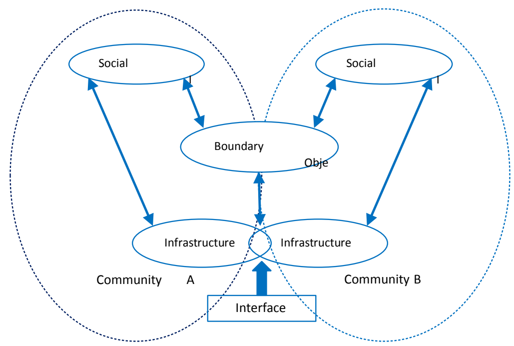

Figure 1a. (Left) Some of the stakeholders throughout the retrofit process adapted from Moseley (2016) Figure 1b. (Right) Representation of a boundary object.

Boundary objects (Figure 1b) are mediating artefacts that have interpretive flexibility and can be a means of achieving collaboration and promoting the sharing of knowledge among diverse groups (Sapsed & Salter 2004). The practice of reducing and managing domestic energy consumption, as well as upgrading or retrofitting a house, incorporates numerous objects (interventions) including requirements (specifications) and user behaviour methodologies. By combining elements with an architectural model, we seek to bridge and overcome knowledge boundaries between those with technical knowledge (e.g. an engineer) and others with domainspecific knowledge (e.g. home users with knowledge of their individual needs and requirements) (Tiwana & Mclean 2005).

Ishii & Ullmer (1997) define a tangible user interface (TUI), as a device that "augments the real physical world by coupling digital information to everyday physical objects and environments." Fishkin’s (2004) taxonomy for tangible interfaces defined them as a device which allows "the user to use their hands to manipulate some physical object(s) via physical gestures, and a computer detects this and alters its state and gives feedback accordingly." Some researchers have demonstrated the advantages of TUIs, regarding a more natural, intuitive, user-friendly experience with the potential to promote stronger and long-lasting engagement with stakeholders. In this paper, we define an enabled Boundary Object (BO) as a TUI realised as a boundary object.

HOUSE: A NEW MEDIUM TO EXPLORE ENERGY EFFICIENCY

One of the most common UK residential typologies is the semi-detached house built in the 1930's. There are currently 1,731,000 semi-detached dwellings in England built between 1919 and 1944, equating to approximately 1 in 6 UK homes. Because of its prevalence, the 1930's semi-detached house can be defined as "the average UK dwelling" (Beizaee et al. 2015). We used a plan of a 1930's house situated in London as a reference for the development of the scale model. The floor plan of the house and the elements relevant to energy efficiency interventions such as suspended floor and cavity walls were integrated into the scale model. The final model of the case study dwelling is shown in Figure 3. Table 1 provides a list of the interventions considered in the study. The interventions were exemplified as physical objects that could be manipulated by users and added and removed from the model to represent the process of retrofitting.

Table 1. Energy efficiency interventions

1	Internal wall insulation	7	Draught stripping
2	Cavity wall insulation	8	Low energy lights
3	External wall insulation	9	Replacement gas boiler
4	Floor Insulation	10	Upgrading heating controls
5	Loft insulation	11	1 kW Solar Photovoltaic Panels
6	Replacement windows and doors	12	3 kW Solar Photovoltaic Panels
		13	Solar hot water heating

A digital application, developed in Objective-C in Xcode 8.2 and displayed on an iPad, was designed to provide a visualisation of the model HOUSE status. When an intervention was applied to the model (input), the digital application senses this input event and alters its state. The digital application provides feedback (output event) to show the impact of the addition or removal of an intervention. The digital application displays a series of properties such as total installation cost, annual savings on bills and annual CO_2 savings based on the interventions currently added to the property. The costs and savings were calculated based on straightforward calculations and were therefore provided instantaneously on the iPad. The final HOUSE tool, as shown in Figure 3 was an interactive tool of enabled interventions allowing customers to 'play' with a representation of their home.

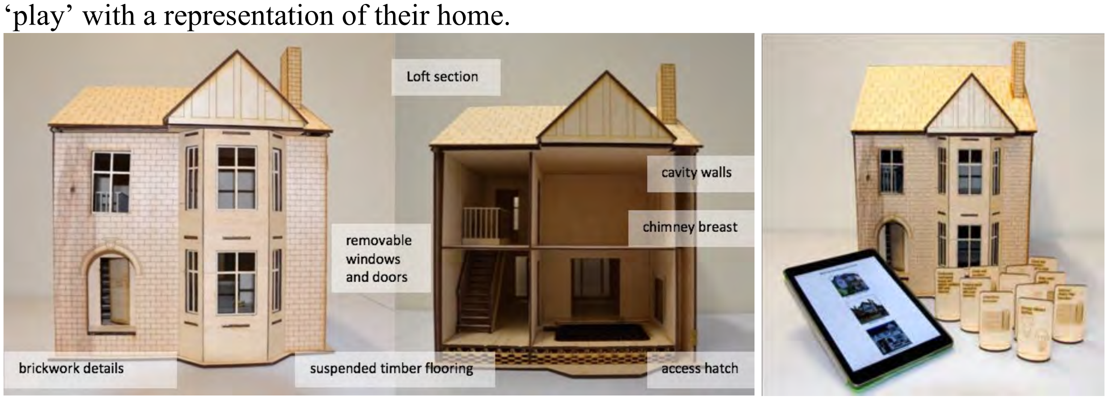

Figure 3 The Model of the case study dwelling

METHOD

This exploratory study aimed to understand the contribution of the HOUSE application. To design the HOUSE tool a mix of literature review and stakeholder input through interviews and discussions were used to develop the initial HOUSE prototype. In the descriptive study, firstly, a non-expert (academic) workshop was held to provide an evaluation of the tool and the workshop design. Secondly, an expert (industrial) workshop was held to provide an assessment of the prototype and to gather suggestions for improvements. An identical design exercise took place in each workshop; participants were split into three groups and using three different tools sets (c.f. Table 2) were asked to address the same design brief. The design exercise was designed to compare the effect of the various tool sets on the behaviour (e.g. interactions, collaboration, discussions, manipulations, solutions and intervention selections) of participants.

Table 2. Schematic setup of the tool sets provided to each workshop group

Group	HOUSE model	Digital Application	Pens and Paper
A non-expert	Yes	Yes	Yes
B non-expert	No	Yes	Yes
C non-expert	No	No	Yes
D expert	Yes	Yes	Yes
E expert	No	Yes	Yes
F expert	No	No	Yes

RESULTS

The initial academic (non-expert) workshop was conducted with 12 non-specialists, during a one-hour session, to evaluate the functionality of the device and its impact on the group. The non-specialists were split into three groups A, B & C with four participants in each group. The groups were asked on a Likert scale if they felt the tool set provided (Table 2) increased collaboration and improved consensus. To compare participants' subjective experience while using the three different tool sets, we conducted several two-way analyses of variance (ANOVA) with the format of presenting tool sets as independent variables. The ANOVA (Table 3) was significant for collaboration (question 1): $F(2, 9) = 13.286$, $p<.05$ ($p = .002$) and consensus (question 2): $F(2, 9) = 6.643$, $p<.05$ ($p = .017$). Thus, there is evidence to reject the null hypothesis and conclude there is a self-reported increase in the collaboration and consensus for Group A conducting the same task using the HOUSE interactive application tool set.

Table 3. Academic workshop one-way between groups ANOVA for each domain and group

ANOVA		Sum of squares	df	Mean Square	F	Sig.
1) Do you feel HOUSE provided increased collaboration amongst your group?	Between Groups	5.167	2	2.583	13.286[a]	.002[b]
	Within Groups	1.750	9	.194		
	Total	6.917	11			
2) Do you feel HOUSE provided improved consensus?	Between Groups	5.167	2	2.583	6.643[a]	.017[b]
	Within Groups	3.500	9	.389		
	Total	8.667	11			

[a]Critical Value 4.26, [b]Statistical significance testing ($p > .05$).

The industry (expert) workshop was conducted with 18 specialists, during a longer three-hour session, to further evaluate the functionality of the device and its impact on decision making. The specialists were split into three groups D, E & F with six participants in each group. During this workshop participants were given a longer questionnaire and were asked additional questions on a Likert scale to investigate if they felt the tool set provided improved the decisionmaking process and if they thought the tool set provided could assist in transmitting findings.

The ANOVA (Table 4) was significant for decision-making (question 3): F (2, 15) = 4.239 p = .035 and transmitting findings to non-experts in the field (question 4): F (2, 15) = 5.648 p = .015. Thus, there is evidence to reject the null hypothesis for question 3 and conclude there is a self-reported difference in the decision-making process surrounding retrofit selection for Group A using the HOUSE. There is also evidence to reject the null hypothesis for question 4 and conclude there is self-reported evidence that the HOUSE can assist in transmitting findings in meaningful ways to those (non-experts in the field). However, the actual difference in mean score between groups was quite small based on Cohen's (1992) conventions for interpreting effect size.

Table 4. Industry workshop one-way between groups ANOVA for each domain and group

ANOVA		Sum of squares	df	Mean Square	F	Sig.
1) Do you feel HOUSE provided increased collaboration amongst your group?	Between Groups	.778	2	.389	.530	.599
	Within Groups	11.00	15	.733		
	Total	11.778	17			
2) Do you feel HOUSE provided improved consensus?	Between Groups	2.778	2	1.389	3.378	.061
	Within Groups	6.167	15	.411		
	Total	8.944	17			
3) I feel HOUSE improved the decisionmaking process surrounding retrofit selection.	Between Groups	4.333	2	2.167	4.239[a]	.035[b]
	Within Groups	7.667	15	.511		
	Total	12.000	17			
4) I feel HOUSE could assist in transmitting findings in meaningful ways to non-experts in the field.	Between Groups	6.778	2	3.389	5.648[a]	.015[b]
	Within Groups	9.000	15	.600		
	Total	15.778	17			

[a]Critical Value 3.68, [b] Statistical significance testing (p > 0.05).

DISCUSSION

As boundaries pose difficulties in knowledge flows, we aimed to reduce the influence of boundaries on multi-stakeholder and multi-domain collaboration by finding a way to communicate across them. There is a need for a comprehensive but easy to use tool to allow interaction amongst stakeholders during retrofit selection. Current retrofit selection tools are complex methodologies and software tools, requiring extensive training and guidance. These tools do not utilise tangible representations or allow for stakeholder interaction.

The evidence from the non-expert workshop suggests that participants felt that the HOUSE tool provided increased collaboration amongst the group of participants and improved consensus. The evidence from the industry workshop suggests that the participants perceived that the HOUSE tool improved the decision-making process surrounding retrofit selection and that the HOUSE tool could assist in transmitting findings in meaningful ways to non-experts in the field. The HOUSE concept was found to have the potential to act as a transdisciplinary boundary object, engaging non-scientists in shaping and achieving societal goals.

It is interesting to note there was no significant self-reported increase in the collaboration and consensus amongst the experts (Group D) conducting the same task using the HOUSE interactive application tool set. This lack of significance may be as a result of the group's dynamic and requires further exploration. It would have been ideal to have asked the first workshop groups the longer questionnaire, to investigate if they felt the tool set provided improved the decision-making process surrounding retrofit selection and if they thought it could be used to assist in transmitting findings in meaningful ways to non-experts in the field.

CONCLUSION

This article has introduced the HOUSE tangible application. Although this presents a preliminary study, the workshops yielded important insights and show that a tool such as HOUSE can support collaboration, consensus, improve decision making and transmit findings in meaningful ways. The results of the stakeholder workshops also demonstrate that the HOUSE tool has the potential for further development and implementation as part of a user-centred engagement process. Because participants were taking part in a theoretical design exercise rather than real-world selection and implementation – there are some limitations to this study although the initial results are promising. The tool should adapt to answer the questions and priorities that emerged from stakeholder engagement. The authors agree with the proposition given by Underkoffler & Ishii (1999) when outlining areas for future work "the proposition of giving additional meaning and animate life to ordinary inert objects is a cognitively powerful and intriguing one."

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