Title: Buildings for Occupant-Oriented Management

1. Summary

This project will investigate holistic "closed-loop" campus-scale management of shared environments in response to occupant behaviour. Traditionally, a building's BMS applies a centrally-controlled policy based on limited sensor data combined with norms based on assumed, rather than actual, occupant behaviour. This leads to situations where the occupants, through actions that are aimed at increasing sensory comfort, work against the system, resulting in reduced energy efficiency and increased carbon emissions. In a well-instrumented modern building, there is a lot of sensor data that is currently under-utilized (typically archived after collection via the BMS), including data that can provide crucial information on occupant behaviour (and thus occupant "desires"). Our objective for this proposal is to build and test an end-to-end solution that closes the loop between the BMS, sensor data (existing and new) and the occupants, in such a building (East Building[1], University of Bath, completed 2011). This solution will enable (i) a comparison of actual patterns against expected, as enshrined in operational policies (ii) identify trends and anomalies, and (iii) propose policy revisions and better informed occupant behaviour, thus effectively "closing the loop". The experiment will comprehensively test the commonly-held, but insufficiently substantiated, belief that better information management and accessibility will result in significant resource / energy savings. Only if the scale of savings that are achievable with such an approach in a modern well-instrumented building are significant does the broader question of the level of sensing required in legacy buildings (which represent a much higher proportion of building stock) become worthy of investigation.

2. Proposed Research

The enablers for this research are (live) data sources, the means to analyse them and formal representations of policy, by which actions may be governed. However, we seek to go beyond purely reactive systems with static policies. Trend analysis and occupant behaviour models will enable the identification of proposals both for policy change and behavioural change. To do this comprehensively is a large research program, so for this project we aim for a thin, longitudinal slice that demonstrates the whole chain with carefully limited function components. **Figure 1** summarizes the various information flows described in detail in the work packages below.

The software architecture aims for low coupling through the use of message-passing. Decoupling is enhanced by using semantically annotated events (represented in RDF), which means it is straightforward to substitute a semantically equivalent feed without affecting downstream processes. Further decoupling arises from policy-based reasoning, which creates a high-level form of data-driven architecture, where policy modifications enable behavioural change without either restarting the system or replacing component code. We have developed a prototype distributed architecture for complex event processing using XMPP[2] and example clients in Java, Google Web Toolkit, Android, the Jason BDI agent platform and Answer Set Programming (ASP). [Last under development.]

WP1: Building the data substrate. The subject for this project is the new (commissioned May 2011) East Building on the University of Bath campus. It has been built to surpass the requirements for the BREEAM excellent rating and incorporates heavily-instrumented active and passive mechanisms for environment management, but the BMS is a closed system. The main objective of this work package is to collect and store all required sensor data for WP2. **Task 1** will create a building data feed from the BMS (we have recently developed the means to access live data from the 500+ electricity meters across campus). Spatially and temporally coupled weather data is also important to determine energy loads. We propose using the sophisticated weather station on top of Building 6E. Again this is a closed system and so **Task 2** is to create a feed from these sensors (temperature, humidity, solar radiation, wind speed). **Task 3** will build approximate occupancy data for individual spaces using anonymized security data on the use of doors in the building (all which are card controlled). We envisage additional sensing requirements for internal environmental data. **Task 4** will collate these additional data using wireless temperature, humidity and CO_2 sensors from Sciencecope (see Budget and Resources). **Task 5** will semantically annotate the data feeds emanating from all 4 tasks at source, represent in RDF, distribute - using the XMPP-based commnication framework - and collect them in a triple store[3].

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[1] http://www.bath.ac.uk/estates/projects/eastbuilding.shtml

[2] Extensible Message Passing Protocol: http://www.xmpp.org

WP2: Interpretation, analysis and rendering. There are three tasks in this work package. **Task 1** is to turn raw data into usable readings (some sensors are friendlier than others and output a value in the relevant units, others might just report 1 volt). **Task 2** will develop (generic) analysis tools that can be orchestrated into workflows to construct bespoke specialized analyses, and provide a framework for the integration of new analysis components. **Task 3** will develop presentation frameworks for the rendering of results on common platforms, such as desktop browsers and smartphones/tablets[1]. All these components will be connected into the distributed framework of Task 5 in WP1 as subscribers to particular feeds and publishers of new feeds, either directly or via a pub/sub shim for (RESTful) web services (to be developed in this project).

WP3: Policy compliance and revision. We have developed an event-based framework for the specification and compliance monitoring of policies in the domain of intelligent agents built on Answer Set Programming [4,5]. **Task 1** will adapt that framework to the tasks outlined above in respect of an instrumented domain and its actuators (subscribers to the policy model). **Task 2** One challenge here is to present the right events to the policy model (requirements analysis), which means building the right analyses (WP2) that can recognize the events that matter. **Task 3** presents a more substantial challenge: how to connect policies with one another, so they can be specified and verified in a modular way, but function in an integrated manner (e.g. events in one policy cause changes of state in another policy [4], either directly or indirectly, via the pub/sub network). **Task 4** will connect components that can implement policy (ie. take actions) to the policy model (e.g. by subscription). However, policies are not necessarily right first time and static policies are not compatible with changing patterns of behaviour. The first indicator of a policy not being fit for purpose is likely to be an increasing number of policy violations (observable by WP2 components), to which there are two responses: (i) revision of policy, and (ii) revision of behaviour. Although we have developed proof-of-concept techniques for the automatic revision of policy [1], we will only be able to explore manual analyses and revisions within this short project, which will provide valuable case studies for future work.

3. Related work

There is already work ongoing in this area both in the UK and internationally, though with different objectives and technologies. For example, the REDUCE project (http://bit.ly/EPSRC-REDUCE) uses an “autonomous self-learning network of sensors, energy consuming devices and users of energy” within an energy consumption knowledge-base to drive technological interventions that are informed by user behaviour. Rather than learning occupant behaviour to drive technological interventions automatically, our approach focuses on decision support for users (facility manager, occupants) who act as actuators for the data feeds. The goal is to transform raw data such that users can make informed choices without being overloaded. This gives them control of their internal environment: a factor that has been shown to impact both satisfaction and productivity. This approach is consistent with that taken in the EU funded DEHEMS project (http://www.dehems.eu), although our project is in a non-domestic setting which is a much more complex environment, in part due to scale and in part due to more complex control mechanisms.

We are currently running a trial in an on-campus residential block to explore the issue of delivering more useful and accessible occupant feedback, in which students are being shown both their personal (i.e. dorm-room) and communal (kitchen + common area) electricity use. A key feature of this experiment is the provision of different types of visual feedback on Android tablets: numeric, dial-based and ambient (smiley face) for the same energy metric. The effectiveness of ranking data (i.e. which group is doing better than another) is also being tested. This experiment is being delivered using the software architecture outlined at the start of Section 2. A notable aspect of the present proposal is to introduce interactivity through the phone/tablet interface to enable direct occupant feedback to the BMS, thus “closing the loop”. This would form a part of the work under **Part B in Figure 1**.

We have also recently demonstrated an agent-based infrastructure for the collection and analysis of energy data in an earlier campus trial, using the architecture reported in [3], which addresses some of the issues arising under **Part A in Figure 1.** However, a crucial link is the connection with the existing BMS infrastructure and the eventual interpretation of the data for use by the facility manager to enable the introduction of new policies. The proposed work in WP1 and WP2 builds on this to connect with WP3.

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[3] Prototypes of these components exist and are in use in our current campus accommodation energy monitoring study (Feb-Mar 2012). Adaptation and further development are required for this project.

[1] Again, prototypes of the browser/tablet interfaces exist, but adaptation and development are required.

4. References

1. Domenico Corapi, Alessandra Russo, Marina De Vos, **Julian Padget**, and Ken Satoh. Normative Design using Inductive Learning. Theory and Practice of Logic Programming, 27th Int'l. Conference on Logic Programming (ICLP'11) Special Issue, 11(4–5), 2011
2. Tina Balke, Marina De Vos, and **Julian Padget**. Analysing energy-incentivized cooperation in next generation mobile networks using normative frameworks and an agent-based simulation. Future Generation Computer Systems, 27(8):1092–1102, 2011.
3. **Julian Padget**, Harpreet Riat, Benedikt Forchhammer, Martijn Warnier, Frances M. T. Brazier, and **Sukumar Natarajan**. An agent-based infrastructure for energy profile capture and management. In Networking, Sensing and Control (ICNSC), 2011 IEEE International Conference on, pages 50–55. IEEE Systems, Man and Cybernetics Society, IEEE Press, April 2011.
4. Owen Cliffe, Marina De Vos, and **Julian Padget**. Specifying and reasoning about multiple institutions. Vazquez-Salceda et al., eds., COIN 2006, LNCS 4386, pp 63–81. Springer, 2007. ISBN: 978-3-540-74457-3. Available via http://dx.doi.org/10.1007/978-3-540-74459-7_5
5. Owen Cliffe, Marina De Vos, and **Julian Padget**. Answer set programming for representing and reasoning about virtual institutions. Inoue et al, eds., CLIMA VII, LNCS 4371, pp 60–79. Springer, 2006.

5. Budget and Resources

	Units	Unit Cost	GBP	USD (@1.75 GBP[1])
Staff costs				
Dr Julian Padget (PI)	3hrs/wk		5,693	9,963
Dr Sukumar Natarajan (Co-I)	2hrs/wk		3,158	5,527
Mr Gokhan Mevlevioglu (PhD student)	1 yr stipend		17,053	29,843
Research officer (Programming support)	1mo		3,292	5,761
University Overheads			8,544	14,952
Equipment Costs				
T, RH, CO_2 sensors + wireless logger	12	£355*	4260	7,455
			TOTAL COSTS	**73,500**

*includes 25% discount

6. Matched contribution

	Units	Unit Cost	GBP	USD (@1.75 GBP)
University of Bath				
Student Fees (3 yrs)			47,100	82,425
Bench Fees (3 yrs)			3,000	5,250
Android phones	4	£220	880	1,540
Android tablets	6	£400	2400	4,200
Sciencescope				
Consultation fees	1d/mo	£600	7,200	12,600
Equipment discount (25%)	12	£118	1,420	2,485
			TOTAL CONTRIBUTION	**108,500**

[1] This is the University approved USD/GBP exchange rate for proposal costing.

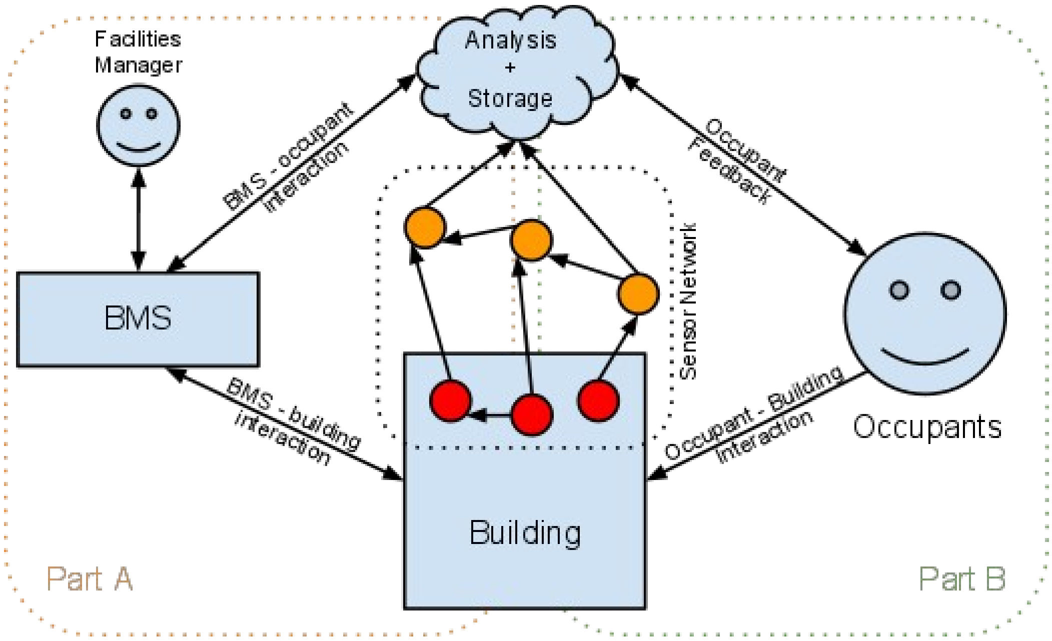

Figure 1: Information flows in the proposed project