PETRAS National Centre of Excellence for
IoT Systems Cybersecurity

BRE Smart Homes and Buildings Research Landscape

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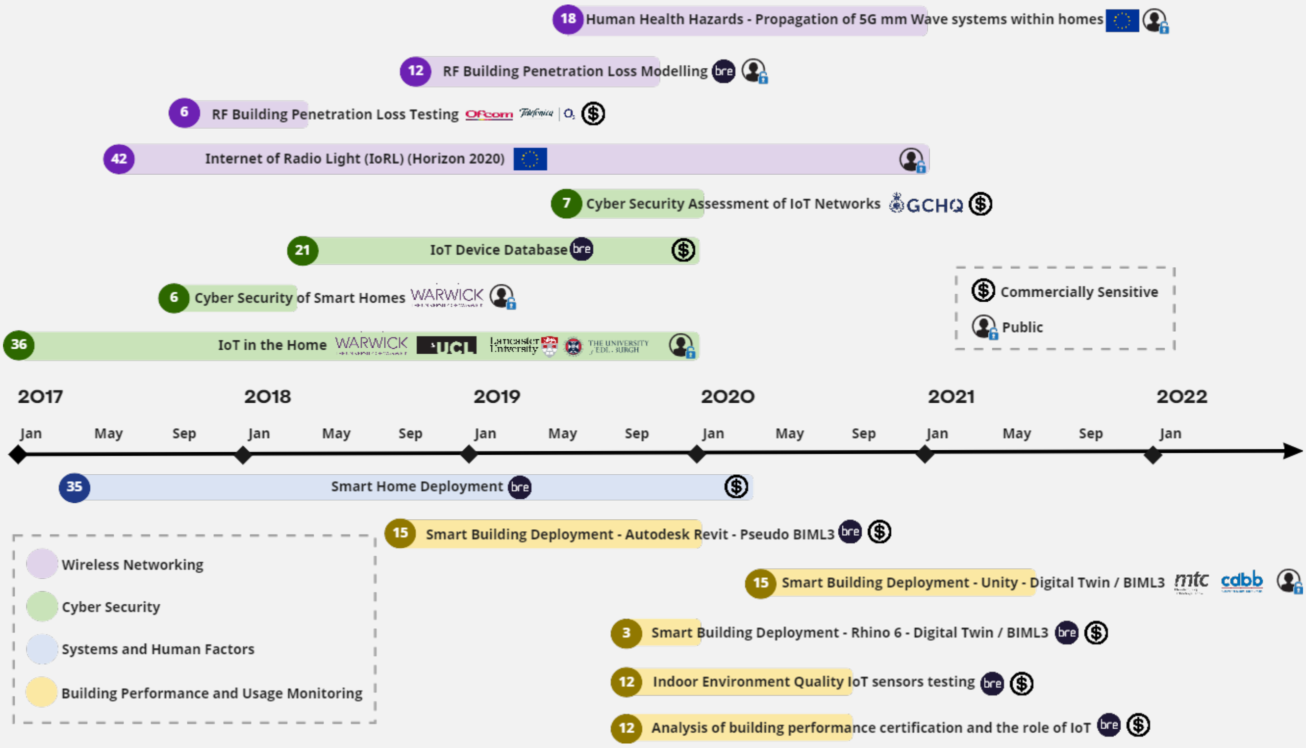
BRE delivers innovative and rigorous products, services, performance, and qualifications used around the globe to make buildings better for people and the environment. BRE's Smart homes and building research agenda is built around the vision of 'Digital Twins'. A digital twin is a virtual representation of a smart home or a building that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help decision-making. The projects were undertaken over the last five years primarily focused on four research themes: (1) Systems and Human Factors, (2) Cyber Security, (3) Building Performance and Usage Monitoring, and (4) Wireless Networking.



Cyber Security

This theme explores cyber security threats and mitigation techniques that would help secure future smart built environments, primarily smart homes and buildings.

Cyber Security of Smart Homes project worked with the University of Warwick to develop a Reference Architecture for Attack Surface Analysis by identifying the attack surfaces of the domestic smart home. This project demonstrates how the architecture can be used to determine the various attack surfaces of a home automation system from which its key vulnerabilities can be determined.

- *Academic Publication (doi: 10.1049/cp.2018.0045)*

Cyber Security Assessment of IoT Networks project collaborated closely with GCHQ to explore and develop a database that captured the security vulnerability of consumer-grade IoT devices. Penetration Testing, Network Mapping and Packet Capture of off-the-shelf IoT devices and systems were part of the assessment. The project analysed manufacturers' practices according to Secure by Design guidelines.

- *Internal Report (IoT Security by Design assessment survey for ten consumer-grade IoT devices)*
- *Network Traffic Analysis and Packet Capture Dataset*

IoT in the Home project, in collaboration with the University of Edinburgh, Lancaster University, University College London, and the University of Warwick, developed a smart home demonstrator by integrating various IoT devices within a domestic building. The project built visual displays for IoT data, including the reconstruction of a floor map using positional data. Some lessons learnt include the challenges around integrating heterogeneous IoT devices and systems, which required intermediary solutions developed using microcontrollers and similar ad-hoc mechanisms due to lack of interoperability and official integration support.

- *Academic Publication (doi: 10.1049/cp.2019.0157)*
- *Smart Home demonstrator developed for PETRAS event*

IoT Device Database project developed a database of devices in the consumer market with a view to develop a schema for IoT devices in BIM by extracting the properties from each IoT device. Each IoT device captures a heterogeneous set of data, and capturing and modelling data, including context information, is important to enabling accurate data analysis.

- *Snapshot Database (Manual), Snapshot Database (Automatic), Web Scraping Scripts, and IoT Schema*

Systems and Human Factors

A key objective of this theme is to design, develop, and deploy smart home systems to better understand their capabilities, performance, characteristics, human factors, system integration challenges, etc.

Smart Home Deployment is an internal project which looked at best practices for developing smart home demonstrates. Developing smart home systems is increasingly challenging due to interoperability issues between systems in the commercial space. They often require significant tinkering and hacking to make sure they can communicate with each other in some fashion. Unfortunately, these intermediatory ad-hoc approaches are most often unreliable and require careful better than maintenance. Further, there are challenges around packet dropping and signal interferences when deploying IoT devices at scale in small spaces such as homes.

- *Internal Report (Learnings to Develop Future Demonstrators)*
- *Smart Home demonstrator developed for PETRAS event*

Building Performance and Usage Monitoring

This theme explores the use of IoT techilogies to measure the buidlings peroemance a from multiple perspective such as energy efficiency, space utlisation, occupant health and wellbeing and so on.

Smart Building Deployment - Autodesk Revit - Pseudo BIML3 project deployed and integrated IoT devices into a domestic building. It then fed historical data into Building Information Modeling (BIM) environment and visualised in over timescale. The project used pre-recorded data over a period of time for visualisation, along with Dynamo. The overall objective was to identify performance anomalies of the building (air leaks, BMS functionality, heating requirement differences between floors).

- *Proof-of-concept BIML3 prototype*
- *Policy Influeance (Engage with Government at Higherlevels)*

Indoor Environment Quality IoT sensors testing project evaluated the performance of Indoor Environmental Quality (IEQ) IoT sensors against recognised standards.

- *Internal Report*
- *Build up BREs expertise in the area*

Smart Building Deployment - Rhino 6 - Digital Twin / BIML3 BIML3 project deployed and integrated IoT devices into a domestic building. It then fed data into BIM environment and visualised in over timescale. The data was streamed to the Digital Twin in real-time, using SmartThings, Python and Grasshopper as intermediaries.

- *Introduction of Digital Twin demonstrator elements into Construction Innovation Hub (CIH) programme (https://constructioninnovationhub.org.uk/)*

Smart Building Deployment - Unity - Digital Twin / BIML3 project deployed and integrated IoT devices into a commercial building. Then the BIM data were integrated into a game engine environment and combined with multiple streams of dynamic IoT data to produce a digital twin. Interactive techniques were developed to display historical data, live feeds, and BIM-level product data related to each building element. Sensors deployed include indoor and outdoor air quality (PM1.0, PM2.5, PM4.0, PM10.0, CO, CO_2, NO_2, SO_2), temperature, lux, humidity, motion, UV, tamper, open/close and footfall.

- *Proof-of-concept Digital Twine prototype*
- *Dataset generated*
- *Internal Report (Gap analysis of building certification schemes with IoT in mind)*

Analysis of building performance certification and the role of IoT project aimed at answering the questions: What are the recognised building performance schemes monitoring? Can IoT sensors and systems be used to monitor these elements throughout the whole life cycle of the building?

- *Build up BREs expertise in the area*

Wireless Networking

Internet of Radio Light (IoRL) is a Horizon 2020 project which developed a safer, more secure, customizable and intelligent building network that reliably delivers increased throughput (greater than 10Gbps) from access points pervasively located within buildings, whilst minimizing interference and harmful EM exposure and providing location accuracy of less than 10 cm. It thereby showed how to solve the problem of broadband wireless access in buildings and promotes the establishment of a global standard in ITU. IoRL project provided solutions to the two main barriers to develop this broadband networking solution in buildings.

- *Proof-of-concept prototype*
- *Publication list Available (https://5g-ppp.eu/white-papers)*

RF Building Penetration Loss Testing was a collaborative project with Telefonica-O2, Ofcom which produced commercially sensitive outputs. A subset of the findings were submitted to the International Telecommunication Union (ITU).

RF Building Penetration Loss Modelling project was funded by BRE Trust which aimed at understanding how new building materials and methods impact wireless propagation and how accurate, current modelling techniques are.

- *Build up BREs expertise in the area*

Human Health Hazards - Propagation of 5G mm Wave systems within homes project focused on RF modelling in CADFEKO for field strength and Specific Absorption Rate (SAR) calculations, followed by real-world testing to verify results. Results were compared to International Commission on Non-Ionizing Radiation Protection (ICNIRP) and other similar standards for Human Health Hazards and found to be well within safe limits. This work was done as part of IoRL project.

- *Report (submitted to the European Commission)*

Future Research Directions

The following summary is generated based on a workshop conducted with experts at BRE. Therefore it is not expected to be a comprehensive academic review of the literature. Our chosen expert may have selected or prioritised certain aspects over others based on their personal opinion, past experience and current priorities, and their own analysis of where the sector is currently heading. Therefore we do not aim to generalise their views to all experts across the field (Sustainability, Buildings Performance and Usage, Policy)

Sensors in Multi-Purpose Space: Increasingly, more buildings and spaces are being built to be used for different purposes across the lifetime. For example, a particular building might be built to serve as a school, transformed into a healthcare centre after many years, and then into an office. A key research question is to explore how the IoT sensors could be used to monitor multi-purpose spaces so that longitudinal data can better understand how the space has been used over time to enable efficient and effective refurbishment.

Microgrids and Community Infrastructure: A microgrid is a localised set of electricity sources and loads that operate as a single system, either connected to a larger grid or in isolation. One of the main benefits of microgrids is that they can improve the reliability and resiliency of the electricity supply in the event of a power outage or other disruption. Microgrids can also help to reduce energy costs, increase energy efficiency, and reduce greenhouse gas emissions by integrating renewable energy sources and energy storage systems. Sensors can be used to monitor the energy production and consumption of microgrids and the quality of the power being generated. This can include sensors that measure the system's voltage, current, frequency, and power factor. Some of the research challenges include developing autonomous systems that can sense both the built environments it serves and the Microgrids to make better decisions towards optimisation, costs, resilience and reliability.

Levels of Smartness in Build Environments: Buildings are increasingly augmented with sensing capabilities. However, further research needs to be conducted to systematically standardise the levels of smartness within buildings and how each benefits both occupants and building managers. Currently, some levels of smartness are identified by the community but are not well specified (Level 0: Traditional Buildings, Level 1: Automated Buildings, Level 2: Connected Buildings, Level 3: Intelligent Buildings, Level 4: Autonomous Buildings). It's important to conduct further research to better understand what kind of sensing capabilities need to be fitted in a building to enable different types of smartness and their pros and cons (cost-benefit analysis). Some other interesting research questions are: Can a building provide a personalised experience for an individual occupant? How to better inform the decisions taken by the building to its occupants, including the justifications?

Policy: Some interesting research questions are What policies and enforcement techniques need to be implemented to secure a building when the occupants increasingly bring their personal smart devices to their office spaces? How to detect these potentially vulnerable smart devices when the occupants bring them to office environments, especially when the office environment is not a high-security building?

Industry 4.0: Some interesting research questions are: how to use sensors to monitor the entire supply chain end-to-end (e.g., from material to construction to refurbishment to recycling)? What is the role of sensors in tracing and monitoring construction items (such as Iron beams or glass panels) from the point it has been created (using raw material) to being used for several decades and then later being considered to recycle and used in a different context? How cost-effective would such tracking be? How to do such tracking at scale in a cost-effective and useful way that encourages material recycling in construction? How to guarantee a given tracking system captures a particular item's lifetime/usage (e.g., iron beam). Some efforts have been taken in this domain, such as material passports in the construction and supply chain domain; however, they are mostly manual processes with less involvement in autonomous and sensor-based tracking. Therefore the challenge is to explore how to incorporate sensor data and technology, such as blockchain, to track material, their transformation and usage in the long term.

Digital Twins: The purpose of a digital twin is to simulate the behaviour and performance of the physical built environment, allowing for more accurate prediction and analysis. An interesting research question is to figure out how sensors can be used to update simulations and be able to learn from each other and get better over time as a collaborative system with the help of sensors and analytics.

Maintenance of Social Housing, Care Homes, and Shared Living Spaces: Over the last few years, we have seen many news articles where shared spaces are not being looked after and maintained properly over time, leading to significant health hazards and higher long-term maintenance costs. Most of these shared spaces don't have any kind of sensors being deployed in the first place; therefore require significant retrofitting. Current retrofitting approaches are quite challenging and painstaking. Interesting research questions are how to make retrofitting a building space simpler and cost-effective? How to develop adaptive analytics that can autonomously configure themselves to generate insights using a given set of sensors available in a given space?

Characteristics of Future-Built Environments: Finally, we identified a few areas where further research needs to be done to understand how the IoT sensors could help improve each aspect.

Key Characteristics

- Resilient
- Security
- Safety
- Privacy
- Energy-awareness

Resilience in the context of smart buildings refers to the ability of a building to withstand and recover from disruptions and disturbances, such as power outages, natural disasters, and cyber-attacks. What is the role of sensors when dealing with different types of resilience, such as energy, climate, and cybersecurity? How to deal if part of the sensing system itself is compromised?

Security in a smart building would include both physical and cyber security. Physical security in smart buildings refers to the measures taken to protect the building and its occupants from physical threats, such as theft, vandalism, or violence. Cybersecurity in smart buildings refers to the measures taken to protect the building and its systems from cyber threats, such as hacking, malware, or data breaches. A key research question would be exploring how to develop an integrated system to tackle cyber and physical security.

There are many aspects to **safety,** such as the safety of the building, equipment, occupants, buildings managers, etc. Safety in smart buildings requires a comprehensive and integrated approach that addresses all potential safety risks and includes ongoing monitoring and testing of safety systems and protocols. A key research question is how to enable an intelligent building to understand safety parameters by itself without manually feeding exhaustive safety information. How can the buildings learn from each other by sharing safety information and customise the safety measures to a given building with minimum human intervention

Privacy in smart buildings encompasses a wide range of considerations, including data privacy, physical privacy, and behavioural privacy. Smart buildings may use sensors, cameras, and other technologies to collect data on occupants, such as their movements, behaviours, and preferences. Smart buildings may also use access controls and biometric identification to capture personal information.

According to the International Energy Agency (IEA), buildings are responsible for around 40% of global energy consumption and 33% of greenhouse gas emissions. This includes energy used for heating, cooling, lighting, and appliances in residential and commercial buildings. A key research question is how to develop **energy-aware** and self-configuring smart buildings that are capable of communicating with other buildings in an area to optimise energy consumption as a whole while managing the occupant's preferences and expectations in the context of the building are heterogenous in nature (in terms of layouts, sensing systems, actuation systems, occupant behaviours, etc.)