Data-driven smart buildings: narratives of drivers and barriers from real-world implementation

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Abstract
Progress in the digitalisation of building services has been slow. Data-driven insights combined with innovative business models have the potential to unlock value. Yet barriers associated with implementing smart building technologies in the real world include an unclear value proposition, differing stakeholder perspectives, and limited evidence of the benefits and disbenefits.

This paper reports ongoing work within the International Energy Agency Annex 81, “Data-driven smart buildings,” to understand the current technology landscape and opportunities by implementing data-driven building services in non-domestic buildings. Several case studies were collected from around the world, contributed by Annex 81 participants. This paper discusses stakeholder narratives on the value proposition and lessons learnt from the case studies collected and gives practical suggestions to overcome digitalisation barriers.

Keywords Data-driven smart buildings; energy efficiency; operational performance; digitalisation; building control.

Introduction
The recent revolution in digital technology and cyber-physical systems has the potential to reduce costs and overcome barriers to energy efficiency through advanced control and operation of building services. Emerging technologies include [1,2]:

- The Internet of Things (IoT); provides access to more diverse, low-cost data on the status and activity of equipment and people in buildings.
- Artificial intelligence and data analytics; enable more comprehensive energy performance assessment and predictive management of assets.
- Sharing economy platforms; supporting new business models for connecting users and energy-efficiency software services providers.

Progress in the digitalisation of building services has been slow, and the application of digitalisation towards unlocking value, including improving the energy efficiency in buildings, has not reached its full potential [3]. Common barriers to the uptake of such new technologies have often been: (i) lack of clear value proposition that aligns with existing processes and stakeholder needs; (ii) clear implementation pathways including business cases and incentives; (iii) limited practical evidence of real-world smart technology implementation; and (iv) lack of standardisation. To date, buildings have usually been treated as stand-alone entities, replete with bespoke engineering solutions utilising a mix of standardised and bespoke way of capturing data and metadata [4]. This has been creating inefficiencies in adopting digital technologies in buildings, often making such solutions impractical and hard to scale up adoption.

It is not uncommon that new technology innovations fuel hype and raise expectations to unrealistic levels. While such hype might drive early adopters and researchers, actual adoption at scale is only possible when a clear value proposition exists and can be demonstrated in practice. While building data analytics has demonstrated the potential of data-driven operation, adopting such approaches within the current state of practice remains low.

Activities within the International Energy Agency Annex 81 “Data-driven smart buildings” project aim at consolidating knowledge from the academic state-of-the-art and providing an evidence basis to support knowledge and technology transfer, contextualised to support accelerated adoption of such technologies in current practice. This is achieved by several activities aiming at mapping the current technology and innovation landscape in non-domestic smart buildings and data-driven building services. In particular, information on technical details, business cases, implementation journeys and stakeholders’ stories associated with real-world smart buildings implementations is being gathered and compiled in exemplar case studies. Each case study was contributed by Annex 81 participants (more than 100 expert members across 19 countries) and extended network, focusing on a particular building, technology or dataset. The case studies are showcased on a dedicated website [5] to communicate the knowledge generated to non-technical audiences. Individually, each case study elicits a particular facet of applying data-driven smart building technologies considering its benefits and disbenefits, the challenges related to applying such technologies, the lessons learnt and unintended consequences. Collectively, the case studies provide evidence on the value-proposition and barriers to smart building technologies and possibly help identify a path forward to understand some of the benefits and challenges critically.

By analysing the evidence gathered from the case studies collected so far, including the stakeholder narratives from early adopters of smart technology, this paper aims to provide practical recommendations to overcome barriers in implementing digital technologies at scale.

Methodology for collection of case studies

Capturing relevant context is crucial to understanding the potential for technology-innovation adoption and success. As part of the activities in subtask D of Annex 81, evidence on real-word data driven implementation is being compiled in case-study exemplars and published on a dedicated online repository under a creative commons licence agreement. The case study collection had the following aims: a) gathering knowledge from early adopters on the value proposition for various stakeholders to understand how this can drive technological and business model innovation; b) collect lessons learnt and challenges faced; and c) distil the knowledge generated so that the benefits can be understood by a wider audience and support evidence-based decision making or the development of relevant policies.

A two-page case study template was designed through an iterative process for standardised collection of information. An understanding of the current state of practice, needs and challenges for real-word implementation of data-driven smart technologies was gathered from a) a panel discussion comprising researchers, building managers and engineers, and smart-building services suppliers; b) interaction with different stakeholders; and c) constant exchange of information with activities in other subtasks of the Annex 81 project. From these activities, there was common agreement that case study exemplars should focus on (in descending order of importance) collecting evidence on data-driven smart technology implementations in real buildings; capturing stakeholders' perspectives and context; summarising emergent business models, applications and specific technologies/technology stacks. The knowledge generated was summarised in a draft case study template, which was systematically refined through a number of co-creation workshops aiming at testing the template with different stakeholder groups to ensure it captured relevant information to their field of work. The final template aims at gathering a) general information on the case study, including location, technology installed, data availability and implementation status (Figure 1 top); b) information of technical details and business models, including project aim, implementation, value and business proposition, and impact (Figure 1 bottom left); and c) stakeholder stories and knowledge generation, including lessons learnt and actors involved in the process (Figure 1 bottom right). Each case study can focus on a particular non-domestic smart building, technology or dataset.

Project Information			
Continent:	☐ Europe ☐ Africa	☐ Asia ☐ North America	☐ Australia ☐ South America
City, Country:			
Building typology:	☐ Agriculture ☐ Community ☐ Education ☐ Hospitality ☐ Office ☐ Transport	☐ Arts and Leisure ☐ Defence ☐ Emergency ☐ Industry ☐ Retail (Shops) ☐ Utilities	☐ Commercial Offices ☐ Domestic (Residential) ☐ Health ☐ Miscellaneous ☐ Sport ☐ Warehouse
Technology installed/proposed:	☐ Model-based control ☐ Fault detection and diagnostics ☐ Energy benchmark ☐ Demand response ☐ Open data and data platform ☐ Other: **Please provide a brief description of the technology:**		
Data availability:			
Status:	☐ Design/Development ☐ Construction ☐ Testing/Commissioning ☐ Operational - awaiting results ☐ Operational - results available		

Description
Short introduction paragraph giving the context and a short description of the case study

Project aim
This section may include a short discussion on: a. Project design background; b. Project aims and objectives; c. Project motivation; d. The key technology to be/has been included.

Implementation
This section may include a short discussion on: a. General information for the building, the building services, and energy management system (if applicable); b. Data-driven approaches applied (e.g. improved control, FDD, etc.) (*if applicable*); c. Description of data requirements and data sources.

Value proposition
This section may include a short discussion on: a. Operational performance (e.g.: how well did it work, is it easy to use?); b. Significant benefits compared to traditional technologies/the past.

Impacts
This section may include a short discussion on: a. Benefits gained; b. Comparison to expectations; c. Reasons for any discrepancies; d. Scalability/Transferability.

Business Proposition/Business model
Discuss the business case, or potential business model for the innovation like: a. Annual contract for service? b. Software as a service? c. At-risk with shared savings? d. Install only (customer manages)? e. Other?

Lessons learnt
This section might include the following: a. Unsolved issues during/after the design, implementation and commission of the technologies; b. Lessons learned in the design, implementation and commission of the data-driven technologies; c. Occupant acceptance (complaints/endorsement); d. Challenges faced (e.g., delays, installation issues, commissioning problems, complexity, user complaints?) e. Unintended consequences (e.g., unexpected impact on other systems? Safety issues/ Reliability issues? Privacy/security risks?) f. Other concerns.

Key stakeholders (as appropriate)]	Information providers
Select one/some of the followings: ☐ Client ☐ Designers ☐ Consultants ☐ Manufacturers / Suppliers ☐ Contractors ☐ Monitoring and reporting ☐ Others (e.g., building operator / manager)	Who provided information for the case study and their role/perspective in this project?

Other information

For more information on the Case Study:

Contact person:	Name/E-mail address/Affiliation

Figure 1 – Case study template.

Annex 81 members (and/or their extended network) who have been involved in the decision-making or implementation of smart-building technology solutions were invited to participate on a voluntary basis to this research and fill in the case study template. Once a template was returned to the coordinating team, it was checked to ensure completeness of information, consistency in the level of detail provided across case studies, and language accessibility for non-technical audiences. In cases where some editing was deemed necessary, an iterative email exchange with the case study contributor(s) was undertaken before the final publication of the case study online.

The online repository [5] aims at communicating the knowledge generated, associated visual information (e.g., images, graphs, workflows) and relevant supplementary documentation (including building plans, models, external links to datasets, publications, project information, if available) to relevant stakeholders such as academic, industry and government groups.

Synthesis of drivers and barriers to data-driven smart buildings

During the panel discussion and co-creation workshops, the stakeholders involved came to a common consensus that innovation acceleration in the smart-building technologies space should be driven by access to open data; promotion of standardisation (e.g., for data labelling, control sequences) and interoperability; exchange of experiences, know-how and best practices by means of information repositories and positive case studies capturing international perspectives.

At the time of writing this manuscript, nine case studies had been collected from Annex 81 participants and shared on the web repository under a CC BY-NC-ND 4.0 license agreement. The contributions (summarised in Table 1) were spread from across the world and spanned a number of building types. The technologies supported included model predictive control (MPC), demand response (DR), open data (OD), and fault detection and diagnostics (FDD).

Case study	Location	Building type	Technical detail
ZUB Building	Germany	Office	MPC, FDD
LBNL Building 59	U.S.A.	Office	MPC
OMV Head Office	Austria	Office	MPC
EV Building	Canada	Education	OD
Infineon R&D Building	Austria	Education, Office	MPC, FDD
CSIRO Synergy Building	Australia	Education, Office	MPC, OD
Factory Cooling Plant	Japan	Industrial	FDD
Post Am Rochus	Austria	Office, Retail	MPC
Campus Inffeldgasse	Austria	Education, Office	FDD, DR

Table 1 – Summary of the case studies analysed.

The reported value proposition and lessons learnt for the nine case studies were analysed to identify common themes and peculiar features of the different technologies, which were then reviewed and categorised to synthesise drivers and barriers of data-driven smart buildings implementation.

The common value proposition for the projects gathered was to reduce energy demand while improving (or maintaining) comfortable conditions, with applications to both new and retrofitted buildings. In a number of cases, novel data-driven models were devised as part of the project to enhance decision-making and operation of the building. Such models focussed on improving the quality and accuracy of the prediction made while enhancing transparency, reducing commissioning time, and providing tailored control strategies and errors.

For example, the CSIRO Synergy Building project further developed and integrated a cloud-based machine-learning-enabled chiller plant optimisation engine with the CSIRO's cloud-based building data management platform to produce optimal control setpoints for the site's chilled plant and reduce energy demand. A platform developed by CSIRO is used to store and make data collected from the building readily findable and accessible. Operational data is used to train advanced machine learning and artificial-intelligence-driven algorithms to do forecasting by simulating possible operational scenarios and optimisation of relevant control parameters. This plant optimisation enables the system to operate at peak performance, under widely variable weather conditions.

The value proposition of the optimisation engine overcomes several limitations of traditional building cooling system controls. Key points of differentiation include: a) transparency of solutions priorities to provide full visibility of current performance, control strategy recommendations, and forecasted energy savings; b) ease of implementation thanks to a cloud-based optimisation engine that leverages existing data from the building's monitoring system (BMS) and outputs control strategies in simple formats that can be integrated with existing BMS providers; c) tailored chiller plant control strategy updates at scale, while still incorporating site knowledge to maximise impact; d) moderate costs compared to labour-intensive methods currently available (this case study consistently achieved payback periods of under 12 months for clients).

Similarly, the data collected in the EV Building created an opportunity to develop data-driven models to enable the facility management to improve the accuracy and quality of decision making. The tool uses machine learning clustering techniques and operational data to infer hourly occupant-related patterns and schedules, which are subsequently used to generate stochastic occupancy profiles for simulation (in EnergyPlus) and building management (e.g., to control the BEM system) purposes. This novel approach provides more realistic electrical peak demand projections that enhance how organisations learn about boundary conditions and respond to changes, empowering facility managers to control the system more actively. Besides allowing tailored control strategies, accurate peak loads predictions pave the way to implement peak shifting strategies and reduce electricity costs of commercial buildings.

The reported lessons learnt revolved around four themes: i) data quality and data collection; ii) technology specification and implementation; iii) occupants and thermal comfort; iv) legal implications.

Data quality and data collection was by far the most recurrent issue. Integration and maintenance of different data streams from different proprietary platforms and data richness may represent a significant issue for the smooth operation of real-time tools and data usability. For example, huge effort was required in the LBNL Building 59 to integrate and maintain data continuity and quality, as the data streams came from dozen sources each with their own platforms. Similarly, lack of sensor information in standard format and open data availability for the ZUB Building reduced the returns of the investment made to install logic control strategies due to difficulties (and associated costs) in linking and reusing the data. Conversely, in the OMV Head Office and Infineon case studies, several typical problems during the installation and commissioning phase of building services (e.g., hydraulic errors, errors in the control logic) could be detected automatically with the fully operational digital twin implemented.

Cataloguing metadata represents another key challenge in the current state of data collection and storage practice. This operation is time-consuming as it is usually performed manually by interrogating several additional knowledge sources; this is currently the case for example for the CSIRO Synergy Building. An increasing focus on digitalisation is therefore advocated (and will be the focus for future work) to automatically include location and relevant tags (e.g., equipment hierarchy, make/model and serial numbers) as part of operational/telemetry data storage. Finally, a diversified and accurate set of data streams (e.g., detailed information about occupancy and their interaction with the energy system; sub-metering) is critical to reducing uncertainty in energy simulation (this was observed in both the EV Building and LBNL Building 59 case studies).

The limited amount (or, in some cases, lack) of information during the early phases of technical specification and implementation and the subsequent reliance on a high number of assumptions were identified as potential barriers to the final quality and reliability of data-driven smart technology implementations. For example, reduced availability or low-resolution of measured data was observed to hinder the applicability of data-driven algorithms, interfering with information extraction and inference making (as observed in the Factory Cooling Plant and CSIRO Synergy Building case studies). Therefore, it is advised to held discussions on data requirements since the early stages of a project. Additionally, some components may require to be fixed at short notice during the execution phase, and adjustments to complex simulation models may be lengthy and impractical. Assumptions might change during the planning and construction phase, with implications for the use of design values as simulation targets. Additionally, decision-making is often time-critical and extra time entails extra costs, which is usually a problem in building construction processes. Thus, recommendations for the commissioning and trial operation phases based on the experience of the Post Am Rochus case study included: the definition of suitable overall control strategies and operational modes for the whole system; the provision of clear documentation for the commissioning phase of all major components; and functional quality management on the component level. Quality management schemes were also recommended during the trial operation phase to guarantee an efficient performance of the system and allow synergies with control engineers for clear major operational-mode strategies and procedural steps to be tested.

Experience from the ZUB Building showed that occupants were more reluctant to accept and adjust to fully automated systems where the option for direct control or setting overriding is not available (a perceived lack of control in fully automated buildings seems to be a common source of occupants' dissatisfaction [6]). Additionally, occupants were more likely to accept setpoint variations when the user did not notice the change. Based on the experience in the Factory Cooling Plant and Campus Inffeldgasse case studies, training and knowledge transfer were also recommended to allow stakeholders familiarise with best-practice operation of a new data-driven smart technology and associated benefits, for example to help on-site operators to interpret results or occupants to operate the system as intended (e.g., favour the use of mechanical systems to window opening).

The legal implications of novel implementations of data-driven smart technologies have still not been fully addressed or refined. For example, the need for precise regulation was identified in the Post Am Rochus case study to regulate how to deal with changes in design simulation and assumptions when information or functional technical descriptions may need to be revised or updated during the construction process (e.g., recalibration of models with as-built values may be required and monitored data should be used for validation purposes). Another legal issue encountered related to operators' contracts, which often contain energy saving targets. These values are usually measured in relative savings compared to a previous period over the first 3-5 years of operation, which is not the best solution. Finally, data collection on occupancy (based on people's counts) and GDPR-related concerns were found to pose some privacy concerns in some countries (e.g., in Canada), which is still an unsolved issue.

Conclusions

By analysing interim evidence collected from activities (e.g., panel discussions, case study exemplars) undertaken in the Annex 81 "Data-driven smart buildings" project, this paper summarises stakeholder narratives from early adopters of smart-building technologies and lessons learnt. General lack of open data from real smart-building implementations and widespread agreement on standardisation (e.g., metadata cataloguing, data labelling and interoperability) often lead to the adoption of ad hoc approaches and proprietary solutions that hamper exchange and reuse of possibly valuable information. Data quality and data collection was the most recurrent issue reported in the nine case studies analysed in this work. It may have significant effects on several aspects such as applicability of data-driven algorithms, information extraction and inference making, quality and accuracy of predictions, and ultimately costs.

Limited availability of clear narratives, examples of real-world technical implementation, and a need for more clear articulation of the value proposition were also recognised as factors hindering the implementation of smart-building digital technologies at scale. It was generally agreed that the conservative industrial structure, the limited skill integration characterising the field, and the widespread siloed thinking limit the sharing of know-how and best practices. Similarly, training and engagement of occupants to familiarise with the best-practice operation of a new data-driven smart technology and associated benefits was deemed essential. Information repositories and positive case studies capturing international perspectives, such as those being developed within Annex 81, should be encouraged to corroborate evidence on benefits (e.g., costs, comfort, fault management) in investing in data-driven smart buildings and drive innovation.

Finally, perception of losing control, cybersecurity and privacy concerns, and legal implications of novel implementations of data-driven smart technologies more in general (e.g., how to deal with changes to operating agreements) should be fully addressed or refined to foster more confidence in the adoption of such solutions.

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Acknowledgements

This research was made possible by support from the UK Engineering and Physical Science Research Council, grant EP/V011936/1. The authors wish to thank all the Annex 81 experts and their extended network for their valuable contributions.