EXCHANGE REQUIREMENTS TO SUPPORT DEMAND SIDE MANAGEMENT USING BIM AND BUILDING AUTOMATION SYSTEM DOMAINS

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ABSTRACT

Demand Side Management (DSM) programmes promote energy flexibility, cost reduction and resilience in both grids and buildings, which can be supported by integrating Building Information Modelling (BIM) and Building Automation System (BAS). Despite recent advances in the field, research to date remains limited in defining data requirement structures and interoperable approaches to exploit the potential of this integration. This paper defines a set of exchange requirements (ERs) to support DSM using BIM and BAS domains. The definition of these ERs is the foundation to create a common data model that enables context-aware DSM optimisation strategies.

INTRODUCTION

The smart grid concept is increasingly being used to describe a modern power grid system that leverages intensive use of information and communication frameworks, advanced computing and automation technologies to achieve optimal grid performance and cost reduction (Desai et al. 2019). Emerging architectures for the smart grid aim to integrate the traditional grid, based on robust transmission and distribution systems and large-scale power plants, with low-capacity Distributed Generation (DG) units. Power generation systems classified as DG units are mainly based on renewable energy resources and are placed at or near consumption sites, promoting active involvement of consumers in the grid (Hashmi et al. 2011). Among the applications that this ecosystem can host, Demand Side Management (DSM) is an important mechanism that sustains a systematic interaction between the utility and consumers, fostering active and dynamic consumption management in response to market incentive programmes (Howell et al. 2016). This application promotes energy flexibility, cost reduction and resilience through transmission and distribution congestion management.

Similar to the smart grid concept, a smart building applies advances in information and communication technologies to design buildings embedded with sensors, actuators and controllers. Through a common network, smart buildings can exchange information to dynamically manage the operation of electrical and thermal energy loads. Hence, the role of smart buildings is essential to enable DSM capabilities. Due to the overlapping targets between smart grid applications and smart buildings, terms such as Smart Grid Ready Buildings (SGRB) are proposed to describe buildings that not only have intelligent systems applied to the building itself, but also with built-in capabilities that address communication and interoperability challenges of connecting multiple information sources in the form of building and grid infrastructures (Zhang 2017). One of the main components to optimally enable intelligent buildings to be part of intelligent grids is the implementation of well designed building information models.

Building Information Modelling (BIM) refers to a data-rich digital representation of physical and functional characteristics of a building across its entire life cycle, from conception, through design, construction and operation to refurbishment or demolition (Volk et al. 2014). As such, BIMs can act as central data repositories through which all relevant building information is consistently structured and integrated between various stakeholders on a project (Pinheiro 2019). This collaborative aspect is supported by various tools and technologies that foster the information value chain of this industry, revealing an excellent productivity and harmony among the agents (Eastman et al. 2011, Azhar et al. 2008).

One of the main functionalities that benefit from BIM, acting as a virtual data model based on interoperable workflows, is the management of automation systems. A Building Automation System (BAS) is a distributed system designed to manage and control building services (Vieira 2015). The main purposes of BAS are to improve energy efficiency and indoor environmental quality, ensure building user safety and security, and reduce operating costs. To this end, the core functionalities of BAS include monitoring building parameters, such as temperature and ventilation rates; operating systems, such as lighting and Heating, Ventilation, and Air Conditioning (HVAC), based on the monitored data and occupancy schedules; and evaluating and reporting performance (Domingues et al. 2016). The availability of load management functions in BAS is vital to support

SGRB solutions, especially DSM implementation.

The integration between the BIM and BAS domains has been investigated in previous studies both to translate BAS design information into BIM (Vieira 2015, Tang et al. 2020), and to apply various building services, including HVAC control strategies (Sanz et al. 2018, Benndorf et al. 2017, Sporr et al. 2019), and fault detection and diagnostics algorithms (Andriamamonjy et al. 2018). While these methods revealed that BAS information can be properly represented by BIM, the integration between BIM and multiple BAS communication protocols and control applications remains limited. As stated by these studies, some information from BAS is not available in the specification of existing BIM, requiring the definition of custom properties-set or even the addition of new entities, the latter requiring a complex certification process. Furthermore, the mapping process required to integrate both domains has been observed to be manual (error-prone) and customised for a given BAS communication protocol, restricting the consistency and scalability of the data. Finally, most BIM-based BAS use cases have focused on operation and maintenance functionalities.

In addition, few studies have also assessed BIM information to assist building energy management for smart grid applications. Zhang (2017) proposes an approach to integrate BIM and Software Defined Networks (SDN) for the design and management of a SGRB. Yu & Ergan (2018) evaluate the capabilities of BIM in providing demand response related information. However, to the best of the authors' knowledge, BIM-based grid-interactive functionalities have, to date, not been associated with BAS communication protocols, such as BACnet and LonWorks.

The aim of this paper is to present a definition of BIM and BAS exchange requirements (ERs) that enable context-aware DSM programmes. This integration provides a more granular and adaptive response to DSM signals than the one available through currently implemented DSM approaches. The use of BIM-based processes provide relevant building spatial information and foster interoperability between data environments, while BAS control and communication infrastructures monitor and actuate devices in the field. The definition of such ERs is the first proposed step towards a BIM-BAS common data model that allow DSM optimisation strategies and unlock the potential of SGRB.

This paper is structured as follows: first, an overview of the DSM programmes is presented along with the fundamental concepts of BAS and BIM, and their related interoperability issues; second, the proposed business use case, process map and BIM and BAS ERs to support DMS programmes are described; finally the results, concluding remarks and proposed future work are discussed.

BACKGROUND

Demand Side Management

DSM, as the name suggests, consists of a series of measures and services designed to alter consumer demand in a way that improves the performance, efficiency and stability of the grid (Howell et al. 2016). DSM can be categorised into static and dynamic programmes, as proposed by Meyabadi & Deihimi (2017). The static DSM promotes a reduction in energy demand by end users through policies defined by utilities and governments that support strategic conservation and load growth strategies. These policies can be energy efficiency standards and labeling programmes, or electrification plans that motivates the use of electric technologies such as electrical vehicles and heat pumps. This programme has no onus on the consumers, but empowers them to change their demand pattern usually in exchange of reduced energy costs. Dynamic DSM refers to the direct participation of end users who integrate their resources in the operations of the grid and electricity market. This programme rewards consumers to reduce or offset energy consumption when the energy demand exceeds the ability of the grid to supply it, or under stressed grid conditions. One of the most relevant dynamic DSM programmes is Demand Response (DR), which promotes change in energy consumption by end users in response to incentive payments and dynamic electricity pricing schemes.

The DSM application requires an extensive communication infrastructure that can transmit pricing information and inquiries from the grid, as well as manage DSM commands at the demand side to act accordingly. These communication and control structures are the backbone of a BAS.

Building Automation System

BAS assists facility management activities by optimising energy consumption, improving the quality of the indoor environment and reducing the overall operating costs through effective strategies designed based on control and communication infrastructures. In terms of communication, the introduction of standardised communication protocols has greatly assisted the integration of heterogeneous building assets. These protocols define rules and procedures to manage the information exchange between devices from multiple vendors and building systems within a network, moving away from proprietary constraints (Kastner et al. 2005). By adhering to standardised communication protocols, a BAS's level of interoperability is enhanced as it becomes more flexible and accessible. At present, BACnet and LonWorks play a significant role as open communication protocols in the BAS domain.

BACnet

BACnet, standardised by the ASHRAE Standard 135, is a communication protocol based on an object-oriented approach that defines the representation of devices' data and procedures as objects. Each BACnet object contains a set of properties that describe the object and influence its behavior (Domingues et al. 2016). In addition to the abstraction representation of the network given by objects, BACnet also relies on services as a means of accessing and providing information between devices, or command requests to perform actions (Kastner et al. 2005).

BACnet has positioned itself to support smart grid initiatives by adding some objects applicable to DSM solutions. Among the objects, there are the load control and the accumulator (Hong et al. 2014). The load control object represents the requirements for a load management mechanism, and the accumulator object hosts measurement information such as energy consumption. The use of these objects is valuable for addressing DSM commands and analysis as they provide an interface to perform predefined control actions, view load shed status, and analyse peak demand and billing data.

In addition, through the BACnet Web Services specification (BACnet/WS), BACnet can be integrated into the Open Automated Demand Response (OpenADR) architecture, enabling fully automated DR events. OpenADR is an information exchange model that facilitates the communication of DR signals from utilities or aggregators to consumers. This model is supported by BACnet/WS that allow BAS data to be read and written by external applications (Ghatikar & Bienert 2011). In this scenario, BACnet/WS acts as an interface between the utility server and the BACnet control points, performing pre-programmed actions based DR signals. Moreover, since non-BACnet network technologies (e.g., LonWorks) can be accessed through BACnet/WS, this application can be extended to them as well.

LonWorks

The LonWorks communication protocol, known as LonTalk, standardised by the ISO/IEC 14908-1, defines the communication method between devices across a local operating network. In LonWorks, devices are defined as nodes, which are addressable and can implement multiple functional blocks. These functional blocks specify different applications of a device including functionalities, properties and network variables. The latter are data points used to exchange information between functional blocks, hence between devices (Kastner et al. 2005). LonWorks uses peer-to-peer architecture meaning that there is no single master point of control. Using a binding process, each device can communicate with each other and the resulting action is based on the embedded control logic of the functional blocks which decide what to do when receiving an input in a certain network variable (Domingues et al. 2016).

LonWorks has also addressed DSM solutions by supporting bidirectional communication with client-server network management architectures (Kastner et al. 2005). This functionality allows LonWorks to be one of the network technologies that can be accessed by BACnet/WS gateways, which translate LonWorks representations into BACnet objects, enabling DSM applications through OpenADR.

Building Information Modelling

BIM, as a shared information repository, relies on data transfer between different buildings' applications using data formats. Developed and maintained by the buildingSMART alliance, the Industry Foundation Classes (IFC) open standard, or ISO 16739 standard, is the dominant non-proprietary data format which allows the exchange of building data for BIM applications across the asset's entire life cycle (Sporr et al. 2019). Based on an object-oriented data schema, IFC describes an object as an entity and the relation between the entities as a concept (Andriamamonjy et al. 2018). Since IFC data models can contain a wide range of building information, an integrated process for delivering IFC-based data exchange for domain-specific functionalities has been developed by the buildingSMART alliance. This approach defines subsets of the IFC schema to support assigned capabilities by means of Information Delivery Manual (IDM) and Model View Definition (MVD) frameworks. In this process, industry-led groups define the scope, workflow and requirements for the exchange of information, allowing software applications to translate them properly (Tang et al. 2020). While the IDM captures business processes and ERs, the MVD maps them to the IFC schema definitions. This mapping process is the basis of MVDs, as it defines the relationship of each ER with a set of the IFC schema, identifying the relevant IFC entities, attributes and properties to represent the required information of a given use case.

Interoperability

Interoperability refers to the ability of exchanging semantically consistent information between multiple devices, applications, networks and systems (Eastman et al. 2011). Despite the recent advances provided by communication protocols in defining structures to represent, characterise and relate BAS concepts, interoperability in the domain remains an issue. An explicit integration between multiple BAS devices requires the use of well-known communication protocols, well-defined interfaces and data representations, which are based on syntactic data structures, and semantic understanding of concepts and relationships within the data structures (Sofos et al. 2020). Although the communication protocols address the syntactic aspects, the semantics of BAS are still limited as there are no existing data schemes that provide standardised concepts for semantic information exchange between protocols which, to date, is based on error-prone data mapping methodologies.

Similar semantic-related issues occur with BIM-based software during exchange processes. Although the potential for BIM exchange capabilities through IFC data models is promising, it is yet to be fully exploited. For instance, due to semantic differences among domain knowledge, when exchanging IFC files, certain software misinterpret objects from other disciplines resulting in inaccurate geometric representation or loss of properties and relations. Additionally, because distinct tools often define their own mapping mechanism between internal data schemas and IFC schemas (i.e. using different entities to represent the same object), data models can become inconsistent (Lai & Deng 2018). Hence, explicit semantic definitions and relations of building models would be beneficial to enhance data quality and reliability.

To summarise, in spite of recent advances in BAS and BIM research, there is a gap in the provision of semantic interoperability approaches to deal with heterogeneous BIM and BAS data sets, sources and domain representations, and of BIM-BAS common data models to assist DSM decision support and control mechanisms from the building perspective. This can assist in the individualisation and optimisation of load management.

RESEARCH METHODS

Based on the methodology proposed by Lee et al. (2016) for formalising domain knowledge and model views, this work specifies the ERs to support DSM as a basis for the development of an IDM-MDV ontology that captures the semantic descriptions and relationships in integrating BIM and BAS domains (Figure 1). The first step describes the scope of work for the selected business use case. The second step defines a process map representing the actors and their roles in the exchange of information through the building's life cycle. The third step identifies the ERs based on the scope of work. The final step captures these ERs into an IDM-MVD ontology formalising the DSM knowledge. This formalised framework is expected to support explicit semantic definitions and reasoning features for querying BIM and BAS data models into a common data model. The deployment of this final step is beyond the scope of this paper.

Use Case Definition

This work proposes semantic interoperability specifications to enable SGRB solutions integrated to BIM and BAS data models. To develop this, a use case-driven approach is applied to prioritise the scope of work and the capture of the related business process and ERs. DSM is an important mechanism in the

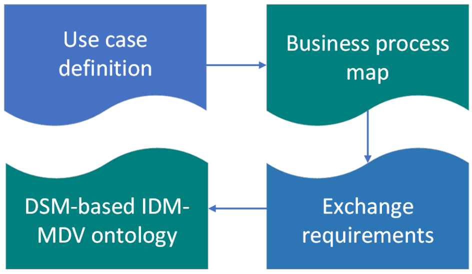

Figure 1: Process overview to define a DSM-based IDM-MVD ontology to represent BIM and BAS exchange requirements.

SGRB scenario, which improves the grid flexibility and resilience by optimising the demand side consumption, performance and costs, thus it is defined as the core focus of this paper.

BAS architectures include many data points that allow automation systems to provide crucial services particularly for the deployment of DSM solutions, including monitoring, control and management of input and output devices (e.g., sensors and actuators). Hence, BAS becomes an essential means of providing technical and economical optimisation strategies for DSM. BIM could play a similarly significant role for managing DSM solutions, providing comprehensive building asset information that can be leveraged for decision-making processes related to the provision of load management applications.

Within the scope of this work, holistic ERs are identified to provide dynamic DSM programmes supported by BIM and BAS repositories. Based on the work by Meyabadi & Deihimi (2017), dynamic DSM programmes can be categorised by four types referred to as peak-clipping, valley filling, load shifting and flexible load shape.

- Peak-clipping programmes reward consumers for reducing energy use during on-peak periods (e.g., increasing temperature setpoints).
- Valley filling programmes reward consumers for building energy use during off-peak periods (e.g., storing thermal energy).
- Load shifting programmes reward consumers for shifting energy consumption from on-peak to off-peak periods (e.g., queuing IT jobs).
- Flexible load shape programmes reward consumers for varying loads when the grid reliability is jeopardised (e.g., turning on and off electrical vehicle charges).

Dynamic DSM programmes support grid operation, providing load profiles and factor corrections that reduce energy consumption differences between peak and off-peak periods, as well as promoting ancillary services that assist the grid to restore stability under unforeseen events, such as network failures or other unplanned conditions.

Given that static DSM programmes refer to strategies that do not depend on active interaction between the end user and the grid, they are outside the scope of this work.

Business Process Map

For a successful integration and seamless data exchange between BAS, BIM and grid information to enable DSM programmes, all concerned parties must be aware of which information shall be inserted into the model at which stage in the building life cycle. Figure 2 shows the overall process map, based on Business Process Modelling Notation (BPMN), proposed in this work for leveraging BIM and BAS information for DSM programmes. In the design phase, the BAS model is created in reference to the BIM spatial model, building energy systems (e.g., HVAC and lighting) and DSM control logic specifications. Inspired by the work of Jiang et al. (2015), the BIM and BAS domains are integrated/linked using a query code generator that leverages the ERs defined in DSM-based IDM-MVD ontology as an input, and output a BIM-BAS common data model. In the operational phase, this common data model, which is enriched and validated with BIM and BAS information, is used to support context-aware DSM optimisation strategies. These optimisation strategies are focused on the building perspective, relying on the BIM spatial context, BAS parameters and real-time data, and grid signals.

Exchange Requirements

The proposed ERs to enable DSM using BAS and BIM are derived from the fundamental BAS concepts of the ISO 16484-3:2005 (International Organisation for Standardisation 2005) as assessed by Vieira et al. (2020), and the required data to assist the deployment of the DSM programmes as defined in the use case definition section. To foster interoperability between heterogeneous data environments and communication protocols, the ERs are defined abstractly and holistically within three main BAS levels: field, control and management. The field level focus on the interaction and specifications of building energy systems and spatial context. The control level defines the logic that coordinate the field level systems to trigger actuation scenarios in response to corresponding input data and threshold values. Lastly, the management level provides configuration and data acquisition functions for the high level supervision and coordination of the controllers, being responsible for the interaction between the building and the grid. Since BAS-related data does not include spatial containment information, BIM is used to provide environmental contexts to drive load management measures. To comply with the DSM programmes, Table 1 defines the relevant functional units and network properties for each BAS level along with their short description and source of information, either from the BIM or BAS.

At the field level, the spatial information is exploited to locate the equipment and device placements within the building premises, which can be used to target optimisation strategies based on thermal zones and space types. The equipment (e.g., boiler, light fixture and plug-in office equipment) and device (e.g., meter, sensor, actuator and controller) information defines their type, vendor and user-defined specifications and descriptions, as well as physical characteristics. Lastly, the connectivity property defines the physical connection between equipment and devices and the group property aggregates them based on common interfaces.

At the control level, the data points represent the addressable logical points of the devices, including physical points that refer to I/O ports and virtual points that provide services, such as configuration of a given parameter according to the status of an associated physical data point or input data. Each data point is described through metadata attributes (e.g., network address, data type and unit). The binding property describes the logical connection among the data points and devices, stating, for example, their relationship with each other as an input or output. In addition, the operation mode and setpoints properties define the control logic configuration set for each building energy systems during regular operation, while the limit demand and setpoint parameters specify the minimum and maximum levels and values acceptable to maintain their operation during DSM program provision. Lastly, the event property represents the request command from the grid, the active period property defines the time frames for the deployment of DSM programmes.

Finally, at the management level, the occupancy schedule for each building space is suitable to efficient design approaches for the building energy system operation schedule. The comfort profiles define the indoor environmental quality requirements (e.g., thermal comfort, hazard mitigation, and others). The baseline value is powerful in terms of performance and attribute-based metrics by comparing expected setpoints and consumption targets with the device value readings and accumulator measurements. In addition, the occupancy reading is beneficial to optimise the energy consumption per space by adjusting control parameters to respond to occupation status. For visualisation purposes, the historical data is used for reporting and management functionalities, such as energy use pattern recognition, and the demand level reading presents the real-time demand use. Lastly, the DSM duration and reduction state required information to be shared with the utility, while the DSM signals identify the energy rates and incentives to perform a given DSM programme from the utility.

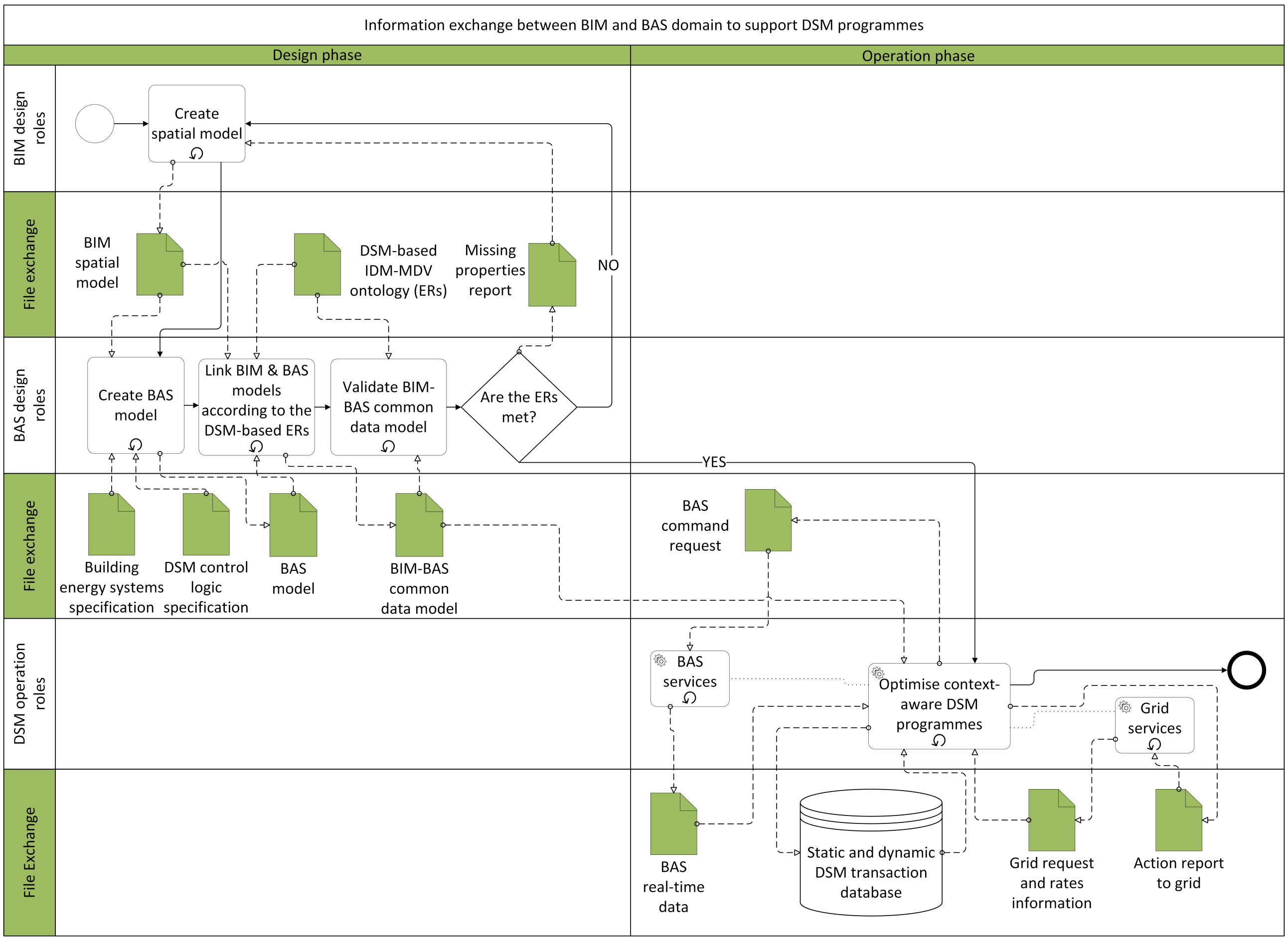

Figure 2: Process map of the information exchange between BIM and BAS domains to support DSM programmes.

DISCUSSION

This study identifies ERs to represent BIM and BAS required domain knowledge to enable DSM programmes as a basis for the development of a DSM-based IDM-MVD ontology. Leveraging the semantic definitions and reasoning features of this ontology, heterogeneous BIM and BAS models can be queried creating a BIM-BAS common data model (schema-agnostic). The use of graph-based technologies for the knowledge representation of this common data model is viewed as a promising strategy to enhance this proposed cross-domain data exchange and will form the future work.

The integration of BIM and BAS domains adds value to current DSM programmes, supporting decision-making processes for load management from the perspective of the building. Driven by DSM signals, data monitored by BAS and building environmental contexts provided by BIM, each load can be evaluated in terms of its qualified flexibility to promote DSM optimisation strategies. For example, by adjusting specific setpoints, such as fan speed, power rate and temperature, to be based on occupation schedules, sensor data as well as indoor environmental quality requirements, the demand for given loads can be adjusted automatically to deliver DSM measures while maintaining the required comfort levels. The potential contribution of this study includes the interaction between the BIM, BAS and grid repositories to deliver fully automated context-aware DSM programmes at various levels of a building hierarchy (e.g., by thermal zones or individual devices).

CONCLUSIONS

This paper defines ERs for integrating BIM and BAS domains within a DSM context. While BIM processes provide relevant information about building elements and promote collaborative data exchange, BAS control and communication infrastructure enables buildings to function as active participants in DSM programmes. Future work concerns a comprehensive definition of BIM and BAS ERs, the development of a DSM-based IDM-MVD ontology to explicitly define the semantic descriptions and relationships of these ERs and of a query code generator to create a BIM-BAS common data model based on them. This combined approach can mitigate semantic interoperability issues between BIM and BAS data environments, enhance data quality and consistency and foster the deployment of SGRB applications as vital contributors to future smart grids.

Table 1: BIM and BAS ERs to support DSM programmes.

Level	Function	Property	Description	Source
Field	Spatial	Location	Sets equipment and device placement	BIM
		Space type	Sets space type	BIM
		Thermal zone	Sets influenced zones	BIM
	Systems	Identifier	Sets vendors ID	BAS
		Name	Sets user-defined ID	BAS
		Type	Sets type	BAS
		Description	Sets descriptions	BAS
		Representation	Sets characteristics	BIM
	Relation	Connectivity	Sets physical connection	BAS
		Group	Sets groups of equipment and devices	BAS
Control	Logic	Datapoints	Sets metadata attributes	BAS
		Binding	Sets logical connection	BAS
		Setpoint	Sets setpoints	BAS
		Setpoint limit	Sets allowed magnitude of change	BAS
		Demand limit	Sets allowed magnitude of change	BAS
		DSM sequences	Sets DSM controls description	BAS
		DSM operation	Sets DSM actuation scenarios	BAS
		DSM event	Sets DSM event request	BAS
		DSM active period	Sets DSM time frames	BAS
Management	Setup	Space schedule	Sets occupancy time frames	BIM
		Comfort profiles	Sets comfort requirements	BIM
		Baseline	Sets expected values	BAS
	Data acquisition	Setpoints and status	Reads setpoints and device status	BAS
		Sensor data	Reads sensor data	BAS
		Occupancy	Reads occupancy status	BAS
		Demand level	Reads effective demand	BAS
		Energy accumulator	States energy consumption	BAS
		Historical data	Retrieves archived data	BAS
		DSM reduction	States demand and energy reduction	BAS
		DSM duration	States DSM duration	BAS
		DSM signals	Reads DSM signals	BAS

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