Open BMS – IoT driven Architecture for the Internet of Buildings

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***Abstract*—This paper describes the creation of an IoT driven architecture to support the realization of an OpenBMS approach to managing blocks of buildings. The objective is to overcome the complexities of integration, operation and management of heterogeneous building systems by leveraging existing IoT approaches. The goal is to eliminate vertical data silos and enable the holistic management of energy across existing and new building blocks.**

***Keywords*—OpenBMS; architecture; IoT; internet of buildings; energy management.**

I. Introduction

Buildings often contain legacy systems that are not well integrated with other systems [1]. This hinders the deployment of system that enable further energy savings such as analytic systems, predictive control, or demand response [2-4]. Opening the building interfaces to such tools is the first step. The second step is connecting these systems into a collaborative platform that allows the management of blocks of buildings across the globe. This is essential in particular for multinational companies that have global building portfolios and that are looking for integrated management solutions [5].

We define an open building management system (OpenBMS) approach for energy management as infrastructure that can be easily deployed across existing and new building blocks across the globe to open the use of building data for multiple systems and allow easy access and exchange of data. Such an infrastructure would inherently need to be complemented by a secure communications infrastructure backbone that scales from building to multiple buildings. This open cloud based infrastructure would need to offer different extension points for enhanced cooperation from easy programming tools for control logic to secure web services for backend systems. In line with this vision for an Open BMS approach, Internet of Things (IoT) technology brings with it the opportunity to roll out integrated building management systems on an international scale.

Current practices for building automation and management that control heating, ventilation and air conditioning (HVAC), lighting, access control and security traditionally act as silos which are operated independently and are provided as proprietary systems by multiple vendors. This leads to vendor lock-in and isolated systems that are operated independently of the organization's core IT networks which further limits the accessibility and integration potential of these systems. The need for cooperation, interaction, and coordinated operation of multiple systems is being recognized by system integrators, facilities managers and BMS manufacturers alike and is spurning a need to look towards technologies that can bridge the gaps between systems.

An OpenBMS approach powered by IoT technology offers a systems of systems solution that makes integration of heterogeneous systems easier, reduces administration in terms of managing multiple standalone systems and will be readily deployable across existing and new building blocks. In addition it will offer the ability to accurately assess actual performance through continuous fined grained data extraction over standards compliant, secure data channels.

IoT enablement means that objects (devices and systems) are accessible over the internet moving their reach beyond their local built environment. This can assist in the identification, classification and cataloguing of all objects across buildings and can be used to optimize the current operating conditions for specific targets, i.e. use IoT technology to provide greater insight into the energy performance across and within a block of buildings. IoT provides the capability to position intelligence where it is needed, where data processing and analytics can be positioned at the edge devices or in the cloud offering both scalability and flexibility. Self-managing and intelligent edge devices and systems can make local decision concerning when and who they share data with in relation to other devices, systems, the cloud and external third party services. In stark contrast is the traditional BMS which acts as a monolithic centralized infrastructure for individual buildings. Cloud side capability can lend itself to providing a single administrative user interface, real time performance monitoring and analytics incorporating energy data, occupancy data, air quality and other data (such as weather, energy storage, grid pricing, etc.) to facilitate informed decision making in order to reduce energy use and operating costs.

II. Related Work

Several concepts for open BMS approaches exist. Dawson-Haggerty [1] defined a layered software architecture that has a hardware abstraction layer to integrate various systems, a time series layer and a software layer. Fierro extended this in [4] to an extensible architecture that includes more systems. A similar architecture is proposed by Palmer [3] that utilizes an XMPP message bus as a transport layer. While these architectures already facilitate hardware abstraction, they do not consider the new concepts in the IoT space that support scalability.

One of the central goals of the OpenBMS architecture is to support for access and data-exchange from and between the various buildings on global scale to form an internet of buildings. Recent developments in the domain of Internet of Things (IoT) have driven concepts that can facilitate the creation of an Open BMS architecture, including wireless IP-enabled building automation devices, secure messaging protocols (e.g. AMQP, MQTT), web APIs (e.g. REST, COAP), IoT gateway devices (e.g. Intel IoT Gateway, Dell IoT Gateway), stream processing, and analytic services, among other. The TOPAs architecture aims to leverage these concepts addressing the need for affordable monitoring and control solutions when managing multiple buildings. A number of IoT related reference architectures have been already specified driven both from academic and industrial perspectives. The Industrial Internet Consortium Reference Architecture (IIRA) [6], IOT-A [7], ETSI oneM2M [8], AIOTI-HLA [9] and ITU-T IoT Architecture [10] are leading concepts for the development of a reference model to support a common understanding of the IoT, and a reference architecture to provide a common foundation for the development of interoperable IoT systems. A common trait among the reference architectures is a three tier pattern, which consists of enterprise, platform and edge tiers:

- The *edge tier* abstracts data from the edge nodes, the characteristics of which vary depending on the specific use cases.
- The *platform tier* is responsible for consolidated processes and data analysis for flows generated from the edge tier. It provides management functions for edge devices and assets and offers non-domain specific services such as data storage, query and analytics.
- The *enterprise tier* implements domain-specific applications, decision support tools and provides interfaces to end-users including operation specialists.

III. IoT DRIVEN ARCHITECTURE

Building owners and facilities managers are being tasked with driving down energy and operational costs and to move towards managing across buildings. This level of cross building coordination and management and the target reductions required cannot be delivered by human intervention alone. This increased focus on energy efficient buildings and block of buildings is driving significant expansion in the energy management market. As discussed earlier, BMS platforms are typically closed systems, customized for clients where the vendor and/or system integrator are required for upgrades and extensions. IoT technology offers a reduced cost point in comparison to vendor proprietary infrastructure and in terms of system administration. Cloud based services (including analytics, reporting, diagnostics etc.) can offer lower operating costs and greater flexibility in comparison to traditional BMS solutions.

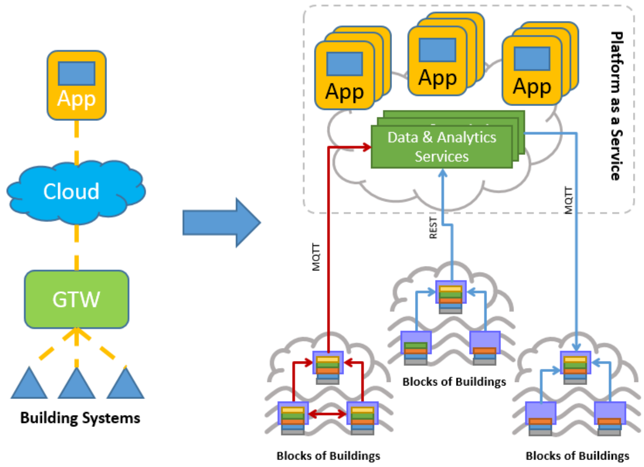

Fig. 1. TOPAs Open BMS high-level architecture

In terms of retrofit, widely available multi-functional, easy to use IoT devices are an attractive alternative to specialized and often wired BMS end devices. As part of the EU H2020 project - Tools for cOntinuous Building Performance Auditing (TOPAs) we investigate the design and development of an IoT driven architecture capable of managing blocks of buildings. An OpenBMS approach can be viewed as being analogous to typical IoT architectures that connects end devices (or Things) to enterprise applications via cloud platforms as depicted to the left of Fig. 1. However, this approach can lead to the formation of vertical silos when considering blocks of buildings or district level management. TOPAs enhances this approach by focusing on developing functional blocks that support ease of deployment across the three tiers of IoT systems. This includes decision support at the enterprise tier, analytics services at the platform tier and data integration which is split into two sublayers, namely a cloud based Open BMS Data layer and an on-site Integration Middleware Layer forming the edge tier. The top tiers reside on a cloud based platform as a service (PaaS) that allows scalable deployment and ease of access from various client applications. Application services can be deployed either on-site, remotely, or on the PaaS. Information can be exchanged across these layers via common API using machine to machine based protocols and\or web service interfaces.

Fig. 2 provides a representation of the OpenBMS reference architecture proposed by TOPAs in the form of a functional model which is mapped to a three tier architecture pattern. In general terms the *enterprise tier* manages domain-specific applications and management tools to support the definition of business logic that can be pushed down to the lower tiers to drive the operation, tuning and optimisation of underlying building systems. It also incorporates end-user interfaces which receives and presents data from the platform tier to provide decision support. The *platform tier* is responsible for the management of data flows from the edge level tier, implementation of models (e.g. occupancy, energy, and building) and the provision of analytics services. The *edge tier* is responsible for data collection from field devices, depending on the specific building systems and to support legacy integration. The edge tier requirements can be represented as an edge-mediated architecture pattern where a gateway device is utilised to provide an abstraction between the underlying building system interfaces and the platform layer or a direct interface to end devices if available. Each layer of the reference architecture contains a number of functional groups that represent a container for system components with common goals and functionality. The following sections describe the role of each functional group.

A. Edge Tier

The first phase of realizing an OpenBMS approach is the ability to cost effectively and seamlessly integrate with existing legacy systems. A building can consist of many heterogeneous systems and devices to support the building operation (e.g. Heating, Ventilation, Lighting, Air Conditioning (HVAC) and Electrical systems). To abstract from the underlying sensing and control infrastructure there exists a significant number of *building system interfaces* and automation protocols that are currently being used across the BMS market (BACnet, KNX, LONWORKS, DALI, Modbus, oBIX, OPC, Zigbee, Z-Wave etc). This in itself poses a significant challenge in terms of integration and coordination between building systems. Often even when standardized protocols are utilized, many of the BMS vendors implement their own proprietary version on top of their existing solutions. This results in vendor lock-in and limits openness and ease of integration with other building systems. Hence, from an architecture perspective it is critical to be cognizant of this challenge and to some degree be agnostic of the type of underlying system through the development of reusable system connectors.The management of multiple buildings first requires the abstraction of individual building systems; this is achieved via a building system connector. A *building system connector* can be classified as gateways or mediators between the building systems/devices and the upper tiers of the architecture. This can be a hardware/software combination incorporating a middleware component to act as a translator between data abstraction and the invocation of control actions. Connectors should provide support for multiple protocols and require minimal configuration to minimize integration of building systems. The next step is to provide a secure communications channel and data exchange from the individual building proximity network.

To interact with the building systems TOPAs utilizes as a hardware base an IoT gateway – the Motorola Remote Terminal Unit is utilised. It is a Linux based system that provides interfaces to physical systems as well as secure communications to the internet using encrypted internet protocols such as TSL and SSL. To connect to the various BMS protocols we utilize the lightweight resource based LINC middleware [16], [17].

LINC provides a uniform abstraction layer to encapsulate different software and hardware components (OPC, LON, KNX, ZigBee). This layer simplifies the integration and coordination of legacy components. LINC provides a coordination environment with transactional guarantees ensuring consistency of the system. LINC embedded on hardware devices such as the Motorola RTU SCADA system provides a secure remotely managed gateway to act as a mediator between the building systems and the monitoring and control logic, models and ultimately the business goals.

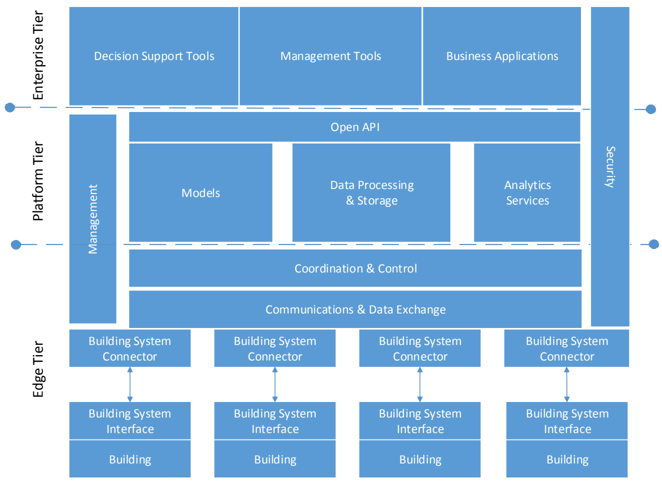

Fig. 2. TOPAs Open BMS Reference Architecture: Functional Model

The advantage of integrating blocks of buildings can only be realised if there is a coordinated exchange of data between buildings to impact operational decisions and also a combination of localized control to meet immediate operational objectives, and coordinated/supervisory control to ensure the global objectives of the blocks of buildings, are achieved. *Coordination and Control* may also be achieved between building systems running in the same building.

B. Platform Tier

This functional group is responsible for providing secure and *reliable interfaces*, south bound to building systems using the building system connectors, north bound to platform and enterprise tier and east/west between buildings considering Internet of Things compliant protocols (e.g. REST, MQTT). *Data exchange* across the north and east/west communication channels will follow a common data format, with JavaScript Object Notation (JSON) being initially considered. JSON provides a lightweight data-interchange format that is easy to understand and supports interoperability across different languages that can be used for implementation.

Building System data can come in many different forms from time series data from sensors, to their meta-information such as the sensor type and location; to event streams for alarms, logs, or room booking information. We differentiate the data into structured, unstructured and semantic data and store it on the cloud platform using appropriate modern storage technologies. Times series are well structured and are stored in a scalable relational database (DB2). Meta-data is of particular importance for automating analytics [12]. It is stored in a Neighbourhood Information Model that is an extension of the BASont [11]. We assume that event streams are unstructured data such as text entries in logs. They are stored in a No-SQL database (Cloudant). It would be possible to store everything in a Cloudant database [17], but, the representation and querying is not that efficient for analysis. The combination of different database formats allows for a compact representation of the data and an easy retrieval for analysis. A homogenous open API hides the various technologies such that user does not need to deal with the various storage technologies underneath.

The platform tier also hosts *analytic services* to support domain specific components from energy modelling to fault detection and diagnosis. It provides a highly modular concept that allows the agile development of specialized analytics that can be hosted in a cloud environment (e.g. using a PaaS infrastructure), deployed on-site or embedded into remotely accessible services. The data exchange between the analytics services happens via an Open API. A direct interaction between services is not required, nor restricted. This loose coupling of the analytic services provides high flexibility for developing and connecting new analytics and is one of the core concepts of TOPAs Open BMS architecture.

Modelling plays a significant role to effectively manage blocks of buildings, this include a neighbourhood information model providing a district level view i.e. meta-data on sensors (e.g. their semantic type) and the building assets (e.g. air handling units) as well as locations (e.g. rooms) [12]. Other models that fall under the remit of this functional group should include energy prediction and occupancy to understand the building usage and the impact changes to the operational strategy have on actual energy usage.

An *Open API* provides a common interface firstly between the enterprise tier and the platform tier and secondly between the platform function blocks. It is important to consider the requirements for the different services that will interact with the platform tier when specifying the Open API requirements. Our open API offers web based service interfaces (e.g. REST) and message brokers (MQTT). The REST API follows retrieval concepts defined by oBIX, but, provides way more information ranging from meta-data, to time series and event data. It exposes different sub-APIs that are best suited to the requirements (e.g. specific API for meta-data and models). The complexity of deploying and supporting the OpenBMS requires *management* tools that can be integrated into existing business processes to ensure stability and reliability during the operation of the building systems. The management functional group also spans across the edge and platform tier. Management functionality at the platform tier can be accommodated by utilising existing Platform as a Service (PaaS) deployment strategies such as those offered by IBM Bluemix. From an edge perspective the deployment and maintenance of building system connectivity requires additional processes and tools to ensure the devices\systems and interfaces for building system interaction are reliable and stable. For an OpenBMS perspective, *security* is a paramount concern, similar to the management functional group, security must be provided at all tiers. This includes functional security capabilities, including user authentication, access authorization, auditing of critical operations, and data protection and encryption.

C. Enterprise Tier

Decision support tools provide services to support the operation of buildings and blocks of buildings. These can include, for example, design and configuration services, fault detection and diagnosis tools, and a common monitoring interface for energy flows within and across buildings. *Management tools* are required to allow users of the system monitor and manage the configuration of the OpenBMS system through a common interface. This can constitute an operator facing human machine interface (HMI) composed of modular user views, dashboards and control panels providing configuration and implementation functionalities. The OpenBMS approach must facilitate the extensibility of the overall system through the ability to create additional third-party services on top of existing infrastructure. This can be achieved via boilerplate implementations of specific functionality and data access.

The component also provides a container to encapsulate other TOPAs (or approved third party) web based interfaces and tools accessed via their pre-configured URL. Other decision support tools includes a Fault Detection and Diagnosis (FDD) component that implements routines for automated FDD on building services such as HVAC systems on the basis of time-series data generated from the edge tier. AUTERAS [17] is a vendor- and platform-independent room automation design suite, which allows building managers to plan standardized, functional room automation schemes and also to search for devices, which fulfill the user's functional requirements to the room automation systems according to the VDI3813. In case of faulty devices, it is possible to detect the affected underlying functionality, which helps to suggest repair strategies to overhaul the room automation system. The WiSuite toolset [17] provides deployment planning services for users considering the installation of wireless sensor systems including for example WiFi™, ZigBee, Z-Wave, EnOcean, or BLE. Based on site specific requirements (building layout, sensor and application requirements) the WiSuite tool provides a deployment plan for sensor placement to support reliable data collection and in the case of wireless solutions this will also include connectivity. The Coordination Scheme Editor (CSE) [17] provides a graphical interface to monitor buildings, BMSs and to edit coordination rules that can be directly executed in the buildings coordinated by LINC and is extended to provide advanced validation to guaranty that adding new BMS interaction rules will not compromise the operational boundaries of the underlying systems. The CSE supports zones and blocks of buildings, accessible from the same HMI. This section introduced the TOPAs reference architecture which was derived based on the three tier pattern common to reference architectures in the IoT and industrial domains. The functional groups shown in Fig. 2 and described above provide the basis for realising an OpenBMS approach to effectively manage energy across blocks of buildings.

IV. OpenBMS Concrete Architecture Example

The OpenBMS reference architecture presented in Section III provides a basis for realising the concrete architecture that will encapsulate the components developed by the TOPAs project and deployed in the pilot sites at the IBM technology campus in Dublin, the Bouyguess Imobilia HQ in Paris as well as the Cork Institute of Technology (CIT) campus. CIT (shown in *Fig. 3*) is located in Cork City, south of Ireland in the west of Europe, its climatic zone is temperate maritime; modified by North Atlantic current; mild winters, cool summers; consistently humid and regular rain. Buildings on the Campus includes Offices and Labs, University Buildings (Class Rooms, Kitchens, and Canteens) and Student Accommodation. Currently the campus does not have a model to predict energy consumption.

Fig. 3. Ariel view of the CIT Campus

As a public body CIT has committed to a 33% reduction in energy use from 2009 (base year) to 2020, up to 2013 this stands at a reduction of 16% from the base year. CIT have a rough estimate of the expected energy use at the campus level and various strategies for energy savings have been put in place. However, without a more accurate understanding of energy prediction and performance at the level of individual building blocks. It is difficult to ascertain if the energy saving strategies are as effective as they could be. There are two primary buildings within the campus that were selected as the focus of the TOPAs project: the Nimbus building and the Melbourne building. The Nimbus building provides about 970 m^2 work space over two floors in the building front. The Nimbus building is primarily utilised as a research facility for undergraduate, postgraduate and PhD students. The Melbourne building is a repurposed factory site and is divided into a two storey area at the front of the building which contains office areas and meeting rooms and a double height area to the rear hosting an open plan collaborative learning environment for the department of architecture and an exam hall as well as a number of offices. These buildings offer two contrasting areas, one highly instrumented with a high degree of control and the other with minimal instrumentation and no automated controls. A number of challenges have been as identified by the CIT Buildings and Estates office relating to the operation of the campus buildings, these include a number of independent systems across campus buildings of varying levels of functionality and control. A lot of manual checks need to be done both at BMS and in physical plant rooms. There is no overall visibility of the campus wide performance. Air quality issues between blocks due to lack of natural ventilation. And finally it is difficult to effectively quantify the energy performance across the campus on a continuous basis. The target for TOPAs is to demonstrate how the OpenBMS approach can be used to easily manage multiple buildings with different constraints on the one campus which are currently managed independently. This scalability will be achieved by integrating cost effective monitoring to enable easy data extraction, new models and fault detection of a number of the distributed systems and the application of the distributed Model Predictive Control (MPC) to manage energy consumption across the various buildings all with different constraints. This will result in a cost sensitive approach to bridging the gap between actual versus real energy consumption. *Fig. 4* presents the application of the TOPAs architecture for the CIT site. The following presents more details regarding the functional groups utilised for the CIT site. The Nimbus Building has 21 EnOcean temperature sensors linked to the Building Management System (BMS) to control sixteen heating zones, CO_2 is also monitored.

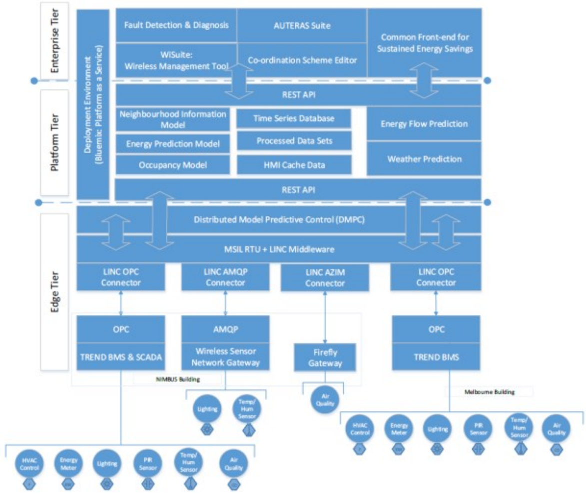

Fig. 4. TOPAs Architecture for CIT Demonstration Site

The feedback is linked to the automated windows and is part of the criteria used to control them. There are no internal building sensors recorded within the Melbourne Building. There are three different metering systems in the Nimbus Building that record and log metering data. The BMS records metering data for the Ground Floor, First Floor, three separate laboratory areas, the server room, lighting and the main electricity incomer to both the Nimbus and the adjacent Building. There is a SCADA system controlling the microgrid and records the CHP electrical output, the wind turbine output, the input/output from the battery storage, gas use in the CHP and heat dumped or sent to a thermal store. Finally, a separate proprietary system records gas use in the boilers. As an interface to the BMS an OLE for Process Control (OPC) server is installed, this allows for an abstraction of the underlying automation systems via the OPC protocol. Additional wireless sensor systems provide an AMQP gateway for data extraction. The Distributed Model Predictive Control (DMPC) component constitutes algorithms for the real time optimization of energy that can be applied to building zones, buildings and blocks of buildings. MPC uses a model to predict the system future evolution. An optimization problem is solved to identify the best control action that minimizes a cost function related to the system prediction. The ability to handle constraints and binary values has enabled MPC to be used in varied applications. For heating and cooling systems, various cost functions and constraints have been analyzed to minimize consumption or to ensure a desired level of comfort. While centralized MPC suffers from high computational complexity, DMPC uses many local controllers (agents) to control the overall process and to achieve general goals over the whole energy building performance. Each agent is responsible for the performance of a single zone, significantly reducing the complexity. The global optimal solution or the Nash equilibrium point is achieved by the exchange of future behavior (predictions) between local MPCs over sensor networks. Local controls strategies for CIT focus on three aspects, firstly minimizing the energy usage while maintaining the comfort level in buildings, secondly optimizing the cost associated with operating a Combined Heat and Power (CHP) in buildings and finally managing the global performance objectives based on interactions between control agents across blocks of buildings. The edge tier is responsible for the interaction with the underlying building systems and across blocks of buildings, it leverages the platform layer in terms of analytics to support control systems and the translation of business objectives into control strategies. Energy Prediction Models are applied to allow continuous supervision of the actual energy demand. Innovative prediction models for one-day-ahead energy consumption forecast within 10% deviation. The prediction models integrate measurements from BAS/BMS, weather forecast data and occupancy models. With the predicted energy consumption, optimized proactive control strategies can be implemented. For the CIT site, the models are transformed to State Space Models to enable DMPC. The Neighborhood Information Model (NIM) contains the structure of the considered building district, from the buildings down to the rooms. For each room the contained room automation devices as well as the functionality are stored. Additional information (links to other Data like energy models or time series) can be attached to each element in the model. The NIM provides a central information point for storing and accessing all the information about the components in the buildings as well as the buildings or their structures themselves. The enterprise tier at the CIT site includes a common user interface (UI) which utilizes a set of reusable HMI components that are integrated into a web based UI to support Facilities Managers/Building Operators manage their facilities better. This is achieved by identifying the most relevant information that allows the user gain a better understanding of the current status across their site and provide insight to support their decision making process.

V. Summary and Conclusion

An OpenBMS platform is a key to open up the data silos of current buildings to various tools from analytics, to fault detection and model predictive control. Our design utilizes IoT technologies to enable a distributed system, which allows components from different parties, e.g. vendors that implement the platform appropriate interfaces, to be integrated. This approach provides flexibility as it allows an OpenBMS architecture compliant system to work with a subset of the functionality and also allows for upgrading functions during the lifetime of a specific implementation. The OpenBMS platform integrates distributed software components, which can be developed and maintained by individual vendors. The distributed approach with clearly defined interfaces simplifies integration of a diverse set of software components from multiple manufacturers and service providers. The OpenBMS platform will offer ready to use tools, services, management components and a replicable platform that can accelerate the time to market for new product and service offerings as well as reducing interoperability issues. In essence it has to potential to offer data as a service where the quality, timeliness and utility of the data available represent the key business opportunity – the OpenBMS platform enables an IoT market place for data exchange (sellers, buyers, and subscribers) underpinned by a scalable and secure platform. IoT based architectures for blocks of buildings offers future proofing and can reduce long term capital and operational expenditure outlays. Being able to continuously monitor and control multiple buildings and assets will support the detection of operational inefficiencies and potential systems failures, which in turn reduces maintenance and operating costs. IoT technology can be used to augment rather than replace existing building management technology and can be used to integrate blocks of buildings at reduced complexity and cost rates.

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