B-SMART: A Reference Architecture for Autonomic Smart Buildings.

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Abstract. There has been increased interest in Smart and Ongoing Commissioning solutions to address the performance drift in existing buildings. Autonomous/autonomic systems are valuable tools to support the development such solutions, working towards a set of goals while sensing changes in their environment and adapting to them without human intervention. An autonomic approach to smart building design can thus maintain optimum energy efficiency while reducing operating costs. To support this development, this paper presents B-SMART: the first reference architecture for autonomic smart buildings to support smart commissioning. This research was informed by a comprehensive review of existing autonomic properties and domain-relevant autonomic properties and conceptual architecture. By decoupling conceptually distinct layers of functionality and organizing them into an autonomic energy optimization control loop, B-SMART facilitates the autonomic optimization of smart buildings.

1. Introduction

Buildings are responsible for approximately 32% of global energy use and 19% of CO2 emissions and their longevity as well as the ability to reduce these values have made it a significant priority for emissions reduction [1]. In this context, the ability to manage buildings most efficiently is critical. Significant research and best practice development have formed a body of commissioning practices implemented throughout the building life-cycle. This paper seeks to build upon the state-of-the-art to present the first reference architecture for autonomic smart buildings to enable Smart and Ongoing Commissioning (SOCx) occurring throughout the building life-cycle.

1.1. Smart Buildings and SOCx

The term (Smart Buildings) was initially defined as those buildings whose “design and construction require the integration of complex new technologies into the fabric of the building” [2]. In the intervening decades, several new developments have expanded the definition of Smart Buildings, but at the core remains this need for integration of a diversity of new technologies including those yet to be developed. This anticipation of future learning has led to significant applications of artificial intelligence and machine learning within this domain. Driven by the urgency of climate change, energy management has been a particular focus for this research with sub-focuses on monitoring, fault detection and diagnosis, and scheduling problems [3]. Advances in Building Information Modeling (BIM) have been developed to integrate the information required to support such Smart Building applications throughout the building life-cycle [4]. Further complicating this challenge is the ever-evolving diversity of Internet of Things (IoT)devices and applications enabling Smart Building operations [5].

Within this context of complex, heterogeneous systems integrated into Smart Buildings, the ongoing optimization of building performance is a significant challenge. Smart and Ongoing Commissioning (SOCx) is the integration of traditional commissioning processes with online monitoring and data analysis drawn from IoT devices and traditional building systems such as Building Management Systems (BMS) to maintain optimum building performance. Recognizing the diversity of data required to support these practices, several SOCx ontologies have been developed [6], as have data streaming approaches to collect this data [7] and algorithms to support fault detection and energy optimization [8].

Despite considerable focus on optimizing power consumption by smart buildings, there remains a paucity of literature regarding autonomic smart building approaches. Those that do exist and represent the current state-of-the-art in autonomic architectures for smart buildings fail to fully address the needs of SOCx processes. Several key autonomic systems properties have also been omitted in such studies. Manual data collection, transformation, and analysis are slow and expensive processes. This is a major factor slowing smart building adoption. Ideally a smart building, like advanced Industrial IoT systems [9], should be able to commission itself, re-commission itself if the situation calls for it, and maintain optimal systems performance on an on-going basis. The future of smart buildings is autonomic. To overcome this set of challenges, we propose the first reference architecture for smart buildings. Our architecture supports all the key properties of autonomic systems and is tailored specifically for smart buildings implementing the SOCx process to serve as a guide for continuing research and development activities in this very important area.

1.2. Background

Recent advances in Artificial Intelligence (AI) and Machine Learning (ML) have triggered revolutionary changes across many industries known as Industry 4.0. Examples include self-driving cars, autonomous drones, robotic production lines, AI-assisted medical diagnosis, social network algorithms, facial-recognition features in smart phones and cameras, and many other examples. Such modern autonomic systems pervasively apply ML algorithms to identify objects that collectively comprise their environment and classify them into useful categories. Once detected and classified, the autonomic system needs to decide what actions need to be performed on, or in response to, those objects. The actions to be performed could be either learned using ML algorithms or selected using a rules-based system.

Autonomous systems typically need to co-exist and interact with humans. This interaction can be either *(*human-in-the-loop) and *(*human-on-the-loop). Human-in-the loop systems typically identify and classify the objects in their environment, present a human operator with a proposed set of actions, and wait for the human to confirm which action should be taken. Human-on-the-loop systems provide the human operator with the same level of information but do not wait for human operator to confirmation; instead, the action will be performed automatically. The human operator will be able to observe and, if necessary, intervene in the autonomic cycle.

The field of autonomic computing was introduced by IBM in 2001 with the goal of creating computer systems capable of self-management. Since then, there has been considerable research focusing on developing autonomic systems. Originally IBM defined autonomic systems to exhibit

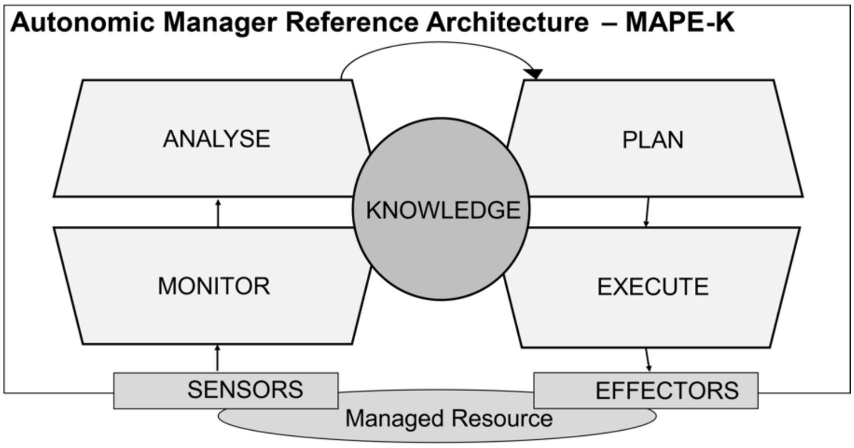

Figure 1. The IBM MAPE-reference architecture for autonomic managers.

the following characteristics:

(i) ***Self-configuration***. The ability to configure its own components without human intervention.
(ii) ***Self-healing***. The ability to recognize and correct faults without human intervention.
(iii) ***Self-optimization***. The ability to monitor and optimize their own performance.
(iv) ***Self-protection***. The ability of the system to detect intrusion and defend itself from its unwanted effects.

Additional research ([10], [11]) expanded these desirable characteristics as-follows:

(i) ***Self-regulation***. The ability to maintain a key parameter, such as the quality of service.
(ii) ***Self-learning***. The ability to learn about its environment without external intervention.
(iii) ***Self-awareness***. The ability to be aware of its constituent components and key external dependencies.
(iv) ***Self-organization***. The ability to the system to organize its own structure.
(v) ***Self-creation/Self-assembly/Self-replication***. The ability to organize itself in response to changing strategic goals.
(vi) ***Self-Management/Self-Governance***. The ability to manage all its constituent components.
(vii) ***Self-description/Self-representation***. Humans should be able to understand an autonomous system.

In 2005 IBM published its reference architecture for autonomic systems [12]. This reference architecture, referred to as MAPE-K, is shown in 1. The acronym MAPE-K stands for Monitor (M), Analyze (A), Plan (P), Execute (E), and Knowledge (K).

There have been very few published studies focusing on how to make smart buildings autonomic. Chevallier et al. [13] describe a reference architecture for a smart building digital twin, which is used to model physical building performance. Their reference architecture focuses on how to collect, store, and expose the static and dynamic information produced by smart buildings for query by human operators. Their reference architecture does not specifically address the autonomic aspect of smart building operation, nor does it discuss the implementation of autonomic properties, encouraging instead human interaction with the digital twin.

Bashir et al. [14] describe a conceptual framework (IBDMA), a reference architecture, and a metamodel for smart buildings. This metamodel describes the different conceptual entities and processes that comprise the smart building, and how they interact with each other. Their reference architecture describes how the big data stack technologies can be used to implement these processes. but do not discuss the autonomic properties, nor how these can be implemented in smart buildings. Mazzara et al. [15] also propose a reference architecture for smart and software-defined buildings. Their reference architecture also does not specifically focus on the autonomic aspects of managing smart buildings. It does include a layered view of smart building technologies. The key layers include: Hardware; Network; Management; and Application and Service. Mazzara et al. [15] discuss automating some of the smart building features but do not describe or discuss the implementation of autonomic properties by their architecture layers. Their architecture targets the more conventional smart building that relies on human interaction, supplemented by a rules engine to manage and optimize building operation.

Aguilar et al. [3] [16] propose a self-managing architecture for multi-HVAC systems in buildings based on an "Autonomous cycle of Data Analysis Tasks" (ACODAT) concept. While their work is a significant step towards defining an autonomic architecture for smart buildings, it has several shortcomings. Their architecture does not explain layering, or separation of responsibilities among the different technologies. It also does not support several key autonomic systems properties – such as self-organization and self-creation. Further, Aguillar et al. [16] focus on the optimization aspect of a smart building already in operation, but do not engage with questions of new implementation where there will be no historical data to work with, and thus there must be a lengthy period when it will not be possible to optimize the building power consumption.

In summary, most prior works focus on implementing the self-configuration and self-optimization autonomic properties. Autonomic architectures can be either centralized or decentralized. Many autonomic architectures leverage ML algorithms and AI techniques that are often grouped into a separate cognitive layer which, among other things, is responsible for detecting change and updating the models. These observations are reflected in the design of the B-SMART reference architecture discussed in more detail below.

2. Research Methodology

The literature review above provided insight on the existing, published, definitions of autonomic computing and autonomic properties that should be supported by autonomic systems as well as the existing, published, autonomic architectures were reviewed for both Smart Buildings and relevant domains (networking, cloud computing, and big data analytics). A gap analysis of autonomic properties within these architectures was undertaken to inform this current research, described in the section below. Based on this literature review and gap analysis, a new conceptual reference architecture, the **B**uilding **S**ystems **M**anagement **A**utonomic **R**eference **T**emplate (B-SMART) for autonomic smart buildings capable of supporting the SOCx process was developed as follows. First, a computational architecture concept based on MAPE-K was used as the starting point. Next, layers were defined to ensure they were fully decoupled in order to avoid circular dependencies. Third, a control loop was added to support autonomic functionality. Finally, these were synthesized into the architecture presented.

3. B-SMART Reference Architecture for Autonomic Smart Buildings

To inform the B-SMART reference architecture, we first conducted a gap analysis, summarized in Table 1. It was evident from this analysis that most autonomic properties remain unsupported. Further, to address existing shortcomings noted in our literature review, we propose an architecture that includes both a layered and an autonomic control loop view. The rationale in the detailed development of this architecture is discussed in the following sections.

Table 1. Review of Autonomic Architectures Applicable to Smart Buildings.

Architecture	Domain	Supported Autonomic Properties
ACODAT [16] [3]	Smart Buildings	Self-optimization
Chevallier et al. [13]	Smart Buildings	None
SSDB [15]	Smart Buildings	None
IBDMA [14]	Smart Buildings	None
Qin et al. [17]	Smart Grid/Cloud	Self-optimization
PSP [18]	Database	Self-optimization Self-configuration
KERMIT [19] [20]	Big Data	Self-optimization Self-configuration
ANA [21]	Networking	Self-configuration
CAN [22]	Networking	Self-configuration Self-optimization
Tomar et al. [23]	Cloud Computing	Self-optimization
Gergin et al. [24]	Cloud Computing	Self-optimization Self-healing

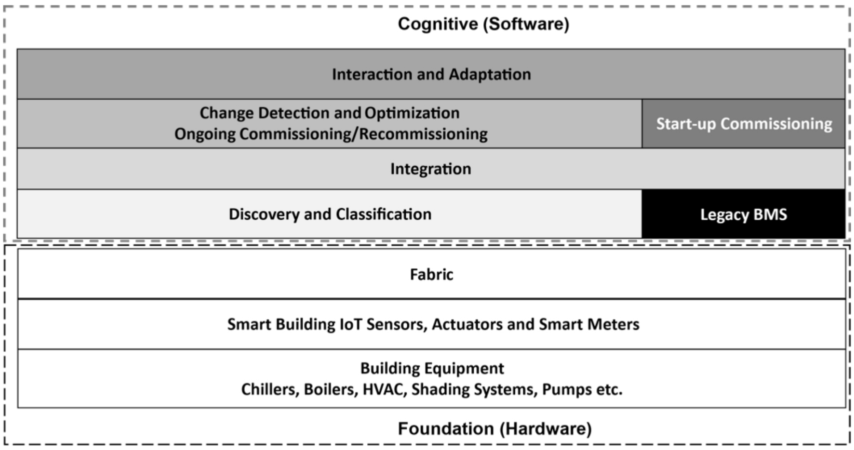

Figure 2. The B-SMART layered architecture view.

4. The B-SMART Layered View

The layered view of B-SMART describes the static relationships between autonomic smart building sub-systems. It is shown in Figure 2. In computer science and software engineering layered architecture diagrams are used to illustrate the conceptual dependency relationship between the sub-systems and components that comprise the architecture. As with a building, lower layers of the architecture form the foundation. Each successive layer in the architecture builds its functionality using functionality provided by the lower layer. Functionality provided by each layer is discussed in the paragraphs below. Table 2 summarizes the autonomic properties that must be implemented by each layer of the architecture, and its key responsibilities.

The base layer of B-SMART, Building Equipment (BE), groups all the key energy-related

Table 2. The B-SMART Architectural Layers and Supported Autonomic Properties.

Layer	Key Autonomic Properties	Responsibilities
Building Equipment	None	Must be capable of being instrumented with sensor and actuators.
Sensors and Actuators	Self-configuration Self-description	Enable automation for the building equipment layer.
Fabric	Self-assembly	Ensures connectivity among the sensors and actuators and the cognitive sub-system components. Sensors, actuators, and fabric networking elements form a self-organizing system.
Discovery and Classification	Self-learning Self awareness	Searches the Fabric layer to discover and classify sources of data.
Integration	Self-organization	Organizes data sources discovered by the D&C layer into more complex data flows. Incorporates legacy BIM/BAS.
Change Detection and Optimization	Self-optimization Self-protection Self-awareness Self-healing	Detects faults and concept drift in building systems. Mitigates faults and optimizes building performance in response to changes.
Interaction and Adaptation	Self-description Self-regulation	Interacts with human operators and systems external to the building.

systems of the building. HVAC systems and their integral components, such as chillers, boilers, shading systems, and pumps, play an especially important role. This layer also includes additional energy producing and storage systems such as electrical panels, transformers, and capacitors. These systems do not necessarily need to be 'smart', but they need to be capable of being instrumented with sensors and actuators to support the next layer up. It is important to note that although these BE elements may be designed with integrated sensors and actuators – the B-SMART reference architecture does not require this to be so. These technologies should be considered and allowed to evolve separately because the computer and electronic hardware used to implement the sensors and actuators has historically evolved at a much faster rate than BE elements.

The Sensors and Actuators (S&A) layer enables the interface between the higher cognitive layers in the B-SMART reference architecture. Sensors are information sources for the higher layers in reference architecture. Actuators enable actions to be performed on BE elements. Changing the set-point for the building boiler or chiller is one example of an action performed by an actuator. Note that although physically an actuator could be an integral part of a BE element, the B-SMART architecture treats it as different conceptual entity. This allows S&A and BE technologies to evolve at different rates. S&A devices could then be upgraded if necessary multiple times during the building life cycle.

The Fabric layer connects the sensors and actuators to each other and to the functionality in the higher Discovery and Classification (D&C) layer. The Fabric layer is predominantly a hardware layer, with software-defined aspects, that consists of specialized controllers and networking elements such as WiFi routers, network switches, network wires, telephone cables, the required power supplies, and data storage needed to establish secure and reliable communications and support the functionality of the D&C layer.

The Fabric layer should ultimately be an autonomic networking layer – capable of supporting the self-creation, self-description, self-configuration, and self-management autonomic properties. Architectures summarized in [25] provide examples of how this can be accomplished. The currently used BACnet protocol conceptually fits here as well. The Fabric layer, though, needs to go further than the currently available protocols, such as BACnet, to support the automated discovery and classification of building equipment.

Together, the BE, the S&A and the Fabric layers form the Foundation subsystem of the B-SMART architecture. This predominantly hardware subsystem enables the functionality of the higher-level Cognitive subsystem. The Cognitive subsystem implements the main autonomic control loop of the building and supports the SOCx process. The overview of the functionality of each layer in the SOCx subsystem is given in the paragraphs below.

The role of the Discovery and Classification (D&C) layer is to automatically find and classify different types of sensors, actuators, and other IoT devices available in the building. Automatic discovery and classification of endpoints was demonstrated by El Mokhtari and McArthur [26]. These authors demonstrated that once data feeds from the various sensors, actuators and smart meters that instrument the smart building are made available, these devices can be classified by type using machine learning algorithms. The D&C layer relies on the data feeds exposed by the Fabric layer to be able to discover and connect to the different devices in the building.

The legacy Building Information Management (BIM) and Building Management Systems (BMS) are architecturally peers to the D&C layer. These legacy systems are not currently capable of automatic discovery and classification of the different sensors and actuators. The BIM/BMS systems must be manually configured to receive data from these endpoints. For the purposes of the B-SMART reference architecture the legacy BIM/BMS act as a higher-level data source, but do not actively participate in the autonomic control loop discussed in greater detail in the next section.

The next layer in the B-SMART architecture is the Integration layer. This layer takes as input the raw, but identified and classified data feeds from the D&C layer and transforms them so that they can be effectively used by the higher cognitive layers. Data transformation operations can include mapping and transformation of data to a canonical format, normalization, imputation, filtering, anonymization, and security and confidentiality-related operations.

The Integration layer includes and supports the Start-Up Commissioning process that is a part of broader SOCx process. Another way to look at this relationship is to consider that one of the key goals of the start-up commissioning process for a smart building must include achieving tight integration of all sensors and actuators, and legacy BIM/BMS, with layers implementing higher-level autonomic functionality. The start-up commissioning process bootstraps the main autonomic control loop of the smart building by populating the Building Knowledge Repository (BKR, Figure 3) with information that establishes the initial normal operating parameters of the smart building.

The next two layers of the architecture implement the main autonomic control loop for the smart building. The Change Detection and Optimization (CDO) layer supports three distinct processes: 1) Optimization; 2) Change detection; 3) On-going commissioning (high-frequency recommissioning).

The CDO layer uses data stored in the BKR in combination with the data feeds provided by the Integration layer to continually find the optimal operating parameters of the smart building. This layer is also responsible detecting changes in the operating characteristics of the smart building. Changes can be broadly classified into two types: 1) Faults; 2) Concept drift.

Faults are sudden changes in the operating characteristics of a building system or component that fall well outside it's normal or desired operating characteristics. The term concept drift refers to more gradual changes in the operating characteristics or a building component or system. This type of change is more difficult to detect, but it does frequently require a new search for optimal operating parameters to be performed. Both types of changes can trigger an autonomic recommissioning cycle as part of the SOCx process.

The top layer of the B-SMART, the Interaction and Adaptation layer, receives input from the CDO layer. It is responsible for planning actions that need to be taken in response to changes detected in the operating characteristics of the smart building. These actions can be fully autonomic, for example changing the set-points for HVAC equipment, or they could involve initiating workflows with humans in the loop to, for example, replace faulty equipment.

4.1. The B-SMART Autonomic Control Loop View

Below we discuss the Autonomic Control Loop of the B-SMART reference architecture.The autonomic cycle view of our reference architecture which describes the dynamic relationships between the smart building sub-systems is shown in Figure 3.

The BKR is the central component used by the CDO and the Interaction and Adaptation layers to implement the control loop. Knowledge stored in BKR could be in the form of raw data, or in the form of more informative information distilled from raw data. Our reference architecture also does not mandate any specific form factor for implement the BKR. The BKR can be implemented as an integrated on-premises appliance combining hardware and software, a cloud-computing-based solution, or a hybrid of these two approaches.

The BKR is populated during the start-up phase of the SOCx process, whenever a new smart building is commissioned, or an existing traditional building is converted into a smart building. Start-up commissioning involves leveraging the functionality provided by the D&C layer and the Integration layer to establish the data streams that will continuously update the BKR. The autonomic control loop starts once the start-up commission process successfully completes. Monitor functionality of the CD&O layer is used to analyze the incoming data. Change detection functionality of the same layer is used to identify situations that require an action to be performed by the autonomic smart building manager. It will Optimize the operating parameters of the building systems such as the chiller set point and/or the position of the automatic shading system if concept drift is detected. It will initiate an Interaction with either human operators or other autonomic systems if a fault is detected. Monitoring is subsequently resumed.

These interactions are an integral part of the on-going commissioning portion of the SOCx. Throughout the autonomic control cycle the BKR is continuously updated with either knowledge distilled from data, and/or the actual raw data collected during each stage of the cycle.

5. Conclusions

In this paper we presented B-SMART - the first autonomic reference architecture for smart buildings designed to support the SOCx process. The B-SMART reference architecture is designed to guide the development of new generation of autonomic BIM/BMS for smart buildings.

Our architecture provides a layered view that encourages decoupling of functionality and independent evolution for key technologies used to construct smart buildings alongside includes an autonomic control loop view that elaborates on how these technologies should interact with

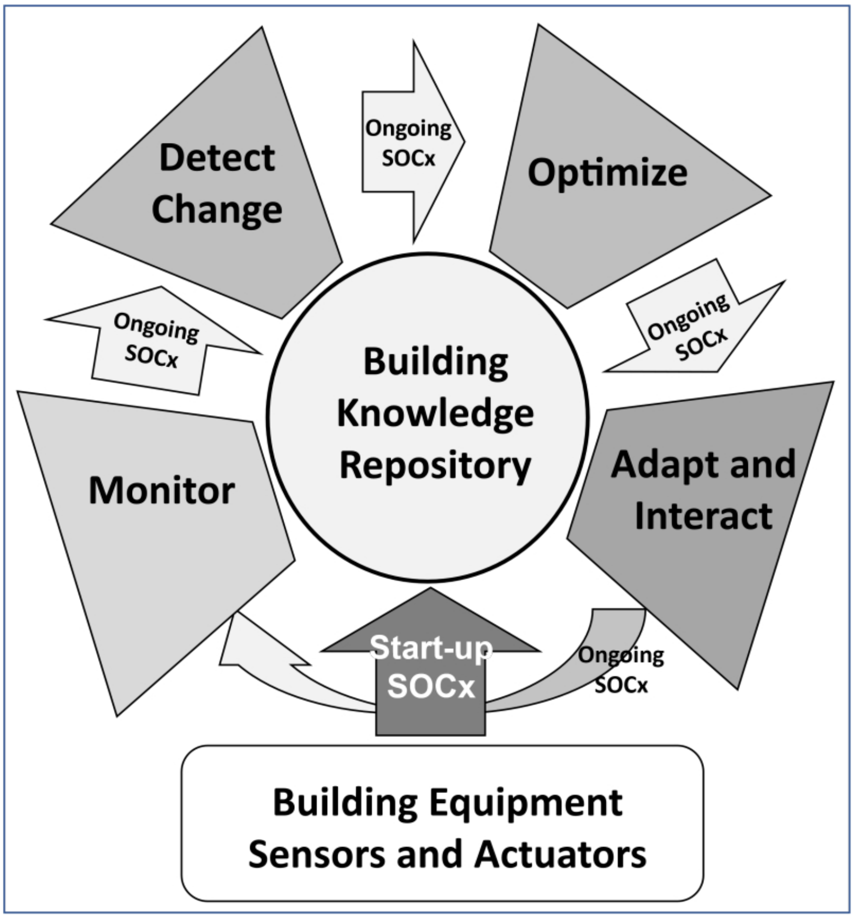

Figure 3. The B-SMART autonomic cycle.

each other. This contributes to the ongoing discourse within the AEC community regarding Smart Building performance optimization, providing a framework for the development of future SOCx systems to optimize and maintain building performance.

6. Acknowledgment

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