Chapter 4
Buildings' Energy Flexibility: A Bottom-Up, Multiagent, User-Based Approach to System Integration of Energy Infrastructures to Support the Smart Grid

Wim Zeiler, Timilehin Labeodan, Kennedy Aduda, and Gert Boxem

Abstract Using the flexibility within energy generation, distribution infrastructure, renewable energy sources, and the built environment is the ultimate sustainable strategy within the built environment. However, at the moment this flexibility on the building level has yet to be defined. The new IEA Annex 67 is just starting to define this specific flexibility. Our research is aimed at developing, implementing, and evaluating new process control strategies for improving the energy interaction within a building, its environment, and the energy infrastructure by effectively incorporating occupant needs for health (ventilation) and comfort heating/cooling. An integral approach based on general systems theory is used that divides the whole system into different layers from user up to centralized power generation. A bottom-up approach, starting from the user up to the smart grid, offers new possibilities for buildings' energy flexibility. To make use of the dynamic possibilities offered by the flexibility, new intelligent process control concepts are necessary. Multiagent systems, in combination with building energy management systems, can offer the required additional functionalities. The approach is tested in a case-study building.

Keywords Energy flexibility • User • Smart grid

1 Introduction

Energy infrastructures form the backbone of modern society since energy is needed for nearly all necessary services [1]. The built environment is currently a major consumer of fossil energy, at nearly 40 % [2], but it also has huge potential to contribute to the supply and management of renewable energy. The built

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environment is the most complex distributed technical system with its energy infrastructures for electricity, gas, heating, and cooling at the utility level, as well as all the ducts, pipes, and cables within buildings. As concerns grow about the environmental cost and limited supply of fossil energy resources, so too does the importance to society of carefully managing the availability of energy resources and developing and implementing renewable energy sources such as wind turbines, geothermal heat pumps, and photovoltaic systems. Traditionally top-down organized energy supplies in electricity and gas networks have had to cope with decentralized renewable energy production. Energy consumption is quite predictable on the macro level, and large power plants preschedule their power generation based on such predictions.

Coping with complex and unpredictable factors related to decentralized renewable energy sources (DRESs) and the grid requires a more flexible approach to process control that is increasingly bottom-up rather than top-down. As a result, the influence of a building's design and its users' interactions becomes more important. Buildings, building service systems, and energy infrastructure must be designed to be more flexible. It is widely recognized that increasing flexibility is key for the reliable operation of future power systems with very high penetration levels of DRESs [3]. Using the flexibility within energy generation, distribution infrastructure, renewable energy sources, and the built environment is the ultimate sustainable strategy. However, at the moment this flexibility at the building level has yet to be defined. The new IEA Annex 67 is just starting to define this specific flexibility. Clearly the energy demand characteristics of buildings, available from building energy management systems (BEMSs), constitute very valuable information for grid optimization. Smart control of energy consumption and generation inside (nanogrid) and around buildings (microgrid) can make major contributions to addressing imminent energy problems within the total energy infrastructure, the smart grid. However, a working definition of the IEA Annex 67 Energy Flexible Buildings is its ability to manage energy demand and generation according to local climatic conditions, occupant needs, and energy grid requirements [2]. There is a need to take a more holistic approach to system flexibility, which looks at the potential interactions between new and traditional sources of flexibility and how these sources are used by different parties [4]. New integral approaches are needed to increase buildings' flexibility in relation to the smart grid.

2   Methodology

To optimize the energy infrastructure in the built environment, an integral approach based on general systems theory developed by von Bertalanffy [5] is proposed [6, 7]. To cope with the complexity of the energy infrastructure of the built environment, this system-engineering-like method uses functional decomposition and different levels of abstraction (Fig. 4.1) as follows:
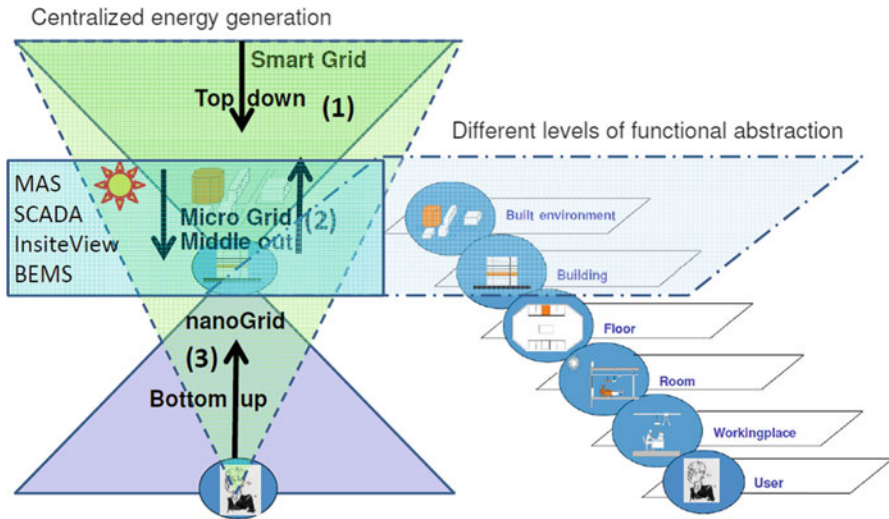
Fig. 4.1 Representation of building interaction with smart grid

– Built environment (possible energy supply from the smart grid, large renewable energy sources);
– Building level (possible energy supply from microgrid, nanogrid; Small renewable energy sources, storage, and other buildings);
– Floor level (distribution of occupancy and the necessary energy flows);
– Room level (energy needs depend on outside environmental conditions and internal heat load);
– Workplace level (workplace conditions and energy needs from appliances); and
– User level (different comfort needs of individuals).

Applying the principles of systems engineering to the optimization of the energy infrastructure of a building makes it possible to integrate in a flexible way the energy flows connected to heating, cooling, ventilation, lighting, and power demand within a building and between buildings and the built environment. This leads to a flexibility of energy exchange between different energy requirements and sustainable energy supply on the different levels of abstraction in the built environment. Traditionally, the energy approach to the built environment is top-down (centralized energy generation/distribution through the smart grid). We want to use instead a middle-out (control at the building level by the BEMSs) as well as a bottom-up approach (demand driven by human needs for energy/comfort) (Fig. 4.1).

An energy infrastructure's functionalities boil down to energy management, making use of the flexibilities of all grid-connected systems, which will lead to a more balanced and controlled network at all levels [8–11]. In general, two kinds of flexibility can be distinguished in energy infrastructures [1]:

– Architectural flexibility makes it possible to modify the configurations of a
  system based on future uncertainty;
– Operational flexibility allows energy modification of operating strategies with-
  out major changes.

The energy demand characteristics of buildings available in building automation
systems represent crucial information for grid optimization [12] to activate partic-
ipation of buildings in the grid. For an optimal smart grid from a system-of-systems
point of view, the BEMS must be coupled with the management platform of the
grid [9].

3   Multiagent System

The concept of intelligent agent technology is at an intriguing stage in its
development as commercial-strength agent applications are increasingly being
developed in domains as diverse as manufacturing and defense systems as well
as in the operation and management of the smart grid [13, 14]. In artificial
intelligence, agents are physical or virtual entities that intelligently interact in
an environment by both perceiving and affecting it. Consequently, an agent can
be described as a computational system with a high degree of autonomy
performing actions based on the information received from the environment.
Within a multiagent system (MAS), agents interact to achieve cooperative (e.g.,
distributed problem solving) or competitive (e.g., coalition formation, auction)
group behavior. Agents achieve this by sharing a minimum amount of informa-
tion between modules and asynchronous operation implemented via message
exchanges. The agent paradigm promotes the use of independent, loosely coupled
software entities that encapsulate some specific functionality and interaction with
each other to solve tasks [15].

The proposed framework is based on the MAS paradigm owing to its easier
manageability and distributed and robust properties. As depicted in Table 4.1,
distinct levels of hierarchy that include the user, room, zone, building, neigh-
borhood aggregators, low-voltage aggregators, medium-voltage aggregators,
distribution service operator (DSO), and transmission service operator (TSO)
are notable.

Because the primary goal is to ensure that occupants' comfort is not
compromised in the process of attaining the maximum possible peak-load reduction
for use in Demand Response (DR), information on building occupancy as depicted
in Fig. 4.3 is obtained using embedded chair sensors [16]. The availability and use
of fine-grained building occupancy information, in addition to contributing to
improving the energy performance of buildings through demand-driven control,
can also contribute to the improvement of building responsiveness to Demand
Response (DR).

Table 4.1 Hierarchy levels in distributed approach

Actor/hierarchy level	Role
User	Registers comprehensive user preference, associated comfort, and energy profile
Room	Aggregate comfort and energy profile inside room
Zone	Aggregate comfort and energy profile for all spaces associated with a zone
Building	Aggregate energy use and available power flexibility for whole building dynamically
Neighborhood aggregator	Dynamically aggregates available power flexibility for buildings in a neighborhood
Low-voltage aggregator	Dynamically aggregates available power flexibility for a number of neighborhoods at low voltage level of network
Medium-voltage aggregator	Dynamically aggregates available power flexibility of connections at medium-voltage level of network
DSO	Ensures network reliability and integrity of power distribution network
TSO	1. Operates and manages market
	2. Ensures network reliability and integrity of power transmission network

Leveraging on the distributed but cooperative properties of MASs, the agent architecture (Fig. 4.2) is composed of the following agents: user, room, zone, building, services, and admin agents.

User agent: The user agent represents each room occupant. It communicates with its environment via installed sensors to ensure that information on building occupancy and individual user preferences is readily available.

Room agent: The room level is critical for striking a balance between user comfort and energy efficiency because this is where both goals have contradictory requirements [17]. In addition, the orientation, occupancy use pattern, appliance, and equipment type, as well as room function, are contributory factors that determine the amount of flexibility available for participation in a DR event. The concept of utility function and the available service table (AST) are introduced at the room level. A utility function is a very useful decision-making mechanism that is often used in MASs, particularly in situations where there are conflicting goals (e.g., comfort and energy consumption). The utility function is used in describing the appropriate tradeoff [18]. The AST, on the other hand, is a concept derived from networking protocols [19] and information push strategy [20]. Table-driven routing protocols attempt to maintain consistent, up-to-date routing information from each node to every other node in a network. These protocols require that each node maintain one or more tables to store routing information, and they respond to changes in network topology by propagating updates throughout the network in order to maintain a consistent network view.
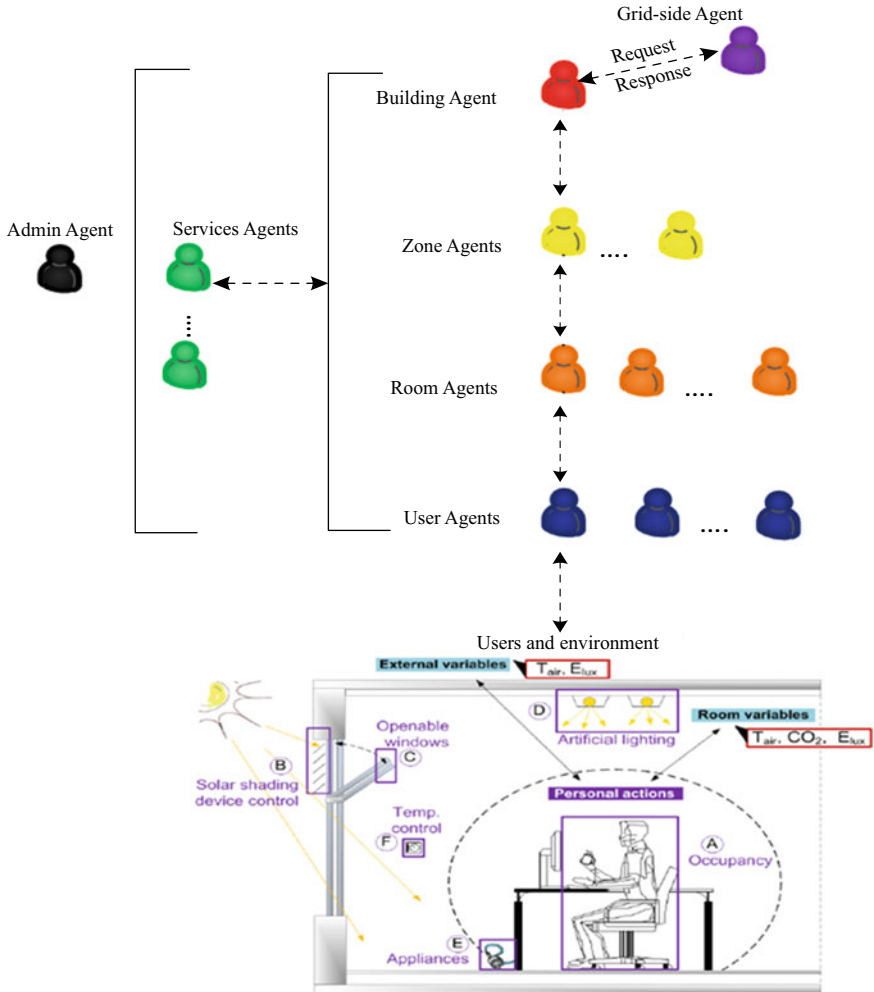
Fig. 4.2 MAS structure

Within this framework, information on available services that can be used in a DR event is pushed up from the room level and aggregated on the building level in the building's AST (Table 4.2).

The basic information pushed to the AST is the available energy in kilowatts (kW) and the duration of availability. The room agent, in addition to ensuring that the room is running optimally in terms of energy efficiency, also continuously updates the AST with the available electrical power in kilowatts (kW) that can be used during a DR event without causing disruptions to occupants' activities or deterioration in the comfort index of occupants. This approach, in addition to ensuring that buildings are constantly operating at optimal performance, also

Table 4.2 AST

	S[8–9] kW	S[9–10] kW	S[10–11] kW	S[11–12] kW	S [12–13] kW	S[13–14] kW	S[14–15] kW	S[15–16] kW	S[16–17] kW
Zone agent	0–24				0–24			0–24	
Building agent			14		14		14		
Available service	0–24	0	14	0	14–24	0	14	0–24	0

ensures that building occupants will not have to experience disruptions or tolerate discomfort for an extended period of time.

Zone agent: In the design of buildings, spaces with identical or similar comfort requirements, such as solar shading, heating, cooling, and ventilation requirements, are often grouped together. The zone agent is hence an aggregator, as identified earlier in Table 4.1. It computes the sum of services available for its zone using the information provided by the room agents in the zone.

Building agent: The building agent is the contact point between the grid and the building. The building agent receives a DR request from the grid and responds appropriately to the request. In most typical MAS coordinated DR events [21], the building agent is often responsible for making decisions on both comfort and a building's participation in a DR event. However, within this framework, the building agent is mainly tasked with negotiating a building's participation using available information in the AST as depicted in Fig. 7.

Services agent: The services agent introduces more task distribution in the agent structure. Because it is in daily human interactions where specialized tasks are often assigned to specialists, the services agent offers specialized services to the agents within the system. Within this framework, the services agent performs a data-mining function that could be utilized by any of the agents in the system.

Admin agent: The MAS design paradigm provides a flexible framework in which agents can be included and removed at any time without causing disruption in the system's operation. It is, however, necessary to have up-to-date information about the state of agents operating in the system. The task of the admin agent is thus to monitor all agents (active, passive, dead, or alive) operating in the system.

4 Multiagent Platform

An agent platform is an execution environment for agents. It supplies the agents with various functionalities, such as agent intercommunication, autonomy, and mobility [22]. In selecting a suitable agent design platform, it is essential that the chosen design platform be easily accessible, supported, compatible with standards, and interoperable with other technologies. The agents are designed using an open-source Web-based agent design platform called EVE [23]. The EVE agent design platform is a fully decentralized and Web-based agent design platform that promotes distributed problem solving. It is also a very scalable and robust agent design platform.

5   Resulting Concept

There is a different focus on the processes that occur in a building, which also depends on the leading strategy: bottom-up (user oriented), middle-out (building services systems oriented), and top-down (smart grid). A top-down approach gives mainly the boundaries for energy consumption related to occupancy behavior [24]. A bottom-up approach is able to estimate the individual energy consumption and then aggregate it to predict the total building energy demand, based on end-user behaviors in time and space. Based on each of these approaches, the results and insights are used to specify specific functionalities for the level below and the level above. In this way, flexibility enables developers to gain from upside opportunities and minimize downside risks [1, 25]. Taking our cue from the required dynamism and flexible operations, we adapt the framework of Kofler et al. [15] as ideal for realization of the pervasive control envisioned by Kolokotsa et al. [26], with a central role for BEMS and MAS (Fig. 4.3).

6   Case Study

This chapter uses an office building in the Netherlands to illustrate typical building-centered electrical flexibility. The case-study building has three floors with an approximate total floor area of 1500 m^2 and average occupancy count of 35 when busy. Electrical installation in the case-study building is as illustrated in Fig. 4.4; the key electrical system load groups in the building are cooling, humidifier, ventilation, lighting, and office appliances. The installed cooling system in the building has a maximum power consumption rating of 25 kW; the ventilation system is consumption rated at 9.5 kW, with 6 kW of the demand dedicated to the fan system. Cooling is effected by cold-air circulation dedicated to serving the three main cooling zones. Total ventilation fan capacity is 15,000 m^3/h.

During periods when the air is cold and dry (normally during winter and specifically when the ambient temperature is less than 15 °C and the ambient relative humidity is less than 30 %), the humidifier is activated. At a 30 kW power consumption rating the humidifier is the single biggest load in the building. The lighting system in the building accounts for 16 kW demand. Lighting is provided by florescent tubes (T5 type). The scope of this chapter is the summertime operation of building processes; in what follows, flexibility will only be discussed with respect to the cooling and ventilation processes.

Building service control in the case-study building is effected by a Web-based building management system that is operated based on optimal rules on set-point manipulation. Based on temperature and relative humidity readings from installed sensors, feedback is given for switching on or off or upwards or downwards adjustments of settings for optimal operation of the building. Cooling can be achieved in two ways: night ventilation or chiller use. The night ventilation setting
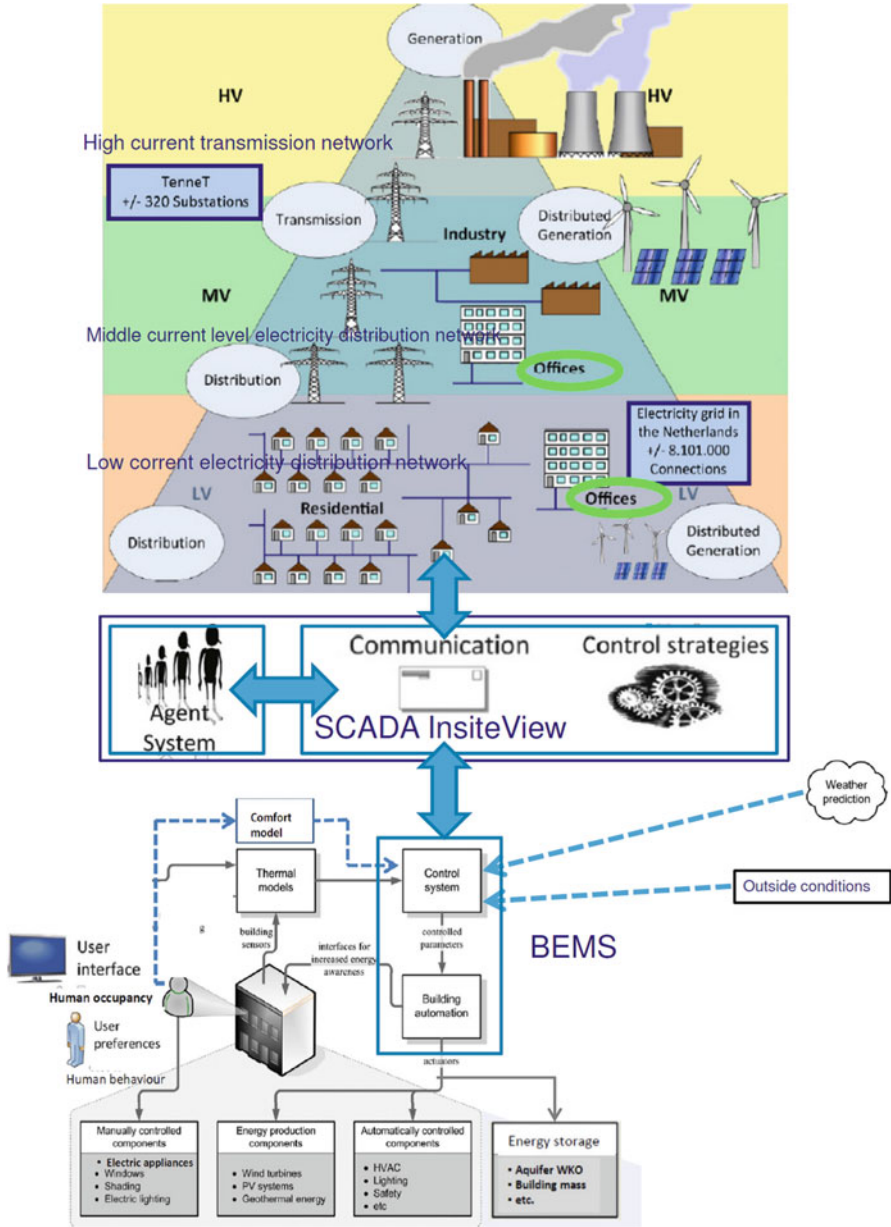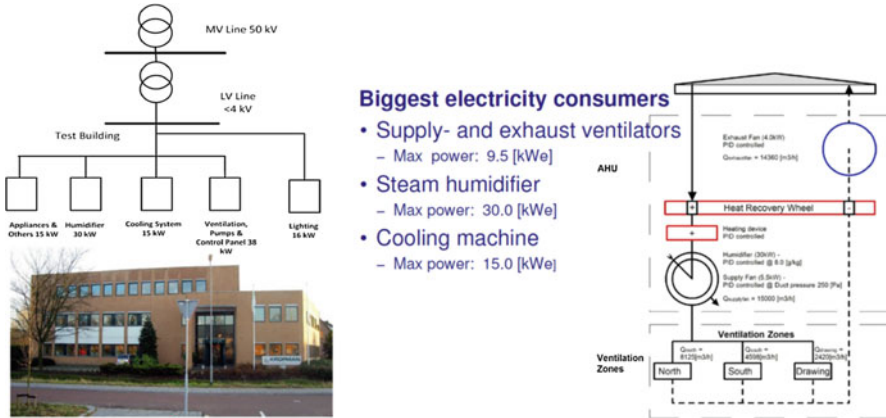
Fig. 4.3 Smart grid and user interaction, based on Kolokotsa et al. [26] and Kofler et al. [15]

cools the building with outside air (free cooling) during the night or early morning (between 10:00 p.m. and 5:00 a.m.) whenever the average room temperature exceeds

Fig. 4.4 Electrical connections from mid-voltage grid to building and its major electricity consumers

23 °C and outside/ambient temperature is below 12 °C. Night ventilation is stopped when the room temperature has dropped to 21 °C or when the end time is reached. The chiller system is switched on whenever the following preconditions are satisfied:

1. For stage 1 operations, the outside/ambient temperature should have been above 18 °C for over 1 h and the circulation pump for the chiller is also at an operational position. For stage 2 operation, the outdoor temperature should be above 26 °C for 30 min.
2. In stage 2, the chiller is switched off again when the outside temperature continues for 30 min under 24 °C. The chiller is switched off again when the outside temperature is below 16 °C for an hour or if there is no more cooling demand from the coolers.

If no differential pressure is present on the chiller, the chiller is switched off and a fault message is generated. Also, the ventilation system remains on whenever night ventilation is required and when the building is occupied. The building is occupied during weekdays between 7:00 a.m. and 5:00 p.m.

7   The Concept

In the case study, energy-related performance and comfort profiles were captured at 100 % nominal operational capacity for the cooling and ventilation systems. Thereafter, cooling and ventilation systems were operated outside the nominal range or at varied sequences with the aim of harvesting demand-side flexibility. For the ventilation system, performance was monitored at 100, 80, 70, and 60 % nominal settings; for the cooling system, performance was monitored for operations under
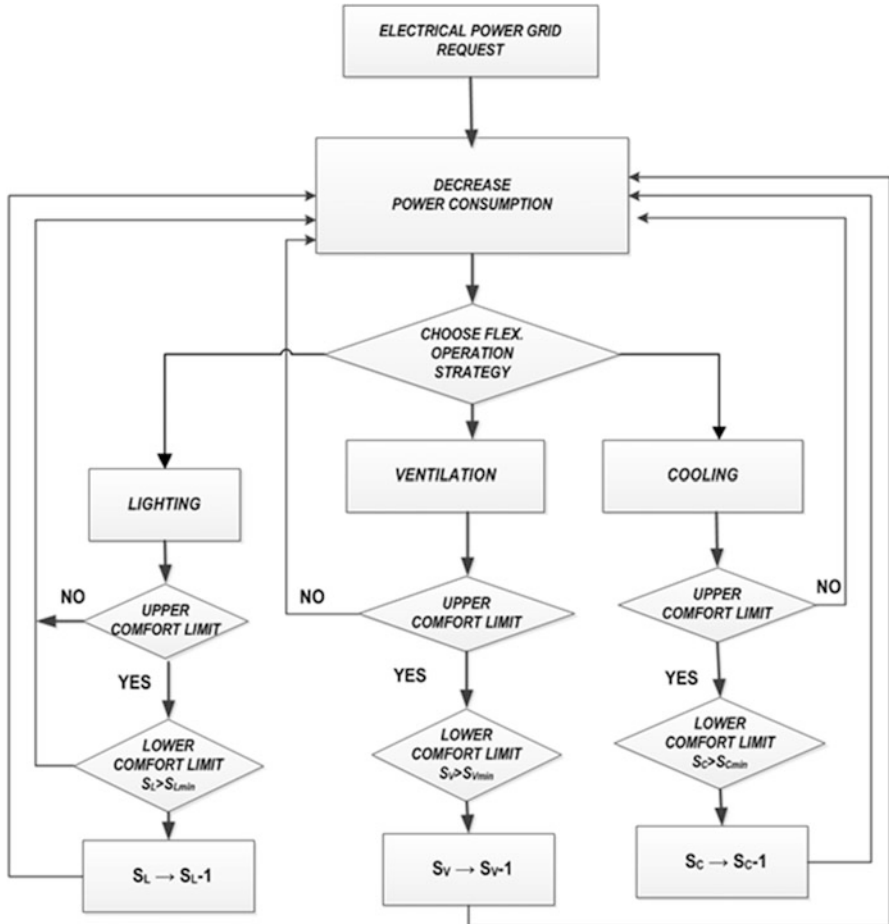
Fig. 4.5 Deployment of building service processes as ramp-up of flexibility resources for power grid support activities

normal settings and operations with zonal cooling set-point temperature reset of 2 °C higher than normal. The conceptual basis of the case study entails the intelligent manipulation of visual, ventilation, and thermal comfort bandwidths (Table 4.2) to yield building-centered electrical power flexibility. Figure 4.5 outlines the operational sequence in realizing this concept. During the whole period of experiments, the monitored parameters included (1) load category power consumption; (2) space comfort parameters, including duct airflow rate, room temperature, radiant temperature, carbon dioxide concentration, relative humidity, and occupant feedback on satisfaction with the thermal comfort and indoor air quality; and (3) ambient weather data, specifically relative humidity, solar irradiation, and air temperature.

8 Discussion and Conclusion

The problems of the smart grid are partly caused by the use of DRESs. Breakthroughs need to be made in the field of process control of heat, cold and electricity storage, demand, and distribution.

New process control strategies are needed for improving energy interactions within buildings, their environment, and the energy infrastructure by effectively incorporating occupant behavior. Energy system integration is a key issue; however, most research is aimed at the high system level of existing energy infrastructures, whereas in a building the different energy systems are already integrated to supply the necessary comfort of the occupants. Starting from this bottom-up insight, an integral approach was used to divide the whole system into different layers from the user up to centralized power generation. On different scale levels, from individuals to the building level, possibilities are being investigated both within laboratory conditions as well as in a real office building as case studies. Specific control strategies were applied on the existing HVAC systems. The initial results showed that in the process of developing the optimal interaction between the smart grid and the nanogrid of a building, more than just a contribution to optimizing smart grid control is possible. The next step is to define neighborhood energy management systems and to look for the possibilities of a virtual coupling with the SCADA systems of the grid operators. Grouping the energy demand of end users and local renewable producers in neighborhoods will enforce end-user involvement and automated load shifting, which greatly improves the efficiency of advanced energy management. This allows for maximizing the utilization of flexible demand resources within neighborhoods and forms a bottom-up approach to system integration of energy infrastructures, starting from the user, to support the smart grid.

The responsiveness of the smart grid to changing uncertainties and requirements can be realized through the intrinsic flexibility measures embedded in the energy infrastructures of buildings. A systems engineering approach presents an opportunity to systematically integrate architectural and operational flexibility early on in the conceptual design phase of energy infrastructures of the built environment. This hierarchical framework aims at providing support for integrating the flexibility of the infrastructure systems to build MAS structures based on it. The manner of description of a system influences the identification of the possible changes that may take place and the interpretation of their demands for flexibility. In this paper the focus was on operational flexibility for which the integration of the end user through a bottom-up approach is essential for supporting the smart grid.

References

1. Melese YG, Heijnen PW, Stikkelman RM (2014) Designing networked energy infrastructure with architectural flexibility. Procedia Comput Sci 28:179–186
2. IEA (2015) International energy agency, energy in buildings and communities programme. EBC annual report 2014

3. Papaefthymiou G, Grave K, Dragoon K (2014) Flexibility options in electricity systems. Project number: POWDE14426, Ecofys 2014 by order of European Copper Institute
4. Frerk M (2015) Open letter: facilitating efficient use of flexibility sources in the GB electricity system. OFGEM, The Office of Gas and Electricity Markets, 28 Jan 2015
5. Blanchard BS, Fabrycky WJ (2005) Systems engineering and analysis, 4th edn. Prentice Hall, Upper Saddle River
6. Savanović P (2009) Integral design method in the context of sustainable building design. PhD thesis, Technische Universiteit Eindhoven
7. Zeiler W, Savanović P (2009) General systems theory based integral design method. Proceedings ICED'09, Stanford, USA
8. Lo C, Ansari N (2011) The progressive smart grid system from both power and communications aspects. IEEE Commun Surv Tutor 14(99):1–23
9. Dave S, Sooriyabandara M, Yearworth M (2011) A systems approach to the smart grid. In: The first international conference on smart grids, Green Communications and IT Energy-aware Technologies
10. Lopes AJ, Lezama R, Pineda R (2011) Model based systems engineering for smart grids as systems of systems. Procedia Comput Sci 6:441–450
11. Acevedo S, Molinas M (2012) Identifying unstable region of operation in a micro-grid system. Energy Procedia 20:237–246
12. Wang S (2013) Intelligent building electricity demand management and interactions with smart grid. In: Proceedings Clima, Prague, 2013
13. Jarvis D, Jarvis J, Rönnquist R, Jain L (2013) Multiagent systems and applications. Intell Syst Ref Libr 46:1–12
14. Basso G, Gaud N, Gechter F, Hilaire V, Lauri F (2013) A framework for qualifying and evaluating smart grids approaches: focus on multi-agent technologies. Smart Grid Renew Energy 4(4):333–347
15. Kofler MJ, Reinisch C, Kastner W (2012) A semantic representation of energy-related information in future smart homes. Energy Build 47:169–179
16. Timilehin L, Zeiler W, Boxem G, Yang Z (2015) Occupancy measurement in commercial office buildings for demand-driven control applications—a survey and detection system evaluation. Energy Build 93:303–314
17. Clarke JA, Janak M, Ruyssevelt P (1998) Assessing the overall performance of advanced glazing systems. Sol Energy 63(4):231–241
18. Dounis AI (2010) Artificial intelligence for energy conservation in buildings. Adv Build Energy Res 4(1):267–299
19. Royer EM, Toh C-K (1999) A review of current routing protocols for ad hoc mobile wireless networks. IEEE Pers Commun 6(2):46–55
20. Kim JJ (2014) Automated demand response technologies and demonstration in New York city using OpenADR, Sep 2014
21. Hurtado LA, Nguyen PH, Kling WL (2015) Smart grid and smart building inter-operation using agent-based particle swarm optimization. Sustain Energy Grids Netw 2:32–40
22. Leszczyna R (2008) Evaluation of agent platforms
23. de Jong J, Stellingwerff L, Pazienza GE (2013) Eve: a novel open-source web-based agent platform. In: Proceedings of the 2013 I.E. international conference on systems, man, and cybernetics, 2013
24. Bloem JJ, Strachan P (2012) Evaluating and modelling near-zero energy buildings; are we ready for 2018? Expert meeting 30-31 January 2012 Glasgow, JRC Technical report
25. de Neufville R, Scholtes S (2011) Flexibility in engineering design. MIT Press, Cambridge
26. Kolokotsa D, Rovas D, Kosmatopoulos E, Kalaitzakis K (2011) A roadmap towards intelligent net zero- and positive-energy buildings. Sol Energy 85:3067–3084