Building and Environment 149 (2019) 446–457

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Responsive building envelope concepts in zero emission neighborhoods and smart cities - A roadmap to implementation

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ARTICLE INFO

Keywords:
Building envelopes
Smart cities
Responsive
Façade
Zero emission neighborhoods

ABSTRACT

Designing a zero emission neighborhood (ZEN) from an energy point of view, has the benefit of distributing loads over time by creating a mosaic of buildings which individually may not have a zero emission balance, but reach it as an ensemble. Responsive building envelopes (RBEs) are expected to play an important role in the design of ZENs and future smart sustainable cities. RBEs are useful to optimize the balance between several energy flows at single- and multi building scale, as well as to actively manage both on-site renewable- and purchased energy in addition to improving user experience and indoor comfort by providing an interactive interface with the outdoors. This article provides a review of the potential and the requirements associated with using RBEs to manage complex interactions between buildings, clusters of buildings and utility grids. A six-step pathway for the implementation of RBEs in ZEN-like projects are proposed. The six steps are related to identifying; purpose of response, scale and interdependency, functionality, trigger and control, interactions and finally to identifying technical solutions. The proposed process emphasizes the importance of defining specific information such as the responsive goal hierarchies, the scale of the responses in relation to their purpose, and the importance of the aesthetic expression to foster positive user experience.

1. Introduction: from zero emission buildings to neighborhoods and the role of building envelopes

Zero energy and zero emission building design revolve around two main strategies [1–3] that are to reduce energy use and to harvest renewable energy to compensate for the energy used [4,5]. Reducing energy use is achieved through installing highly efficient energy recovery systems [6] and increasing the performance of building envelopes by using passive design solutions such as building shape optimization [7], improving envelope insulation and airtightness, and using highly insulating windows [8,9]. However, as pointed out by Loonen et al. [10], this static building design approach can be flawed despite allowing to meet sustainability goals. This is because it is most often based on structuring building envelopes as a sequence of independent solutions, which creates the risk of the final design becoming a sub-optimized assembly of competing solutions [11] with limited grid friendliness in terms of load matching of renewable energy flows [12,13]. Furthermore, this approach also largely favors energy savings over user satisfaction and comfort [14] which is against recommendations in research [15]. Instead, zero energy building design should consider alternative solutions that offer higher system flexibility [10,16,17], or that are optimized to reduce the effect of competing parameters [18–20], and which could provide better overall building performance and potentially surpass the traditionally defined limits of cost-optimal façade design [9].

“Responsive building design” and design using “responsive building envelopes” (RBEs) (also known as smart, climate-adaptive, or intelligent) is one of these flexible alternative approaches, and has been a popular topic in literature for decades [21,22]. In the field of building envelope design, RBEs are often found under the names responsive, dynamic, adaptive, kinetic, advanced, or multifunctional building elements. Despite the minor semantic differences introduced, most RBE technologies can be described as an extension of the definition for “climate adaptive building shells” (CABS) given in Ref. [10]. The core concept is the result of architects and engineers being inspired to design buildings that could express similar responses to the ones found in plants, or that could imitate human physiological responses like sweating or shivering [10,23–27]. In order to replicate such functionalities in buildings, RBEs rely on integrated technologies that are designed to enable the building to respond to a range of triggers (stimuli),

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https://doi.org/10.1016/j.buildenv.2018.12.045
Received 11 September 2018; Received in revised form 19 December 2018; Accepted 20 December 2018

using a combination of passive, active, and/or cognitive control strategies. This design approach is particularly interesting given that building envelopes have a significant impact on the performance of buildings [28]. By incorporating more advanced control strategies and renewable energy harvesting systems (RES), it is possible to improve the overall performance of the building in terms of energy management (purchased and renewably harvested), occupant comfort, and operational costs. Such concepts becomes even more powerful when applied to a cluster of buildings as distributing energy flows currently are more advantageous at aggregated levels [29]. In fact, implementing a range of RBEs in a cluster of different typologies of buildings allows diversifying the functionalities and types of systems or controls used. This can be combined to efficiently harvest larger amounts of renewable energy, but also increase possibilities for storing and distributing energy within networks of different sizes, and on different time scales. A cluster of buildings equipped with RBEs can be designed to resemble a mosaic of buildings, which individually may not have a zero emission balance, but reach it as a group [30]. Hence, introducing clusters of responsive buildings could be used as a mean of reducing carbon emissions in urban forms, and can be integrated into sustainability strategies for zero emission neighborhoods (ZEN) and smart sustainable cities [31]. However, there is still very little material or guidance available in literature regarding the challenges associated with scaling up the use of RBE technologies from the design of a single building to designing an entire neighborhood, and how synergies between networks of RBEs could help in achieving zero emission neighborhood or smart sustainable cities goals.

The aim of this article is to begin bridging this gap by investigating how the existing work on responsive building envelopes and systems can be extended to designing a network of responsive buildings and to explore the potential role of RBEs in the design of smart sustainable cities and zero emission neighborhoods. This task requires defining the specificities of RBE technologies and characterizing their potential scales of application in clusters of buildings along with identifying the opportunities and challenges that come with the change of scale. The outcomes of this work are presented as a roadmap for architects and engineers to help them define strategies for implementing RBEs in large-scale projects and aim to provide an understanding of the complexity of the challenges associated with RBE networks.

The remainder of this paper is organized as follows: section 2 presents the state of the art of the topics which are essential to include when evaluating the opportunities and challenges associated with implementing RBEs in neighborhoods. Section 3 details the existing classifications for RBEs at single building scale, and outlines the elements which have yet to be addressed in the context of a neighborhood project. In section 4, the resulting proposal for a pathway to implementing RBEs at neighborhood scale is presented in the form of a roadmap, with a description of the different additional elements that need to be accounted for as result of the change of scale. The issues this roadmap does not cover are presented and discussed in section 5, and the conclusion are drawn in section 6.

2. State of the art: responsive building envelopes in neighborhoods and smart cities

Smart sustainable cities are described by the authors of [32] as the interlinking of sustainability awareness, urban growth and technological developments in urban planning. Hence, urban forms such as smart sustainable cities and zero emission neighborhoods, inherently require a strong presence of ICT and IoT (Internet of Things) integrated in the urban domain to manage the complex set of relations between clusters of buildings and services [33]. Currently, there are still many gaps in the research field of smart sustainable cities, particularly regarding how to connect smart city concepts and real urban development. There are also need for approaches for integrating smart ICT technologies in design concepts of sustainable urban forms [33]. As argued by Ref. [34], it is also crucial that design frameworks for sustainability in cities have interdisciplinary and transdisciplinary approaches to be successful. This finding also applies to the subfield of energy and carbon emission management in smart cities, where the models used are limited to certain aspects [35], and should be combined with research on micro-grids and demand-response strategies so as to be able to include district energy networks. With this in mind, the following section highlights the different disciplines and aspects that a framework for implementing RBEs in zero emission neighborhoods must include.

2.1. Carbon emissions

RBEs have a large potential for reducing carbon emissions as they allow acting on both energy harvesting and energy management. In this paper, a neighborhood is "*a group of interconnected buildings with associated infrastructure, located within a confined geographical area. A zero emission neighborhood aims to reduce its direct and indirect greenhouse gas emissions towards zero over the analysis period. The area has a defined physical boundary to external grids (electricity and heat, and if included, water, sewage, waste, mobility and ICT). However, the system boundary for analysis of energy facilities serving the neighborhood is not necessarily the same as the geographical area*" [31]. In ZENs and in most buildings, facades take on many roles. From an energy point of view, facades are designed to minimize total life cycle costs, have high energy efficiency and can integrate technologies allowing to power the neighborhood with a high share of renewable energy, as well as manage energy flows in single buildings and in conjunction with the surrounding energy systems. These roles must be fulfilled without sacrificing occupant comfort, the aspects of which are discussed in section 2.3.

At single building scale, responsive building envelopes can improve energy management by reducing overall energy use and harvest renewable energy by converting it to electricity or by storing it as thermal energy in the building mass. For example, RBEs using glazed components with controllable optical and physical properties have shown to provide significant energy demand reductions compared to traditional facades [36–38]. The same effects can be expected when connecting buildings together in a cluster, with the additional benefit of reducing risks of system redundancy in installed renewable energy conversion systems or HVAC compared to having many independent buildings. The diversity of building typologies in a neighborhood provides the opportunity to consider a broader range of RBE systems, and these can be designed in a way that their functionalities are beneficial to the building they are installed on, and other buildings in the neighborhood [39]. Bigger RBE installations also contribute to harvesting and storing larger amounts of electrical and thermal energy, which can be used to modify load shapes of buildings (the daily and seasonal electricity demand by time-of-day, day-of-week, and season). This can be done either directly [40–43] or indirectly by taking advantage of the coupling between the building envelope and its effect on the technical systems used for space conditioning, as well as contribute to increasing energy flexibility potential. Scaling the use of this strategy up to a cluster of buildings, introduces the capacity to change the total load shape of the neighborhood and implement different strategies for demand side management (DSM) [44]. DSM is a central element for reducing operational costs or carbon intensity of purchased energy, and allows timing grid interactions so that electricity is purchased at strategic moments and in accordance with climatic parameters, as well as the current and forecasted needs of the neighborhood [45,46].

2.2. Architecture

Zero emission buildings have a variety of architectural expressions and concepts [47]. The aesthetic expression of responsive elements is critical to explore as a technical solution given that what is perceived as attractive will also be easier to choose for architects, building -owners and –investors [48]. Responsive building design can present interesting new architectural features in building due to the introduced dynamic aspects. A building envelope can then be thought as having multiple configurations, depending on the time of the day, the season and the use, which may result in a certain architectural quality [49]. This aspect should be incorporate to strengthen the most common design strategies for zero emission buildings [50,51]. These strategies include the use of a climate adapted building form (in cold climates this often results in a compact building to reduce heat loss) in combination with informed design and placement of glazing elements (with or without solar shading systems) for optimal solar energy management, the reduction embodied emissions with strategic material choices, the implementation integrated HVAC system, and the integration of solar energy harvesting systems. The last element will highly influence the design of the building since the performance of solar based RES systems is very much dependent on their orientation [47]. However, when changing the scale of design from single building to multi-building, and because of the realities of city planning and the complexity of existing urban context such as street orientations or shading from adjacent buildings, design guidelines must be versatile. This is especially true when creating new smart sustainable urban environments with increased interactions between buildings and the people living in the neighborhood.

2.3. *User comfort and acceptance*

Responsive systems can also be used to improve and personalize thermal comfort [52,53]. Research indicates that offering occupants control over their indoor climate leads to fewer health issues, higher comfort, and improved mental productivity [54,55]. Furthermore, new European directives and standards recognize the importance of maintaining occupant's comfort when improving energy and environmental performance of buildings, a trend that is likely to stay. However, while it is recognized that buildings should be designed to meet their users' needs, their performance will to a large degree be dependent on the occupant's behavior and attitude. This is demonstrated by e.g. Refs. [56–62] which all highlighted differences between actual and predicted performance in a vast number of buildings. It appears that the occupant's attitude to energy use is often ambivalent, and even though many regard energy saving as positive, they are not willing to sacrifice personal comfort [61]. Research also indicates that users are often insufficiently informed about the technologies they interact with, or know little about how their own behavior affects the resulting energy use in the building [14,63]. In general, occupants are pleased with living or working in energy-efficient buildings, but feel frustrated when they cannot interact in a simple way to regulate temperature, ventilation systems [64–66] or automatic shading systems [67,68]. A combination of user control and intelligent controls with robust and intuitive design seems to be a promising solution to solving these issues [69]. User-acceptance strategies must be paired with automation strategies (e.g. using “smart controllers and software) to avoid competing control strategies. User parameters and behaviors should be carefully considered when changing the scale of design from single building scale to multi-building scale as the role of users in smart cities is often misunderstood or overly simplified [70].

2.4. *Characterization of performance*

According to the International Energy Agency (IEA ECBCS) in Annex 44 *Integrating Environmentally Responsive Elements in Buildings* [71], responsive buildings show great promise as a concept. However, successful implementation in occupied buildings is often being made difficult [72] by the lack of information available about the technologies, their integration process and their expected performance. There is also little understanding of the new challenges RBEs introduce since the physical parameters needed to describe them are inherently more complex than those of most non-responsive types. Characterization of building envelope components have traditionally been based on static parameters such as annual single value thermal transmittance values (U-values) and solar heat gain coefficients (g-values). However these are not typically used for characterizing advanced facades due to the dynamic nature of RBEs [52,73,74] and their multi-domain impacts [75]. Instead, more holistic approaches are preferred including net energy use, and user thermal or visual comfort [41,76].

The gap between in-design performance and real-life performance in buildings with more traditional technologies can be substantial [61] and these discrepancies are likely to grow larger when increasingly complex technologies are introduced. As a result, several research efforts following the one of the IEA have proposed methods for classifying responsive building elements and improve the understanding of these technologies at single-building scale. These classifications are reviewed in the following section.

3. Existing classification systems for adaptive and responsive building envelopes

3.1. *Single technology classification schemes*

Many suggestions of frameworks to classify dynamic, adaptive or responsive building elements have been proposed [77]. Three of the most recent proposals for a unified characterization of stand-alone responsive building envelope technologies were reviewed and used to define some of the key parameters for the proposed final framework. These proposals are described in the following paragraphs.

The first classification system this framework builds upon, is the work that was carried out in IEA ECBCS Annex 44 [22,71,78,79]. The Annex 44 was a considerable effort to map environmentally responsive technologies and resulted in a classification system with a given technology as a starting point. The proposed characterization scheme is flexible in that it can be applied to any given technology like a mask to map out its *responsiveness*. Despite this strength, the scope of this work was limited to RBEs in the context of climate triggers only. The work did not cover technologies with user-defined controls, schedule controls, advanced ICT controls or AI (artificial intelligence) controls; all of which are required to characterize newer technologies and neighborhood scale implementations, and hence the framework as such cannot be used as is in the scope of this paper.

The second classification reviewed is proposed by Loonen et al. [77] as part of the work carried out in EU COST Action TU1403. This work review existing taxonomies for adaptive facades, and results in a new framework where the purpose of the adaptive façade is the starting point. The characterization matrix proposed does not separate the type of stimuli (indoor and outdoor climate variables, user's experience etc.), but distinguishes two fundamental types of control “extrinsic” and “intrinsic” (see section 4.4 for definitions). Although this classification is one of the most comprehensive, it is not perfectly suited to the context of planning ZENs. Firstly, the solutions are not scalable to neighborhoods meaning the potential for load management (electrical and thermal energy) at multi-building level is not explicitly discussed. Secondly, the existing classification is designed to characterize a given responsive technology solution as a standalone. In order to implement RBEs at a neighborhood scale, the purpose of the technology has to be put in relation to the needs of the whole network. This aspect is deemed critical by the ZEN research center which insists that neighborhood interaction should facilitate the transition to a decarbonized energy system and reduction of power and heat capacity requirements [27]. Further discussions on neighborhood interactions are provided in section 3.3.

In the third classification, Basarir et al. [80] describe a framework for adaptive facades based on the previously mentioned definition of climate adaptive building shells (CABS) [10]. The authors point out that the criteria used in RBE classifications are ambiguous and make it difficult to use for comparison. This classification uses the “element of adaptation" (façade, component, element, material) and the "agent of adaptation" e.g. the stimulus, as the two starting elements to define the mechanisms of the adaptation. A strength of this work is that the architectural features of RBEs are described in much more detail than in the two previous classifications and it includes the level of architectural visibility, the effect of the adaptation and performance with regard to human experience. The limitation of this classification, seen in a neighborhood context, is that it is most suited for RBEs that rely on moveable parts as it provides much higher levels of detail for systems that require physical movement. This means that e.g., an electrochromic window does not have a full explicit and thus, the classification leaves out technologies that should be considered in ZENs or smart sustainable city projects.

3.2. *Holistic building perspective of responsive systems*

Looman [81] describes a comprehensive framework with a holistic approach to climate responsive design. In his work, he proposes seven basic response functions relevant for the building level: conserve, recover, prevent, promote, distribute, store and buffer. This approach allows a clear definition of concepts for architecture and the purpose of different climate responsive features. The resulting characterization addresses the role of different technologies in climate responsive design. However, for the task of using RBEs to design neighborhoods, there is a need for a clearer link between the suggested functionalities of the system and their purpose, as well as more clarification about the different control strategies and timeframes. Finally, the characterization proposed only addresses the role of different technologies in climate responsive design and architecture. It leaves out most user related aspects as well as advanced control strategies and neighborhood related requirements.

3.3. *The knowledge gap in a neighborhood perspective*

The existing classification systems have many strengths but they mostly adopt different areas of focus and/or approaches, which fall short of fulfilling the interdisciplinary approach required in a neighborhood perspective described in section 2. The work presented in the next section builds upon the reviewed existing classification but attempts to fill in the gaps identified by introducing the missing elements required to characterize RBE clusters. The result is an extended classification which should be seen as a roadmap to implementing RBEs in the design of ZENs and smart sustainable cities. This roadmap can be useful in both early- and later planning stages, and provides sufficient flexibility to be applicable to existing and future envelope technologies.

4. Results – defining a roadmap for implementing responsive building envelopes in zero emission neighborhoods

4.1. *A strategy for responsive building envelope implementation at neighborhood scale*

Defining a strategy for integrating different responsive building technologies in building envelopes is a key process in planning the energy concept of zero emission neighborhoods. As there are many technologies and solutions to choose from, a systematic breakdown of the properties and requirements of the responsive technologies is necessary to have a portfolio of solutions that can pave the way towards a zero emission goal for the neighborhood. The approach developed in this work is based on the work presented in Ref. [77], but incorporates energy load management and renewable energy harvesting within the cluster of buildings, as well as the interactions with a larger grid system (see Fig. 1).

In order to do this, a strategy to define performance goals is proposed in a six-step procedure as shown in Fig. 2. The initial five steps build the foundation for decision-makers to be able to assess possible design strategies and solutions that are relevant for the particular project. Step 5 includes the identification of interactions between the building users and the responsive system, and presents the definition of the criteria and building design requirements. Step six consists of the identification of technological solutions and verification that the system performance is in line with the defined purpose.

4.2. *Defining the purpose and objective of the response*

Given the large variety of responsive technologies and RBE systems, the first step is to define the purpose of the response as part of the building design strategy in the neighborhood. RBE functionalities as an element in the design of a ZEN, and the different response scales (single building, cluster of buildings and neighborhood) of the technologies are nested into each other (Fig. 2) (the scales of responses are described in section 4.3).

The main categories of purpose for RBEs are defined as energy performance, user needs, and demand side management as shown in Fig. 4. It is important to note that these purposes are not mutually exclusive as a single system could (and should) have more than one purpose. These purposes can sometimes also present competing parameters because of the nature of the RBE, in which case it advised to develop more advanced design strategies to balancing competing aspects [82]. In this framework, each purpose is described by a set of specific objectives, with target actions and associated functionalities to achieve the given purpose (see section 4.4 for more detail).

4.3. *Identifying the scale and interdependencies of the response*

Planning ZENs around responsive buildings requires looking at different scales of action and understanding how smaller groups of buildings can function alone, and together with others in a cluster. The idea is to design groups of buildings as interconnected nodes that share resources such as information, thermal and electrical energy. The nodes are connected to the grid through a main energy management center or part of an intelligent operation center (IOC), which regulates interactions based on the set goal using specific strategies and/or "learning responses" (Fig. 5). IOCs process a large variety of information as described in Ref. [83]. However for the specific scope of this paper, only energy management information is considered here.

The building nodes can form smaller secondary networks, which exchange resources in different patterns or timescales. Buildings can e.g. exchange thermal energy surplus directly without intermittent storage. This distributed configuration is useful to create multiple levels (named secondary information networks in Fig. 3) of management within a neighborhood. The complexity of the responsive cluster requires a network for information flow between the buildings, so that energy use can be managed both in real-time conditions and ahead of time. The type of information exchanged includes for example live schedules, live and forecasted energy use profiles, live and forecasted energy prices, and live and forecasted weather data. This information is useful to define the parameters relevant to the dynamic energy flexibility index status of the different buildings. Since RBEs should be designed as an integrated part of the buildings, their operations are designed in coordination with the technical systems in the building, the inner structural elements of the buildings (such as thermal mass enabling), and with regard to their impact on the user environment.

Due to the diversity of systems and features in responsive building envelopes, it is paramount to identify the different scales of the associated responses as well as time related parameters. The responses may have shorter or longer timeframes, and may have varying degrees of influence over the whole building. Some technologies may respond to stimuli within seconds or minutes (i.e. window opening, daylighting control, natural ventilation systems etc.) others will have much slower response times (i.e. thermal energy storage and release, set point change management etc.).

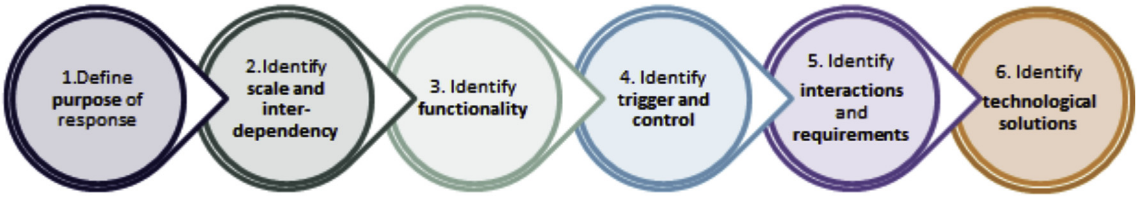


Fig. 1. The six-step performance goal strategy.

4.4. Identifying the functionality of the response

The functionalities of responsive envelopes are linked to objectives aimed at being fulfilled. This can relate to a larger scale of the neighborhood as well as on building level as shown in Table 1.

4.4.1. Building and neighborhood functionality

In a ZEN context the ability to modify the electrical energy demand after the anticipated load-curve shape is crucial. At neighborhood scale, this can be achieved by changing the profile of the total energy requirements of each building according to a strategy aimed at e.g. lowering costs, limiting grid interactions or reducing the carbon footprint. Demand side management (DSM) functionalities can allow for improved grid-friendliness. As described in section 2, DSM is the planning, implementation, and monitoring of grid interaction designed to produce changes in the neighborhoods load shape by changing the energy use magnitude and time related patterns. The functionalities of DSM revolve around the six strategies shown in Fig. 6. E.g.; a properly designed (and controlled) solar shading device can reduce peak cooling demands (peak clipping) in warm periods, thermal storage (thermal mass) in the envelope can shift heating and cooling loads and BIPV (with proper storage) can contribute to a more flexible load shape.

4.4.2. Envelope functionality

As previously mentioned, the framework presented by Loomans in Ref. [81] lacks the ability to have a neighborhood perspective. Therefore, in this work, two new RBE functionalities have been added (modulate and convert) to the ones already described by Looman. Additional types of the triggers for RBEs have also been made explicit to include grid related demands, neighborhood demands and user demands, all of which emphasizes the importance of considering response times in RBE functionalities. Fig. 5 shows Looman's illustration with the inclusion of the functionalities conversion and magnify/modulate as well as the identified triggers (as described in 4.5).

4.5. Types of response and triggers for responsive building envelopes

4.5.1. Single building related triggers

The types of triggers for response at a building level differ from the ones at a larger cluster- or neighborhood level both in terms of scale and time horizons. At the scale of single buildings located within a ZEN, triggers categories are local external climate (e.g., incoming solar radiation, wind speed or outdoor temperature), indoor climate (e.g. operative temperature or lighting level) or user requests (e.g. personal preference or change in building schedule). At single building level, the control mechanisms used are for short term responses (seconds, minutes or hours), and the *responsiveness* of the building is directly connected to the nature of the control strategy. These can be intrinsic (e.g. phase change materials, thermal mass, thermotropic glazing, photochromic glazing) or extrinsic (e.g. opening windows, activating solar shading, activating artificial lighting or natural ventilation). Intrinsic and extrinsic behaviors are described in Refs. [10,52]: *"Intrinsic indicates that the adaptive mechanism is automatically triggered by a stimulus (surface temperature, solar radiation, etc.). Extrinsic refers to the presence of an external decision-making component that trigger the adaptive mechanisms according to a feedback rule"*. In essence, intrinsic or cognitive controls refer to embedded properties in the material or assembly, which are typically only triggered by climatic (indoor and outdoor climate) stimuli. Extrinsic controls offer a much larger range of actions and can include strategies such as fixed control, schedules, ruled based control, model predictive control and direct real time user control. These technologies are able to respond to all 4 categories of triggers described Fig. 5 (climatic, grid, neighborhood, and user). However, because of the above mentioned differences in nature of the control mechanisms, technologies with the lowest degree of artificial control (i.e. intrinsic) will provide smaller ranges of maneuver in terms of real-time DSM

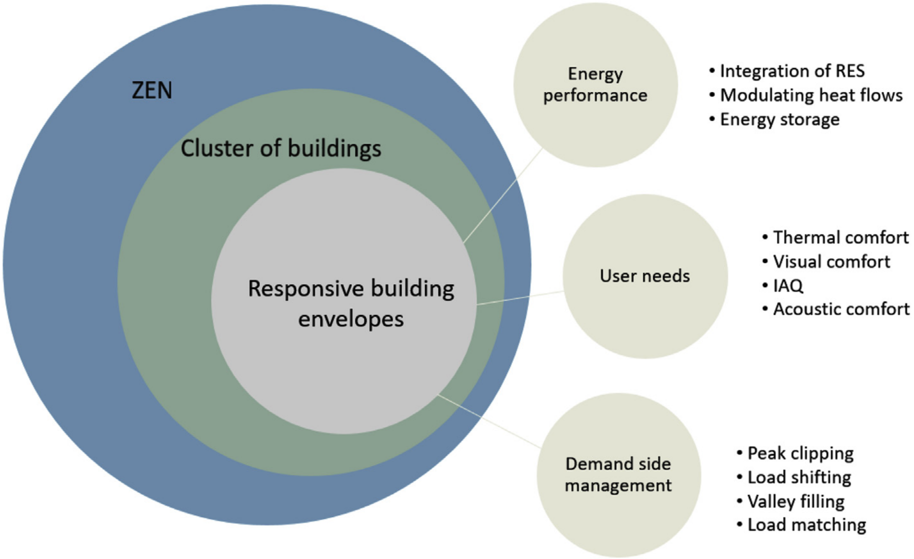


Fig. 2. Responsive building envelope design in a Zero Emission Neighborhoods context.

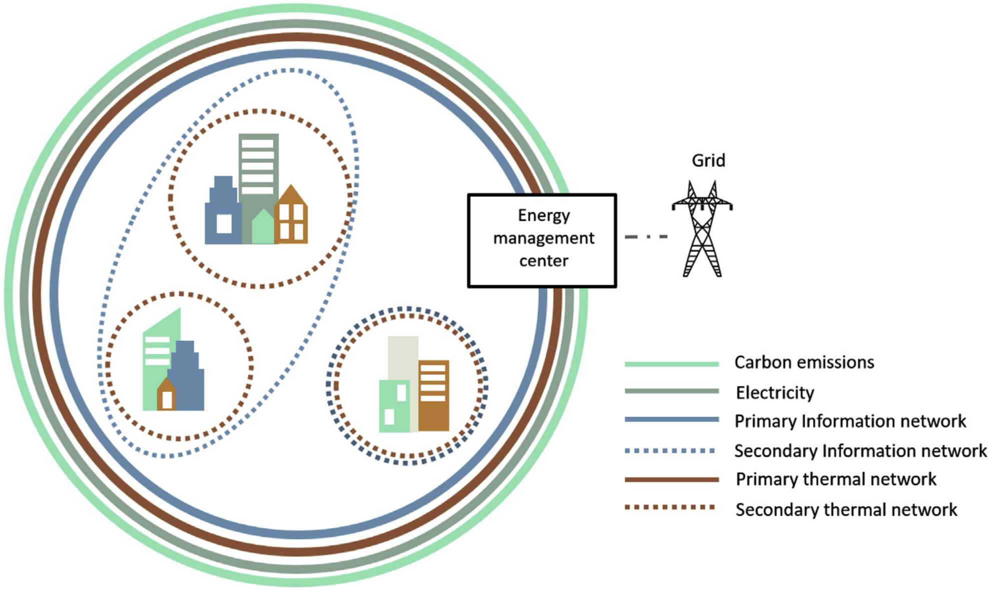


Fig. 3. Scales of exchange between clusters of buildings within the larger scale of the neighborhood. The interactions between RES and buildings are described in detail in section 4.4.2.

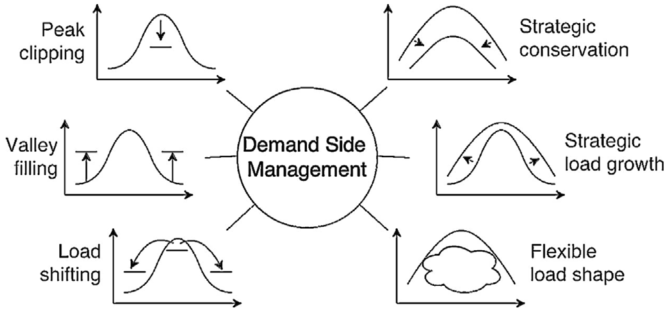


Fig. 4. Strategies for demand side management (from Ref. [44]).

options and will require the building to rely more heavily on both electrical and thermal storage options to improve energy management.

Triggers types can also be broken down further into different subgroups for each category, which are fixed, scheduled and real-time. Fixed triggers are mostly used for passive design (e.g. average annual ambient temperatures, sun angles or annual average internal load). Envelope designs based on fixed triggers encompass for example fixed shading systems. Scheduled are based on diurnal cycles whereas real-time stimuli are direct (real-time) feedback parameters measured by sensors (e.g. CO_2 levels, operative temperature or presence). These designs englobe systems for natural ventilation systems by use of double skin facades for example.

4.5.2. Neighborhood related triggers

Neighborhoods comprise different types of buildings and

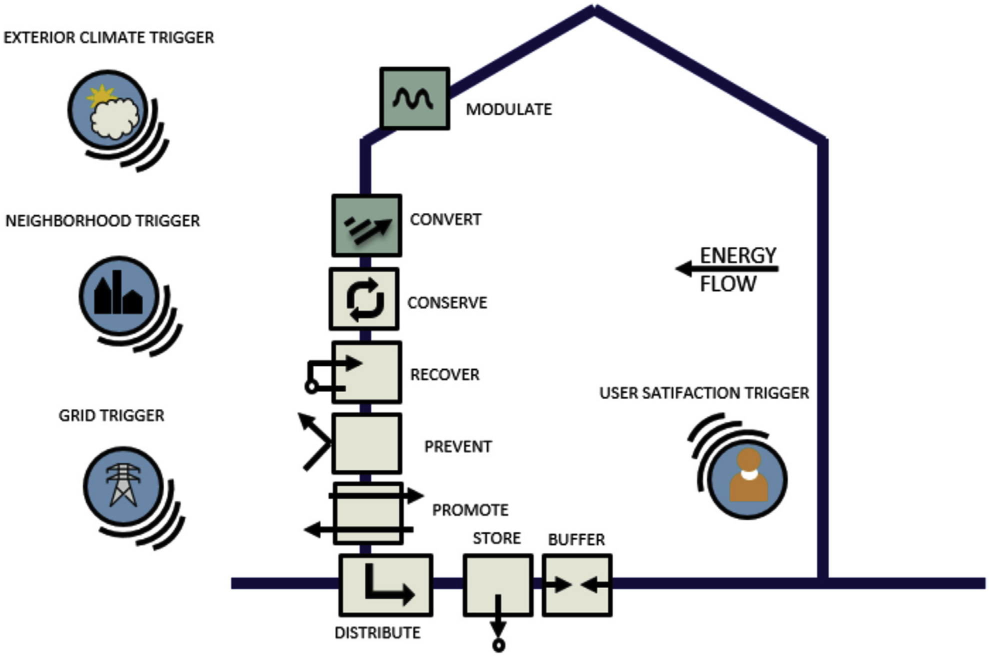


Fig. 5. Triggers and functionalities. Adopted (and refined) from Ref. [81].

Table 1
Functionalities of responsive building envelopes.

Purpose	Objective	Functionality	Description
Building energy performance	Intelligent energy management to reduce energy use	Recovery and conservation of available energy	Reduce energy use by modulating heat flows to maintain an optimum energy balance by promoting (admitting ingoing energy flows), preventing (protecting the indoor space from undesirable energy flows) and reducing energy flow through the envelope
		Energy buffering	Peak clipping by using solutions to reduce the magnitude of the impact of an energy flow
	Increase self-sufficiency	Energy storage	Load shifting by storing energy within the building
		Renewable energy integration	Optimize energy conversion at building scale by changing system configuration to maximize renewable energy harvesting
User comfort	Ensure health and wellness of users	Indoor air quality	Reduce pollutant concentration in indoor spaces
	Increase productivity	Thermal comfort	Prevent discomfort due to drafts and vertical temperature gradients Prevent overheating Maintain comfortable operative temperatures
		Visual comfort	Limit risk of glare Provide sufficient levels of daylighting Provide spaces with comfortable color temperatures Provide satisfying color rendering View to the outdoors
		Acoustic comfort	Reduce exposure to sources of aural discomfort Maintain privacy
Demand side management	Intelligent energy management to increase grid-friendliness	Reduce peak loads	Manage energy flows and energy sharing of electrical and thermal energy in clusters of buildings via use of smart control technologies Control of high efficiency renewable energy systems to reduce peak loads and optimize conversion parameters in building clusters
		Peak load shifting Valley filling	Control of energy storage systems for surplus energy storage and distribution within cluster
		Strategic conservation and load growth Flexible load shape	Use of model predictive control to set up grid energy consumption/resell strategies based on given parameters (energy source, carbon intensity of energy, energy cost …)

constructions and it is important to realize that not all buildings can offer the same flexibility in operation [45]. The varying degrees of responsiveness imply that not all elements of the building should include complicated technologies. Some of the design features can be static design features and will allow the building to respond to predictable changes in the building's operation (typically; schedules, or climate sensors for shading systems control) and allow to prevent a drop in performance. However, the more advanced responsive components allow the building or cluster of buildings to respond to unexpected changes and allow for a more diverse range of response. This typically requires using technologies with pro-active features based on anticipation (i.e. building systems or model predictive control [84,85]). The result is that a responsive building can react to exploit the modifications in its environment, and take advantage of the changes instead of merely sustaining them, overall continuously striving to operate at optimal conditions on multiple levels.

At a cluster- or neighborhood level, the stimuli are linked to extrinsic control strategies (e.g. DSM), and typically aim to fulfill optimization goals with longer time horizons (hours, days, weeks or months). These controls may be based on the current or predicted energy use of the building cluster, grid energy prices and/or carbon intensity of the energy. The responses can be similar to those for weather triggers but should mainly involve components, which preferably do not directly affect the occupants, as they cannot exert any direct control over the responses. The possibilities for responsive building envelopes to act on different types of triggers makes up a large part of their robustness. Table 2 provides a matrix of the trigger categories and type with the associated type of control of the response.

4.6. Interactions and requirements - the building users

Responsive facades with extrinsic controls play an important role in balancing different parameters of indoor environmental quality such as glare discomfort, operative temperature, daylighting levels, air quality, privacy and view to the outdoors. However, user interaction and satisfaction are two primary factors that must not be disregarded in the implementation and operation of automated building systems. User well-being and acceptance is directly correlated to the perception of

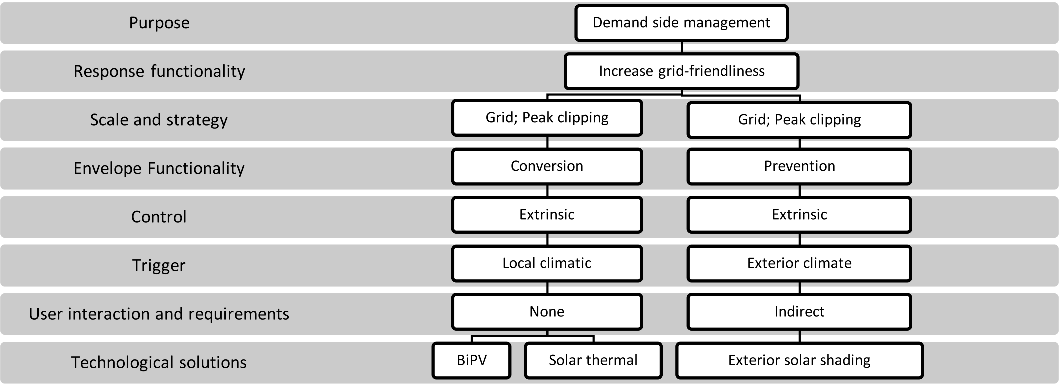


Fig. 6. Example of pathways to achieve good demand side management.

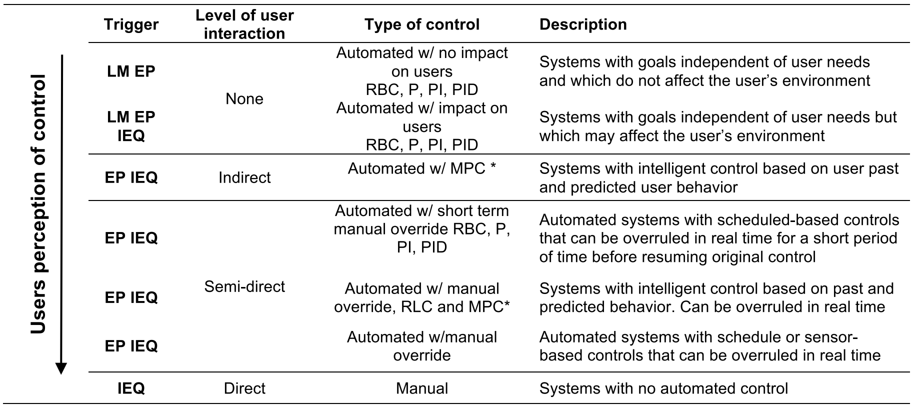
Table 2

Typology of responsive components for single buildings (adapted from Ref. [56]). Showing combinations of control and related trigger categories with sub-categories.

	Trigger category	Type	Type of control		
			Passive – Non-responsive	Active - Extrinsic	Cognitive - Intrinsic
Single building scale control strategies and related trigger types	Local climatic	Fixed value			
		Scheduled value			
		Real time value			
	User demand	Fixed value			Not Applicable
		Scheduled value			N.A.
		Real time value			N.A.
	Neighborhood management	Fixed value			N.A.
		Scheduled value			N.A.
		Real time value			N.A.

Table 3

Typology of user interactions with responsive systems. (*Model Predictive Control).



Users perception of control

Trigger	Level of user interaction	Type of control	Description
LM EP	None	Automated w/ no impact on users RBC, P, PI, PID	Systems with goals independent of user needs and which do not affect the user's environment
LM EP IEQ		Automated w/ impact on users RBC, P, PI, PID	Systems with goals independent of user needs but which may affect the user's environment
EP IEQ	Indirect	Automated w/ MPC *	Systems with intelligent control based on user past and predicted user behavior
EP IEQ	Semi-direct	Automated w/ short term manual override RBC, P, PI, PID	Automated systems with scheduled-based controls that can be overruled in real time for a short period of time before resuming original control
EP IEQ		Automated w/ manual override, RLC and MPC*	Systems with intelligent control based on past and predicted behavior. Can be overruled in real time
EP IEQ		Automated w/manual override	Automated systems with schedule or sensor-based controls that can be overruled in real time
IEQ	Direct	Manual	Systems with no automated control

and exercised personal control the occupants have over the systems [86] and the possibility to overrule systems is primordial to ensure user satisfaction [87]. When planning responsive buildings, it is important to consider different types of control for the systems depending on the type of system, the trigger and the response characteristics (scale of response and timeline associated). An overview of different response typologies is given in Table 3 with a short description of the control details.

Not all responsive systems should be designed to interact directly with occupants. For example, systems that respond to objectives of load management (LM) or some energy performance (EP) strategies may have no need for interaction with users. The larger part of these systems use rule based or reactive rule base controls (RBC), proportional response, PI or PID. These systems may implement advanced controls such as model predictive controls (MPC) or reinforced learning controls (RLC) in order to be most efficient in their responses and adjust to user patterns [83]. Other systems may be fully automated and user independent in their primary objectives, but affect the indoor environmental quality (IEQ) to a certain extent. Automated system with intelligent controls aimed at improving IEQ and support EP strategies are based on previous and predicted user behavior to determine their current state or actions, meaning that users indirectly influence them. These MPC/RLC are seen as an essential attribute to reconcile user needs and the energy saving potential of the responsive systems, two objectives that may sometimes compete. Control strategies that can be overruled by users are considered as semi-direct interactions and include controls driven by sensors, MPC/RLC or schedule based rules. The override function can be temporary, meaning the system will resume to its normal function after a certain amount of time, or independent in time until it is reset. Finally, some systems allow for direct manual control from the users, which allow occupants to have direct interaction with the system a perception of control. In these cases, it is essential that the user interface for the controls is easily understood. It must also be physically accessible to users. In past times that might have meant a nearby wall switch; today it might be based on an app on a cell phone. Spaces occupied by many people may have special challenges since the desires of different occupants may vary widely.

4.7. Choice of potential technological solution

4.7.1. The performance goal procedure exemplified

The aim of the step-by-step procedure presented is to provide a foundation for the evaluation of technologies that could be effective and serve a desired purpose. In the next section, two examples of application are presented (see Figs. 6 and 7).

A Top-down example is shown in Figs. 6 and 7. A dwelling is to be placed within a zero-emission neighborhood. In this neighborhood, power is scarce during periods of the day. Hence, the first purpose is chosen; to ensure a well-functioning demand side management system, with the reduction of peak-loads as the primary objective. A limitation in the grid calls for a strategy relating to peak-power reduction (Fig. 6). This, in term lead to the need for an extrinsic (grid-based) control. Solar radiation- and power is abundant, so on-site solar conversion and cooling prevention during peak solar hours are chosen as key functionalities. User comfort is chosen as the second purpose (Fig. 7). The building owner wants large windows facing south to provide view. Preventing overheating as well as glare becomes key response functionalities in the envelope. Both energy optimization (peak clipping) and comfort optimization are the governing purposes, and extrinsic control seems pertinent. Ultimately, this gives two distinct performance goal definition pathways (illustrated in Figs. 6 and 7). To achieve a purpose, several pathways may be chosen. The aim should be to identify one or more technological solution that can provide several, or all of the, response functionalities under each purpose. In this case, an exterior solar shading should be paired with building integrated solar energy conversion (BIPV and solar thermal). Figs. 6 and 7 shows that

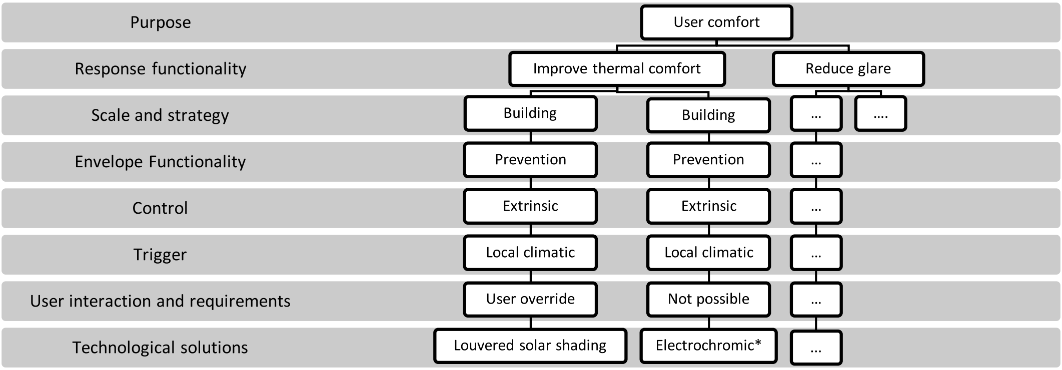


Fig. 7. Example of pathways to achieve desirable user comfort.

both grid demand and user comfort purposes can be addressed. Even though the functionality has different goals and the scale and strategy differs, a common denominator is that the local climate is a governing trigger. However, user interaction and requirements differs, pointing to the need to strike the proper balance at this level. This could include the design of control systems and strategies of the solar shading where users have the possibility to override an automatic system. It is imperative that users are informed of how manual override affect the energy performance. It should be noted that these examples are meant to illustrate a decision process. If using this in a real design-process, it is imperative that documentation of choices are provided.

4.7.2. *Classification of technologies – the reversed pathway*

The procedure can be used as both a top-down and a bottom-up tool to either determine or characterize a potential choice of technological solution. Starting with a technology the pathway scheme can be used to identify a technology's inherent functionality in a responsive building framework. By doing this, it can be used to map out and make a matrix of functionalities, possible control algorithms, triggers and finally which purposes the existing technologies are suited for. Although evident for this case, following the examples given in Figs. 6 and 7 in reverse, one can see that exterior solar shading enhances comfort as well as contribute to demands side management purposes.

5. Discussion

One of the major barriers preventing a large-scale uptake of RBEs is the lack of understanding of their behavior and the difficulties associated with predicting their performance in building simulation tools. Reliable methods for performance assessment are needed to improve system design and to carry out cost benefit analysis of the systems along with code compliance assessments. In the current state of simulation tools available, modelling and simulating responsive building elements is not a straightforward task. This is because of the complexity of the interplay of the different physical aspects, the difficulty of measuring performance in relation to the purpose and because as for most models, it requires identifying tradeoffs between the input in the structure of the model and the needed accuracy of the simulation results.

Modelling responsive buildings is further made complicated because RBEs by nature are more sensitive to weather data than non-responsive buildings, and this is particularly true for buildings with responsive behavior controlled by climatic stimuli. Obtaining reliable local weather data is a common issue in the field building performance simulation. It may require extensive post-processing of weather-data from weather stations far away or even setting up weather stations in the vicinity in order to have meaningful weather data inputs. The availability of high quality local solar data is especially scarce and data handling is cumbersome [88,89]. Additionally, RBEs require a lot of work regarding the choice of which technologies will be controlled by users and to what extent users may impact their function. The choice of user-technology interaction (see Table 3) affect the complexity of the control strategy and may require to model users with elaborate approaches. The process of selecting a modelling approach should be done according to the fit for purpose methodology in order to avoid unnecessary complexity [90]. Additionally, it is always useful to model not only the “final” solution but to parametrize key designs features or operating assumptions to estimate the sensitivity of output to these values. These issues are compounded when the focus includes performance measures for occupant comfort, energy and carbon goals, and grid impacts too.

The following subsections discuss two different approaches that can be adopted to tackle some of the discussed issues, and allow a smoother transition from a single building-to a neighborhood level model and simulation.

5.1. *Neighborhood level characterization*

5.1.1. *Modelling and simulating urban clusters with simplified models*

One way of dealing with the complexity required to model clusters of buildings has been to use lumped capacitance models and grey box modelling approaches [35]. These approaches are much less input intensive than traditional integrated whole building simulations models in widely used software such as EnergyPlus, TRNSYS, ESP-r or IDA ICE, which require large amounts of data and information related to the geometry of the building, the thermal properties of the envelope, HVAC system performance and so on. The suitability of such models to predict energy needs and thermal behavior has been recently investigated in Ref. [70]. This method of using simple components and grey box modelling approaches has also proven to be useful to model clusters of buildings as demonstrated in Refs. [70,91,92].

Many of the issues discussed in Ref. [35] for modelling urban areas apply to the scope of neighborhoods too. For instance modelling larger scales of urban areas requires identifying the tradeoffs between model accuracy and model complexity. This leading to the necessity to model key characteristics of elements and using these as inputs for meta-scale simulations where faster run-times are a requirement. This is in particular relevant in the case of RBEs as the requirements for the model are more advanced [52]. Information can be extracted from more detailed simulations such as the ones presented in the following section and reused as inputs for the larger scale models.

5.1.2. *Co-simulation of several entities*

Simulating and connecting multiple models of different systems or buildings is possible via co-simulation, but at the scale of a neighborhood the approach required is beyond the level of modelling used in industry and might even be beyond what regular co-simulation allows. Model based design (MBD) approaches are new and currently only used in research but this could help solving such issues if used in industry. MBD allow using a common simulation test bed to connect and share mixtures of models of computation (i.e. models in different BPS software). MBD supports designing and analyzing non-conventional energy and control strategies with a faster implementation of models for equipment, building systems and control algorithms at different levels. In the context of zero emission neighborhoods, it could permit the use of simulation models in combination with nonlinear programming algorithms. These are interesting because they can limit numerical noise in cost functions such as energy use, or carbon intensity during operation. This enables solving control problems, potentially involving state trajectory constraints or control functions with a large number of independent parameters. Other possibilities are to manage load prediction data-driven demand response schemes, analysis of the operation of building systems while allowing reusing models during operation for functional testing, verification of energy minimizing control sequences, fault detection and diagnostics. These features come in addition to options for modelling HVAC systems, multi-zone heat transfer and airflows, single zone computational fluid dynamics coupled to thermal parameters as well as electrical systems.

The framework presented in this work assumes that solutions are put in place so that most problems can be solved at any given level (material, system, building, or neighborhood) and that issues with the scalability of the selected solution can be handled in the modelling. In reality it is likely that modelling a system at different scales will present several pros and cons and require sophisticated tools for decisions making. These parameters, together with the skill of the modeler and the simulation tool used, could shape the modelling approach and the choice of system implemented.

6. Concluding remarks and further work

A roadmap to help architects and building designers identify pathways for implementation of RBE solutions in zero emission neighborhoods (ZENs) and smart sustainable cities is presented. Because neighborhoods consist of a combination of buildings of different types, e.g. new, existing, retrofitted, they can accommodate a large variety of RBEs with different functionalities and purposes. In the context of ZENs, the overarching goal should be to achieve a zero balance of greenhouse gas (GHG) emissions over a defined period of time, but this goal may be broader in the context of a smart sustainable city. For the scope of this work, three main purposes were selected: demand-side management-, energy performance- and user comfort. The resulting framework proposes a bidirectional pathway approach, which can be used to map out functionalities and concepts for responsive building envelopes.

Future research should aim at developing performance indicators for the facades of the future. Indicators should provide a comprehensive, yet easily understandable, description of how the buildings and their envelopes perform related to a defined series of purposes. The performance goals approach proposed in this paper is a step towards the development of such indicators but falls short of providing concrete benchmarks of responsiveness. The use of validated simulation tools for detailed analyses should be used as a steppingstone towards the development of simplified tools useable for a broader audience outside the research communities. The definition of control strategies and definition of triggers will require more attention in the continuation of this work, including the development of new approaches like Model predictive control (MPC), Model based design (MBD) and co-simulation for RBEs. This will become especially interesting when looking at it from a neighborhood perspective where grid optimization based on e.g. power abundancy, energy prices etc. can be implemented. Future work should also focus on identifying user needs in relation to RBEs in more detail. Looking ahead at the future of occupants and building controls, one must account for the rapidly growing capabilities of the Internet of Things (IoT) using low cost sensors, cell phone based apps, and cloud computing. It must address the rapid deployment of home automation-based control solutions, e.g. “Siri/Alexa, please close the shades in the living room when the sun sets and open the shades in the kitchen when I arrive”. As homeowners become accustomed to these smart technologies, they more readily accept complex systems in offices and commercial buildings.

Finally, the coupling between the façade and technical installations should be further developed to avoid the previously described dangers of sub-optimization when only parts of the bigger picture are addressed. RBEs should be thoroughly planned with regard to their goals, modes of action, control typologies and impacts on the different aspects of building operation as well as user experience. This analysis should be done early in the building design phase and accompanied by appropriate modelling efforts in building performance simulation tools to ensure that the system meets the defined goals. The modelling and simulation of RBE and RSEs in coordination with energy systems must also account for the differences between assumed behaviors and the reality of imperfect control and fuzzy user behavior. This issue is tightly connected with the challenges of data and model availability, which were existing a single building scale and pertain at neighborhood scale too, due to the need to communicate large amounts of simulation with varying temporal and spatial scales.

Acknowledgements

The authors gratefully acknowledge the support from the Research Council of Norway and several partners through the Research Center on Zero Emission Neighbourhoods in Smart Cities (FME ZEN) under grant No. 257660. This paper is also supported by the SkinTech project funded by the Research Council of Norway under grant No. 255252 and the industrial partners in the project.

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