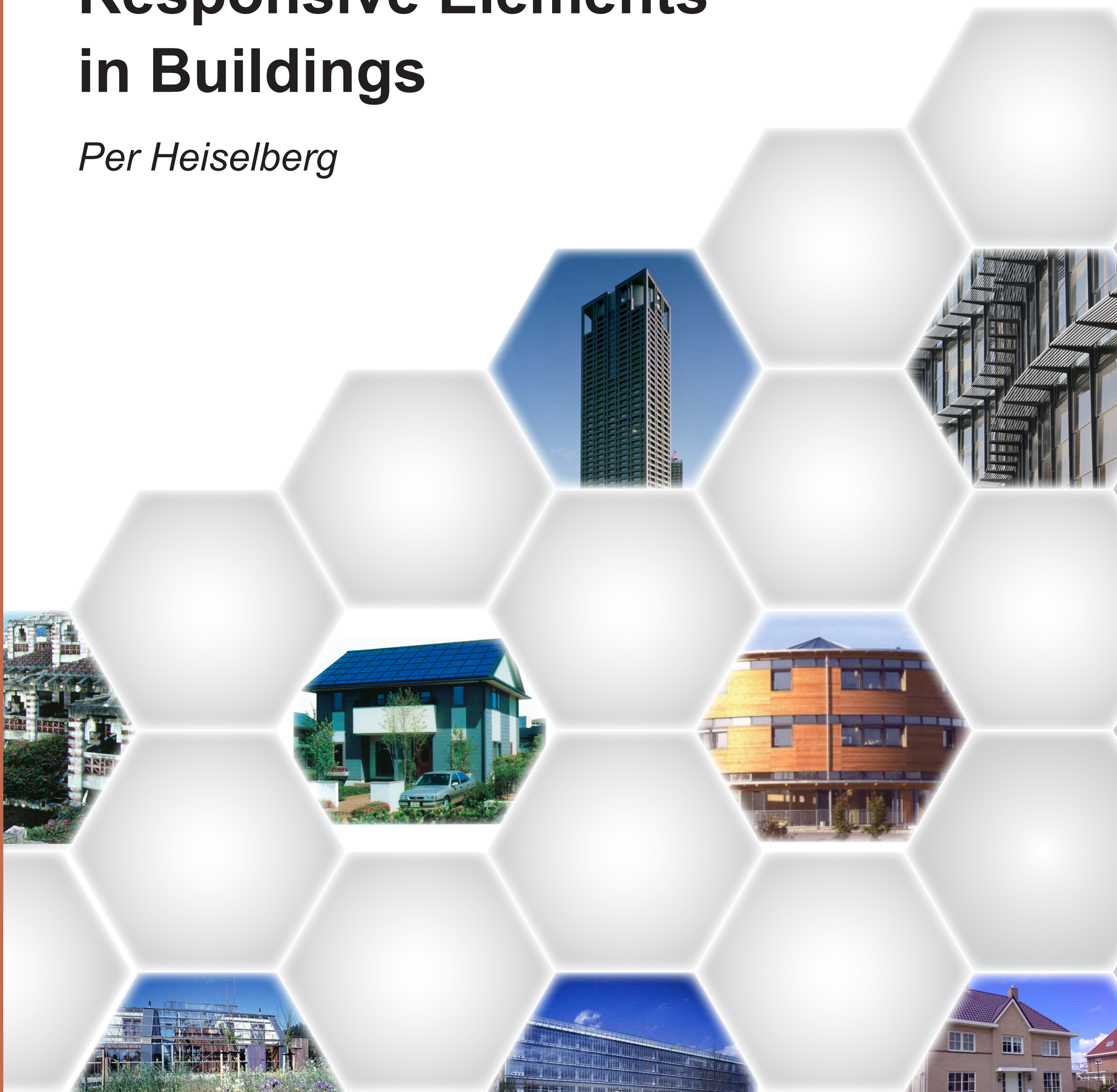
Project Summary Report

International Energy Agency
Energy Conservation in Buildings and Community Systems Programme

ECBCS Annex 44

Integrating Environmentally Responsive Elements in Buildings

Per Heiselberg



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International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-eight IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA co-ordinates research and development in a number of areas related to energy. The mission of one of those areas, the ECBCS - Energy Conservation for Building and Community Systems Programme (**www.ecbcs.org**), is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research.

The research and development strategies of the ECBCS Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Building Forum Think Tank Workshop, held in March 2007. The R&D strategies represent a collective input of the Executive Committee members to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy conservation technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in three focus areas of R&D activities:

- Dissemination,
- Decision-making,
- Building products and systems.

The Executive Committee

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the following projects have been initiated by the executive committee on Energy Conservation in Buildings and Community Systems (completed projects are identified in grey):

Annex 1: Load Energy Determination of Buildings
Annex 2: Ekistics and Advanced Community Energy Systems
Annex 3: Energy Conservation in Residential Buildings
Annex 4: Glasgow Commercial Building Monitoring
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities
Annex 7: Local Government Energy Planning
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Working Group - Energy Efficiency in Educational Buildings
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings
Working Group - Annex 36 Extension: The Energy Concept Adviser
Working Group - Energy Efficient Communities

General Information

Project leader: **Per Heiselberg, Aalborg University, Denmark**
Project duration: **2004 - 2011**
Further information: **www.ecbcs.org/annexes/annex44.htm**

In a responsive building, an optimum must be found between the sometimes contradictory requirements arising from energy use, health and comfort. Responsive buildings no longer act as rigid objects that need a large heating installation in winter and substantial cooling equipment during summer to 'correct' the indoor climate. Such a building becomes an additional 'living' skin around occupants, keeping them in contact with nature, but at the same time protecting them when necessary.

Within the ECBCS research project, **'Annex 44: Integrating Environmentally Responsive Elements in Buildings'**, attention has been focused on those responsive building elements for each of which the outlook for the building sector seems to be among the most promising. The key principles for a responsive building element are based on the ability to perform a responsive action based on:

- dynamic behaviour,
- adaptability,
- capability to perform different functions, and
- intelligent controls.

The 'dynamic' and 'adaptability' principles are based on the changeability of functionality, features and thermo-physical properties of these elements over time. Only by integrating responsive building elements under the supervision of intelligent controls and driven by a suitable strategy, is it possible to effectively exploit their potential.

Some responsive building elements are well known and have already been used for a long time (such as basic technologies for thermal energy storage and ventilated façades). However, their adoption has traditionally lacked integration and intelligent control. They have simply been used as dynamic elements in an 'unplugged' way. For this reason their actual performance in the field has frequently been revealed to be poorer than expected. Other responsive building elements are relatively new, like dynamic insulation, or in further cases they are advanced technologies so far only tested in the laboratory, but not yet applied in practice.

The ranges of application of responsive building elements and their conceptual working principles are extremely wide, varying from building envelope components with 'adjustable' heat loss coefficients and / or with variable air permeability, to building structures or components able to store thermal energy, to glazed systems with variable optical properties and on to elements exploiting evaporative cooling. In the ECBCS project, five specific responsive building elements have been investigated. These are:

- advanced integrated façades,
- thermal mass activation,

Participating Countries:

Austria
Canada
China
Denmark
France
Italy
Japan
Norway
Portugal
Sweden
Netherlands
UK
USA

Definitions

'**Responsive building concepts**' **(RBCs)** are design solutions that maintain an appropriate balance between optimum interior conditions and environmental performance by reacting in a controlled and holistic manner to changes in external or internal conditions and to occupant intervention.

A '**responsive building element**' **(RBE)** is a building component that assists in maintaining an appropriate balance by reacting in a controlled and holistic manner to changes in external or internal conditions and to occupant intervention. In this respect, responsive building elements are essential technologies for the exploitation of environmental and renewable energy resources.

- earth coupling,
- phase change materials;
- dynamic insulation.

With the integration of responsive building elements, building services and renewable energy systems, building design completely changes from design of individual systems to integrated design of responsive building concepts, which should allow for optimal use of natural energy strategies (daylight, natural ventilation, passive cooling, and so on), as well as integration of renewable energy devices. Design teams including both architects and engineers should be formed and the building design developed in an iterative process, progressing from the conceptual design ideas to the final detailed design.

An integrated design process ensures that the knowledge and experience gained by an analytical consideration of design is formalized, structured and incorporated into design practice. In such a process the expertise of the engineers is available from the very beginning at the preliminary design stage. The result is that participants collectively contribute their ideas and technical knowledge very early in the process. In this way, the energy and building services systems will not be designed independently from the architectural design, rather they are an integral part of the building design from a very early stage.

The integrated design process developed in the project creates a synergy of competencies and skills throughout the process based on inter-disciplinary work between architects, engineers, and others right from the beginning. It ensures that different specialist knowledge is introduced at an early project phase and takes into account a wide variety of opportunities and options from the very outset. It involves state-of-the-art simulation tools, and leads to a high level of systems integration. It enables the designer to control the numerous parameters that must be considered and integrated when creating more holistic sustainable buildings. The building design is developed in an iterative process from the conceptual design ideas to the final detailed design.

To facilitate the integrated design approach, different types of design methods and tools can be used which, in a strategic way, make it possible to select the most suitable technical solutions for the specific building and context. The report 'Expert Guide - Part 1 Responsive Building Concepts' (Heiselberg, 2009) describes design methods and simulation tools that can be used for the selection of responsive building components and the evaluation of responsive building elements for inclusion in the design. It attempts to classify methods and tools according to responsive building concept design phases and presents some examples of developed methods and tools. The methods and tools enable both qualitative and quantitative evaluation of those techniques and the results can be fed back to decisions on choice and specification. There are a range of methods and tools applicable in different phases of the design process and for various types of responsive building elements and other techniques.

Target Audiences

The ECBCS project 'Annex 44: Integrating Environmentally Responsive Elements in Buildings' had explored building integration of renewable energy and other technologies. The outcomes are of significant interest to construction product developers, architects, engineers, building contractors, owners, operators and users.

Project Outcomes

Project leader: Per Heiselberg, Aalborg University, Denmark
Project duration: 2004 - 2011
Further information: www.ecbcs.org/annexes/annex44.htm

Introduction

The buildings sector has been identified as providing the largest potential for energy-related carbon dioxide (CO_2) reduction by 2020. Therefore, many countries across the world have set very ambitious targets for energy efficiency improvements in buildings. To successfully achieve these targets, it is necessary to identify and develop innovative building and energy technologies and solutions for the medium and long term. These should facilitate considerable energy savings and the implementation and integration of renewable energy devices within the built environment. Rapid developments in materials science, information and sensor technologies offer considerable opportunities for development of new intelligent building components and systems.

'Responsive building concepts' are design solutions that:

a) maintain an appropriate balance between optimum interior conditions and environmental performance by reacting:

i. in a controlled and holistic manner to changes in external or internal conditions, and

ii. to occupant intervention, and

b) develop from an integrated multidisciplinary design process, which optimizes energy efficiency and includes integration of human factors and architectural considerations.

In this respect, responsive building elements are essential technologies for the exploitation of environmental and renewable energy resources and in the development of integrated building concepts. The challenge is to achieve an optimum combination of responsive building elements and integration of these with the building services systems and renewable energy systems to reach an optimal environmental performance.

Environmental design and control of buildings can be divided into two very different approaches. In the usual 'exclusive' approach energy efficient building concepts are created by excluding the indoor environment from the outdoor environment through a very well insulated and air tight building construction. Acceptable indoor environmental conditions are established by automatic control of efficient mechanical systems. Alongside this, there is growing interest in developing buildings that co-operate with nature and make use of the available environmental conditions. In this 'selective' approach energy efficient building concepts are created by using the building form and envelope as an intermediate between the outdoor and indoor environments. Acceptable indoor environmental conditions are established by user control of the building envelope and of the mechanical systems. It is important that the building is responsive to the fluctuations in the outdoor environment and the changing needs of the occupants, which means that the building should have the capability to dynamically adjust its physical properties and energy performance. This capability could pertain to energy capture (as in glazing systems), energy transport (as in air movement in cavities), and energy storage (as in building materials with high thermal storage capacity).

In a responsive building, an optimum must be found between the sometimes contradictory requirements arising from energy use, health and comfort. From the viewpoint of human coexistence with nature the approach is to make buildings generally 'open' to the environment and to avoid barriers between indoors and outdoors, while from the viewpoint of energy savings this approach actually excludes buildings from the outdoor environment for certain periods. in this way, the area between indoors and outdoors becomes a more or less hybrid zone in which energy gains are not simply rejected, but can be stored, tempered, admitted or redirected, depending on the desired indoor conditions. In this respect, responsive building elements (RBEs) are essential technologies for the exploitation of environmental and renewable energy resources and in the development of responsive building concepts (RBCs).

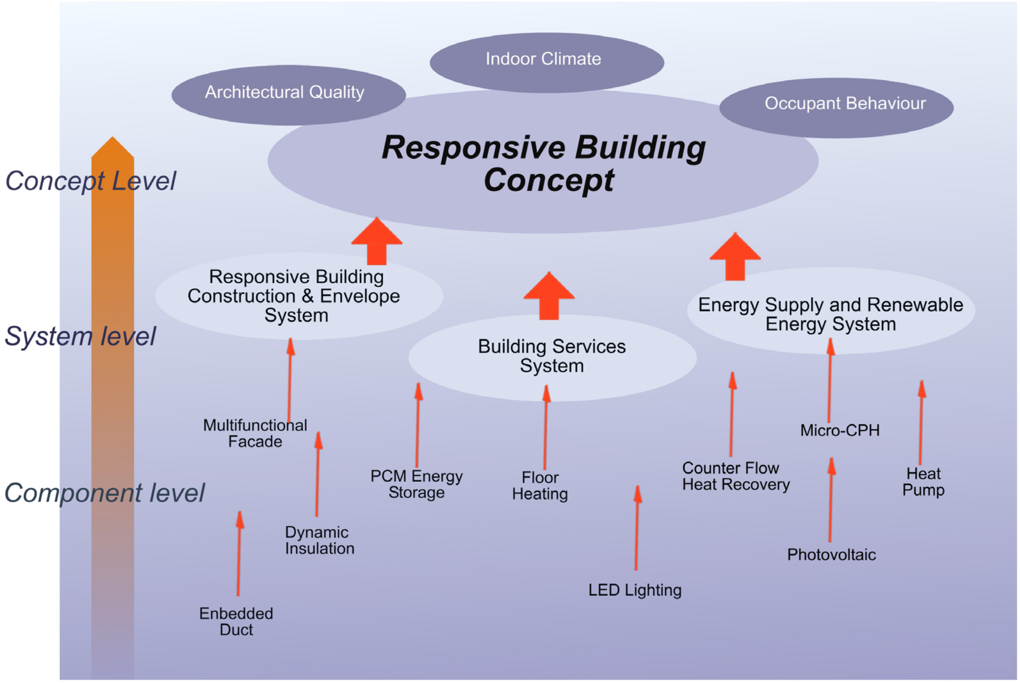


Figure 1. Illustration of the responsive building concept.consumption.

Nowadays we are able to measure and control the performance of buildings, building services and energy systems with an advanced building management system. This opens a new world of opportunities. A building no longer acts as a rigid object that needs a large heating installation in winter and substantial cooling equipment during summer to 'correct' the indoor climate. It becomes an additional 'living skin' around the occupants, keeping them in contact with nature, but at the same time protecting them when necessary.

Proper integration of responsive building elements with building services and energy-systems in responsive building concepts has a number of important advantages:

- Integration of responsive building elements with energy-systems will lead to substantial improvement in environmental and operating cost performance.
- It enhances the use and exploits the quality of energy sources (exergy) and stimulates the use of renewable and low valued energy sources (such as waste heat, ambient heat, residual heat, and so on).
- It will further enable and enhance the possibilities of passive and active storage of energy (buffering).
- It will integrate architectural principles into energy efficient building concepts.
- Responsive building elements lead to a better tuning of available technologies in relation to the building users and their behaviour.
- It enhances the development of new technologies and elements, in which multiple functions are combined in the same building element.
- It leads to a better understanding of integrated design principles among architects and engineers.

With the integration of responsive building elements, building services and renewable energy systems, building design completely changes from design of individual systems to integrated design of responsive building concepts. This should allow for optimal use of natural energy strategies (daylight, natural ventilation, passive cooling, and so on), as well as integration of renewable energy devices. Design teams including both architects and engineers are formed from the outset and the building design is then developed in an iterative process from the conceptual design ideas through to the final detailed design. However, a number of barriers appear when the borderline between architecture and engineering is crossed; the design process may contain many challenges to those who participate in the process. The main barriers to achieving an integrated design process are lack of:

- knowledge,
- information and guidelines,
- successful examples, and
- expertise.

The ECBCS research project 'Annex 44: Integrating Environmentally Responsive Elements in Buildings' has dealt with these issues and has delivered three publications addressing the challenges identified. These are available from **www.ecbcs.org/annexes/annex44.htm**:

- Designing with Responsive Building Components (van der Aa and others, 2011)
- Expert Guide - Part 1 Responsive Building Concepts (Heiselberg, 2009)
- Expert Guide - Part 2 Responsive Building Elements (Aschehoug, Perino, 2009)

This report summarizes the work and main achievements of the project.

Responsive Building Concepts

In the project, a 'responsive building concept' is defined as, "an integrated design solution where responsive building elements, building services systems and energy-systems are integrated into one system to reach an optimal environmental performance in terms of energy performance, resource consumption, ecological loadings and indoor environmental quality".

In the development of existing energy efficient building concepts, the main focus has typically been on application of only a few of the available technical solutions. Examples include:

- The 'Passive House' concept, which mainly focuses on super insulated and airtight envelopes, combined with high efficiency heat recovery and passive solar heating
- The 'Solar House' concept, which mainly focuses on use of renewable energy technologies such as passive and active solar heating and solar cells
- The 'Smart House' concept, which mainly focuses on advanced solutions for demand control and efficient control of fossil fuel technologies
- The 'Adaptive Building' concept, in which building elements actively respond to changing climate conditions and indoor environmental conditions as required by the occupants

Table 1. Categories and parameters for classification of responsive building concepts.

Category	Parameters
Climate	Cold, moderate, warm, hot-dry, hot humid, …
Context	Urban, suburban, rural
Building use	Office, school, residential, ...
Building type	High-rise, low-rise, row-houses, single houses, multifamily buildings, ...
Design approach	Selective, exclusive
Demand reduction strategies	Thermal insulation, air tightness, buffering, reduction of heat and contaminant loads, building form, zoning, demand control, efficient air distribution, solar shading, …
Responsive building elements	Multifunctional façades, earth coupling, thermal mass activation, dynamic insulation, …
Building services systems	Low temperature heating, high temperature cooling, low pressure mechanical ventilation, …
Renewable energy technologies	Passive and active solar heating, wind, natural cooling, geothermal heat / cool, biomass, daylight, natural ventilation, ...
Efficient energy conversion	Combined heat and power, high efficient gas boiler, heat pump, …
Control strategy	Adaptive / rigid, user control / automatic

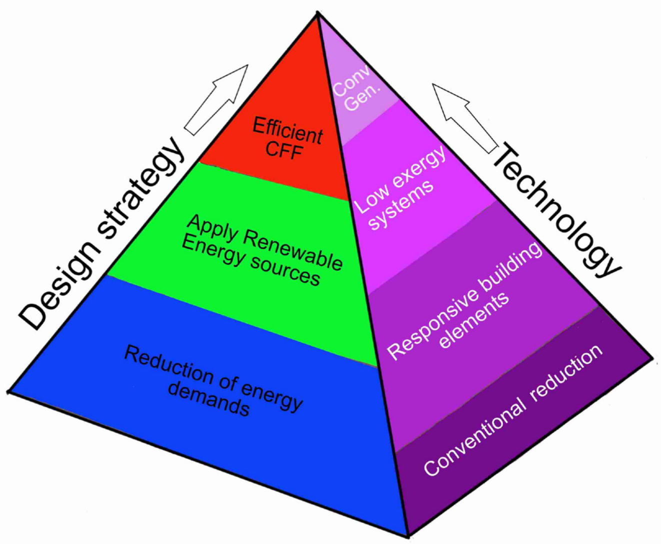


Figure 2. Illustration of the ECBCS Annex 44 design strategy and corresponding technologies. CFF: Clean fossil fuels.

These concepts are clearly the result of a sub-optimization by an expert, either in building physics, renewable energy, or control engineering. The responsive building concepts developed within this project can be considered as design solutions that are optimum combinations of the existing concepts by integration of the full range of technical solutions into one system. The main difference between responsive building concepts and other energy-efficient building concepts is the application of responsive building elements and their integration with building services and energy systems.

In the project, responsive building concepts were classified to define / specify the concept according the most important issues, shown in Table 1.

Typical strategies and solutions for responsive building concepts developed in the project are described in the report, 'Expert Guide - Part 1' (Heiselberg, 2009), which also includes seven examples described in detail and with lessons learned. The main characteristics of the selected examples are:

- **Demand Reduction Strategies.** For all examples it can be seen that climatic design and demand reduction strategies are a very important part of all concepts. In colder climates the main focus is on high thermal insulation, high airtightness, high heat recovery of ventilation air and demand control, while in warmer climates the main focus is on solar shading, façade design, passive cooling and daylighting.
- **Responsive Building Elements.** With regard to the application of responsive building elements it seems that thermal mass activation (by natural night ventilation in colder climates and ground coupling in warmer climates) is a key technology for all climates and building types while other responsive elements are applicable only for certain climates and / or building types.
- **Low Exergy Building Services Systems.** In order to optimise the use of renewable energy sources and improve heat pump performance floor (and wall) heating and cooling is used in many buildings. Secondly, low pressure ventilation with very efficient heat recovery is used.
- **Renewable Energy Technologies.** Typical technologies used include active solar thermal systems for domestic hot water (and heating), photovoltaic panels for electricity production and different systems for earth coupling, either water based (deep sonds, energy piles) or air based (underground culverts).
- **Efficient Energy Conversion.** In order to achieve high efficiency the systems often include heat pumps, high efficiency fans and heat recovery systems.

Good control is very important to maintain the optimum balance between energy efficiency and indoor conditions in responsive building concepts. However, controls need to operate according to a number of different requirements. Outdoor conditions as well as the availability of renewable resources are variable, and so is the demand for the indoor climate, depending on factors such as activities, preferences and time of day. If well designed, the right conditions for the inhabitants and the activities at any given moment can be provided, while saving energy by only providing these conditions when and where necessary.

The project showed that many controls were found to be poorly functioning in practice, causing discomfort to the user and frequently leading to inefficient operation of the systems. Giving the user his own control possibilities is essential, as it is proven by various studies that individuals tend to accept a wider range of conditions as comfortable, if they feel in control of their own environment. However, to be able to provide people with this essential control over their environment, while taking account energy efficiency, it is important to understand some basics of human behaviour when regulating thermal comfort, such as adaptation and usability. While best practice in this field is still not fully resolved, these vital issues need to be carefully addressed when designing usable controls for operating an energy efficient and comfortable building.

Responsive Building Elements

A 'responsive building element' (RBE) is a building component that assists in maintaining an appropriate balance between optimum interior conditions and environmental performance by reacting in a controlled and holistic manner to changes in external or internal conditions and to occupant intervention. Within the research activities of the project, attention has been focused on those RBEs whose prospects for the building sector seem to be the most promising. However, RBE technologies are generally only at the beginning of their evolution.

The key principles for a RBE are based on the ability to perform a responsive action based on:

- dynamic behaviour,
- adaptability,
- capability to perform different functions, and
- intelligent control.

The 'dynamic' and 'adaptability' principles imply that the functionality, features and thermo-physical properties of these elements may be required to change over time and be suitable for varying:

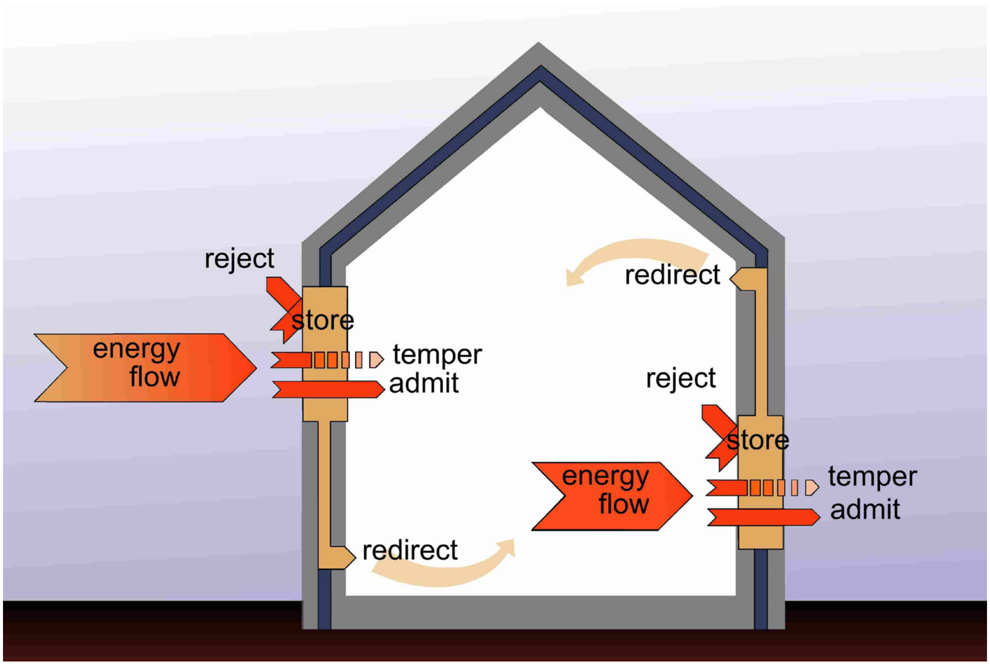


Figure 3. Illustration of the responsive actions of the building envelope.

- building and occupants requirements, for example heating / cooling or higher / lower ventilation, and
- boundary conditions, for example meteorological conditions or internal heat / pollution loads.

An optimum balance between energy efficiency and indoor conditions is guaranteed by 'intelligent' control of the RBEs. Only by integrating the RBEs under the supervision of an intelligent control system, driven by a suitable strategy, is it possible to effectively exploit their potential.

Some RBEs are well known and have been used for a long time, for example basic technologies for thermal energy storage and ventilated façades. However, their adoption has traditionally lacked integration and control. They have simply been used as dynamic elements in an 'unplugged' way. For this reason, their actual performance in the field frequently has been revealed to be poorer than expected. Other RBEs are relatively new, such as dynamic insulation, or in further cases, they are advanced technologies so far only tested in the laboratory, but not yet applied in practice.

RBEs can be classified based on their responsive action in surface intervention, internal intervention and physical behaviour, which can be divided into heat flux, thermal storage, permeability (ventilation) or transparency (daylight and solar radiation):

- **Surface and internal intervention**: By changing the conditions on or along the surface of a construction, the physical behaviour of the construction will change. Intervention in the inner part of the component can change the energy flow in the construction.
- **Heat flux related RBEs** have a variable (adaptive) thermal insulation performance. The characteristic feature of this category is that the heat flow is proportional to the insulation level and a certain separating area, for instance the glass area or the façade area. Examples of this category of RBE are double skin façades and dynamic insulation. Heat flux related RBEs can reduce the demand for heating and cooling by increasing the insulation level in winter and decreasing it in summer. Heat flux related RBEs can also control the amount of solar energy that is transmitted through glazing.
- **Thermal energy storage related RBEs** have a capability to store (thermal) energy in time periods with excess heat and to release this energy again in periods with a heating demand and therefore lead to a reduction of the total energy demand. Examples of this type of RBEs are earth coupling systems, thermal mass activation and phase change materials.
- **Transparency related RBEs** have a variable transparency to solar radiation and daylight. The characteristic feature of this category is the choice of transparent material and how its transparency depends of the radiation wavelength (mainly heat or mainly daylight). Examples of this type of RBEs mainly include fenestration and glazed façades.
- **Permeability (ventilation) related RBEs** have a variable (adaptive) permeability, that is ventilation performance. The characteristic feature of this category is that the heat flow is proportional to an air flow rate. Examples of this type of RBE are ventilated façades and embedded ducts. By regulating the flow of outside air, the heat exchange with the outside is controlled. Some ventilation related RBEs include pre-heating of the air before it enters the building.

Based on their technological function (envelope, structure, and so on) responsive building elements are part of the building construction and have to fulfil other requirements. This limits the capabilities for a responsive action.

The range of application of RBEs and their conceptual working principles are extremely wide, switching from building envelope components with 'adjustable' U-values and / or with variable air permeabilities, to building structures or components able to store thermal energy, to glazed systems with variable optical properties, to elements exploiting evaporative cooling. In the research activities of the project, attention has been focused on five specific responsive building elements, whose prospects for improvement and widespread implementation in the buildings sector seem to be most promising. These are:

- advanced integrated façades,
- thermal mass activation,

Project Outcomes

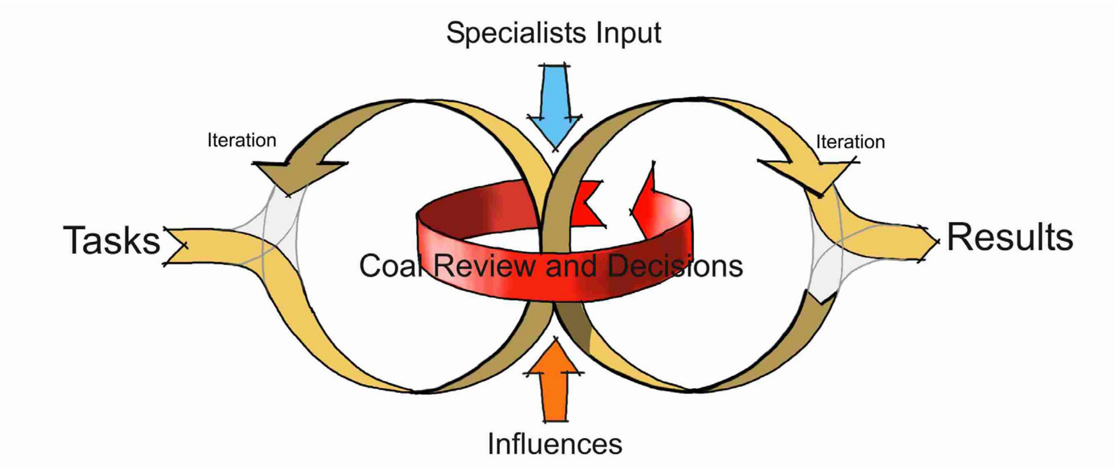


Figure 4. Iteration loops in the design process stages.

- earth coupling,
- phase change materials,
- dynamic insulation.

The main results regarding these RBEs and further detailed information can be found in the report, 'Expert Guide - Part 2' (Aschehoug, Perino, 2009)

Integrated Design Process

With the integration of responsive building elements and building services, building design completely changes from design of individual systems to a design based on integrated building concepts, which can only be developed using an integrated design approach.

An integrated design process ensures that the knowledge and experience gained by an analytical consideration of design is formalized, structured and incorporated into design practice. In such a process, the expertise of the engineers is available from the very beginning at the preliminary design stage and the optimization of the architectural and HVAC designs can start at the same time as the first conceptual design ideas are developed. The result is that participants collectively contribute their ideas and technical knowledge very early in the process. In this way, the energy and building services systems will not be designed independently from the architectural design, rather they are an integral part of the building design from a very early stage.

The project has identified that a number of barriers appear when the boundary between architecture and engineering is crossed. Architects belong to the humanistic arts tradition while engineers belong to a technical natural science tradition. This often creates problems for architects and engineers working as a team, as communication between the two groups should rely on a common language and in this case their languages are very different at the outset.

The integrated design process is a holistic method that intertwines elements of knowledge from engineering with the design process of architecture to form a new comprehensive strategy to optimize building performance. This implies evaluation and weighting of very different building performance characteristics that often are non-comparable, which requires willingness from all participants to reach acceptable compromises. The goal of integrated design is an improved and optimized building performance for the benefit of the building owner and the occupants. Changes in design processes and methods will require investment in education and in the beginning will always be more expensive for the designers. Therefore, it cannot be expected that architects and engineering consultants will be the main drivers for these changes unless the building owners and clients recognize the benefits and are willing to contribute to the investments needed to implement the changes.

The design strategy used in the project includes the following three main steps:

Step 1. Reduce energy demand

Optimize building form and zoning, apply well insulated and air tight conventional envelope constructions, apply efficient heat recovery of ventilation air during the heating season, apply energy efficient electric lighting and equipment, ensure low pressure drops in ventilation air paths, and so on.

Apply responsive building elements if appropriate, including advanced façades with optimum window orientation, exploitation of daylight, proper use of thermal mass, redistribution of heat within the building, dynamic insulation, and so on.

Step 2. Apply renewable energy sources

Provide optimal use of passive solar heating, daylight, natural ventilation, night cooling and earth coupling. Apply solar collectors, solar cells, geothermal energy, ground water storage, biomass, and so on. Optimise the use of renewable energy by application of low exergy systems.

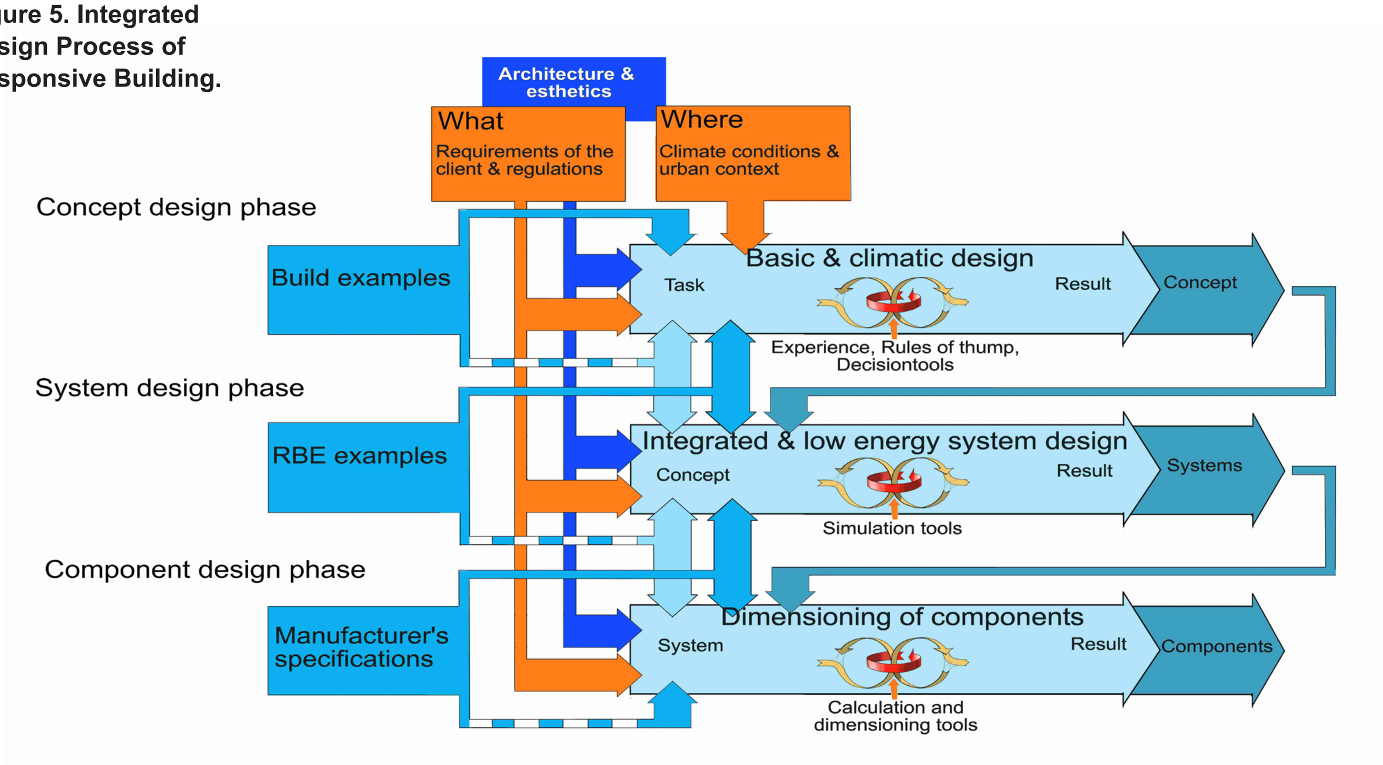
Step 3. Efficient use of auxiliary energy

If any auxiliary energy is needed, use the least polluting fuels in an efficient way, for instance heat pumps, high-efficiency gas fired boilers, gas fired combined heat and power-units, and so on. Provide intelligent control of systems including demand control of heating, ventilation, lighting and equipment.

The main benefit of the method is that it stresses the importance of reducing the energy load before adding systems for energy supply. This promotes robust solutions with the lowest possible environmental loadings. A more detailed description of the strategy and roadmap for practical implementation can be found in the report, 'Expert Guide - Part 1' (Heiselberg, 2009).

The project integrated design process (IDP) creates a synergy of competencies and skills throughout the process by the inter-disciplinary work between architects, engineers, and others right from the beginning of the process. It ensures that different knowledge of specialists is introduced at an early project phase and takes into account a wide variety of opportunities and options from the very outset. It involves up-to-date simulation tools, and leads to a high level of systems integration. It enables the designer to control the many parameters that must be considered and integrated when creating more holistic sustainable buildings. The building design is developed in an iterative process from the conceptual design ideas through to the final detailed design.

Figure 5. Integrated Design Process of Responsive Building.



Project Outcomes

It is important to consider the whole process, structuring it into clearly defined sequences to improve the overview of goals, activities, actors and products and to switch between them. The intermediate workflows in each rough phase can be characterized by iteration loops. These loops provide problem-oriented analyses of design alternatives and optimization based on the design strategy. They are able to take into consideration input from other specialists, influences from context and society to provide possibilities for and / or limitations to design solutions, as well as evaluating the solutions according to the design goals and criteria.

The actual design process is made up of a number of coarsely-defined phases that demand individual iterations within the phases. It needs to be accompanied by a continuous review of project goals, objectives and criteria, which serve as a 'roadmap' throughout the entire design process.

The ECBCS Annex 44 integrated design process is described in more detail in the report, 'Expert Guide - Part 1' (Heiselberg, 2009)., and includes the following main phases:

Phase 1: Where to build and what to build

It is essential to understand the climatic characteristics of the building site for responsive building design. Climate data are useful not only for estimating heating- and cooling loads of the building, but also for creating passive design concepts.

Analysis of site potential, including wind, sun and landscaping, and urban development plans and analysis of the client's preferences and organisational structure help to create a roadmap for energy system principles, renewable energy systems, the indoor environment and construction solutions. The outcomes are an analysis of the context, site and building design potential and a road map of possible design strategies.

Phase 2: Development of design concept

Through the sketching process, architectural ideas and concepts, functional demands, as well as principles of construction are linked to energy and environmental building concepts and the indoor environment through application of the design strategy. Different conceptual design solutions are developed and their relative estimated merits are continuously evaluated, including architectural qualities, against the goals in the building design brief. The outcome is an integrated building concept.

Phase 3: System design and preliminary performance evaluation

In the system design phase the building concept develops into specific architectural and technical solutions and systems through sketches, further calculations and adjustments. Architectural, spatial and functional qualities, the construction approach and demands for energy consumption and the indoor environment converge in this phase. The basic building form and its site location are determined after a series of functional analyses, defined in design strategy 'step 1'. At the same time by applying 'steps 2 to 4' in the design strategy, a framework for responsive design is created, taking into account various ideas of integration of passive- and active systems. This is as reflected in the design concept with explicit consideration of RBEs and renewable energy technologies.

Phase 4: Component design

In this phase, the final design will be completed after the performance of the system design has been confirmed. At this point technical solutions are refined and design documents are created, including final drawings and specifications in co-operation with construction companies, suppliers and product manufacturers. The outcome is a comprehensive description of the entire project.

Phase 5: Operation and management

Many energy problems can be traced to conflicts between building services and many of these are control issues. An energy efficient design strategy should overcome this and the underlying reasons for conflict should be identified and eliminated to prevent taking forward a flawed design.

To facilitate the integrated design approach, different types of design methods and tools can be used which makes it possible, in a strategic way, to select the most suitable technical solutions for the specific building and context. The report, 'Expert Guide – Part 1' (Heiselberg, 2009) describes design methods and simulation tools that can be used for the selection of RBCs and the evaluation of RBEs for inclusion in the design. It classifies methods and tools according to defined RBC design phases and presents some examples of developed methods and tools.

The methods and tools enable both qualitative and quantitative evaluation of techniques and the results can be fed back to inform decisions on choice and specification. There are different kinds of methods and tools applicable in different phases of the design process and for different types of RBEs and other techniques.

Building Performance Prediction

In the design of responsive building concepts it is crucial to be able to predict the building performance with satisfactory accuracy, especially when selection between alternative design solutions is needed, or if the aim is to perform an optimization of the building performance. When expressed in suitable indicators as primary energy use, environmental load and / or the indoor environmental quality, the building performance simulation provide the decision maker with a quantitative measure of the extent to which the design solution satisfies the design requirements and objectives.

It is essential that the simulation reflects the characteristics of the building construction and its building services systems and is able to simulate the building performance with satisfactory accuracy, in particular that the results are reliable and comparable. Traditionally, building performance simulation is based on a deterministic approach. However, to be able to compare different design alternatives against one another, it is necessary to also estimate how reliable a design is: That is to quantify the uncertainty associated with the simulated results for each design alternative. This can contribute to more rational design decisions. At the same time it may lead to a more robust design because the influence of variations in important design parameters has been considered.

An uncertainty analysis determines the total uncertainty in model predictions due to imprecisely known input variables, while a sensitivity analysis determines the contribution of each individual input variable to the total uncertainty in model predictions. The sequence of the two analysis methods is quite arbitrary as it is an iterative process, especially for large models, which is the case for simulation of the performance of integrated building concepts. A number of different mathematical methods for sensitivity analysis can be found in the literature. Based on the available information, the Morris method has been evaluated as the most appropriate for sensitivity analysis in sustainable building design. A description of this method and examples of its application can be found in the report, 'Expert Guide – Part 1' (Heiselberg, 2009).

Uncertainty analysis makes it possible to identify the most important parameters for building performance assessment and to focus the building design and optimization on these few parameters. The results give a much better setting for evaluating the design than a single value (uncertainty quantified) analysis, which is often based on cautious selection of input parameters and therefore tends to under predict the potential of passive technologies.

In many cases, evaluation of a design solution is based on a calculation of the thermal comfort expressed by a performance indicator such as 'predicted percentage of dissatisfied' and / or the number of hours the temperature is higher than a certain value. Due to complexity of modelling the building envelope and services systems, as well as the variation of boundary conditions and possible user scenarios, it is actually irresponsible to base decisions on a single calculation using a single sample of input parameters. An uncertainty analysis gives much more information about the performance and a much better background to make decisions.

The main barrier, however, for application of uncertainty analysis in building performance assessment is the increase in calculation time and complexity. Uncertainty analysis is far from being a central issue in consultancy. Explicit appraisal of uncertainty is the exception rather than the rule and most decisions are based on single valued estimates for performance indicators. At the moment experiences from practical design cases are almost non-existent. These are needed to demonstrate the benefits and transform the methods into practice. So, it is important to include uncertainty analysis in commercially available building simulation tools.

Futher Information

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Project Reports

www.ecbcs.org/annexes/annex44.htm

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France	CSTB Institut National d'Energie Solaire et Savoie Technolac
Italy	Politecnico di Torino Università Politecnica delle Marche
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International Energy Agency
Energy Conservation in Buildings and Community Systems Programme