Sustainable and resilient building design
approaches, methods and tools

Kosanović, Saja; Klein, Tillmann; Konstantinou, Thaleia; Radivojević, Ana; Hildebrand, Linda

Publication date
2018

Document Version
Final published version

Citation (APA)
Kosanović, S., Klein, T., Konstantinou, T., Radivojević, A., & Hildebrand, L. (Eds.) (2018). *Sustainable and resilient building design: approaches, methods and tools*. (Reviews of Sustainability and Resilience of the Built Environment for Education, Research and Design; Vol. 5). TU Delft OPEN Publishing.
https://books.bk.tudelft.nl/index.php/press/catalog/book/isbn.9789463660327

Saja Kosanović, Tillmann Klein, Thaleia Konstantinou, Ana Radivojević and Linda Hildebrand [eds.]

sustainable and resilient building design

approaches, methods and tools

labs

BOOK SERIES

reviews of sustainability and resilience of the built environment for education, research and design

Saja Kosanović, Alenka Fikfak, Nevena Novaković and Tillmann Klein [eds.]

This thematic book series is a result of the Erasmus+ project, *Creating the Network of Knowledge Labs for Sustainable and Resilient Environments (KLABS)*. The books are dedicated to establishing a comprehensive educational platform within the second cycle of higher education across the Western Balkan region. The series comprises five volumes in the English language:

Sustainability and Resilience _ Socio-Spatial Perspective
Realms of Urban Design _ Mapping Sustainability
Integrated Urban Planning _ Directions, Resources and Territories
Energy _ Resources and Building Performance
Sustainable and Resilient Building Design _ Approaches, Methods and Tools

labs
FOR SUSTAINABLE & RESILIENT ENVIRONMENTS

Creating the Network of Knowledge Labs for Sustainable and Resilient Environments – KLABS

Co-funded by the Erasmus+ Programme of the European Union

Erasmus+ Capacity Building in Higher Education project

Sustainable and Resilient Building Design
Approaches, Methods and Tools

Editors
Saja Kosanović, Tillmann Klein, Thaleia Konstantinou, Ana Radivojević and Linda Hildebrand

Reviewers
Steve Lo, Radomir Folić, Nadja Kurtović-Folić

Publisher
TU Delft Open, 2018

ISBN 978-94-6366-032-7

THIS BOOK IS PART OF THE BOOK SERIES
Reviews of Sustainability and Resilience of the Built Environment for Education, Research and Design

Copyediting
Caitriona McArdle, Architectural Copyeditor, Dublin

Design & layout
Véro Crickx, Sirene Ontwerpers, Rotterdam
Nienke Blaauw, Faculty of Architecture and the Built Environment, TUDelft

sustainable and resilient building design
approaches, methods and tools

Saja Kosanović, Tillmann Klein, Thaleia Konstantinou, Ana Radivojević, and Linda Hildebrand [eds.]

Preface

Saja Kosanović, Alenka Fikfak, Nevena Novaković and Tillmann Klein

The continuous evolution of the notion of a sustainable and resilient built environment demands repeated examination. For this reason, the state-of-the-art thematic series *Reviews of Sustainability and Resilience of the Built Environment for Education, Research and Design* contributes to the comprehensive understanding of the two approaches and their interrelations in the built environment by retrospectively investigating their development, addressing current issues, and speculating on possible futures. The series represents one of the results of the Erasmus+ project, Creating the Network of Knowledge Labs for Sustainable and Resilient Environments – KLABS, dedicated to establishing a comprehensive educational platform within the second cycle of higher education across the Western Balkan Region.

The sustainable and resilient built environment is a multi-layered and multi-disciplinary construct. To successfully tackle the intricacy of the points in question, the series of books comprises five thematic volumes that initially approach sustainability and resilience from the socio-spatial perspective, subsequently address sustainable and resilient urban planning and urban design, and then focus on individual buildings and a range of approaches, methods, and tools for sustainable and resilient design, placing particular emphasis on energy issues. By addressing different levels of the built environment and different aspects of sustainability and resilience in a systemic way, 83 academics from 12 different countries gave 54 contributions in the form of narrative or best evidence articles with the main objectives of informing the development of specialised knowledge, building critical awareness of interdisciplinary and transdisciplinary knowledge issues, and connecting university education with the domain of scientific research. The broad aim is to develop the collection of reviews of sustainability and resilience of the built environment that are useful for students, educators, professionals, and researchers, all of whom are dealing with these two important subjects internationally.

We express our gratitude to all authors, editors, reviewers, and members of the publication board for investing significant efforts in the development of the book series in the framework of the Erasmus+ project, KLABS.

Contents

Reviews

Steve Lo, Radomir Folić and Nadja Kurtović-Folić

I

This book should attract graduate and postgraduate students with some prior knowledge of sustainable building design who wish to develop their simultaneous multi-parameter analysis and assessment of this environmental domain.

The origins of environmental design and the evolution of environmental terminology are clarified along a complex timeline. The interrelated challenges of more efficient and optimised design processes, the multi-parameter design conflicts of meeting ever more demanding operational energy targets, and the increasing drive to reduce the initial embodied carbon of materials, are clearly presented.

The challenges of integrating vernacular responses into a more contemporary design language through mitigation and adaptation, in an ever-changing climate, are examined. The resulting generic resilience framework expands an already complex and multi-variate design process, but is essential for a more informed and collaborative design future, at both a micro- and macroscopic level.

A detailed appraisal of fire protection in buildings is valuable and timely. Following the Grenfell disaster, a number of national and international bodies are pooling their relevant expertise to address this issue, to ensure more resilient fire protection in buildings.

A comparison of the distinctions between sustainability and resilience, and the interrelationship of the two, form the basis of a clear roadmap for their mutual future development with more regionally specific solutions.

A detailed chronology of certification models demonstrates how they now aspire to a common environmental quality, combined with the impact of user engagement on low carbon buildings along the design process, for a range of building typologies and climates.

It is good to see a comprehensive overview of risk management and its assessment discussed in light of a generally very conservative industry.

Clearly defined distinctions are made between the different scales of ecological material impact leading to a comprehensive and informative review of the multi-valent, but iterative nature of LCA analyses and their scope in-use. An equally thorough examination of environmental assessment tools by material, component, and building along the design process provides an invaluable glimpse into the vast body of work undertaken in this field for novices and experts alike.

Evaluating the resilience of common construction materials provides a fundamental and informative insight into the temporal effects of regional environments on their service life. This is supported with selected contemporary alternatives with enhanced properties, but does not neglect time-honoured, locally-sourced natural and recycled solutions.

The challenges of meeting the international, local, and environmental drivers for both new and existing building typologies shows a full understanding of the impact of the total building stock for a more sustainable and resilient future for building design. Recommendations that inform best practice will ensure that the growing number of new, and refurbished, built exemplars across many climatic regions will act as beacons of sustainable and resilient building design. It is also heartening to see how social engagement for more embedded inclusion, can drive the rehabilitation of a more demanding and organically evolving built environment, to fully engage and inform more carbon-aware lifetime users.

The final chapter provides a vision of regenerative design through multi-functional biological entities where users find their place in a truly sustainable and resilient environment.

This book series should form the basis for continued lifelong learning and act as a road map for interested students, researchers, and academics alike, as they journey into a more sustainable and resilient, if uncertain, future. Industry professionals with domain specific experience, and a thirst for more continuous professional development, may also benefit from being able to immerse themselves in the more academically rigorous methodologies and strategies evaluated. Delving deeper requires dedication and persistence, as opportunities to do so are often bypassed when trying to manage the commercially driven pressures of life in practice.

Overall, the approaches and methods presented carefully tread the fine line between meeting the, sometimes, academic aloofness of university level learning outcomes, and the more pragmatic tools and guidelines required by practitioners, to produce accessible and useable outputs for both sectors.

Dr. Steve Lo
Bath, United Kingdom, March 2018

II

The manuscript Sustainable and Resilient Building Design: Approaches, Methods and Tools represents one of five thematic volumes encompassed by the international thematic publication Reviews of Sustainability and Resilience of the Built Environment for Education, Research and Design. The volume is a collection of 13 scientific reviews and professional papers authored by academics and researchers from Germany, the Netherlands, Slovenia, Italy, United Kingdom, Spain, Switzerland, and Croatia, and the Western Balkan countries, including Serbia. The collaboration and synthesis of different experiences, methodologies, and recommendations for advancement in the studied fields are of particular significance.

The papers encompassed by the manuscript deal with two important aspects of building planning and design, scilicet, sustainability and resilience, which primarily relate to climate change. In parallel, the contributions of the authors from the Higher Technical Professional School in Zvečan, which contain the elements of the state-of-the-art reviews, address two topics that are currently very relevant in the building context – risk management and fire protection. In methodological terms, the papers are well structured, which further indicates that the instructions to authors were adequate and that the editors worked devotedly on manuscript development.

The analysis of the text of proposed thematic collection shows that the appropriate functional connection between some papers has been established on the basis of the overview of development of environmental design, analysis of its current state, and the indication of possible directions of future development. After considering the environmental impact of buildings and the principles of the efficiency of resources, the manuscript immediately unfolds the approach for resilience to climate change, corroborating the proposed design framework with the introduction of a theoretical basis of analysis. All subsequent papers in the manuscript aim to examine these two main research subjects, by illuminating their intricacies and revealing their interconnections. Some observations that are brought forth in the first papers of the manuscript are elaborated in detail in the final papers that deal with more advanced interpretations of sustainability and resilience, and emphasise the necessity of a profound inclusion of a social component in building-related processes, as well as of a shift from the idea of reducing the negative environmental impact to the idea of achieving net positive effects through design.

The manuscript fundamentally deals with reviews of sustainability and resilience relating to buildings. In their papers, the authors use an extensive number of references. The systematic and comprehensive presentation of the concepts as they relate to sustainable and resilient buildings assign an interdisciplinary character to the collection. The proposed manuscript is a valuable, contemporary, and specialised educational material for the technical-technological field of knowledge.

The terminology used throughout the manuscript and the applied research methods are adequate. The overall content is a contribution to the improvement of current professional practice in accordance with the generally accepted principles of sustainable development and resilience to climate change. The importance assigned to methods such as life cycle analysis and building certification, and tools like software and databases referring to the ecological quality of building materials, represents another recognised value. The manuscript entitled Sustainable and Resilient Building Design: Approaches, Methods and Tools is significant for students, academics, researchers, and professionals dealing with the buildings of various types, and I recommend it for publishing.

Prof. Emeritus Dr. Ing. Radomir Folić
Novi Sad, Serbia, February 2018

III

The manuscript Sustainable and Resilient Building Design: Approaches, Methods and Tools is the fifth and last of five thematic volumes encompassed by the international thematic series Reviews of Sustainability and Resilience of the Built Environment for Education, Research and Design.

The total of 13 scientific, review, and professional articles in Volume 5 encompass several important preconditions for well-designed sustainable and resilient buildings. They include the most current topics such as environmental design (Origin and development of environmental design, Methodology for assessing environmental quality of materials and construction, A comparative overview of tools for environmental assessment of materials, components and buildings), climate change and pollution (Approach to design for resilience to climate change, Impact of climate and pollution on resilience of some conventional building materials), fire and other risks (Understanding fire and protecting the buildings, Risk management and risk assessment methods), advocacy for natural and regionally available materials (Natural and regionally available materials for sustainable future: Reviving tradition in contemporary construction), adaptability of the built environment (Sustainable refurbishment for an adaptable built environment), social impacts on sustainable development (Adaptive socio-technical devices: social inclusion as a rehabilitation tool) and contemporary problems of ignoring the absence of biological entities (Biological entities and regeneration by design). Two articles deserve special attention because they deal with the direct correlation of sustainability and resilience and their institutional treatment in the community (Sustainability and resilience, Building certification systems and processes).

From the composition of the authors' teams who wrote the articles, it can be concluded that the participants from many countries achieved very good levels of cooperation and communication. The papers present concordant attitudes that are a feature of good knowledge of the problems that are being observed and for which solutions are being proposed.

Sustainability is a topic that has already been largely processed, but the issues of resilience are relatively recent and solving them is especially important. In this volume, both problems are closely interconnected, which is especially significant during the design process when it comes to risk management problems, climate change, environmental pollution, and the selection of the methodology for assessing environmental quality of applied materials and construction.

Since the articles should serve the education of students and others in practice, as well as researchers and designers, they are methodologically well structured, provide explanations for the terminology used in these fields, and are equipped with a complete scientific apparatus. The authors are very well informed about the latest research and work of other scientists (extensive number of references in all papers!), but the texts are original and represent the results of good cooperation between researchers from countries of different levels of development.

I consider that all articles in Volume 5 are of high-quality and can be fully used in the fields of education, research, and design, and I strongly recommend Volume 5 for publishing.

Prof. Dr. Ing. Nadja Kurtović-Folić
Novi Sad, Serbia, February 2018

Introduction

Saja Kosanović, Tillmann Klein, Thaleia Konstantinou, Ana Radivojević and Linda Hildebrand

The challenges to which contemporary building design needs to respond grow steadily. They originate from the influence of changing environmental conditions on buildings, as well as from the need to reduce the impact of buildings on the environment. The increasing complexity requires the continual revision of design principles and their harmonisation with current scientific findings, technological development, and environmental, social, and economic factors. It is precisely these issues that form the backbone of the thematic book, *Sustainable and Resilient Building Design: Approaches, Methods, and Tools*.

The book starts with the exploration of the origin, development, and the state-of-the-art notions of environmental design and resource efficiency. Subsequently, climate change complexity and dynamics are studied, and the design strategy for climate-proof buildings is articulated. The investigation into the resilience of buildings is further deepened by examining a case study of fire protection. The book then investigates interrelations between sustainable and resilient building design, compares their key postulates and objectives, and searches for the possibilities of their integration into an outreaching approach. The fifth article in the book deals with potentials and constraints in relation to the assessment of the sustainability (and resilience) of buildings. It critically analyses different existing building certification models, their development paths, systems, and processes, and compares them with the general objectives of building ratings. The subsequent paper outlines the basis and the meaning of the risk and its management system, and provides an overview of different visual, auxiliary, and statistical risk assessment methods and tools.

Following the studies of the meanings of sustainable and resilient buildings, the book focuses on the aspects of building components and materials. Here, the life cycle assessment (LCA) method for quantifying the environmental impact of building products is introduced and analysed in detail, followed by a comprehensive comparative overview of the LCA-based software and databases that enable both individual assessment and the comparison of different design alternatives. The impact of climate and pollution on the resilience of building materials is analysed using the examples of stone, wood, concrete, and ceramic materials. Accordingly, the contribution of traditional and alternative building materials to the reduction of negative environmental impact is discussed and depicted through different examples.

The book subsequently addresses existing building stock, in which environmental, social, and economic benefits of building refurbishment

TOC

are outlined by different case studies. Further on, a method for the upgrade of existing buildings, described as ‘integrated rehabilitation’, is deliberated and supported by best practice examples of exoskeleton architectural prosthesis. The final paper reflects on the principles of regenerative design, reveals the significance of biological entities, and recognises the need to assign to buildings and their elements a more advanced role towards natural systems in human environments.

Origin and Development of Environmental Design

Linda Hildebrand [1*], Thaleia Konstantinou[2], Saja Kosanović[3], Tillmann Klein[4] and Ulrich Knaack[5]

* Corresponding Author
1 Faculty of Architecture, RWTH Aachen University, e-mail: lhildebrand@rb.arch.rwth-aachen.de
2 Faculty of Architecture and the Built Environment, Delft University of Technology, e-mail: T.Konstantinou@tudelft.nl
3 Faculty of Technical Sciences – Architecture Department, University of Priština in Kosovska Mitrovica, e-mail: saja.kosanovic@pr.ac.rs
4 Faculty of Architecture and the Built Environment, Delft University of Technology, e-mail: T.Klein@tudelft.nl
5 Faculty of Architecture, Technical University Darmstadt / Faculty of Architecture and the Built Environment, Delft University of Technology, e-mail: knaack@ismd.tu-darmstadt.de

ABSTRACT **Buildings are characterised as some of the greatest consumers and pollutants of the planet. However, the genesis of environmental design, in the context of its modern meaning, as shown in this paper, is not so much based on initial requests to reduce the negative pressure on the environment, but more on the tendency to ensure the continuity of the supply of resources. Only when awareness of the state of environment and the negative anthropogenic contribution matured enough in the second half of the 20th century, the idea of environmental design started to grow and become more complex. Eventually, environmental design became a framework comprising various strategies and measures that aim to reduce the negative ecological impact of buildings by aligning conventional design requirements with their environmental significance. By connecting resource efficiency with the reduction of environmental impact of buildings, this paper reviews current trends and challenges in the utilisation of energy, materials, water, and land, and reflects the scenarios of possible resource-efficient futures in which wider social and economic schemes could become increasingly relevant for the successful outcomes of environmental design.**

KEYWORDS buildings; environmental impact; life cycle; resource efficiency

1 Introduction

Throughout history, mankind has learned to cultivate and exploit the broad variety of resources in the Earth's systems, in order to secure the species' survival and wellbeing. Along with industrialisation came the intensification of human interference, and the increase in the consumption of resources, causing changes with unpredictable and irreversible ecological effects. While massive impacts on nature took place during the last two hundred years, the social awareness of such impacts developed only in the second half of the last century, when politically and socially motivated environmentalism became a new focus.

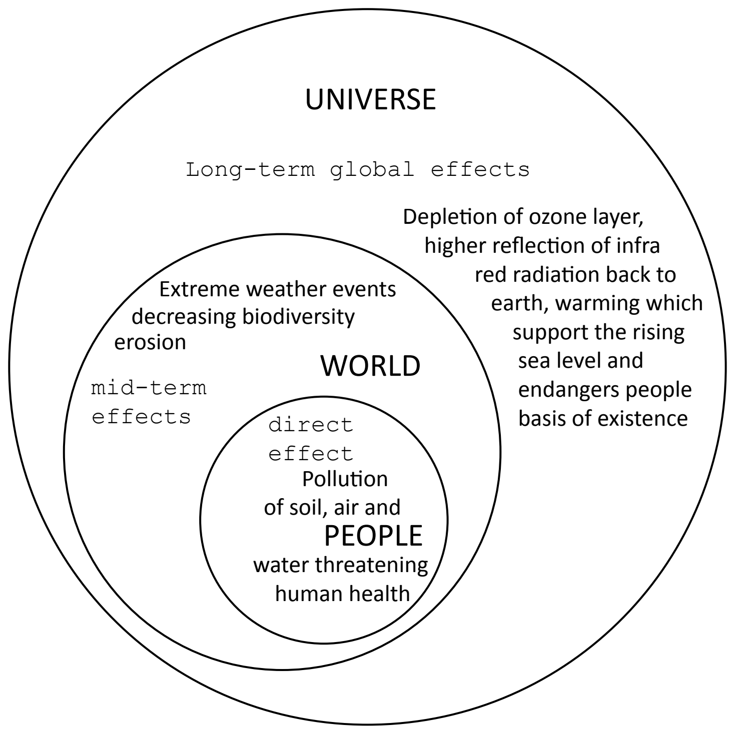


FIG. 1.1 Three levels of ecological impact *(Hildebrand, 2014)*

Anthropogenic interaction with nature provides a living basis for society. Therefore, the impact of humans on the environment is not necessarily problematic. The level of harm, on the other hand, is determined by the type, extent, and consequences of the interference that is either planned (e.g., energy generation, raw materials extraction, land conversion, etc.) or accidental (e.g., Chernobyl and Fukushima nuclear disasters).

Tracing the ecological effects may be a difficult task due to the complex interaction of natural cycles with mankind. While some human actions result in immediate repercussions on nature, other effects cannot be easily linked to their cause. Therefore, the impact on nature can be categorised as direct, medium, or long term global effects. Gradation helps to define the interventions that should be carried out at the level of their cause, having regarded that the improvement can be made only when the interrelation between the cause and the effect has been proven. For example, levelling aims to distinguish between the urban heat island and the stable temperature increase due to global warming, in the case when both phenomena occur at the location of a building. There are building measures at hand to actively reduce heat islands, whereas designers can only react to global warming and generally try to reduce CO_2 emissions with a long-term prospect.

Pollution occurring at a defined spatial level, causing in-situ consequences with immediate effects, is a manifestation of a direct ecological impact. The leakage of toxic substances into water, air, or soil during the production stage of building materials is an example of such a level of ecological impact.

Medium-term ecological effects produce consequences that mark a broader range of changes across time and place. A triggering event firstly changes natural conditions, thus harming human life. Such an example is deforestation, which leads to soil erosion, further worsening of air quality, changes in weather conditions, and other influences. The consequences for human life might not be immediate and directly detectable at the site of the event, but they can be related to certain man-made impacts.

Long-term effects include consequences that occur after a certain time delay and affect the entire globe. Man-made emissions that cause a chain of events (from pollution to global warming, to rising sea levels, to flood occurrence in coastal areas, etc.) can be identified within this category of ecological effects.

This differentiation between levels of ecological impact builds understanding about their intricacies, and paves the way for them to be addressed. The distances in time and place from the generation of a negative effect to its manifestation account for the main factors that influence the type and scope of reaction that is required. While direct harmful consequences require immediate reactions, larger distances in time and space require more profound knowledge, increased responsibility, and a global approach. The time of occurrence also influences the regulatory process; the earlier a harmful consequence is manifested, the earlier a regulation is established to prevent its repetition.

The awareness of the implications of human actions is essential to adequately address environmental pollution and degradation. The type and scope of actions aimed to reduce the negative environmental effects are field-specific. In building design, knowledge of the environmental dimension is fundamental in being able to define technical, social, or economic measures. In that regard, this paper unfolds the platform of facts necessary for the understanding of the progressive anthropogenic impact on the environment, explains the genesis and development of environmental design in wider social conditions, and considers in detail the segments that are most well developed currently. The paper further reveals the main challenges in contemporary building design with respect to the use of natural resources: water, land, energy, and materials, and simultaneously reflects upon possible scenarios for a resource-efficient future.

2 Anthropogenic Impact on the Environment Through History

Ecological systems on Earth encompass living entities and their non-living environments. They function in complex cycles that have undergone tremendous changes over the last million years, together with the shifts in environmental conditions and living matter. Since the beginning of life on Earth, mainland has become water, continents have changed their position and size, temperatures have varied from cold to hot extremes, and living species have disappeared or emerged. All of these changes were accompanied by slow and stable cosmic processes and conditions, and their manifestation and responses (self-regulation) on Earth, because of which the cycles of the past may be considered as consistent. The evidence of such consistent cycles can be found in records of ice cores, boreholes, plants, etc. Nevertheless, the cycles on Earth in the past could also have been interrupted by surprise events such as volcano activation, which often instigated massive changes in ecosystem conditions.

Over the last 12,000 years, a human-friendly climate on Earth has developed. This period began after the last glacial epoch and is called the Holocene or Interglacial period. In this phase, only minor climate shifts, such as temperature variations and less intensive cold periods, e.g., during the 16th and the 17th century (Feulner, 2011), could be experienced.

Tangible traces of the development of civilisations and societies allow for the reconstruction of past systems of human functioning, the ways of using available resources and the impact on nature. Through the centuries, humans and their activities affected natural environments primarily though the transformation of land cover, and when transportation methods became better developed, the exploitation of surface resources (e.g., the wood) increased disproportionately (Hornborg, McNeill, & Martinez-Alier, 2007). New inventions and technological developments, from the 19th century and beyond, intensified extraction and utilisation of natural resources and became the impetus for a new generation of changes made to the Earth's systems, which today are known as anthropogenic impacts on the environment.

From the beginning of industrialisation period, the consumption of resources has been increasing continuously. Consequently, the environmental impact at all levels was growing and the rate of changes in the environment was accelerating. The economic boom of the 1950s offered a whole variety of products that used electrical energy to a broad portion of society. Along with the rising standards of living and comfort requirements, energy consumption increased enormously. The zest in the construction industry led to the massive production of different types of building materials whose ecological performance over the life cycle phases is now questioned. Continuous growth in the consumption of natural resources - non-renewable energy, fresh water, land and raw materials - has been followed by the intensification of the environmental pollution of water, air, and soil with huge amounts of generated waste and emissions. At this time, the relationship between humans and other parts of nature has already been largely broken, as a result of modern lifestyles. In parallel, the global population marked a trend of increase. New artefacts in the built environment and its expansion into the natural environment became new sources of environmental pollution and degradation. Concurrently, the number and intensity of 'surprises', i.e. extreme weather events grew with the increase of global temperature.

To secure continuous functioning of the Earth's systems, it is necessary to address both current patterns in resource consumption, and the future demands. At the same time, it is necessary to deal with the consequences of past anthropogenic actions, such as climate change.

3 Environmentalism and Sustainability

The awareness of connections between people and other living beings, natural resources and the environmental issues represents the core of environmentalism (Armiero & Sedrez, 2014, p.1). As a cultural phenomenon, environmentalism relates to the active involvement of individuals, groups, and organisations, motivated towards the preservation of the planet's diverse systems and values.

Apart from the events and ideas that shaped Western environmentalism, from the 13th century onwards, and the warnings of the 19th century scientists with regard to the threats to nature (Grove, 1992), a collective reaction to the state of the environment was strengthened only during the second half of the 20th century. In Europe, social and political awareness of environmental consequences developed during the 1960s, in left-oriented groups that aimed to draw attention to nature and its proclaimed value, whereas the book *Silent Spring* (Carson, 2002) was deemed to be a trailblazer for environmentalism in the US. On the 22nd of April 1970, Earth Day was celebrated first time. In 1972, the organisation Greenpeace was established, and the Club of Rome published *The Limits to Growth*, drawing a dramatic picture of the near future (Meadows, Meadows, Randers, & Behrens III, 1972). Although the predictions (e.g., shortage of the oil by 1990) were proven to be rather unrealistic, the report's translation into 30 languages demonstrated an international interest for environmental issues.

With the Brundtland Report (Brundtland, 1987), the consequences of mankind's relationship to nature became a worldwide concern, and the use of the term *sustainability* was revived, marking a shift from the original meaning in the context of forestry, where this term was introduced in the 18th century by Hans Carlowitz (1713) to describe the dimension of wood harvest; the amount of wood withdrawn from the forest should not exceed the amount growing back. In the years following the publishing of the *Our Common Future* (Brundtland, 1987), the terms environmentalism, ecology, and sustainability were often used interchangeably, until their notions later became better distinguished. To bring sustainability and environmentalism into context, O'Riordan (1991, p. 7) defined the 'new environmentalism' that aims to "devise a series of strategies that enables people to see how their interests, as well as those of the earth as a whole, are served by reforms that enshrine the triad of sustainability, ecologically appropriate development at the local level, and the provision of basic needs and political rights". In contemporary terms, the word *sustainability* is used in different contexts and scales of society, and its notion is therefore complex. To understand the significance of sustainability nowadays, it is necessary to elaborate upon both the general and field-specific frames of reference to which this term relates.

In general, the verb 'to sustain', according to the Oxford Dictionary, refers, inter alia, to the "cause to continue for an extended period or without interruption" (Simpson & Weiner, 2010). Sustainability therefore represents a prerequisite for the continual progress of global society. Because of the complexity of sustainable direction of human development, sustainability nowadays encompasses aspects of ecology, economy, and social considerations, as well as their interlinkages through culture. In building design, sustainability most commonly relates to the environmental dimension, although the inclusion of other aspects of sustainability is necessary too.

4 Environmentalism in Building Sector

The building sector is responsible for the consumption of about 50% of resources on a global level, as well as the production of about 60% of global waste, and 40% of greenhouse gases (Hegger, Fuchs, Stark, & Zeumer, 2008). Although the environmental impact of buildings increased steadily from the beginning of the period of industrialisation, awareness started to grow only from the second half of the 20th century, when the recognition of environmental risks resulted in different actions that are nowadays considered as retarders of negative trends on Earth (Fig. 4.1).

In general, modern architecture did not operate within natural limitations, state of environment, or ecological consequences of expressed creativity. Instead of ecological issues, priority was assigned to mass production and the opportunities created by it, especially in the early phases of the Modern Movement from the 1920s to the 1950s (Fig 4.2).

TOC

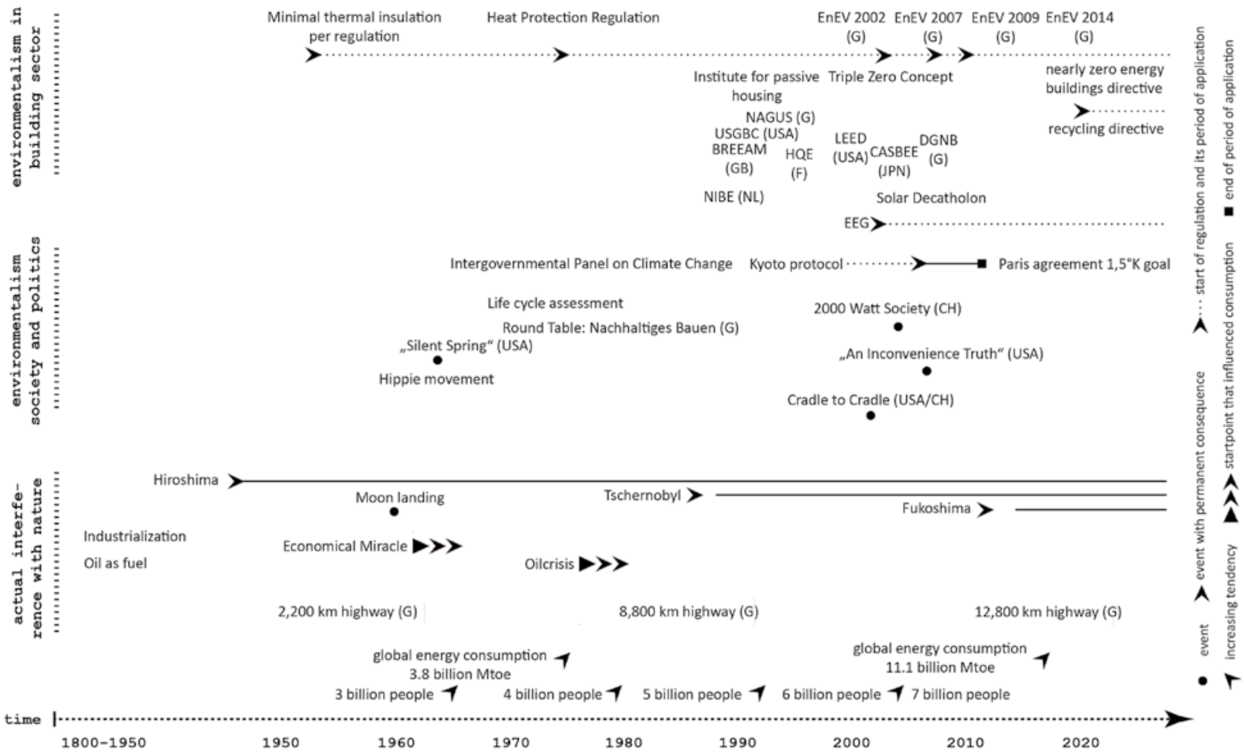


FIG. 4.1 Environmentally significant trends and events, and the responses to them *(Hildebrand, 2014)*

FIG. 4.2 Bauhaus Dessau, Walter Gropius, 1925-26. *(Image by Marcel Bilow)*

The modern movement set a new architectural trend with transparency and uninsulated large glass facades but often caused high energy consumption and discomfort. Environmental issues were not on the agenda in such times.

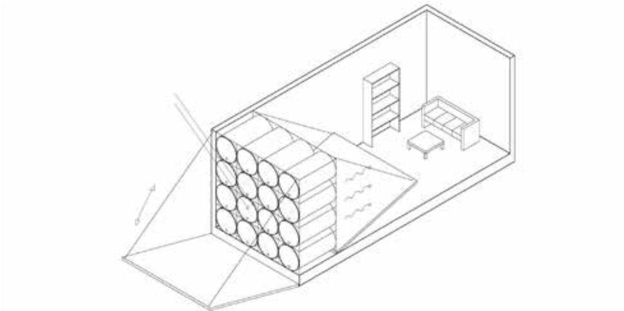
From today's perspective, nevertheless, some developmental trends that influenced the shaping of modern buildings, such as the blossoming of prefabrication, could fit well into the environmental design postulates. To that end, it can be added that some notable modern architects gave an unintended contribution to the development of environmental design. Among them stand Le Corbusier, who included roof gardens and free designing of the ground plan in his five points of architecture; Frank Lloyd Right and Alvar Aalto, who offered modern interpretations of organic architecture; or Oscar Niemeyer, who integrated solar control measures into architectural configuration (Fig. 4.3).

FIG. 4.3 Banco Mineiro de Produção, Belo Horizonte, Oscar Niemeyer, 1953. *(Image by the author)*

High sun radiation in Brazil caused high cooling loads and discomfort in modern style buildings. Niemeyer integrated environmental strategies in his architecture by installing fixed louvres on those facades that are oriented towards the sun.

The enthusiasm for bio-climatic design during the 1960s was articulated in the work of Hassan Fathy, who explored vernacular design principles, or Buckminster Fuller, who relied on the ability of technology to provide a dynamic architectural response to varying external conditions, etc. With the energy crisis of the 1970s, energy consumption in buildings became a relevant political, research, and design topic. Consciousness of resource dependence has raised the interests for energy performance of buildings and possibilities for the generation of useful forms of energy from renewable sources. Some energy-efficient solutions, like active solar systems and energy controls, and passive design strategies were offered (e.g., Steve Baer's inventions, Fig. 4.4), and the number of publications about energy conservation, and technological and design reactions started to increase. During the same decade, material recycling opportunities began to be researched in the US.

The Postmodern Movement transformed the architectural expression and (re)introduced a variety of previous forms. The context of place again became relevant in design, as opposed to preceding International Style, and this further influenced the change in perception of relationship between architectural artefacts and the environment. During the 1980s, the measures aimed to decrease the amount of operational energy in buildings expanded notably. At the same time, research on the ecological impact of building materials (primarily in the field of toxic emissions) was initiated, together with possibilities to reduce the value of their embodied energy. At the end of this decade, the significance of water conservation measures was revealed. In the last decade of the 20th century and the first decade of the 21st century, comprehensive environmental design principles for various building typologies were established, and terms like 'green architecture', 'sustainable architecture', 'eco-friendly architecture', 'eco-tech architecture' (although viewed as an architectural direction, rather than the quality of buildings), 'environmentally conscious design', etc. became extensively used. In parallel, different international methods and building certificates have been developed to measure the level of achieved environmental quality.



A

B

FIG. 4.4 A+B: Detached House, Corrales, New Mexico, Steve Baer, 1973. *(Image A by the author, image B by Steve Baer, Zomeworks)*

An early low-tech approach towards sustainable architecture. During the day, the desert sun heats up water barrels. At night, when it is cold, energy is released to heat the interior. The energy flow is controlled by operable insulated doors on both sides of the façade.

Next to the improvement of the physical quality of buildings, efforts today also aim at improving the energy performance of existing buildings by optimising the design process (e.g., Konstantinou & Knaack, 2013). Other attempts aim to create new business models, for example leasing concepts, in order to align incentives of demand side (investors and users) and supply side (industry and designers). The traditional building world rewards an approach of minimal initial investment to meet the minimal legal requirements. The idea is to shift towards an attitude that rather rewards an optimal environmental performance over the whole life cycle of buildings including the end of life scenarios (e.g. Azcarate-Aguerre et al., 2017) (Fig. 4.5). The difficulty lies, amongst other things, in the long product life span of buildings in comparison to other product service models such as the leasing of cars or printers.

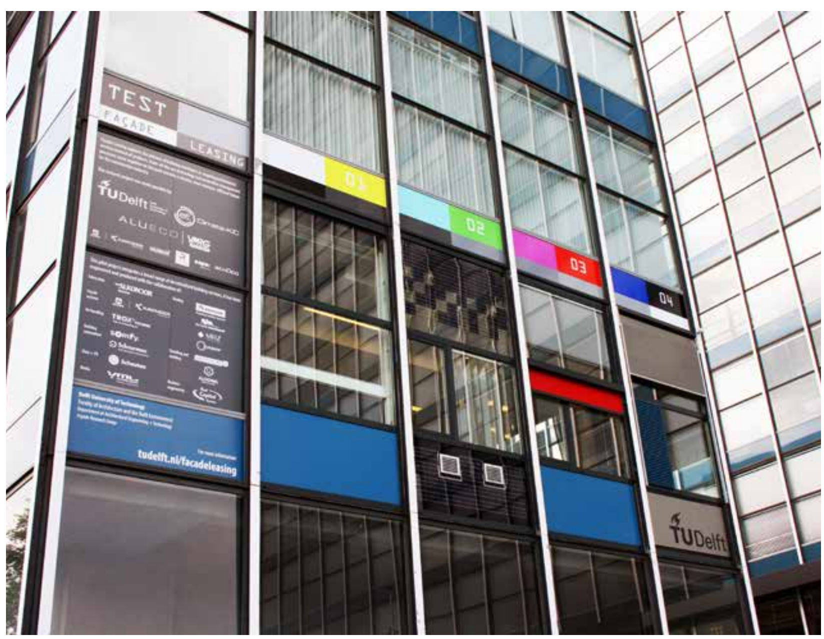


FIG. 4.5 Façade leasing at Delft Technical University. *(Image by Marcel Bilow)*

Testing the value of different façade configurations of the predicted whole life cycle for the refurbishment of a high-rise building on the university campus. The aim is to find new business models for optimal energy performance and CO_2 reduction.

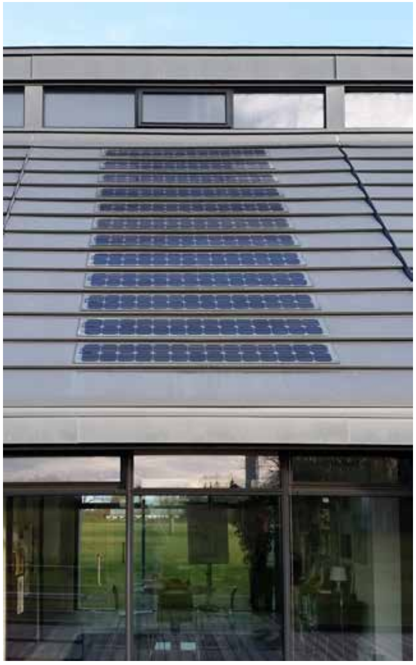
Although the characteristics of spatial context largely inform environmental design strategies, for which reason this approach is accentuated as being place-specific, the consumption of operational energy and the ecological impact of building materials today account for the main universal fields of activity in the framework of environmental building design.

4.1 Energy

Energy in buildings is used for heating, ventilation, cooling, lighting, water heating, etc., i.e. for the operation of different electrical systems and individual appliances, equipment, and machines. The amount of operational energy used in a building for the aforementioned purposes depends on its position, typology, and physical and spatial characteristics, used electrical systems, climatic conditions, occupant's behaviour, etc. Heat losses from ventilation and transmission through the building fabric, together with the gains from the sun and indoor equipment and other heat sources result in energy demand for heating and cooling (McMullan, 2002). Fabric heat losses or transmission heat losses refer to the energy that flows through the building envelope. They are directly dependent on the thermal transmittance of materials and temperature differences between inside and outside, which are expressed by the thermal resistance coefficient U-values. On the other hand, ventilation heat losses depend on the permeability of façade, the size and quality of openings, the nature of mechanical ventilation systems, etc. The location of a building, its orientation, and façade design also define solar heat gains. More generally, location plays the dominant role in defining the type of sources used for building operation and optimising supply and demand.

More than 50% of energy consumed in residential buildings in the European Union is used for space heating (Itard & Meijer, 2008), reaching up to 70% depending on climate variations (BPIE, 2011). Although heating demand was the most significant operational energy issue in the past decades, other forms of energy consumption, such as water heating, cooling, and electrical lighting are also important to address.

Since the 1970s, there has been a tendency to reduce the total amount of operational energy. Accordingly, the terms like 'energy-efficient', 'low-energy', or 'zero-net energy' buildings have emerged. Following the oil embargo in the winter of 1973/1974, a series of energy-related standards were introduced internationally to limit the level of dependence by limiting consumption, such as the German thermal insulation ordinance *Wärmeschutzverordnung* (Heat Conservation Regulation) from 1976, which focused on building envelope and the reduction of its transmission heat losses. Over time, national standards and regulations in European countries became higher and more comprehensive, both regarding energy consumption and comfort provision. Several nationally applicable European building codes were additionally developed to regulate the passive features of a building envelope and to define active energy methods of building operation. The standards aiming to reduce operational energy in buildings have developed into a broad catalogue over the last decade. The adoption of the *Directive 2010/31/EU on the Energy Performance of Buildings* (European Parliament and the Council of the European Union, 2010) marked a significant legal step towards the reduction of operational energy in newly constructed buildings, as well as in buildings undergoing major renovation, and the evidence of the level of operational energy utilisation became supported through labelling.



A

B

FIG. 4.6 Building Integrated Photovoltaics (BIPV) or other means of energy generation is needed to create buildings that are almost energy neutral Balancing energy demand and generation is difficult because it depends on buildings and installations but also on the type of use, comfort demand, and user behaviour. The architectural integration of components is a future challenge for designers. *(Image by the author)*

FIG. 4.7 A+B: Manitoba Hydro, Kuwabara Payne McKenna Blumberg Architects and Transsolar KlimaEngineering, Winnipeg, 2009. *(Images by the author)*

The harsh climate (extreme cold in winter and heat in summer) demands special measures. The building relies on natural energy resources such as geothermal energy and sunlight, which makes it one of the most efficient buildings in Canada. In contrast to most buildings in the region, which are fully climatised, it is 100% naturally ventilated. In combination with the atrium, a solar chimney is used, driving the ventilation system and preheating or precooling air before it enters the offices.

According to this document, from 2020 onwards, it will be mandatory to provide the energy label for tenants and purchasers of buildings. Additionally, public buildings larger than 500 sqm must put the energy label on display. The Directive 2010/31/EU also prescribes that all newly constructed buildings in the EU must be 'nearly zero energy' buildings by the 31st December 2020 (public buildings by the 31st December 2018). This means that more than just the active and passive capacities will have to be exploited to achieve the functional and physical qualities that are required for the current level of comfort while maintaining nearly zero energy consumption to operate the building. The Directive leaves it up to individual EU countries to define national ways for achieving standards and adapting to different climatic conditions, i.e. to set national minimum energy performance requirements.

The reduction of the operational energy of buildings is tightly connected to the consideration of the source of the energy used. In actuality, the source of energy represents a key factor in influencing the ecological impact caused by operational energy utilisation. An energy carrier is subject to treatment before it becomes useful energy, delivered in the form of heat or electricity. The efficiency of each source depends on the effort required for its transformation into a form of energy that is useful for building operations. Where less energy is needed to convert the source into useful energy, that source is considered to be more efficient overall. Besides the efficiency of resources needed to deliver heat or electrical energy to the buildings, the evaluation of their ecological performance in relation to the generation of emissions is equally significant. Therefore, the main classification of energy sources, as renewable and non-renewable, reflects not only their availability over time, i.e. the renewal potential, but also the ecological impact created in different phases of energy flow (from extraction to end-use in buildings). To that end, and not only for the end-use in buildings, some energy sources, such as coal, are being gradually excluded from future energy supply strategies.

By summing up the needs to regulate energy consumption, emission generation, and related climate change mitigation, the European Commission has developed the *Europe 2020 Strategy for Smart, Sustainable and Inclusive Growth,* which targets bringing CO_2 emissions 20% lower than the 1990 level, to reach at least 20% of energy coming from renewable sources and to achieve a 20% increase in energy efficiency (European Commission, 2010). More recently, new targets and policy objectives have been set for 2030, dictating that a 40% cut in greenhouse gas emissions compared to 1990 levels should be achieved, together with at least a 27% share of renewable energy consumption, i.e. at least 27% of energy savings compared with the business-as-usual scenario (European Commission, n.d.).

4.2 Materials

The continuous implementation and upgrade of energy-related regulations, on the one hand, and the development of new technologies and energy systems, as well as the increased use of renewable energy sources on the other, have expanded the basic focus of environmental design towards the comprehensive consideration of the environmental performance of materials. The achievement of material resource efficiency complements the achievement of sustainable development goals (e.g., United Nations, 2015), and relates not only to the reduced use of materials, but also to a range of their characteristics, such as origin, availability, production inputs (e.g., water, energy and raw materials) and outputs (like emissions and waste), possibilities for reuse, and recycling, etc.

The study of the environmental performance of materials is based on the analysis of a series of processes and steps that together constitute a life cycle. Potentially, a material makes a negative environmental impact in every phase of its life cycle, from the acquisition of raw materials, through manufacture, transportation, construction (installation), and actual use and maintenance, to the end of life – deconstruction or demolition, waste processing, and recycling. To determine the environmental impact of a material (or a component) closely, the information regarding the different life cycle phases are needed (European Committee for Standardisation, 2011).

Life Cycle Assessment (LCA) today represents a standard method for the evaluation of the ecological impact of building materials. The Integrated Product Policy, introduced in 1998, accounts for one of the first instruments that emphasised the relevance of ecologically friendly materials and the significance of life cycle assessment (Ernst & Young, 2000). In subsequent years, the results obtained from the LCA studies of different materials resulted in increased awareness about ecological impact and correspondingly in formation of different databases and software tools that sort the results according to the type of impact, allow for comparability, and facilitate design decision-making.

The energy used to produce and eventually dismantle the materials and components stored in a building can be calculated, but is neither measurable nor visible. Because of these properties, it was named *grey* or *embodie*d energy. The amount of embodied energy in a building (per gross floor area unit) depends on the type of used materials and construction system (e.g., Hildebrand, 2014). A number of strategies can be implemented to decrease the embodied energy and hence the ecological impact of materials: selection of materials with a closed cycle (reused and recycled materials); inclusion of deconstruction in scenarios by the type of connections; reduction of material amounts in building construction; utilisation of renewable materials; application of durable materials; etc.

5 Current Challenges in Environmental Design and Development Prospects

Even though the environmental impact of buildings can never be completely removed, by continually developing the principles of environmental design, the negative effects can be addressed more successfully. To that end, and having regarded that the environmental impact of buildings primarily represents the consequence of utilisation of natural resources (energy, materials, water, and land), the achievement and advancement of resource efficiency stand out as leading objectives of contemporary environmental design. Differently from the previously discussed aspects of materials and energy, the use of water and land in the activities connected with buildings has been given less attention to date.

5.1 Water Efficiency

The use of any quantity of fresh water in buildings, for any purpose, results in its pollution. Consumption of fresh water also means pressuring the water resources that, in the light of growing population and climate change, form a huge social and ecological problem. Finally, the use of water in buildings is often connected with the use of energy needed for its heating. Only during the last decade, these water-related building issues have been recognised as a challenge on the level of the European Union (e.g., Commission of the European Communities, 2007; BIO Intelligence Service, 2012). Besides that, water efficiency in buildings has been considered to date at the levels of (most often voluntary) building assessment systems, individual, local or, more rarely, national initiatives and measures, and published recommendations.

Proposed measures for achieving water efficiency in buildings encompass the reduction of the fresh water utilisation, introduction of alternative water resources, closing water loops, and purification of wastewater in situ. To achieve these currently ambitious goals and to overcome existing barriers, a set of actions that supplement the design are necessary, from policy establishment (e.g. regarding water metering), to economic measures and changes of occupants' behaviour.

5.2 Land Efficiency

While land use in the built environment has been comprehensively addressed at urban and neighbourhood scales, its consideration, in cases in which action boundaries actually overlap with the lot boundaries, is noticeably more modest, mainly limited to the building assessment systems (e.g., Comprehensive Assessment System for Built Environment Efficiency (CASBEE)). Ecological effects of site preparation, construction, and subsequent land use for the physical base of a completed building and the activities of its users, point to a necessity for appropriate land use management at the level of a lot. Even though the challenge is highlighted in densely built areas, the significance of micro-scale is, with regard to climate change, general, having regarded that the land and the elements on its surface could mitigate the effects of both stable temperature increase and extreme weather events.

Land should be understood as a base resource that allows for the implementation of measures to regulate the parameters of the outdoor air. As such, the treatment of lot surface and cover can be connected with the measures to reduce operational energy demands. At the same time, land is an indispensable agent that brings nature close to the borders of materialised environment, impacts the wellbeing of building occupants, and, ultimately, provides ecosystem services.

To secure stable ecological functioning of the land and to achieve land efficiency, building design should primarily be concerned with the reduction of land use, the reduction of soil pollution, and the disturbance of its structure and content. Therefore, land-efficient design strategies range from the definition of the building form, to the compensation of the occupied portion of land through the interventions on a building (e.g. Fig. 5.1), to the reduction of the surface of materialised (sealed) areas, to the selection of materials and construction systems and methods, to the consideration of natural and built morphologies in immediate surroundings (for example, to enlarge the unfragmented area of free land), etc. (e.g., Kosanović & Fikfak, 2016). Only when these aspects are successfully articulated in design, a building lot (and potentially a building itself) may become a pedestal for unfolding the advanced principles of regenerative design. For this to happen, an interdisciplinary approach to the design, multi-stakeholder support, and the revision of economy-driven actions at the policy level are necessary (e.g., regarding the economic vs. ecological value of construction land).

The consideration of land use in the activities connected with individual buildings, nevertheless, does not end at site boundaries (e.g., Allacker, de Souza, & Sala, 2014). Clearly, if environmental design aims to lessen

TOC

environmental harm, with regard to all types of natural resources and in all phases of a building life cycle, then the scope of current LCA studies needs to be widened.

FIG. 5.1 Bosco Verticale, Boeri Studio, Milan, 2014. *(Image by the author)*

The vertical forest aims to bring nature back into the city. By creating a green zone around the building, the architects want to foster biodiversity and filter fine particles.

5.3 Energy Futures and Human Needs

Negative energy-related issues in the global system represent challenges to overall sustainable development and as such extend far beyond the boundaries of individual buildings. Therefore, the use of energy is primarily a capital socio-economic subject that, according to the current trends, obviously must continue to look for solutions to reduce differences, alleviate energy poverty, and mitigate negative environmental effects. This also means that the base from which current energy challenges should be addressed, and a sustainable energy future planned, differs between countries and regions, even where the common policy platforms have been developed and agreed (e.g., Attia et al., 2017).

In the future, the use of energy in buildings will, according to the current indications, be increasingly impacted by the regulation of relations between different stakeholders and at different key points of energy chain, from generation, to distribution, to end consumption (Bulut, Odlare, Stigson, Wallin, & Vassileva, 2015). While the advancement (or even only the achievement) of energy efficiency of buildings accounts for the already established environmental priority, further technological development and the definition of suitable multi-actor business models are important next steps towards success in reducing non-renewable and increasing renewable energy use in buildings. On the other hand, if future development will enable proportional relations between the available renewable energy and the needs (i.e. the consumption), the understanding of energy demands and limitations that currently represent the key postulate of efficiency might be significantly changed.

It is certain that there exists a time span over which it will be necessary to carry out a comprehensive transformation of some existing social and economic schemes.

Besides demands, some current discussions on sustainable energy futures imply a shift in understanding the comfort. Regardless of the speculations on whether comfort conditions and their definitions will change over time or not, it is unquestionable that the energy performance of buildings will continue to persist as an indication of activity patterns. Even now, the estimation of energy-related behaviour of building users is an intricate task with often inaccurate results (e.g., Delzendeh, Wu, Lee, & Zhou, 2017), for which reason building professionals must, besides the initial settings adjusted to efficiency goals (preferably above the level of prescribed minimum), also consider the ways in which occupants interact with the buildings. Offering different possibilities to the occupants will increase the chances for an adequate response to individual requirements and to changes that may occur with time.

Predicting the occupants' behaviour in the future characterised by climate change manifestations (like temperature changes) seems even more complex. For a climate-resilient energy future, it is necessary to balance users' needs, functional requirements, and design with the range of climate change-related situations that might occur during the service life of a building.

5.4 Models of Material Efficiency

The environmental impact of buildings is based on flows and stocks of matter and energy. Accordingly, a comprehensive approach to the reduction of any negative environmental impact of materials needs to frame both matter and energy. The traditional linearity of the design, construction, and use processes, i.e. of the life cycle, has been identified as a principal constraint. In essence, the linearity of a material life cycle means that transformed natural resources are used only once from cradle to grave, for which reason the balance between what has been taken from nature, what has been used, and what has been returned to nature, left as waste or forwarded to other man-made processes is largely disturbed. In a linear process, input resources, product, and its output form, display significant disproportions in terms of amounts, quality, and related environmental impacts.

Closing the life cycle has been proposed as a method for reducing the environmental impact of materials with main purpose to reduce the demand for new material resources as well as the impact occurring in different life cycle phases. To support the conceptualisation of a closed life cycle approach, several different terms such as *re-use* and *recycling* have been introduced, while the *biological decomposition* remained as the only positive side of linearity.

However, the success in taking measures to increase material efficiency cannot solely be attributed to designers' decisions and precedent analyses, because of the complexity of subject and the variety of actors that participate in the process. Therefore, the achievement of efficiency of material utilisation is a matter of establishing an acceptable, integrated economic-environmental-social model.

In the Cradle-to-Cradle approach, possible end-of-life scenarios have been introduced into two different entities – technosphere and biosphere (Braungart & McDonough, 2002). Like the Cradle-to-Cradle approach, other approaches dealing with the ecology of materials are integrated with industrial and economic models, e.g., industrial ecology (Frosch & Gallopoulos, 1989), green economy, performance economy (Stahel, 2008), blue economy (Pauli, 2015), and circular economy (Pearce & Turner, 1990; Webster, 2017) that synthetise all previously mentioned concepts according to the '6R' methodology (reduce, reuse, recycle, recover, redesign, and remanufacture (Jawahir & Bradley, 2016)), and currently represents the most relevant conceptual framework for sustainable production and utilisation.

Based on the idea to minimise resource input, waste, emissions, and energy leakage by slowing, closing, and narrowing material and energy loops (Geissdoerfer, Savaget, Bocken, & Hultink, 2017), a circular economy model is also known as circularity. In general, circularity concepts provide a spirited incentive in an ongoing debate about comfortable living standards in planetary boundaries. In a short time, interest in studying circularity has increased significantly, which, from one perspective, raised the relevance of the subject and, from another, generated a multitude of definitions, interpretations, and recommendations on the basis of which the lack of coherence in the accurate description of circularity can be noticed (Kirchherr, Reike, & Hekkert, 2017).

FIG. 5.2 ABNAMRO Pavillion, Amsterdam, de Architekten Cie, 2017 *(Image by Ossip van Duivenbode, 2017)*

The building attempts to be as 'circular' as possible. A large proportion of the used materials are biological (wooden primary structure); components can be reused wherever possible and wall finishing are simple to replace or can even be left away.

The implementation of circular economy schemes is influenced by actors who drive the transition (Lazarevic & Valve, 2017); economic implications of supply chains (Nasir, Genovese, Acquaye, Koh, & Yamoah, 2017); barriers to the application of the '6R' principles, particularly regarding closing the material loops; delivery of new options to the customers (Ritzén & Sandström, 2017), such as using or renting instead of owning; etc. Materials and components based on the principles of circularity shift standard design and construction methods. Having regarded the novelty of the approach, additional research and testing in terms of the performance of offered solutions during the exploitation phase are certain, just like systemic re-formulations of the overall building systems. By including different stakeholders into the estimation of circularity prospects and desired implications, it becomes obvious that there is a necessity to bring the design of new concepts closer to the legal regulations, and that the environmental impact will be sufficiently balanced only when both reliability and acceptance of the concept are achieved. Nevertheless, to unite circularity with business and growth means to join together often conflicting environmental and economic interests and to redefine existing production-consumption relations, for which reasons the contribution of a circular economy to sustainable development seems to be promising.

6 Conclusions

Environmental design must be understood as a continuous developmental process (rather than the desired state of a building) that evolves together with new scientific findings, new technological advancements, new users' demands, and wider environmental, social, and economic conditions. The main existing constraint in environmental design, as argued by GhaffarianHoseini et al. (2013), is the lack of national and international policies, in spite of their proven contribution to the mitigation of negative environmental impact. Although the efforts to frame environmental issues are clear, the absence of a standardised basis reflects negatively on the potential of environmental design to act as an agent that is able to anticipate future challenges such as resource scarcities, and to address uncertainties like climate change. Instead of applying a systemic approach that optimises the use of all types of natural resources, the dominant current concerns of environmental design are energy and materials.

Besides the integration of different measures of environmental design into a holistic framework, the integration of environmental design into wider sustainability frameworks is necessary, where the increased relevance of social issues could in turn result in the improved environmental performance of buildings. In that way, the user factor that has been identified as the key maintainer of the environmental quality of design would be more successfully addressed. It also means that the principles of environmental design may be more comprehensively applied only when suitable wider social and economic conditions are established.

TOC

References

Attia, S., Eleftheriou, P., Xeni, F., Morlot, R., Ménézo, C., Kostopoulos, V., ..., & Almeida, M. (2017). Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe. Energy and Buildings, 155, 439-458. https://doi.org/10.1016/j.enbuild.2017.09.043

Allacker, K., de Souza, D.M., & Sala, S. (2014). Land use impact assessment in the construction sector: an analysis of LCIA models and case study application. The International Journal of Life Cycle Assessment, 19(11), 1799-1809. https://doi.org/10.1007/s11367-014-0781-7

Armiero, M. & Sedrez, L.F. (2014). Introduction. In M. Armiero & L.F. Sedrez (Eds.), A history of environmentalism: local struggles, global histories (pp.1-20). London: Bloomsbury.

Azcarate-Aguerre, J.F., Konstantinou, T., Klein, T., Steensma, S., Guerra-Santin, O., & Silvester, S. (2017). Investigating the business case for a zero-energy refurbishment of residential buildings by applying a pre-fabricated façade module. In T. Laitinen Lindström, Y. Blume, M. Regebro, N. Hampus, & V. Hiltunen (Eds.), Proceedings of the ECEEE 2017 Summer Study on Energy Efficiency: Consumption, efficiency and limits (pp. 1113-1122). European Council for an Energy Efficient Economy (ECEEE). Retrieved from https://pure.tudelft.nl/portal/files/18921561/contents.pdf

BIO Intelligence Service. (2012). Water performance of buildings. Final report prepared for European Commission, DG Environment. Retrieved from http://ec.europa.eu/environment/water/quantity/pdf/BIO_WaterPerformanceBuildings.pdf

Braungart, M., & McDonough, W. (2002). Cradle to cradle: remaking the way we make things. New York: North Point Press.

Brundtland, G. H. (1987). The Brundtland Report. World Commission on Environment and Development.

Bulut, M. B., Odlare, M., Stigson, P., Wallin, F., & Vassileva, I. (2015). Buildings in the future energy system–Perspectives of the Swedish energy and buildings sectors on current energy challenges. Energy and Buildings, 107, 254-263. https://doi.org/10.1016/j.enbuild.2015.08.027

BPIE. (2011). Europe's buildings under the microscope. Brussels: Building Performance institute Europe.

Carson, R. (2002). Silent spring (40th anniversary ed.). Mariner Books.

Commission of the European Communities. (2007). COM (2007) 414 Final: Addressing the challenge of water scarcity and droughts in the European Union. Retrieved from http://www.ipex.eu/IPEXL-WEB/dossier/document/COM20070414FIN.do

Delzendeh, E., Wu, S., Lee, A., & Zhou, Y. (2017). The impact of occupants' behaviours on building energy analysis: A research review. Renewable and Sustainable Energy Reviews, 80, 1061-1071. https://doi.org/10.1016/j.rser.2017.05.264

European Commission. (2010). Europe 2020 – a strategy for smart, sustainable and inclusive growth. Retrieved from http://ec.europa.eu/eu2020/pdf/COMPLET%20EN%20BARROSO%20%20%20007%20-%20Europe%202020%20-%20EN%20version.pdf

European Commission. (n.d.). 2030 energy strategy. Retrieved from https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2030-energy-strategy

European Committee for Standardisation. (2011). EN15643-2, Sustainability of construction works, Sustainability assessment of buildings, Part 2: Framework for the assessment of environmental performance. CEN.

European Parliament and the Council of the European Union. (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. [Online]. EUR-Lex: Access to European Union Law. Retrieved from http://eur-lex.europa.eu/legal-content/EN/ALL/;ELX_SESSIONID=FZMjThLLzfxmmMCQGp2Y1s2d3TjwtD-8QS3pqdkhXZbwqGwlgY9KN!2064651424?uri=CELEX:32010L0031

Ernst, & Young. (2000). Developing the foundation for integrated product policy in the EU. Report. Brussels: European Commission, DG Environment. Retrieved from http://ec.europa.eu/environment/ipp/pdf/ipp_devrep.pdf

Feulner, G. (2011). Are the most recent estimates for Maunder Minimum solar irradiance in agreement with temperature reconstructions? Geophysical Research Letters, 38, L16706. Retrieved from http://onlinelibrary.wiley.com/doi/10.1029/2011GL048529/epdf

Frosch, R.A. & Gallopoulos, N.E. (1989). Strategies for manufacturing. Scientific American, 261 (3), 144-152. DOI: 10.1038/scientificamerican0989-144

GhaffarianHoseini, A., Dahlan, N. D., Berardi, U., GhaffarianHoseini, A., Makaremi, N., & GhaffarianHoseini, M. (2013). Sustainable energy performances of green buildings: A review of current theories, implementations and challenges. Renewable and Sustainable Energy Reviews, 25, 1-17. https://doi.org/10.1016/j.rser.2013.01.010

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., & Hultink, E.J. (2017). The Circular Economy –A new sustainability paradigm? Journal of Cleaner Production, 143, 757-768. http://dx.doi.org/10.1016/j.jclepro.2016.12.048

Grove, R. (1992). Origins of Western Environmentalism. Scientific American, 267(1), 42-47. Retrieved from http://www.jstor.org/stable/24939136

Hegger, M., Fuchs, M., Stark, T., & Zeumer, M. (2008). Energy manual: sustainable architecture. Basel: Birkhäuser.

Hildebrand, L. (2014). Strategic investment of embodied energy during the architectural planning process (Doctoral dissertation). Rotterdam: Delft University of Technology.

Hornborg, A., McNeill, J.R., & Martinez-Alier, J. (Eds.). (2007). Rethinking environmental history: world-system history and global environmental change. Rowman Altamira.
Itard, L., & Meijer, F. (2008). Towards a sustainable Northern European housing stock (Vol. 22). Amsterdam: IOS.
Jawahir, I.S., & Bradley, R. (2016). Technological elements of circular economy and the principles of 6r-based closed-loop material flow in sustainable manufacturing. Procedia CIRP, 40, 103-108. DOI: 10.1016/j.procir.2016.01.067
Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation & Recycling, 127, 221-232. http://dx.doi.org/10.1016/j.resconrec.2017.09.005
Konstantinou, T. & Knaack, U. (2013). An approach to integrate energy efficiency upgrade into refurbishment design process, applied in two case-study buildings in Northern European climate. Energy and Buildings, 59, 301-309. https://doi.org/10.1016/j.enbuild.2012.12.023
Kosanović, S. & Fikfak, A. (2016). Development of criteria for ecological evaluation of private residential lots in urban areas. Energy and Buildings, 115, 69-77. https://doi.org/10.1016/j.enbuild.2015.02.037
Lazarevic, D. & Valve, H. (2017). Narrating expectations for the circular economy: Towards a common and contested European transition. Energy Research & Social Science, 31, 60-69. http://dx.doi.org/10.1016/j.erss.2017.05.006
McMullan, R. (2002). Environmental science in building. Basingstoke: Palgrave.
Meadows, D.H., Meadows, D.L, Randers, J., & Behrens III, W.W. (1972). The limits to growth; A report for the Club of Rome's project on the predicament of mankind. New York: Universe Books.
Nasir, M. H. A., Genovese, A., Acquaye, A. A., Koh, S. C. L., & Yamoah, F. (2017). Comparing linear and circular supply chains: A case study from the construction industry. International Journal of Production Economics, 183, 443-457. http://dx.doi.org/10.1016/j.ijpe.2016.06.008
O'Riordan, T. (1991). The new environmentalism and sustainable development. Science of the Total Environment, 108(1), 5-15. https://doi.org/10.1016/0048-9697(91)90230-C
Pauli, G. (2015). The Blue Economy/Version 2.0: 200 projects implemented; Us$ 4 billion invested; 3 million jobs created. Academic Foundation.
Pearce, D.W., & Turner, R.K. (1990). Economics of natural resources and the environment. Baltimore: The Johns Hopkins University Press.
Ritzén, S., & Sandström, G. Ö. (2017). Barriers to the circular economy–integration of perspectives and domains. Procedia CIRP, 64, 7-12. https://doi.org/10.1016/j.procir.2017.03.005
Simpson, J. & Weiner, E. (Eds.). (2010). Oxford Dictionary. New York: Oxford University Press.
Stahel, W.R. (2008). The performance economy: business models for the functional service economy. In K.B. Misra (Ed.), Handbook of Performability Engineering (pp. 127-138). London: Springer. https://doi.org/10.1007/978-1-84800-131-2_10
United Nations. (2015). Transforming our world: The 2030 Agenda for sustainable development. Retrieved from http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E
Webster, K. (2017). The circular economy: a wealth of flows (2nd ed.). Ellen MacArthur Foundation Publishing. SESSIONID=FZMjThLLzfxmmMCQGp2Y1s2d3TjwtD8QS3pqdkhXZb-wqGwlgY9KN!2064651424?uri=CELEX:32010L0031

Approach to Design for Resilience to Climate Change

Saja Kosanović[1*], Branislav Folić[2] and Ana Radivojević[3]

* Corresponding Author
1 Faculty of Technical Sciences – Architecture Department, University of Priština in Kosovska Mitrovica, e-mail: saja.kosanovic@pr.ac.rs
2 Faculty of Technical Sciences – Architecture Department, University of Priština in Kosovska Mitrovica, e-mail: branislav.folic@pr.ac.rs
3 Faculty of Architecture, University of Belgrade, e-mail: ana@arh.bg.ac.rs

ABSTRACT **The occurrence of frequent shifts in weather conditions and extreme weather and climate events brings numerous direct and indirect consequences for the built environment, increases the possibility for disaster occurrence, and accordingly sets new challenges for contemporary architecture. The design focus on climate change mitigation, i.e. on sustainable and, above all, energy efficient buildings, therefore needs to be expanded to strengthen the capacity of such buildings to withstand climate change manifestations while remaining functional. To design for optimal climate change-related performance of buildings, now and in the future, a resilience scenario is needed. This work analyses climate change complexity and dynamics as key factors that articulate the design strategy for climate-resilient buildings. Based on the relevance of reviewed risks, variability, and uncertainty regarding climate change, this work maps a generic design framework, explains the meaning of 'transposed regionalism', and discusses the relationship between resilience and the adaptation of buildings in (un)predictable climate futures.**

KEYWORDS climate change impact, risk, hazard, vulnerability and exposure, resilience and adaptation scenario, design response

1 Introduction: Design Responses to Climate vs. Climate Change

The complexity of purposes and the typological characteristics of buildings have grown throughout history, but the need to provide shelter from (varying) external conditions persists as a basic characteristic of any built space. Examples of vernacular structures, design strategies, and traditional lifestyles from around the world allow for the examination of past methods of coping with the climate. In climates with significant temperature variations, the lifestyles characterised by daily migrations within the same structure, seasonal migrations between the structures positioned in different climatic regions, or migrations characterised by using movable structures, were traditionally practised. Drainage systems, steep roofs, elevated structures, and seasonal migrations between neighbouring, but differently designed, structures within the same household represented a traditional response to precipitations and their variations. To provide protection from the heat, the following measures were applied in traditional architecture: optimisation of the settlement form density; optimisation of the building orientation, layout, surface to volume ratio, and other envelope characteristics; selection of building materials with suitable thermal properties; thermal mass balancing; utilisation of solar control elements; introduction of passive cooling by natural ventilation; various landscaping techniques; and others. Rainwater was harvested and stored to secure water supply in dry periods. To protect buildings from the cold weather, traditional builders optimised building orientation and envelope characteristics, choosing adequate (and available) materials, designing adequate layouts, and applying heat accumulation techniques and insulation, including the earth sheltering (Kosanović, 2007; Radivojević, Roter-Blagojević, & Rajčić, 2012).

Modern design and technologies brought independence from external conditions, imposed a strong barrier between the building and the outside (Levin, 2003), and changed the way in which climate was considered in design. After a multitude of developed architectural directions, distinct design experiments, and theoretical work - some of which took a climatic approach (e.g., Olgyay, 1963) - a wider tendency to unite traditional techniques and contemporary technologies into climate responsive design emerged towards the end of the 20th century, together with the recognition of existence of unwanted changes in the patterns of the external environment. From this time, however, registered changes in climate patterns became so significant and frequent that the definition of climate as average weather for a particular region and period, usually taken over 30-year interval (NASA, 2005), may be questioned. In these new conditions, the traditional understanding of climate as a stable input for design has lost its credibility, and the notion of 'climate design' has altered. Concurrently, the consideration of climate features in design is no longer a question of achieving energy efficiency and underlying sustainability, but a basic requirement for securing the operability of buildings in the long term.

In providing a design response to climate change, the designers are challenged with:

- unpredictability as a basic property of the climate change phenomenon;
- more probable occurrence of extreme weather and climate events in regions where these events did not exist before, which brings a shift in possible direct influences on buildings;
- more probable damaging impact of climate change on building structure and functioning;
- increased energy demands, increased needs to secure indoor comfort and to prevent negative health implications, as well as the need to revise and reintegrate the methods of designing and maintaining comfort, because of sustainability-related and climate change mitigation-related demands; and
- various environmental, social, and economic aggravating circumstances emerging from climate change and representing the indirect implications to architectural design.

Current literature and research addressing climate change adaptation introduce a great variety of terms, definitions, concepts, and approaches, predominantly from a narrow scientific standpoint. However, it is widely accepted that the success in responding to climate change primarily refers to the success in acknowledging and acting in accordance with its complexity and dynamics. This work aims to explore the fundamental scientific facts regarding climate change risks, variability, and uncertainty, to discuss their relevance in building design and to unfold an integrative approach to providing a comprehensive design response to climate change by mapping a general resilience scenario and proposing a generic resilience framework.

2 Addressing Climate Change Complexity and Dynamics

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014) indicates the widespread impacts on natural and human systems caused by climate changee on all continents. In recent decades, the atmosphere and oceans have warmed, ice sheets and glaciers have lost mass, and sea levels have risen; the amounts of ice and snow have decreased; the global water cycle has been affected; and different extreme weather and climate events have been registered (IPCC, 2014). In the future, the climate will continue to change and affect the Earth's systems, specific to regional scales (Champagne & Aktas, 2016).

Climate change shifts the ways in which people organise their everyday activities and use designed spaces. The expected continuation of climate change, and the changes in intensity and frequency of its manifestations in the future, will increase the time spent indoors (for example, during heat or cold waves) and set new requirements for built space. Given their life expectancy, it is certain that buildings built today will encounter

TOC

substantial climate change manifestations (de Wilde & Coley, 2012). New design needs to respond to both present and future variability and impacts, including heat and cold waves, windstorms, droughts, fires, floods, sea level rise, and even landslides (Pacheco-Torgal, 2012).

The complexity of climate change should be addressed in design through mitigation and adaptation. Only concurrent actions within these two complementary approaches, encompassing low greenhouse gas emissions, ability to adapt to the detrimental impacts of climate change and climate resilience (United Nations, 2015), can provide success in reducing the impacts on ecological, social, and technical systems over different time-scales (IPCC, 2014). In order to design buildings that successfully adapt to climate change and resist its impacts, now and in the future, it is necessary to analyse climate change-related risks, uncertainty, and variability.

2.1 Addressing Climate Change Risks

The particularities and austerity of the impacts of climate change, and its manifestations, emerge from risk that depends on climate-related hazards, exposure, and vulnerability (Crichton, 1999; IPCC, 2014). Therefore, risk assessment represents a useful staring point in conceptualising the design response to climate change (Gupta & Gregg, 2012). To calculate the risks arising from the impacts of climate change, Roaf, Crichton, and Nicol (2009) presented the following formula:

(possible) Hazard x Vulnerability x Exposure = (possible) Impact.

Exposure refers to the presence (location) in "places that could be adversely affected by physical events and which, thereby, are subject to potential future harm, loss, or damage" (Lavell et al., 2012, p. 32), such as in areas prone to floods or landslides. Vulnerability refers to the predisposition of a building to be affected adversely, i.e. to the susceptibility to damages and malfunctioning, as well as to the vulnerability of its users, due to the impacts of climate change manifestations. "Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity" (Wilson & Piper, 2010). The reduction of vulnerability and exposure, therefore, is unequivocally related to design efforts to achieve resilience in a building influenced by climate change.

While vulnerability and exposure refer to ecological, social, and technical systems impacted by climate change, as well as to the buildings, hazards (weather and climate events) originate from nature. In their interaction with (vulnerable and exposed) ecological, social, and technical systems, hazards trigger impacts that potentially transform into disasters (Kosanović, Hildebrand, Stević, & Fikfak, 2014). These impacts emerge as direct or indirect consequences of one or more hazards that may occur at the same time and thus generate conjugated effects. For example, droughts are the consequence of the absence of precipitations; floods are the consequence of rising sea levels, extreme precipitation, or the rapid melting of snow; landslides and mudslides are triggered by extreme rainfall events; the combination of strong winds and rainfall leads to a storm; fire is more probable when strong winds are coupled with extreme heat and absence of precipitation; etc. Therefore, climate-related hazards, consequences, magnitude of consequences, and probability of consequences determine the significance of risk (Gupta & Gregg, 2012), and inform the design strategy and measures.

In building design, where the boundaries of the field of action commonly overlap with the site boundaries, only some hazards (e.g. extremely high or low temperatures) can be addressed comprehensively, while the domains of urban planning and urban design may provide larger contributions to the reduction of risks from other climate-related hazards (such as flooding). Spatial conditioning, limitation, and interdependent relations point towards the need to combat climate change risks by reducing vulnerability and exposure at different levels of the built (social) environment simultaneously. Even if a hazard is not extreme, high levels of vulnerability and exposure will more likely result in the occurrence of disastrous effects (Lavell et al., 2012). Indirectly, hazards can be addressed through some sustainability measures. For example, reducing the greenhouse gas emissions now contributes to future climate change mitigation.

2.2 Addressing Uncertainty and Variability

The Intergovernmental Panel on Climate Change (IPCC, 2014) advises that the benefits from adaptation can be achieved by lowering the existent risks, i.e. by addressing vulnerability and exposure to current climate variability. In Europe, for example, the most common climate and weather-related disasters that occurred in the period from 1998-2008 were floods, storms, extreme temperatures, wildfires, and droughts (Escarameia & Stone, 2013). Major threats that require short-term action include extreme precipitation, extreme summer heat events, exposure to heavy rainfall, and rising sea levels (European Commission, 2013a). While the present climate variability may be described and, therefore, addressed, the challenge arises with the aspiration for present reduction of future risks, especially regarding the probability of occurrence of extreme events that will largely determine building design (Steenbergen, Koster, & Geurts, 2012).

Weather and climate events that have already been experienced at a specific location may not occur again with the same character, intensity, or frequency, or may not occur at all during a building’s lifetime (Guan, 2009; Lavell et al., 2012). On the other hand, vulnerability is particularly high in areas that, historically, have not been affected by some weather or climate event, or by their consequential manifestations (Champagne & Aktas, 2016). The uncertainty in future hazard predictions aggravates the process of embedding resilience into building design, and raises doubt about whether the attributed characteristics will be adequate to resist future climate change and its manifestations, which leads to the conclusion that even the risk to future building performance needs to be included in design process. Near-term actions undertaken to manage risks may affect future risks in unplanned ways and alter their perception (Lavell et al., 2012). The impact of current climate change on social, ecological, and technical systems poses additional risk for the future. Even the description of a future, together with the uncertainty surrounding that description, raises new risks (Eiser et al., 2012). The condition of 'deep uncertainty', characterised by the lack of knowledge or the lack of agreement regarding "(1) models that relate key forces that shape the future, (2) probability distributions of key variables and parameters in these models, and/or (3) the volume of alternative outcomes" (Hallegatte, Shah, Lempert, Brown, & Gill, 2012, p. 2) therefore represent the major issue in responding to climate change in building design. Still, risk assessment results, climate change predictions, projections, or scenarios, i.e. climate change models and simulations, represent the pillar support to design. In this regard, the utilisation of 'robust' methodologies for uncertain conditions may guide design decisions aimed at reducing vulnerability. Besides, building character and diverse duration of service life of different building materials and components require consideration of multiple climate change projections regarding both shorter and longer climate periods (Gupta & Gregg, 2012). In addition, researchers are recognising, accenting the need for, and attempting to develop models that, besides incorporating the risks from future events, include anthropogenic climate change, i.e. actions and trends in social and economic spheres (Roaf et al., 2009), as well as the natural and spatial variability. As the way in which building occupants interact with building systems is likely to change with climate conditions, dealing with the human factor should be taken as a significant design concern (de Dear, 2006; de Wilde & Coley, 2012).

2.3 Addressing Territorial Variability of Climate Change

The variability of climate change is twofold; it relates both to the long- and medium trends of changes (like continued increase of the average temperature, modifications in rainfall patterns, or sea level rise) and the 'surprises', i.e. the extreme events (such as storms or floods) that are not expected far in advance. For both types of manifesting variability, the impacts should be considered on regional, local, and micro scales, because of a wide range of influencing factors, from geographical, developmental, and environmental, to social and economic. For illustration, global warming in Europe is happening faster than in other parts of the world (European Commission, 2013b). According to the projections from several different climate models, the average annual temperature in Europe will increase by 1 – 5.5oC over the course of this century. In Serbia, the average annual temperature increase, calculated for the same period, is 2.6oC (Popović, Đurđević, Živković, Jović & Jovanović, 2009), but the capital city of Belgrade, with a projected average annual increase from 1.8oC to as high as 7.5oC in the worst-case scenario (Agencija za zaštitu životne sredine (Environmental Protection Agency), 2009), could, by the end of the 21st century, become significantly warmer than the average temperatures in both Serbia and Europe. The projected temperature increase for Belgrade is not only due to its geographical position, but also the already modified climatic conditions (Kosanović & Fikfak, 2016). At the micro scale, the level of temperature increase will, like in any built area, vary between the different parts due to urban morphology, land cover, and the existence of urban heat island phenomenon (Emmanuel & Krüger, 2012; van der Hoeven & Wandl, 2015), greenery factor, and traffic characteristics (Fikfak, Kosanović, Konjar, Grom & Zbašnik-Senegačnik, 2017), among others. To respond to the changing climate, therefore, climate models, results of risk analyses, regional design approaches, comprehensive analyses of local and micro (site-based) trends, and impact patterns and the interaction of hazard and vulnerability in situ (European Commission, 2013a; Lavell et al., 2012) must concurrently be taken into account. The whole process can be elaborated by applying different methodologies (e.g. Gupta & Gregg, 2012). Changes in regional climate nevertheless demand a shift in the regional design approach, and learning from tradition and experience of both the subject region and the regions characterised by climate trends, patterns, and events that occur, or are predicted to occur, in a concerned area are particularly valuable in reducing vulnerability.

3 Mapping the Resilience Framework

The provision of design response to climate change dynamics, and dealing with climate change risks, uncertainty, and variability, in order to reduce (present and future) impacts, together represent a very complex challenge. On the basis of the facts provided in previous sections of this work, which draw a map to the resilience scenario, it is possible to identify the critical issues in building design methodology and process, and consequently to organise a generic resilience framework that comprises the following design-related component-actions:

- holistic understanding of the character assigned to a place subjected to climate change;
- implementation of regional and 'transposed regionalism' approaches to design;
- concurrent application of resilience and adaptation as two complementary concepts;
- consideration of present and future climate change risks through the application of a 'robust approach';
- optimisation and integration of building design measures for addressing resilience and adaptation with measures that refer to sustainability (Chapter 4 of this book volume);
- optimisation and integration of measures for resilience to climate change at the building level with measures for resilient and sustainable urban planning and design (Volumes 1, 2 and 3 of the book series *Reviews of Sustainability and Resilience of the Built Environment for Education, Research and Design*); and

– integration of technical with ecological, social, and economic resilience (Volume 1 of the book series *Reviews of Sustainability and Resilience of the Built Environment for Education, Research and Design*).

Under the impact of climate change and the possibility of the occurrence of extreme climate and weather events and their consequences, the character of a place is shifting. Besides a series of input data obtained from risk assessment studies and climate change models, the research (preceding design) of local and micro trends, impact patterns, and the interaction of hazards, exposure, and vulnerability, at a specific location, needs to be carried out. The scope of studies on past and traditional design measures, which informs new design at specific location at which certain climate effects are likely to occur in the future, needs to be widened to include the design responses that have been given at places where those climate effects have already manifested. This 'transposed regionalism' approach to design that is responsive to climate change is especially effective in addressing the long- and medium-term impacts.

In the general context of adaptation to climate change, two main terms are commonly used in literature to depict underlying concepts – resilience and adaptation. The main difference between 'resilience concept' and 'adaptation concept' is that the first relates to the ability of a system and its components "to anticipate, absorb, accommodate, or recover from the effects of a potentially hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions" (Lavell et al., 2012, p. 34), while the latter refers to the "process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities" (Lavell et al., 2012, p. 36). The natures of resilience and adaptation are therefore complementary; they both address risks and uncertainty, and, according to Nelson (2011), both aim to contribute to the stability of human societies and their physical environments. In new design, however, resilience is more likely to take dominance over adaptation, precisely for reasons of uncertainty.

To reduce the effect of uncertainty regarding future climate change, occurrence of extreme events, and their manifestations and consequences, the 'robust approach' has been developed. Though not having an optimal performance in any specific scenario (Bakker, 2015), a robust solution is intended to perform well under different climate change futures (Dittrich, Wreford, & Moran, 2016), including the worst-case or over-pessimistic scenarios that consider extreme climate change. Such prioritising is in agreement with the goal of climate change-resilient design to employ robust rather than optimal solutions (Bakker, 2015; Lavell et al., 2012). In addition to this safety-margins strategy, the robust approach encompasses the application of no-regret strategies that address incorrect forecasts and enable good performance that is independent of the climate driver, strategies that are flexible and adjustable, as well as strategies that reduce decision-making time horizons, i.e. offer short-term solutions, which, at building level, refer to the design for shortened service life, especially in highly exposed areas (Dittrich at al., 2016; Hallegatte et al., 2012). To this end, Gupta and Gregg (2012, p. 23) pose the question of whether building adaptation should be implemented incrementally, e.g. every 50 years? In the wider context of resilience, that relates not only to the technical-technological response to climate change, but also to the comprehensive social demands of an adaptive society. Glass, Dainty, and Gibb (2008) introduce the terms 'super-resilient buildings' and 'anything-could-happen-anytime attitude', in order to explain how buildings have to accommodate a wide range of changes throughout their service life, and not only those that directly originate from climate change manifestations.

In the resilience framework, and depending on experienced or probable (predicted) threats, the direct response to climate change is embedded in functional, structural, and aesthetic building concepts, site layout and landscaping, envelope design, comfort provision, selection of building materials and components, etc. and, optimally, in sustainability-related decisions. A systems view, on the other hand, allows for the identification of tension between different spatial scales (Lavell et al., 2012) and therefore for meeting the hazards and impacts generated beyond site boundaries. Building location, and the building itself, can be easily affected by a wide range of external hazardous circumstances, due to the following: spread floods; intensified (outspread) urban heat island effect; damages to municipal resource supply and waste management systems; cuts in accessibility to the critical infrastructure and food supply; jeopardised sanitation and hygiene conditions; increased air pollution; erosion and the activation of large-scale landslides and mudslides; changes in land cover; species migrations; occurrence of invasive species; biodiversity loss; and others. All-round resilient architecture, therefore, aims to respond successfully to both hazards directly affecting the site, as well as the hazards arriving from outside the site boundaries. For this reason, the interdependence of projects (da Silva, n.d.) needs to be recognised at different scales, and the measures for resilience to climate change at building level need to be optimised and integrated with the measures for resilient and sustainable urban planning and design.

4 Discussion and Conclusions

After sustainability, the pursuit of resilience adds another dimension to design projects, gives additional challenges to architects, and redefines the complexity of the design process and methodology, by requiring transdisciplinary and a systemic approach, as well as the inclusion of various correlating agents that determine the future behaviour of a building subjected to climate change. The main objective of a design response to climate change is to reduce the risk that this phenomenon carries, i.e. to successfully overcome the problem of multi-scalar uncertainty of climate change. To achieve the recognised goal, a significant amount of input data, atypical to common design practice, should be used.

Although it seems that it is the uncertainty that informs climate change resilient building design, this condition may be eased by the utilisation of climate models and tools. As it is, however, necessary to take a local- and micro-scale design approach, suited to the specific context of a place affected by climate change, it can be concluded that providing an all-round design response is currently possible only for a limited number of locations. Clearly, further development of climate models and tools that will be usable by designers, especially in developing countries, represents a technical necessity with social justification, having regarded that the buildings represent socio-technical systems, i.e. that the technical resilience ultimately rests with social resilience.

The uncertainty about climate change manifestations, in particular extreme events that carry the highest risks for buildings, as well as the insufficient availability of climate models, and the discrepancy in terms of their accuracy regarding future climate change projections, may be recouped in the design process by adopting a robust approach, time-scaling of the overall building design or of its components, and by reviving regional climate design, which, in the context of climate change, can be renamed as 'transposed regionalism'. Climate-related lessons, gained from experiences at distant places, may be successfully transferred to a place where similar climate change manifestations are happening now or are expected in future, especially when it comes to responding to the medium- and long-term trends of changes.

In addition, the provision of a successful design response to climate change, as recognised by the large body of literature, is conditioned by learning and collaboration. To this end, Lavell at al. (2012) note that, if learning was a central pillar of adaptation efforts, robustness would increase over time. Besides necessary knowledge and an holistic understanding of disaster risk, Da Silva (n.d.) acknowledges the importance of collaboration and partnership with other professionals, policy makers, and decision makers, while Hallegatte et al. (2012) stress the need for comprehensive capacity building, for example by establishing local expertise centres. In all cases, climate change changes the common architectural practice and, just like sustainability, brings research closer to design.

References

Agencija za zaštitu životne sredine (Environmental Protection Agency). (2009). *Izveštaj o stanju životne sredine u Republici Srbiji za 2008. godinu* (Report on the State of Environment in the Republic of Serbia for 2008). Beograd: Ministarstvo životne sredine i prostornog planiranja RS.

Bakker, A. M. R. (2015). *The robustness of the climate modelling paradigm*. Vrije Universiteit. Retrieved from: https://research.vu.nl/ws/portalfiles/portal/1333903

Champagne, L.C. & Aktas, B.C. (2016). Assessing the resilience of LEED certified green buildings. *Procedia Engineering* 145, 380-387. https://doi.org/10.1016/j.proeng.2016.04.095

Crichton, D. (1999). The risk triangle. In: J. Ingleton (Ed.), *Natural Disaster Management* (pp. 102-103). London: Tudor Rose.

da Silva, J. (n.d.). *Shifting agendas: response to resilience – The role of engineer in disaster risk reduction*. The Institution of Civil Engineers 9th Brunel International Lecture Series. Retrieved from http://publications.arup.com/publications/s/shifting_agendas_response_to_resilience

de Dear, R. (2006). Adapting buildings to a changing climate: but what about the occupants? *Building Research & Information,* 34, 78–81. http://dx.doi.org/10.1080/09613210500336594

de Wilde, P. & Coley, D. (2012). The implications of a changing climate for buildings. *Building and Environment,* 55, 1-7. https://doi.org/10.1016/j.buildenv.2012.03.014

Dittrich, R., Wreford, A. & Moran, D. (2016). A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward? *Ecological Economics,* 122, 79-89. https://doi.org/10.1016/j.ecolecon.2015.12.006

Eiser, R.J., Bostrom, A., Burton, I., Johnston, M.D., McClure, J., Paton, D., van der Plight, J. & White, P.M. (2012). Risk interpretation and action: A conceptual framework for responses to natural hazards. *International Journal of Disaster Risk Reduction,* 1(2012), 5-16. https://doi.org/10.1016/j.ijdrr.2012.05.002

Emmanuel, R. & Krüger, E. (2012). Urban heat island and its impact on climate change resilience in a shrinking city: The case of Glasgow, UK. *Building and Environment,* 53, 137-149. https://doi.org/10.1016/j.buildenv.2012.01.020

Escarameia, M. & Stone, K. (2013). *Technologies for flood protection of the built environment – Guidance based on findings from the EU-funded project FloodProBE*. Retrieved from: http://www.floodprobe.eu/partner/assets/documents/Floodprobe-Guidance_10_12_2013.pdf

Hallegatte, S., Shah, A., Lempert, R., Brown, C. & Gill, S. (2012). *Investment decision making under deep uncertainty – Application to climate change*. Policy Research Working Paper 6193. The World Bank. Retrieved from: https://openknowledge.worldbank.org/bitstream/handle/10986/12028/wps6193.pdf?sequence=1

European Commission. (2013a). *Adapting infrastructure to climate change*. Commission Staff Working Document SWD 137 final. Retrieved from: https://ec.europa.eu/clima/sites/clima/files/adaptation/what/docs/swd_2013_137_en.pdf

European Commission. (2013b). *The EU Strategy on adaptation to climate change*. Retrieved from: https://ec.europa.eu/clima/sites/clima/files/docs/eu_strategy_en.pdf

Fikfak, A., Kosanović, S., Konjar, M., Grom, P. J. & Zbašnik-Senegačnik, M. (2017). The impact of morphological features on summer temperature variations on the example of two residential neighbourhoods in Ljubljana, Slovenia. *Sustainability,* 9 (2017), 122. DOI: 10.3390/su9010122

Glass, J., Dainty, J.R.A. & Gibb, F.G.A. (2008). New build: Materials, techniques, skills and innovation. *Energy Policy,* 36, 4534-4538. https://doi.org/10.1016/j.enpol.2008.09.016

Guan L. (2009). Preparation of future weather data to study the impact of climate change on buildings. *Building and Environment,* 44, 793–800. https://doi.org/10.1016/j.buildenv.2008.05.021

Gupta, R. & Gregg, M. (2012). Using UK climate change projections to adapt existing English homes for a warming climate. *Building and Environment* 55, 20-42. https://doi.org/10.1016/j.buildenv.2012.01.014

IPCC. (2014). *Climate change 2014: Synthesis report*. Contribution of working groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: IPCC. Retrieved from: https://www.ipcc.ch/report/ar5/syr/

Kosanović, S. (2007). *Istraživanje mogućnosti za promenu ekoloških uticaja zgrada na okruženje* (A study of the possibilities for change of environmental impact of buildings). (Magistarski rad). Beograd: Arhitektonski fakultet Univerziteta u Beogradu.

Kosanović, S. & Fikfak, A. (2016). Development of criteria for ecological evaluation of private residential lots in urban areas. *Energy and Buildings,* 115, 69-77. https://doi.org/10.1016/j.enbuild.2015.02.037

Kosanović, S., Hildebrand, L., Stević, G. & Fikfak, A. (2014). Resilience of inland urban areas to disasters occurred due to extreme precipitations. *Open Urban Studies and Demography Journal,* 1(2014) (Suppl 1-M5), 41-51. DOI: 10.2174/2352631901401010041

Lavell, A., Oppenheimer, M., Diop, C., Hess, J., Lempert, R., Li, J., Muir-Wood, R. & Myeong, S. (2012). Climate change: new dimensions in disaster risk, exposure, vulnerability, and resilience. In: Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (Eds.), *Managing the risks of extreme events and disasters to advance climate change adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)*. (pp. 25-64). Cambridge: Cambridge University Press.

Levin, H. (2003). Designing for people: What do building occupants really want? Submitted for presentation as a Keynote Lecture at 'Healthy Buildings 2003' -- Singapore, December 7-11, 2003. Retrieved from: http://www.seedengr.com/What%20do%20building%20occupants%20really%20want.pdf

NASA. (2005). *What's the difference between weather and climate*. Retrieved from: https://www.nasa.gov/mission_pages/noaa-n/climate/climate_weather.html

Nelson, R.D. (2011). Adaptation and resilience: responding to a changing climate. *Interdisciplinary Reviews: Climate Change* 2(1), 113-120. DOI: 10.1002/wcc.91

Olgyay, V. (1963). *Design with climate: Bioclimatic approach to architectural regionalism* (4th ed.). Princeton University Press.

Pacheco-Torgal, F. (2012). Eco-efficient construction and building materials research under the EU Framework Programme Horizon 2020. *Construction and Building Materials,* 51, 151–162. https://doi.org/10.1016/j.conbuildmat.2013.10.058

Popović, T., Đurđević, V., Živoković, M., Jović, B i Jovanović, M. (2009). Promena klime u Srbiji i očekivani uticaji.(Climate change in Serbia and expected impacts). *Peta regionalna konferencija „EnE09 – Životna sredina ka Evropi" Beograd, 4-5 jun 2009* (Fifth Regional conference "EnE09 – Living environment towards Europe", Belgrade, June 4-5, 2009). Retrieved from http://www.sepa.gov.rs/download/EnE09_T_%20Popovic_%20V_DJurdjevic%20i%20dr_Pr%20kl%20u%20Srbija%20i%20uticaji.pdf

Radivojević, A., Roter-Blagojević, M. & Rajčić, A. (2012). Preservation of vernacular architecture in Serbia – authenticity versus thermal comfort issues. In: J. Jasieńko (Ed.) *Structural analysis of historical construction: Proceedings of the International Conference on Structural Analysis of Historical Constructions, SAHC 2012, 15-17 October 2012, Wrocław, Poland* (pp. 2750-2759). Wroclaw: Dolnośląskie Wydawnictwo Edukacyjne.

Roaf, S., Crichton, D. & Fergus, N. (2009). *Adapting buildings and cities for climate change: A 21st century survival guide* (2nd ed.). Architectural Press.

Steenbergen R.D.J.M, Koster, T. & Geurts, P.W. (2012). The effects of climate change and natural variability on wind loading values for buildings. *Building and Environment,* 55, 178-186. https://doi.org/10.1016/j.buildenv.2012.03.010

United Nations. (2015). *Paris Agreement*. Retrieved from: http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

Van der Hoeven, F. & Wandl, A. (2015). *Hotterdam - How space is making Rotterdam warmer, how this affects the health of its inhabitants, and what can be done about it*. Delft: TU Delft, Faculty of Architecture and the Built Environment.

Wilson, E. & Piper, J. (2010). *Spatial planning and climate change*. Abingdon: Routledge.

Understanding Fire and Protecting the Buildings

Marijola Božović[1*] and Milan Mišić[2]

* Corresponding Author
1 Higher Technical Professional School, Zvečan, e-mail: marijola.bozovic@gmail.com
2 Higher Technical Professional School, Zvečan, e-mail: milan.misic@pr.ac.rs

ABSTRACT **To achieve effective protection of a building, it is necessary to understand fire as a complex physical and chemical phenomenon. This work describes the aspect of the uncontrolled combustion process, the conditions and probability of combustion formation, the basic parameters of fire within certain development phases, and its dynamics in time and space. However, to understand the combustion process itself is not enough for successful fire control and thus for avoiding material damage and threats to human safety. In this regard, this work indicates what active and passive fire protection measures are necessary in the building planning process, and, using the example of the Republic of Serbia, reviews laws and regulations, thereby providing a basis for understanding the content and structure of the integral building fire protection project.**

KEYWORDS fire, risk, fire phases, fire parameters, building protection, active and passive measures

1 Introduction

The development of new technological processes and techniques; utilisation of flammable materials; new building materials, elements, and components (Meacham, Poole, Echeverria & Cheng, 2012); existing building heritage (Bernardini, 2017); a number of external social, economic (Jennings, 2013), and environmental (Crichton, Nicol, & Roaf, 2009; Kolbert, 2016; California Department of Forestry and Fire Protection, 2017) factors and causes; and the concentration of material assets in a small area, inevitably carry a danger for the occurrence of fire in buildings. It is, however, certain that the appropriate measures can reduce the number of fires, as well as the extent of their consequences. Taking measures means engaging appropriately in the carrying out of a wide range of activities, not only by the bodies that have jurisdiction over fire protection, or professionals and experts, but also by every subject participating in the processes of design, construction, and utilisation of buildings, equipment, and devices.

Considering that it is not possible to predict where and when a fire will happen, in recent years, there have been great scientific research efforts to understand the processes of occurrence, development, and spread of fire so that a comprehensive set of knowledge has resulted in the emergence of a new engineering discipline called fire engineering. Fire engineering offers more advanced methods of predicting the development of fire and its impact on buildings (Purkiss, 2007).

Fire protection includes a set of organisational-technical activities that can be grouped into preventive, repressive, and sanctioning measures. The realisation of effective preventive protection requires a high degree of knowledge about the basic concepts and definitions of uncontrolled combustion processes, as well as the conditions and probability of their formation.

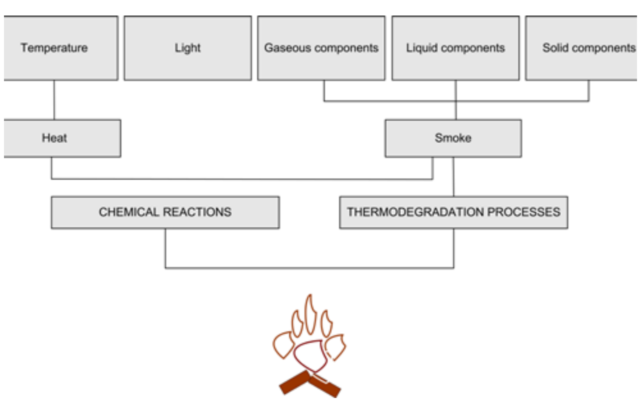
2 Basic Concepts and Definitions of Fire

Every year, about 2.5% of residential buildings worldwide are damaged or destroyed due to the occurrence of fire. The casualties in fire events are not caused only by flame and smoke, but also from the devastation of structures that are not capable of withstanding escalated high temperatures. The research into the emergence and development of the combustion process began in the 17th century, when the interest in finding ways to control fire was born. In order to reduce the risk by undertaking preventive measures, scientists investigated possibilities to predict fire occurrence. It is known today that preparatory (preventive) fire protection measures must be embodied in a building design before the construction process starts (Bisby, Gales, & Maluk, 2013).

Unlike widely elaborated, controlled combustion, this work hereinafter focuses on uncontrolled combustion processes known as fires. A non-stationary combustion process that takes place in time and space is at the basis of the fire. In general terms, the conditions for the occurrence of an uncontrolled combustion process can be divided into necessary and additional conditions.

Necessary conditions are the presence of flammable matter, oxidising agents and ignition sources. However, the fulfilment of these conditions does not necessarily mean that combustion will start. For instance, flammable materials (furniture, clothes, etc.) and oxidisers (oxygen from the air) are always present in residential buildings, and often the ignition sources (such as the flame of a lighter or matches, heated stove plates, flame gas stoves, etc.), but the fire rarely occurs. To create a fire, it is necessary to provide *additional conditions* caused by the physical and chemical properties of the combustible matter, characteristics of the ignition source, nature of the oxidiser, and other factors. This means that the basic principle in preventive fire protection must be based on the exclusion of the additional conditions necessary for the formation of the combustion process.

Every fire is followed by the formation of gaseous, liquid, or solid combustion products, and the release of heat and light emissions (Fig 2.1). Chemical reactions and thermodynamic processes occurring during a fire event depend on the composition of combustible material. When a gas burns, there is only a chemical reaction. However, when free gas mixtures and solid substances are burning, thermodegradation processes are also present. As a result of the chemical reactions and thermodegradation processes, heat is released. Subsequently, the temperature in the combustion zone and the surrounding environment is increased, the light is emitted, and the products of combustion are formed.



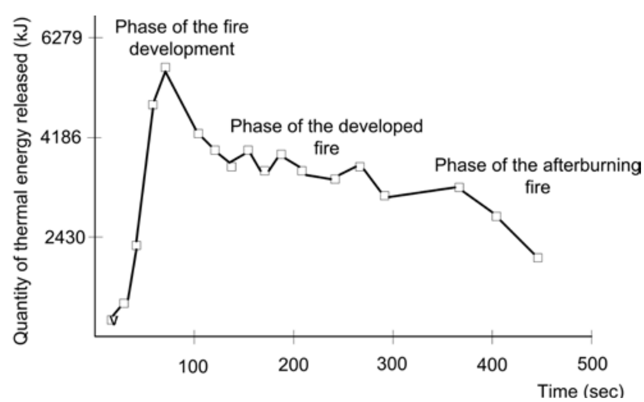


FIG. 2.1 Reactions and processes following the fire occurrence

FIG. 2.2 Fire development stages

The fire *hotspot* is a space, i.e. the area of the most intense combustion. Hotspot performance is influenced by the presence of flammable substances, the continuous inflow of air, i.e. oxygen, and the continuous heat release necessary to maintain the combustion process. Disruption of any of these conditions results in combustion termination.

Fire hotspots are a relative term. In the initial stage of development, the fire focus is on small part of the room or on some objects within that room (initial hotspot). If the fire has spread to the whole building, the hotspot may be the room initially affected.

The fire development process is viewed through three characteristic phases (Fig 2.2). The *fire growth phase* is characterised by the continuous expansion of the initial fire source, catching over 80% of present flammable material. The *phase of fully developed fire*, after reaching the maximum burning rate of the present mass fire load, is characterised by the constant presence of the flame and constant burning of the mass. The *decay phase* is characterised by a rapid reduction in the burning rate of still unburned combustible materials and elements of building structure by smouldering.

Any uncontrolled combustion is followed by the appropriate distribution of gas fractions of the room of fire origin and surrounding environments. In an enclosed space, the inflow of external air to the combustion zone and the removal of formed gaseous combustion products are achieved through the openings, i.e. as a result of a difference between internal and external pressure. The pressure of combustion products in the upper parts of the room is higher than the atmospheric pressure, while it is lesser in the lower layers. At a certain height, the pressure inside the room is equal to the atmospheric pressure, i.e. its difference is zero. The surface of equal pressures is called a neutral zone or plane. In the case of indoor fires (Section 3), the process of exchanging masses of gaseous fractions and the position of the neutral plane are conditioned mainly by the position, height, and volume of the room, as well as the number and position of present openings (e.g. doors, windows, ventilation openings, etc.). In addition to the aforementioned existing conditions of exchange of mass fraction of gaseous fractions, the fire duration and thus its thermal effect on structure and technologies are also conditioned by present fire load.

Thermal fire load is the value of total heat energy that can be freed from the combustion of the combustible material present in the room or open space (SRPS U.J1.030: 1974). The fire load also includes the inflammable structural elements of the buildings.

All flammable substances in the room and those incorporated in the building structure are understood as the *mass fire load*. Depending on the layout of the mass fire load, all rooms, regardless of the purpose, can be divided into two groups. The first group consists of rooms in which the mass fire load is located in one or more parts of the floor area. In this case, combustion takes place only in certain parts of the floor space, not generating the general zone of gasification and combustion of materials. The second group includes rooms in which the mass fire load occupies a larger part of the floor area, so combustion occurs on the entire surface producing the general zone of gasification and combustion of materials.

Every fire occurs on a certain surface, i.e., in a certain area that is conditionally divided into combustion zone, thermal action zone, and smoke zone. Precise limits between these zones cannot be drawn.

The *combustion zone* coincides with the volume of the flame torch in which the processes of thermal decomposition of solid flammable substances, evaporation of liquids, and the combustion of gases and vapours are ongoing. In an enclosed area, the combustion zone is usually limited by the building structure. The combustion zone is linked to the *thermal action zone,* characterised by the heat exchange between surfaces of the flame and surrounding environment, flammable material, structure, etc. (Drysdale, 2011). The heat exchange between the fire source and the surrounding environment is achieved by conduction, convection, and radiation (Fig. 2.3).

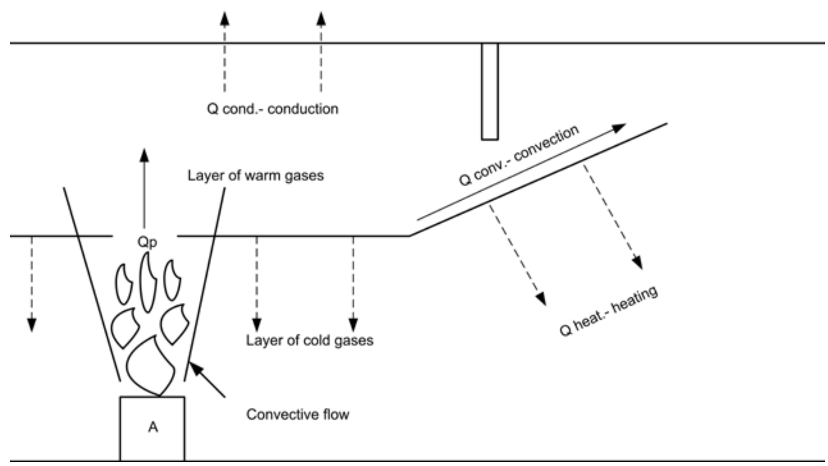


FIG. 2.3 Heat exchange between fire hotspot and surrounding environment

In the initial phase of indoor fire development, transfer of the heat from affected to adjacent rooms is done by conduction through the building structure and components. Until the moment of intense smoking, radiation is the primary mode of spreading the heat from flame surface to affected surrounding space. After a certain degree of smokiness is reached, flame heat radiation is weakened. In developed indoor fires, heat transfer by convection is more emphasised than in open space.

Smoke is a dispersive system of gaseous, liquid, and solid combustion products, generated by the decomposition of flammable matter. Due to the content of certain toxic substances, smoke has a harmful effect on human health. Furthermore, smoke reduces visibility, causes feelings of disorientation in the space, has certain corrosive properties, etc. *Smoke zones* formed by fire have their own characteristics. The extent of the smoke zone in a room affected by fire is conditioned by the physical and chemical characteristics of fire-affected flammable substances, expansion of combustible products, and mass exchange of gaseous fractions with the outside environment. Combustion products rise in the form of convective currents above the combustion zone, and form a smoke layer in the upper part of a room (below the ceiling). As a result of the adequate pressure increase, fire heated electricity combustion products flow through different passages and openings into the external environment or adjacent rooms.

3 Fire Classification

A fire can be classified according to the place of occurrence, material resistance during combustion, development stage characteristics, and the heat emission velocity (Fig. 3.1).

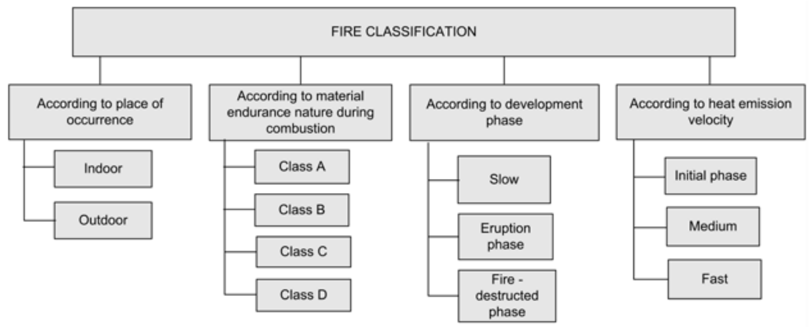


FIG. 3.1 Fire classification

3.1 Indoor Fires

An indoor fire is one that develops in an enclosed space, in one or more premises of a building. Under certain conditions, indoor fires may be converted into outdoor fires. This most often occurs when parts of a building are destroyed in fire, or when a flame reaches the external environment.

Indoor fires are subdivided into open and closed fires. *Open fires (Class IIa)* are characterised by the high speed of the flame front moving in the direction of partially opened windows, passages, and other room openings, which results in flame expansion to adjacent rooms and upper floors. In open fires, the speed of the combustion of flammable substances depends on physical and chemical properties, location in the room, and the existing conditions for exchange of mass gaseous fraction between the affected room and surrounding environment. Open fires are usually divided into two subgroups. The first includes fires in rooms with ceilings up to 6 metres high (such as in residential buildings, schools, hospitals, or administrative buildings), with fresh air inflow and the removal of gaseous combustion products at the same level. The second subgroup includes fires emerging in spaces with a ceiling height above 6 metres (e.g. sport halls, storages, industrial buildings, etc.), with openings for fresh air supply and the exhaust of gaseous combustion products at different levels. In case of fire, there is a fall of pressure in the height, and consequently, an intensive exchange of gaseous fractions mass between the affected space and the surrounding environment, as well as the high burning rate of present mass fire load.

Closed fires (Class IIb) occur in rooms/spaces with fully closed openings. A particular danger in these fires is the presence of substances that contain a large percentage of oxygen, or the presence of materials with highly flammable substances. The combustion of these substances and materials takes place at a high speed, even in the complete absence of an oxidiser.

3.2 Outdoor Fires

Outdoor fires are understood as the processes of uncontrolled combustion developed in open space, i.e. outside the building. Nonetheless, an outdoor fire may also occur at the external part of a building enclosure or at other external building parts, due to spreading from an indoor space, spreading from the exterior environment towards the building, or the conditions at the very location of such exterior building parts. Outdoor fires may be divided, conditionally, into:

- *Fires with progressive enlargement (Class Ia)*, also known as expanding fires. These fires expand at a variable speed and in different directions, depending on the conditions at the initial fire spot, the size of formed flame, the exchange of heat, and the mass of gaseous fractions, the speed, and direction of wind, etc. The size and direction of the fire front primarily depend on the distribution of mass fire load and the environmental parameters (wind and other weather characteristics);

- *Fires with nearly constant size after the termination of development stage (Class Ib)* are also known as non-expanding or spatially limited fires. In the development stage, however, Class Ib fires can spread to surrounding buildings, or develop into expanding fires;

- *Massive fires (Class Ic)* mostly occur in forests, in large warehouses housing solid and liquid combustible substances, or in blocks with buildings at high fire risk.

4 Fire Dynamics and Basic Parameters

Fire parameters are determined based on their influence on the environment (Jovanović & Tomanović, 2002), and are considered in the context of time. While studying fire parameters, their interdependence and connection with environmental (such as meteorological) parameters, fire load parameters, conditions for the exchange of mass gaseous fractions, and the spread of fires at the site should not be neglected.

Fig. 4.1 presents fire development phases with the dynamics of basic fire parameters (Jovanović & Tomanović, 2002). The upper diagram shows the dynamics of combustion of mass fire load through all three fire development phases, where Curve 1 represents the loss of the mass fire load, and Curve 2 indicates the speed of mass fire load loss. The middle diagram shows a change in the height of the flame (Curve 3), the concentration of oxygen in the room affected by the fire (Curve 5), and the concentration of combustion products (carbon monoxide and carbon dioxide) in the room affected by fire (Curve 4). The lower part of the figure provides a graphic illustration of the temperature regime in the room affected by the fire (Curve 6), then the change of the heat flux of the flame (Curve 7), the exhaust of air that touches the combustion zone through the openings (Curve 8), and the position of the neutral plane (curve 9), all on a timescale (Jovanović & Tomanović, 2002).

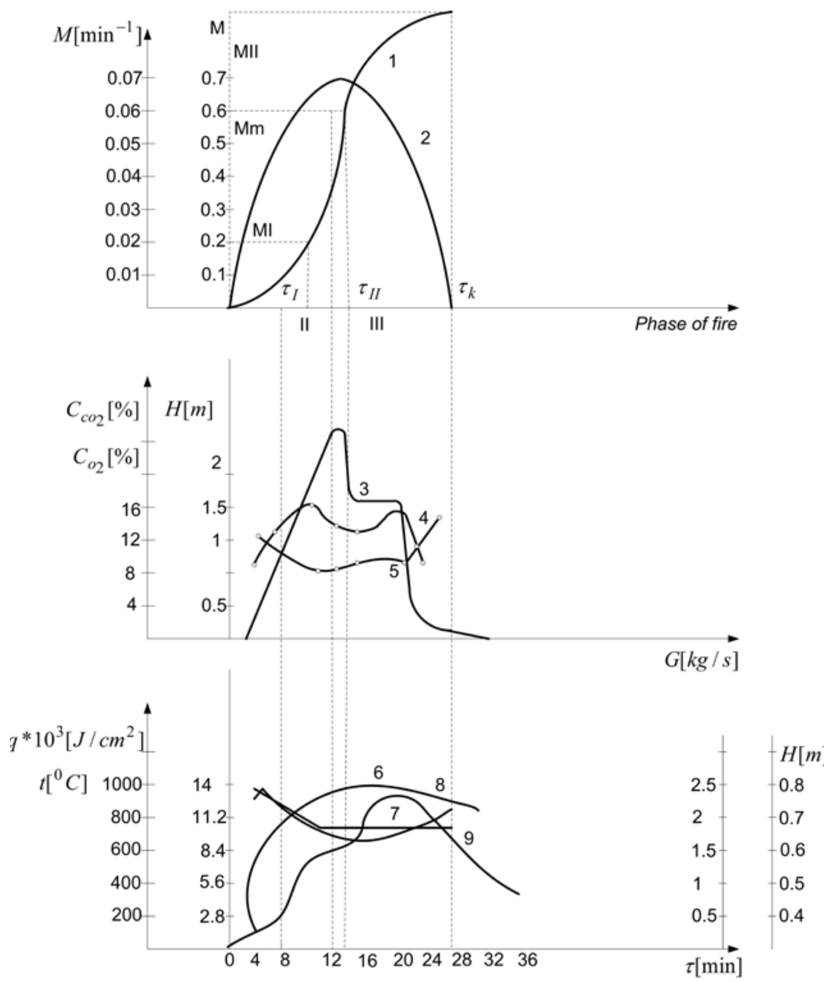


FIG. 4.1 Phases of fire development with the dynamics of basic fire parameters *(Jovanović & Tomanović, 2002)*

First phase

In the first phase of fire development, which is characterised by the continuous expansion of the initial hotspot over 80% of the mass fire load, the increase in the average room temperature, up to 200°C, is accompanied by increased air expenditure. After that, the expenditure of air slowly decreases. At the same time, the level of the neutral plane decreases in the opening region, resulting in a reduction of the surface area of the opening through which it touches the fresh air, i.e., increasing the surface area of the opening through which the formed mixture of combustion products and air leave the room. Due to the reduction of the surface for influx of fresh air, the volume of oxygen that touches the combustion zone reduces (up to 8%) with an increase in the volume of carbon dioxide in the mixture of combustion products and air leaving the room (up to 13%).

This is explained by the fact that, in temperature range of 150-200°C, there are turbulent exothermic decomposition reactions of the flammable substances, which are accompanied by a combustion increase rate under the influence of fire released heat. The amount of heat released in this time unit depends on the lower thermal power of the combustible material, from the combustion surface, the mass speed of material combustion per surface unit, and the incomplete combustion coefficient. In case of fire in an enclosed space, the heating of the present flammable materials and building structure is caused by heat exchange through conduction, convection, and radiation. Regardless of the mode of heat exchange, the time interval of the first fire phase entirely depends on the burning speed of the present mass fire load and the spread of the flame. Depending on the exchange conditions of gaseous fire mass and the surrounding environment, as well as of the composition and arrangement of mass fire load in an enclosed space, the duration of the first phase of the fire varies within the limits of 2-30% of its total length. At the end of the first phase, the temperature in the combustion zone increases rapidly, the flame height increases and catches most of the flammable materials and structures, and the concentration of oxygen decreases with the increase in the concentration of carbon dioxide, carbon monoxide, and other combustion products. These processes are directly dependent on the speed of combustion of a mass fire load affected by fire.

Second phase

In the second phase of the fire development, after reaching the maximum burning rate of the present mass fire load, the process is characterised by the constant presence of the flame and the constant speed of mass loss. During this period, all the aforementioned fire parameters reach extreme values. The maximum values are reached for the average room temperature, the concentrations of products of complete and incomplete combustion in the room, and mixtures of combustion products with the air leaving the room, the height of the flame that penetrates through the holes, its thermal radiation, and the air flow speed in the combustion zone. At the same time, the position of the neutral plane, and thus the fresh air inflow through the lower parts of the hole in the formation zone of the combustible mixture, as well as the oxygen content in the room, fall to a minimum. In this phase, all flammable and highly inflammable materials and materials are ignited, and the combustion of the combustible mixture takes place in the flame outside the room.

With the rise of temperature, the limit resistance of certain structures to the effect of fire is achieved. This is followed by their overheating, crack formation, and collapse. Due to the heat radiation of the flame, the risk of spreading the fire to neighbouring, fire-intact buildings increases.

Third phase

The third phase of the fire development is characterised by a rapid decline in the burning speed of still burning materials and components of the building structure, and their appearance in the form of smouldering. The temperature of the surrounding environment remains high for a long time. During the cooling period, some parts of the building may collapse. The thermal decomposition of the flammable materials can occur without any visible manifestations of the burning process (pyrolysis), smouldering, or combustion with occurrence of flame.

For instance, in a room with openings for the exchange of mass gaseous fractions, two processes can simultaneously occur: combustion of flammable substances near the openings with the appearance of flames, and pyrolysis in the interior of the room, which is conditioned by a reduced concentration of oxygen due to limited air inflow. In a room area near the opening, after thermal decomposition and gasification, flammable materials ignite simultaneously over the entire combustion surface at a high speed. If a fire hotspot is inside the room, two processes unfold simultaneously: the flame front goes in the direction of the opening and the combustion of fire affected materials behind the flame front. With an open fire present in the room, the speed of mass loss, the time of reaching the maximum combustion speed, and the total duration do not depend on the initial ignition co-ordinates. These parameters depend on the exchange conditions of gaseous fractions mass in the room affected by fire and surrounding environments, and from the physical and chemical characteristics of mass fire load.

5 Fire Protection Measures

The term *fire protection measures* refers to the determination of methods and procedures for preventing or eliminating the risk of fire on human lives, material goods, and the environment, while *safe conditions* are determined by the norms contained in the legal or technical regulations.

Preventive measures in achieving fire protection aim to prevent the outbreak of fire and reduce its consequences on people and material assets. One of the most important fire preventive activities is the implementation of fire protection measures at all spatial levels, from a region to a building. Fire protection measures aim to eliminate the causes of fire outbreak, prevent the occurrence and spreading of the fire, and ensure adequate means of fire extinguishing.

The majority of fires in urban areas occur in buildings. When the fire breaks out, the safety of people depends on their preparedness and the successful performance of the evacuation routes. In the past, evacuation was given the greatest importance; it was considered that if the routes are safe from smouldering and fire spreading, then timely and successful evacuation is possible (Kawagoe, 1958). Since the middle of the last century, the standards based on laboratory research have gradually developed. To date, unquestionable progress has been made, but the process has not yet been completed.

The development of fire protection standards, regulations, and practice is based on state interest and the interest of assurance companies

(Vidaković, M. & Vidaković, B., 2008). The state has a clear interest to protect people, material goods, and private capital, and for that purpose uses the following instruments: penal policy for non-compliance with international and domestic standards and regulations, e.g. CEN, ISO, IEC, SRPS (JUS); education programmes and actions; technological and technical protection measures based on laboratory tests; fire extinguishing measures carried out by fire-fighting and rescue units; legal inspections of the causes of occurred fires; judicial function; and national-level statistics envisaged to collect data on previous fires and accidents, so as to gain knowledge and prevent the occurrence of similar events in future.

The interest of insurance companies is aimed at preserving and increasing capital, based on better prevention and safeguarding of funds, through: standards; associations; statistics; tariffing; system of insurance conditions; risk management; preventive actions and preventive funds; education funding; elaboration of the nature of risk and possibilities of the maximum damage; determination of the fire cause; statistical data bases formation; development of new recommendations for legal regulations through laboratory tests; etc.. Fire-fighting activities are also performed by insurance companies that cover fire damages.

Fire protection represents a basic requirement as defined by the European Directive on Construction Products (CPD) (Council Directive 89/106/EEC), while more detailed conditions are prescribed by the legislation of individual member states and adapted regulations of candidate members, e.g. the Republic of Serbia ("Sl. glasnik RS", 132/2014 and 20/15). In 2011, the Directive 89/106/EEC (1988) on the harmonisation of laws, regulations, and administrative provisions of the member states relating to construction products was replaced by Regulation (EU) No 305/11.

International organisations such as the CEA (The European Insurance and Reinsurance Federation) and the CFPA-Europe (The Confederation of Fire Protection Associations Europe, of which Serbian non-governmental organisation DITUR is the full member) deal with the system of quality and reliability of fire protection systems, as well as the philosophy of fire fighting. As the world, and especially Europe, becomes more connected and intertwined (Božović, Živković, & Mihajlović, 2017), all contemporary threats need to be addressed multilaterally, just as in the case of functioning of the mentioned organisations.

5.1 Fire Protection in the Republic of Serbia

The Fire Protection Law of the Republic of Serbia ("Sl. glasnik RS", 111/2009, 132/2014, 20/2015) regulates and defines basic requirements for fire protection during planning and construction phases, and introduces *the main fire protection project* (Section 5.2) into the binding content of the building project documentation. Here, the obligations to estimate fire risks and calculate fire load are prescribed, which significantly influence the effectiveness of the fire safety of a building. The latest amendments to the 2015 law stipulate that the control over the application of preventive fire protection measures should be done in design, construction, and exploitation stages of buildings.

In addition to the Fire Protection Law, fire safety on a national level is further controlled by other regulations that address tall buildings, specific building types, infrastructure such as access roads, etc., as well as by the non-binding technical recommendations. There are also a number of technical regulations referring to electrical and gas installations, hydrant networks, fire detection and alarm systems, fire extinguishing equipment, smoke and heat extraction installations and systems, explosive gas and steam detection systems, and others.

Fire protection measures begin with the development of an investment program for construction, i.e. with the analysis of conditions for the construction of a building of a specific purpose. The National Law on Planning and Construction ("Sl. glasnik RS", 132/2014) prescribes that the investment program must be made on the basis of previous analyses and other experts' findings, inter alia regarding the conditions for fire protection. However, the method of analysing conditions and designing fire protection measures in the preparation of investment-technical documentation has not yet been defined.

5.1.1 Conceptualising the Fire Protection

The conceptualisation of fire protection precedes the development of the main fire protection project (Section 5.2). The conceptual fire protection of a building elaborates upon the optimal solution of complying with the fire requirements of the SRPS (JUS) and ISO standards, as well as insurance requirements for risk reduction, including insurance premiums.

The development of the conceptual fire protection project starts with the analyses of regulations tackling different spatial levels, the conditions at the location, and the purpose of the planned building: residential, educational, health care, cultural, entertainment, sport and recreation, trade, services, industry, etc. (Živković, 2011).

The Fire Protection Law requires that *spatial and urban plans*, as well as the decisions supplementing them with regard to fire protection measures, must provide: sources of water supply and the capacity of urban water supply network for fire extinguishing; distance between the zones envisaged for housing and public purposes from the zones envisaged for industrial facilities and special purposes; access roads and passages for fire-fighting vehicles; safety zones between buildings to prevent fire spreading, safety distance between buildings or their separation regarding fire; and the possibilities for evacuation and rescue.

TOC

Conditions for building construction on a specific cadastral parcel contained within the regulations are twofold, and relate to urban-technical and special requirements. Issued *urban-technical requirements* contain the data on urban and technical possibilities and construction restrictions. *Special requirements* include requirements and approvals from legally authorised bodies and organisations regarding municipal infrastructure and supply networks, protection of natural assets, immovable cultural properties, water management, traffic conditions, sanitation, fire and other conditions for protection against natural disasters, and the conditions for environmental damage prevention.

A fire protection concept for a building must address the above requirements and conditions to draw a solution that reduces the possible fire impact from the external environment on a proposed building, and vice versa, i.e. it eliminates the causative agents of fire, disables fire transfer (spreading) and enables easy, fast, and efficient localisation of a fire if it occurs. This means that the effective fire protection measures are those that are embedded in the urban and architectural concepts of a designed building. The optimal fire protection solution for a specific building reflects the optimal solution for fire protection at the urban level. Only when fire protection measures are integrated on different spatial levels will the protection be truly maximised. This fact gains additional importance in the context of climate change manifestations.

Furthermore, the effective fire protection of a building has to comply with the preconditions prescribed by the Fire Protection Law of the Republic of Serbia (fully adopted from the Annex I of the European CPD Directive 89/106/EEC) as the basic requirements to be fulfilled during the construction phase, regarding:

- maintenance of the load capacity of a building structure for a certain period of time;
- prevention of the spread of fire and smoke within the building;
- prevention of the spread of fire to neighbouring structures;
- enabling secure and safe evacuation of people.

To fulfil all of above-motioned requirements, besides complying with the regulations, standards, and other legal acts in the field of fire protection, it is necessary to conduct a fire risk assessment as the input for the definition of fire protection measures for structures, materials, installations, and protective systems and devices.

According to Milutinović and Mančić (1997), fire protection measures can be divided into:

- *Active measures*, including installation of alarm systems for fire detecting and reporting; incorporation of the smoke control and removal systems; installation of systems and devices for automatic fire extinguishing; providing mobile equipment for initial fire extinguishing; control of flammable substances; providing access to fire-fighting intervention; and fire protection management system; and

- *Passive measures*: division of a building space into fire sectors; evacuation planning; providing fire resistance to building elements and structures; and control of the flammability of elements and structures.

5.2 Main Fire Protection Project

The main fire protection project contains:

- *General conditions of fire protection;*
- *Fire risk analysis,* including designed characteristics of the building (purpose, layout, macro location, micro location, architectural characteristics, structural characteristics, applied materials); fire load; categorisation of the building according to the specific fire load; categorisation according to the type of technological process; possible fire class in the building; fire risk in the building (minimum required time of fire resistance, risk of explosion);
- Urban, architectural and structural *fire protection measures*;
- *Fire extinguishing system*: hydrant fire extinguishing network (external hydrant network, inner hydrant network); stable fire extinguishing system (sprinkler installations); mobile fire extinguishing equipment;
- *Electrical installations* - general and fire detection and alarm systems;
- *Lightning installation;*
- *Forced evacuation from the building;* and
- *Organisational measures for fire protection.*

According to the Fire Protection Law ("Sl. glasnik RS", 111/2009 and 20/2015), all listed segments should be organised into the following parts of the main fire protection project documentation: technical report; calculations; graphical documentation; and the bill of quantities.

Technical report contains: information about the location of a building; building description; fire risk assessment; division of a building into fire sectors; definition of evacuation routes; selection of construction materials on the basis of fire resistance; selection of interior materials with special requirements in terms of fire resistance; assessment of the risk of fire from technological processes and used or stored materials; description of the installations for automatic fire detection and alarming, detection of explosive and flammable gases, as well as the description of stable and mobile installations and fire extinguishers; defined evacuation routes for people and assets; selection of mobile fire-fighting equipment; and others.

Calculations basis of the main fire protection project presents the values for fire load for different fire sectors within one building, capacity of evacuation routes, time required for evacuation, etc.

Graphical documentation of the fire protection project comprises: a situational plan marked with neighbouring buildings and roads; plans of all floors and the roof; characteristic longitudinal and transversal sections with marked fire sectors; disposition of processing technological equipment and equipment belonging to fire extinguishing installations; and schemes of the systems for fire detection and alarming, gas detection, lightning protection installations, automated fire extinguishing systems, smoke and heat exhaust systems, ventilation systems, etc.

Finally, the main fire protection project contains *the bill of quantities* for the equipment and fire protection devices.

5.2.1 Fire Risk Calculation

Fire risk for a building is calculated according to the relevant technical regulations and standards in order to determine the need for the installation of stable systems for fire extinguishing when the obligation of installation is not defined by a special regulation. It depends on the possible intensity and duration of the fire, as well as the constructive characteristics of the bearing elements of the building (the resistance of the construction to the influence of high temperatures), and is calculated on the basis of the following formula (Erić, 2003):

$$Ro = \frac{[(Po * C) + Pk] * B * L * \check{S}}{W * Ri}$$

Here, *Ro* represents fire risk for the building; *Po* is the coefficient of fire load of building contents; *C* – coefficient of combustible contents in the building; *Pk* –fire load coefficient of the material embedded in building structure; *B* – coefficient of size and position of the fire sector; *L* – coefficient of extinguishing start delay; *Š* – coefficient of the fire sector width; *W* – coefficient of fire resistance of the load-bearing structure of the building; and *Ri* – coefficient of risk reduction.

The *fire risk of the building contents* (hazards for people, equipment, stored goods, etc.) (*Rs*) is calculated as:

$$Rs = H * D * F$$

Here, *H* represents the coefficient of hazard for people; *D* – property risk coefficient; and *F* - coefficient of smoke effect.

5.2.2 Fire Risk Assessment

When classifying buildings into fire hazard categories, the following elements are considered: fire risk of the building; significance and size of the building; convenience of the building location; and vicinity of the local fire department. The fire threat to the building, that is, the fire risk, is the basis for the fire protection design.

The assessment of fire risk can be done by using the following factors:

- fire load, which depends on the type of building and, in this respect, the quantities and calorific value of combustible material;
- combustibility of raw materials and materials used in the building, determined by the possibility of ignition and combustion speed, where the combustion rate represents a very important factor, as it also affects the speed of fire spreading;
- properties of combustible material on which the formation of smoke and gases depends, and on the basis of which it is possible to know if smoke is formed as a result of combustion, as well as congestion and corrosive gases;
- layout of rooms, number of floors, and communication routes, and in connection with this, the division of the building into the fire sector, which directly impacts the spreading and transmission of the fire;
- possibility of destruction that depends on the sensitivity of installed materials, machines, and devices;
- concentration of values that depends on the value of materials, installed machines, devices, etc.;
- danger to people possibly affected by smoke, gases, and fire heat, with the emphasis on the concentration of people; and
- intervention time, consisting of three important time periods: time until fire detection, time until fire fighters' arrival, and the time required for fire extinguishing.

To reduce the vulnerability of a building against fire, it is necessary to anticipate appropriate fire protection measures: designing and installation of external and internal hydrant networks; distribution of mobile equipment and fire extinguishers; designing an automatic fire alarm system; planning of the appropriate number of evacuation doors; ensuring that all evacuation routes are always free; and designing the electrical installation according to the conditions of exploitation of the building.

5.2.3 Evacuation Calculation

In the event of a fire in a building, panic followed by very serious consequences may occur. Therefore, general preventive measures may also be considered as those concerning the rapid abandonment of the affected space. Here, building location is of particular importance, followed by access points, corridors, exits, or communications, all of which must ensure both safe movement and safe evacuation.

Evacuation is the removal of persons at risk from a dangerous place to a safe place. It is calculated for all persons who occupy the building. The basic parameter that determines the effective evacuation is the time in which it can be successfully performed. In the absence of appropriate domestic regulations with mandatory application, SPRS (JUS) TP 21 is used for the calculation of evacuation time (Mijović, 2002).

6 Discussion and Conclusions

Fire protection should be organised in accordance with the latest scientific knowledge and the engagement of all responsible and interested stakeholders. This is a basic precondition for the successful protection of human life, material goods, and the environment (Hasofer, Beck, & Bennetts, 2007). Fire protection challenges can be answered by implementing appropriate activities and procedures, as well as taking preventive fire protection measures, which would lead to an increase in fire safety. Given the possible consequences on people and material goods, problems related to fire protection certainly represent the most serious problems when it comes to the safety of buildings. Fire safety implies the implementation of preventive fire protection measures aimed at preventing the occurrence of fire in a building. Unlike the preventive measures, the choice of adequate repressive protection is conditioned by a proper assessment of a possible class of fire and the basic parameters of its development within certain development phases, i.e. its dynamics in time and space, which is in addition to the geometry of the space, the mass fire load, the linear fire development rate, etc., conditioned to a large extent by the influence of the corresponding parameters of the external environment. If a fire occurs in a building, it is necessary to prevent its rapid spread, effectively evacuate people, and prevent the transfer of fire to the surrounding areas.

Effective preventive protection first requires a high degree of knowledge of the uncontrolled combustion process, as well as of the fire development process. The resistance of structural elements of a building is very important for the overall assessment of its integrity. The building should be constructed from such structural elements that, in case of fire, will be stable for a certain period of time. To properly assess the fire risk, identified dangers leading to the fire and the undertaken preventive measures should be addressed through a systemic approach and by understanding its complexity. The fire risk assessment is a complex process requiring the setting up of a multidisciplinary team of experts in the fields of electrical engineering, mechanical and civil engineering, architecture, technology, fire protection, and other relevant occupations (Woodrow, Bisby, & Torero, 2013).

In the Republic of Serbia, the harmonisation with the EU regulations and standards is still on-going. Performing inspection and supervision of the implementation of legal solutions, and raising awareness and culture on the fire safety of all citizens, will create a safer living and working environment for all. The measures aimed at protecting people and property from fire will yield results only in the case of the coordinated and combined activity of all responsible stakeholders in society.

References

Bernardini, G. (2017). *Fire safety of historical buildings: Traditional versus innovative "behavioural design" solutions by using wayfinding systems.* Springer International Publishing.

Bisby, L. A., Gales, J. & Maluk, C. (2013). A contemporary review of large-scale non-standard structural fire testing. *Fire Sci. Rev.*, 2 (1), 27.

Božović, M., Živković,S. & Mihajlović, E. (2017). Integrated system of occupational safety and health and fire protection of the fire rescue brigades members. *International Journal of Injury Control and Safety Promotion* (in press).

California Department of Forestry and Fire Protection. (2017). Current cincidents – Current fire information. Retrieved from: http://www.fire.ca.gov/current_incidents

Crichton, D., Nicol, F. & Roaf, S. (2009). *Adapting buildings and cities for climate change* (2nd ed.). London: Routledge.

Drysdale, D. (2011). *An Introduction to Fire Dynamics.* (3rd ed.). John Wiley & Sons, Inc.

Erić, M. (2003). *Protivpožarna i preventivno-tehnička zaštita.* [Fire and preventive-technical protection]. Čačak: Jel &Mil.

Hasofer, A.M., Beck, V.R. & Bennetts, I.D. (2007). *Risk Analysis in Building Fire Safety Engineering.* London: Routledge.

Jennings, R. C. (2013). Social and economic characteristics as determinants of residential fire risk in urban neighborhoods: A review of the literature. *Fire Safety Journal*, 62 (Part A), 13-19. https://doi.org/10.1016/j.firesaf.2013.07.002

Jovanović, D. & Tomanović, D. (Eds.). (2002). *Dinamika požara* [Fire Dynamics]. Niš: Fakultet zaštite na radu.

Kawagoe, K. (1958). *Fire behaviour in rooms.* Report 27. Tokyo: Building Research Institute, Ministry of Construction.

Kolbert, E. (2016). Fort McMurray and the fires of climate change. *The New Yorker*, 05/05/2016. Retrieved from: https://www.newyorker.com/news/daily-comment/fort-mcmurray-and-the-fires-of-climate-change

Meacham, B., Poole, B., Echeverria, J. & Cheng, R. (2012). *Fire Safety Challenges of Green Buildings.* Final Report. Quincy, MA: The Fire Protection Research Foundation.

Mijović, B. (Ed.). (2002). *JUS TP 21 - Tehnička preporuka za zaštitu od požara stambenih, poslovnih i javnih zgrada.* [Technical recommendation for fire protection of residential, commercial and public buildings]. Beograd: Savezni zavod za standardizaciju.

Milutinović, S. & Mančić, R. (1997). *Zaštita zgrada od požara.* Niš: Fakultet zaštite na radu.

Mišić, M., Tošić, M. & Popović, Z. (2016). Generalized inverses of a linear combination of Moore-Penrose Hermitian Matrices*, FILOMAT*, 30 (11), 2965-2972.

Purkiss, J.A. (2007). *Fire Safety Engineering Design of Structures.* (2nd ed.). Elsevier Ltd.

"Sl. list SFRJ". (1974). *SRPS U.J1.030. Požarno opterećenje i požarni zahtev.* 36/76.

"Sl. glasnik RS". (2014). *Zakon o izmenama i dopunama zakona o planiranju i izgradnji*, 132/2014.

"Sl. glasnik RS". (2014). *Zakon o zaštiti od požara*, 111/2009, 132/2014.

"Sl. glasnik RS". (2015). *Zakon o izmenama i dopunama zakona o zaštiti od požara*, 20/15.

The Council of the European Communities. (1989). Council Directive of 21 December 1988 on the approximation of laws, regulations and administrative provisions of the Member States relating to construction products (89/106/EEC). *Official Journal L 040, 11/02/1989, 0012 – 0026.*

Vidaković, M. &Vidaković, B. (Eds.). (2008). *Požar i arhitektonski inžinjering.*[Fire and architectural engineering]. Beograd: Arhitektonski fakultet.

Woodrow, M., Bisby, L.A. & Torero, J.L. (2013). A nascent educational framework for fire safety engineering. *Fire Saf. J.,* 58, 180–194.

Živković, S. (Ed.). (2011). *Organizacija zaštite od požara.*[Organization of fire protection]. Niš: Fakultet zaštite na radu.

Sustainability and Resilience _
(In)Consistencies in Two Design Realms

Saja Kosanović[1*], Alenka Fikfak[2] and Branislav Folić[3]

* Corresponding Author
1 Faculty of Technical Sciences – Architecture Department, University of Priština in Kosovska Mitrovica, e-mail: saja.kosanovic@pr.ac.rs
2 Faculty of Architecture, University of Ljubljana, e-mail: alenka.fikfak@fa.uni-lj.si
3 Faculty of Technical Sciences – Architecture Department, University of Priština in Kosovska Mitrovica, e-mail: branislav.folic@pr.ac.rs

ABSTRACT **Sustainable design and design for resilience to climate change emerged independently from each other, but their acknowledged correlation gets an increasing importance. This chapter investigates interrelations between sustainable and resilient design realms by comparing their key postulates and analysing key objectives through the prism of mutual (in)consistencies. In this regard, the work presents both general observations and detailed considerations where specificity and complexity of relations between sustainable and resilient building design are found. Results demonstrate that sustainability and resilience display complementarity rather than inconsistency in relation to each other, which leads to the conclusion that their integration into an outreaching, systemic approach is highly possible. By integrating sustainability and resilience, a building advances from a socio-ecological, i.e. a socio-technical, to a socio-ecological-technical system.**

KEYWORDS environmental issues, climate change, design measure, comparison, integration

1 Introduction

Sustainable design has persisted as an interesting subject matter for researchers and academics over the past few decades. Understanding the complexity, abstract component, and intangible meaning of sustainable design (Kosanović & Folić, 2014) has been proven to be particularly challenging. To describe sustainable design as a tangible approach (Marjaba & Chidiac, 2016), many definitions referring to environmental (technical) sustainability have emerged, while social and economic dimensions are often omitted from consideration. Environmentally sustainable design allows exact understanding, thought, causal explanation, classification, measurement, quantification, standardisation, and optimisation. From the environmental standpoint, sustainable design is brought to a set of well-defined engineering measures and scientific methodology aiming to treat nature as an external pre-given entity to be saved or exploited, even though it should be studied and understood from different perspectives (Guy & Moore, 2005). As these pre-given environmental patterns have been progressively altered in the past, and continue to do so in the present, as a result of human ability to change surroundings and develop technologies (Intergovernmental Panel on Climate Change, 2014; Pawley, 1990), nature is consequently transforming into a system in which stability and balance are accompanied by uncertainty and unpredictability.

Climate change represents a clear evidence of natural shifts. To restore balance by mitigating climate change, sustainable building design provides a significant share of contribution through profound energy considerations. In spite of such measures being taken, climate change continues to reinforce existing and create new risks, and to impact upon people and ecosystems, posing a potential threat to sustainability (Aleksić, Kosanović, Tomanović, Grbić & Murgul, 2016; O'Brien et al., 2012). When affected, the built environment generates new environmental issues. Complex and transformative causal relations between environmental (sustainability-related) issues, climate change, and new environmental issues in the built environment therefore represent a closed loop (Fig. 1.1).

The approach to design for resilience to climate change has been developed independently of sustainable design. This is because of the most commonly accepted meaning of sustainable design, which makes reference to the utilisation of natural resources and to the consequent production of negative environmental impact. On the one hand, the two approaches offer opportunities for synergies and reciprocal benefits, while on the other hand, they potentially hinder individual validity and efficiency (Wilson & Piper, 2010; O'Brien et al., 2012). In technical terms, the achievement of sustainability does not necessarily mean the achievement of resilience. When resilience is not developed, sustainability is called into question. Clearly, contemporary building design should respond to requirements of both sustainability and resilience. This work investigates relations between the two design realms, compares their key postulates and analyses their key objectives through the prism of mutual (in)consistencies. The aim is to provide an insight into critical interrelations and to reveal possibilities for the integration of sustainable and resilient design realms into an outreaching, systemic approach.

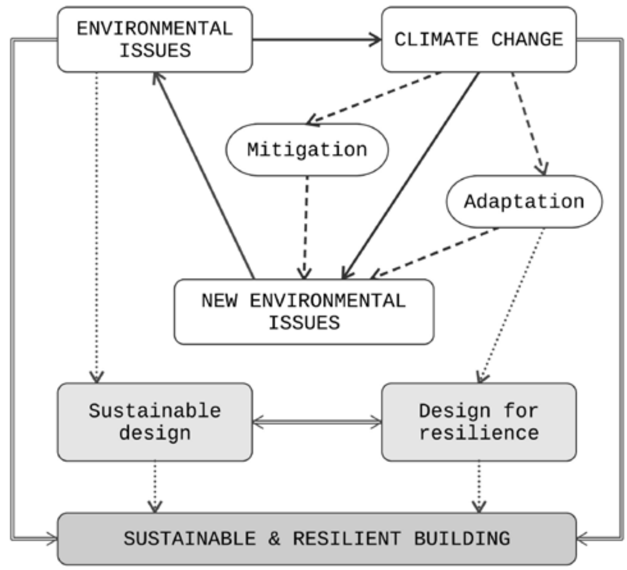


FIG. 1.1 Causal relations between environmental issues, climate change, and design responses

2 General Key (In)Consistencies

From an environmental perspective, sustainable design refers to resource efficiency and reduced pollution. Sustainable building tends to lower the negative environmental impact to the minimum possible level while also using favourable environmental conditions for that purpose. On the other hand, a resilient system is represented by resistance and recovery (Hodgson, McDonald & Hosken, 2015), i.e. the ability to adjust to an unlucky condition, event, or change (Marjaba & Chidiac, 2016) by absorbing disturbances and adapting to change without passing a threshold into a qualitatively different state (Sterner, 2010). Resilience is the potential of a system to return to a baseline after being disturbed (Zolli & Healy, 2013, p. 7), or to reconfigure itself continuously and fluidly to adapt to ever-changing circumstances, while continuing to fulfil its purpose (Zolli & Healy, 2013, p. 13). Fundamental differences between the notions of sustainable design and design for resilience are underpinned by divergent sets of key features of these two approaches (Table 2.1).

Building performance represents a pivotal matter of concern to both sustainability and resilience, but it is addressed from two different standpoints. While sustainable design aims to reduce the impact of a building on the environment throughout the life cycle, resilience refers to the scope of impact of the environment on a building in the use and maintenance phase. This factual difference is identified as a base from which the potential for integration of sustainability and resilience design realms could be explored.

SUSTAINABLE DESIGN	DESIGN FOR RESILIENCE
Building rather viewed as a socio-ecological system (Guy & Moore, 2005)	Building rather viewed as a socio-technical system
Universally accepted environmental postulates	Postulates laid out in specific climate change manifestations
Reduction of impact from a building towards the environment	Reduction of impact from the environment towards a building
Whole life cycle consideration	Use & maintenance phase consideration
Developed methodologies for evaluation (measurement) of achieved sustainability level	Estimation of future behaviour dependent on predicted climate and weather events; Undeveloped assessment methodology
Contribution to climate change mitigation	Contribution to climate change adaptation
Efficient utilisation of resources	Shift in resources demand, secure supply and reduced dependence on external distribution systems
Bioclimatic and regional design	Regional and transposed regional design
Sustainable site design	Site designed to provide protection from direct and indirect climate change impacts
Sustainable building materials, components, and structures	Climate change-resilient building materials, components, and structures
Recoverability of a building and its parts	Recoverability of building operability
Occupants productivity, health, and wellbeing	Occupants behaviour, safety, and health
Optimised combination of sustainability measures	Robust rather than optimal solutions (Bakker, 2015); Redundancy
Durability and flexibility	Adaptability and transformability

TABLE 2.1 Comparison of key issues of sustainable design and design for resilience

To define, describe, and predict the performance of a designed building, measurement and quantifications are needed from both sustainability and resilience perspectives. To measure the level of achieved sustainability, different life cycle assessment methodologies and assessment systems have been developed. On the other hand, methodologies for measuring the degree of resilience to (predicted) climate change manifestations are yet to be developed. To this end, Marjaba and Chidiac (2016, p. 116) argue that even sustainability systems still lack metrics that are repeatable, reproducible, and a true reflection of the building performance, and that the metrics for assessing the resiliency of buildings should be developed in tandem with sustainability metrics.

By definition, sustainable building aims to preserve natural resources. On the contrary, a building exposed to climate change manifestations displays a shift in resources demand, requiring secure supply and reduced dependence on external distribution systems. Nevertheless, the primary concerns in both approaches are water and energy.

While resilience refers to adaptation to climate change, sustainability targets climate change mitigation, although future climate change hazards may, at the present time, be indirectly addressed through measures for reduction of greenhouse gas emissions. As measures for climate change mitigation interact with measures for climate change adaptation, it is necessary to verify that these two sets are in synergy, and that they will not become contradictory and have negative consequences for each other in the future (Gupta & Gregg, 2012; Hallegatte, 2009; Wilson & Piper, 2010).

In addition, sustainable design tends to use (sustainable) materials in an efficient way and to preserve free land, while resilient design concurrently aims to provide protection from direct and indirect climate change impacts, inter alia through adequate site design. Although location characteristics and corresponding site design are crucial for both sustainability and resilience, these two approaches tackle different subjects that should be compared and re-examined in order to establish an integration path, identify synergies, and remove potential mutual intrusions (Table 2.2). In general, sustainable design aims to explore site limitations and potentials, while design for resilience primarily concerns risks to a building and threats to its occupants. As a result, integrated design for sustainability and resilience should consider all three key domains: threats, limitations, and potentials, respectively. Design that is adjusted to the wider spatial sustainability context and design that is in line with the wider spatial resilience framework – all round resilient design – together could be added to the 'positive fragment' approach (Aldallal, AlWaer & Bandyopadhyay, 2016).

SUSTAINABLE BUILDING SITE	RESILIENT BUILDING SITE
Climate and microclimate patterns	Changes in climate and microclimate patterns
Existence of urban heat island	Changes in extensiveness and intensity of urban heat island
Surface and relief characteristics, and water management	Surface drainage, flood, and erosion risks
Soil quality and composition	Susceptibility to erosion and the occurrence of landslides and soil subsidence
Distance from and spatial relation to existing pollution sources: traffic, industry, etc.	Identification of potential pollution sources in the case of extreme weather and climate events
Existence and protection of watercourses	Flood risk and water utilisation
Efficient water utilisation and water quality	Water availability
Renewable energy in situ for decreased emissions	Renewable energy in situ for decreased dependence on external sources
Urban infrastructural equipment	Infrastructural independence
Distance to public amenities	Distance and routes to safe locations and food supply grids
Distance to material suppliers to reduce transportation energy use	Distance to material suppliers for quick repair of the damage
Pavement characteristics: environmental quality of used materials, thermal behaviour, albedo, permeability	Pavement characteristics: thermal behaviour, albedo, water-resistance, resistance to extreme heat and cold, resistance to temperature shifts and solar (UV) radiation , permeability, provision of evacuation routes
Density	Porosity; Evacuation
Built structures in immediate surroundings	Hazards from built structures in immediate surroundings
Site reuse	Porosity

>>>

Efficient site occupation; Ratio between green and materialised surfaces; Porosity	Porosity
Characteristics of materialised surfaces: environmental quality of applied materials, thermal behaviour , albedo, permeability	Thermal behaviour, albedo, water-resistance, resistance to extreme heat and cold, temperature shifts and solar radiation, permeability, provision of evacuation routes
Characteristics of green surfaces; Vegetation type, position and surface; Protected and endemic species	Vegetation type and resilience
Outdoor temperature regulation	Reduction of heat load

TABLE 2.2 Key subjects of sustainable vs. resilient site design

Sustainable design largely depends on local context and issues of relevance and urgency (United Nations Educational, Scientific and Cultural Organization, 2005). Similarly, resilient design is driven by both gradual climate shifts and extreme events at a narrowed spatial level, to the micro-context in which a building is positioned (Crawley, 2008; de Wilde & Coley, 2012; Fikfak, Kosanović, Konjar, Grom, & Zbašnik-Sengačnik, 2017). Both sustainability and resilience explore traditional solutions to climatic conditions, with the difference that resilience looks for design responses in spatial contexts in which forthcoming climate change manifestations have already been experienced.

The system of a sustainable building consists of mutually balanced subsystems and elements that together provide optimised performance, even when their isolated behaviour is not preferential (Kosanović, 2009). On the contrary, optimisation is not a priority for resilience (Bakker, 2015); rather, the system of a resilient building employs robustness and redundancy to counter uncertainty regarding future climate change manifestations. For climate proofing of new buildings and infrastructure within the robust approach, Hallegatte (2009) highlights synergy with mitigation, application of no-regret strategy, and reduced decision-time horizons. In such a way, the durability concept in a sustainable design framework could be impacted. Evidently, the discussion on resilience should be extended to include flexibility and durability considerations (Marjaba & Chidiac, 2016). On the positive side, reduced decision-time horizons make way for new technological solutions possibly applied within the lifetime of a designed building (Schouler, 2016).

Finally, both sustainability and resilience are future oriented, but led by different scenarios that evidently need unification. To carry out a profound discussion about the relationship between sustainability and resilience, responses to questions such as *Resilience to what?* (Carpenter, Walker, Anderies & Abel, 2001), i.e. *Resilience for where?* are needed. This work therefore presents general observations and deepened considerations where the specificity and complexity of relations between sustainable and resilient building design are found.

TOC

3 Building Materialisation and Design

Sustainable design promotes rational spatial organisation, decreased mass flows, and application of materials with satisfying environmental characteristics verified over the life cycle phases. Alternatively, the primary concern of isolated climate change responsive design is material resilience to water, fire, extreme heat or cold, solar radiation, pests, moulds, and other hazards directly or indirectly induced by weather and climate events. Through the systemic considerations, building design should aim to employ materials that are both environmentally friendly and climate resilient, in order to avoid more damage and higher life-cycle impacts due to lower hazard resistance (Matthews, Friedland, & Orooji, 2016). In this necessary integration process, expected climate change manifestations represent a starting point from which sustainability demands should be tackled. The amalgamation is especially challenging in the case of the application of alternative (mainly organic) sustainable building materials because of their resilience related characteristics, and the way in which they are embedded in building components and constructions.

Design that encompasses both sustainability and resilience takes into consideration the exposure of applied materials to weather and climate events. Clearly, climate sensitive materials should be positioned in non-exposed (protected) parts of a building. For example, in areas that are at risk of flood, water-resistant materials will be installed on lower floors of buildings, and flood-sensitive material types on the upper floors. In locations where extreme heat and heat waves are expected or have already been experienced, exposed materials should be resistant to the impact of high temperature, temperature shifts, and solar (ultraviolet) radiation. Regarding long- and medium term temperature increase, the consideration of the thermal properties of applied materials is significant to both sustainability and resilience. In terms of resilience to extreme weather events, building components, constructions, and their connections are given equal importance as materials. Emerged duality between sustainability-related durability, and resilience-related robustness and linked purposeful reduction of service life could possibly be resolved with decreased exposure, increased resistance, and the approaches to design for disassembly and circular design, where particular attention should be given to the optimisation of building envelope characteristics. It is expected that computer software and simulation will play a leading role in this intricate harmonisation process (Andrasek, 2012).

Sustainability and resilience to climate change shift conventional design logic and apply approach-specific design principles. The required integration aims to prevent occurrence of misbalance at the expense of either sustainability or resilience. For instance, to preserve valuable free land, especially in densely built areas, sustainable design promotes vertical development of a designed space, ultimately leading to the design of high-rise buildings (Yeang, 2000). From the standpoint of sole resilience, featured verticality could result in an increased vulnerability to climate change hazards. To this end, Mavrogianni, Wilkinson, Davis, Biddulph, and Oikonomou (2012, p. 123) explain that risk from overheating increases with the floor level, with top floors being warmest, followed by mid floor spaces. Besides temperature, changing wind patterns (such as peak loads or changing frequencies) could also manifest with stronger impact on tall buildings. Other design interventions that influence the achievement of both sustainability and resilience refer to occupant density control by design, determination of surface to volume ratio, definition of the building form, etc.

Flood-proof architecture stands out as the most particular design expression in the context of resilience. The methods for achieving flood resilience encompass the following: design to avoid floodwater (dry flood proofing); design to allow temporary flooding of the lower parts of the building (wet flood proofing); and design for adaptable contact with the water – floating and amphibious structures (Escarameia & Stone, 2013; Escarameia, Tagg, Walliman, Zevenbergen, & Anvarifar, 2012). In accordance with location conditions, level of the risk of floods, building purpose, and chosen flood-proofing method, the design further considers: existence of a basement space; introduction of stilts and mounds; positioning of building entrance, critical equipment, and communications and evacuation routes; drain-out measures; constructions, components and materials that are water-resistant, have good drying ability and low permeability, etc. The inclusion of sustainability-related postulates in design aims to prevent the adverse effects of one-sided choices. For example, the elevation of a building structure on pillars (above expected flood water level) decreases land occupation in conditions when there is no flood, but on the other hand increases the surface of the thermal envelope. Similarly, positioning buildings on artificial hills inevitably generates extensive earthworks; environmentally inadequate materials that get wet during the flood actuate new environmental impact through toxic emissions or leaching of hazardous substances, etc.

By definition, the resilience of a designed building refers to its resistance, recoverability, and adaptability. Although adaptation is traditionally linked to external conditions, adaptable design was developed prior to the resilience approach, as evidenced by various experimental examples of static and dynamic (kinetic) adaptable design solutions that emerged over the course of the 20th century. More recently, adaptable buildings are considered as a possible response to climate change. In this regard, Sterner (2010) distinguishes between 'passive resilience' with given ability to absorb shock and remain in one regime, and 'active resilience' which displays the ability of a system to change its form in order to adjust to changeable external conditions. According to Loonen, Trčka, Cóstola, and Hensen (2013), a static, fixed, or nonflexible system has no in-built capacity to respond to changing conditions. On the contrary, adaptive design (most commonly manifested in climate adaptive building shells) could reconcile robustness, flexibility and multi-ability, but the concept cannot yet be considered mature when regarded in terms of the many current challenges such as design and decision support, operational issues, and human aspects.

Time-scaling approach to resilience allows for the adjustment of architectural responses to temporal climate change variability and leaves space for the development of new adaptation technologies. Indeed, with the advancements in robotics and digital technology, novel dynamic sustainable and resilient models could be developed. To this end, Kohler (2012) proposed the 'aerial architecture' model where "structures can be designed to remain open-ended in order to be partially rearranged and dynamically adjusted over time... It is even possible that large buildings become displaceable 'mobile homes', fully or partially reusable in different locations and contexts, having second or third lives." (Kohler, 2012, p. 31)

4 Energy Issues

Buildings consume energy throughout all phases of their life cycle, but by far the greatest proportion of energy in buildings is used during the phase of use and maintenance (United Nations Environmental Programme, 2007). Increase of average air temperature and the occurrence of heat and/or cold waves raise additional requirements for comfort provision, potentially resulting in impaired operational energy balance and increased energy consumption (Gupta & Gregg, 2012; Wilson & Piper, 2010). According to results of the study that Crawley (2008) carried out by simulating the future impact of climate change in 25 locations around the world, the annual energy consumption in cold climates will be reduced by 10% or more. In tropical climates, total energy consumption in buildings will be increased, in some months even up to 20% compared to current trends. "Temperate, mid-latitude climates will see the largest change, but it will be a swapping from heating to cooling, including a significant reduction of 25% or more in heating energy and up to 15% increase in cooling energy" (Crawley, 2008, p. 91). In accordance with the obtained results, Crawley (2008) emphasised the importance of changing the way buildings are designed, constructed and operated, and, like Hallegatte (2009), indicated an unfavourable relationship between the future price of operational energy and the intensification of climate change. The adaptation to climate change should therefore avoid non-robust, high-energy consuming solutions, and instead aim for integration with mitigation measures and policies (Hallegate, 2009).

Reduced energy demand, energy efficiency, and the use of renewable energy sources account for essential sustainable design attributes, which simultaneously contribute to climate change mitigation by reducing greenhouse gases emissions. Under the impact of climate change, the energy-related quality of a sustainable building may be deteriorated by additional operational requirements, from a small (Crawley, 2008) to a significantly large (Wang, Chen & Ren, 2010) extent. For this reason, even net-zero energy buildings should be designed using weather data that take climate change into account (Robert & Kummert, 2012).

In a climate-resilient design context, the primary energy requirement concerns the stability of supply during and after the occurrence of weather and climate events. A resilient building responds to this requirement by reducing dependence on external systems and by employing energy systems that are resistant, adaptable, and sufficiently robust to overcome future climate change uncertainty. In this regard, and because of expected future increase in energy consumption, the greatest potential for integrating sustainability and resilience principles lies in the utilisation of available renewable energy sources in situ, i.e. in the application of passive energy-related measures: natural ventilation and cooling, solar air and water heating, thermal mass, insulation, solar control, daylight, among others.

Passive design concept plays an important role in reducing energy consumption, achieving energy efficiency, and decreasing dependence on external energy sources, but the resilience demands could nonetheless change the traditional utilisation of passive systems. To this end, the main research question concerns the functioning of region-typical passive mechanisms in future climatic conditions. In principle, the performance of passive mechanisms applied to a building of certain type in the future, will depend on local climate change manifestation, as well as on their intensity and frequency. For instance, according to the predicted climatic temperature increase in Northern European, the application of passive solar design principles to maximise daylight and achieve solar heat gains will no longer be appropriate (ArupResearch+Development, 2004), and new passive solutions typical of areas in which corresponding climate patterns are experienced, and adequate responses provided, could be used through a *transposed regionalism* approach as a basis for design redevelopment. In some warmer regions, like the Mediterranean, passive mechanisms used to combat increasing heat are already in place, just as the social adaptation that is deeply rooted in regional culture. According to ArupResearch+Development (2004), cultures in Northern Europe will have to alter their lifestyle to accommodate to the emerging climate change. Analogously, transposed regionalism may refer not just to architecture, but also to the culture, meaning that the social dimension of resilience inevitably calls for a change. When the threshold of habits and the capacity of traditional passive systems are exceeded (and for that reason become non-responsive to climate change manifestations), developed adaptation to the emphasised climatic parameters can easily imply new energy demands, which is why the passive measures in today's design for the future should be maximised to the fullest (Gupta & Gregg, 2012).

Passive energy measures in the sustainable design framework refer to the provision of heat, cold, and natural ventilation and daylighting. These measures are embedded in the spatial organisation of a building and in its components. Some passive measures, like solar water heating or daylight provision at the greater depth of a building, require installation of special elements, or utilisation of specialised support equipment that, in the light of climate change, must be resilient. In resilience framework, the objectives of passive measures are translated to combating extreme high and low temperatures, and reducing dependence on external energy supply systems.

In terms of spatial organisation, sustainable design employs spatial zoning and introduces distinctive spatial elements such as atria. Spatial zoning enables the physical separation of building areas that are exposed to variable environmental loads or characterised by different indoor regimes, e.g. the separation of naturally ventilated from mechanically ventilated zones, or the separation of heated from non-heated areas. As such, zoning is applicable to different passive solar heating techniques, enhancing the independence from external heat supply systems. In a world that is getting warmer, the role of spatial zoning in isolating internally generated heat and preventing its transition to other building parts is gaining importance. Alternatively, an atrium nested in building layout aims to enhance natural ventilation and introduce natural light deeper into the building space. With regard to natural ventilation, Lomas and Ji (2009) emphasised that simple natural ventilation methods such as cross ventilation will not be sufficient to combat internal heat gains in the future. Accordingly, advanced ventilation strategies were identified.

The building envelope is the recipient of benevolent outdoor conditions, inter alia by acting as an integral part of passive energy mechanisms. Concurrently, the envelope provides protection from external negative impact. Although these attributes may be given different priorities in the two approaches, they are equally significant in relation to energy considerations and as such require balancing. In the sustainable design framework, envelope plays an important role in reducing operational energy consumption and maintaining indoor comfort. Envelope energy performance is determined by a number of parameters such as heat conductivity, absorption and accumulation, insulation, airtightness, glazing characteristics (size, positioning, U-value), window to wall ratio, reflectivity value, solar control, application of greening systems, and others. In a changing climate, the envelope should be resistant to the damages caused by extreme weather events and responsive to the likelihood of reduced heating and increased cooling energy demands (Kharseh & Altorkmany, 2012). This fact initiates the change in current envelope design practice and, having regard to the uncertainty of future climate change manifestations on the one hand and sustainability-related demands on the other, indicates time-scaled adaptable solutions by which incorrect climate change projections can be dealt with by treating non-structural adaptations as a method of nullifying the risk (Coley, Kershaw, & Eames, 2012). In this context, interest in switchable nanotech materials could be increased in future research (Pacheco-Torgal, 2014). Both heavyweight (high-mass) and lightweight (low-mass) constructions are common passive measures used to achieve thermal comfort in the indoor environment. Lightweight constructions respond quickly to temperature changes. For that reason, and when coupled with other passive measures, low-mass constructions are suitable for current warmer climates with low diurnal changes. Nonetheless, current lightweight systems design should also consider future temperature increase. While Kendrick, Odgen, Wang and Baiche (2012) suggest that it is possible to optimise lightweight buildings to provide thermal comfort using ventilation and shading, ArupResearch+Development (2004) demonstrated in their study that future temperature increase will result in near equalisation of daily peak temperature in a lightweight building and peak external air temperature, and that a heavyweight system performs better when exposed to same warming conditions. Evidently, the estimation of passive system performance in the future depends not only on climate change patterns and building characteristics, but also on what research method is used. In colder climates, climates with both cold and warm seasons, and climates with large diurnal changes, lightweight constructions require more energy for thermal comfort maintenance, wherefore the priority in current practice is given to heavyweight systems. When applied, building thermal mass requires appropriate exposition with regard to orientation, as well as the introduction of other passive measures necessary for its regulation and ventilation.

Besides (changing) microclimate characteristics, and the interaction of building systems with climatic parameters and weather events, the decision-making between lightweight and heavyweight constructions should be informed by their sustainability quality throughout the life cycle. In comparison with heavyweight passive systems, lightweight constructions in general have less embodied energy and are less material intensive, but often require more maintenance, are more susceptible to damages during the extreme weather events, and have a shorter service life which, on the one hand, enables a robust approach to resilience, but on the other hand raises new material demands and therefore requires additional circularity studies. A construction that contributes to reduced energy consumption and comfort maintenance in a passive way, now and in future, should therefore reflect a solution that is optimised for robustness, and energy and material issues.

The parameters of air, heat, and light comfort, due to their interconnectedness, require simultaneous consideration in sustainable design. The interactions between comfort parameters, however, are compounded by the impact of the changing climate and the behaviour of occupants whose role in achieving even energy sustainability is still insufficiently predictable. In spite of all design efforts to meet sustainability and resilience demands at the same time, it remains possible that climate change will cause the comfort zone to be extended, especially at locations characterised by significant temperature increase and the existence of urban heat island phenomenon. The recognised doubt can be resolved only by creating a new balance between design interventions and through profound new studies on whether the passive systems will be able to reach even expanded comfort conditions (Ascione, Bianco, De Masi, Mauro, & Vanoli, 2017; Gupta & Gregg, 2012). To that end, it is important to initiate change in occupants' behavioural, physiological, and psychological responses (Levin, 2003), and to concurrently consider the application of robust solutions that show little variation with alternating occupant behaviour patterns (Buso, Fabi, Andersen & Corgnati, 2015).

5 Discussion and Conclusions

According to the Intergovernmental Panel on Climate Change (2014), "comprehensive strategies in response to climate change that are consistent with sustainable development take into account the co-benefits, adverse side effects and risks that may arise from both adaptation and mitigation options" (p. 91). Hence, the notions of sustainability and resilience are built on different foundations. To this regard, Zolli (2012) observes, "Where sustainability aims to put the world back into balance, resilience looks for ways to manage in an imbalanced world".

The integration of sustainability and resilience design principles represents a challenging research topic. This work has demonstrated that sustainability and resilience display complementarity rather than inconsistencies in relation to each other, which leads to the conclusion that their integration is highly possible. Definitions and descriptions of such integration are yet to be developed. Among the few schemes proposed so far, for holistic understanding of sustainability and resilience, Sterner (2010) argues that resilience will be integrated into a holistic approach only when sustainable design is observed from the perspective of complex systems characterised by dynamics and nonlinear structure. In more general context, O'Brien at al. (2012, p. 444) introduce the term 'sustainable adaptation', referring to a process that addresses the underlying causes of vulnerability and poverty, including ecological fragility.

Sustainable and resilient buildings are not new architectural typology. Instead, they represent the essential quality of any building type. Until the principles of sustainability and resilience are fully merged with conventional architectural design, their character will be accentuated. At that point, the terminology used to describe the two approaches will become a part of regular designers' vocabulary. For the importance that sustainable and resilient approaches to design no doubtfully have, and the intricacies in current times (Roche, 2012), their incorporation into common design process and methodology is critical.

References

Aldallal, E., AlWaer, H. & Bandyopadhyay, S. (2016). *Site and composition – design strategies in architecture and urbanism*. Abington: Routledge.

Aleksić, J., Kosanović, S., Tomanović, D., Grbić, M. & Murgul, V. (2016). Housing and climate change-related disasters: a study on architectural typology and practice. *Procedia Engineering,* 165, 869-875. https://doi.org/10.1016/j.proeng.2016.11.786

Andrasek, A. (2012). Open synthesis // Toward a resilient fabric of architecture. In: C. Davidson and F. Roche (Eds.), *Log 25: Reclaim resi[lience]stance* (pp. 47-56). New York: Anyone Corporation.

Ascione, F., Bianco, N., De Masi, R.F., Mauro, G.M. & Vanoli, G.P. (2017). Resilience of robust cost-optimal energy retrofit of buildings to global warming: A multi-stage, multi-objective approach. *Energy and Buildings* (in press). https://doi.org/10.1016/j.enbuild.2017.08.004

ArupResearch+Development. (2004). UK housing and climate change: Heavyweight vs. lightweight construction. Bill Dunster Architects ZedFactory Limited, Feilden Clegg Bradley Architects LLP, RIBA and ARUP. Retrieved from http://arquitecologia.org/ARUP_Mass_Report.pdf

Bakker, A. M. R. (2015). *The robustness of the climate modelling paradigm*. Vrije Universiteit. Retrieved from https://research.vu.nl/ws/portalfiles/portal/1333903

Buso, T., Fabi, V., Andersen, R.K. & Corgnati, S.P. (2015). Occupant behaviour and robustness of building design. *Building and Environment, 94*, 694-703. http://dx.doi.org/10.1016/j.buildenv.2015.11.003

Carpenter, S., Wlaker, B., Anderies, J.M. & Abel, N. (2001). From metaphor to measurement: Resilience of what to what? *Ecosystems, 4* (8), 765-781. https://doi.org/10.1007/s10021-001-0045-9

Coley, D., Kershaw, T. & Eames, M. (2012). A comparison of structural and behavioural adaptations to future proofing buildings against higher temperatures. *Building and Environment, 55*, 159-166. https://doi.org/10.1016/j.buildenv.2011.12.011

Crawley, D.B. (2008). Estimating the impacts of climate change and urbanization on building performance. *Journal of Building Performance Simulation, 1* (2), 91–115. http://dx.doi.org/10.1080/19401490802182079

de Wilde, P. & Coley, D. (2012). The implications of a changing climate for buildings. *Building and Environment, 55*, 1-7. https://doi.org/10.1016/j.buildenv.2012.03.014

Escarameia, M. & Stone, K. (2013). Technologies for flood protection of the built environment – Guidance based on findings from the EU-funded project FloodProBE. Report. Retrieved from http://www.floodprobe.eu/partner/assets/documents/Floodprobe-Guidance_10_12_2013.pdf

Escarameia, M., Tagg, A.F., Walliman, N., Zevenbergen, C. & Anvarifar, F. (2012). The role of building materials in improved flood resilience and routes for implementation. In: F. Klijn & T. Schweckendiek (Eds.), *Comprehensive Flood Risk Management: Research for Policy and Practice* (pp. 333-335). Boca Raton: CRC Press.

Fikfak, A., Kosanović, S., Konjar, M., Grom, P. J. & Zbašnik-Senegačnik, M. (2017). The impact of morphological features on summer temperature variations on the example of two residential neighbourhoods in Ljubljana, Slovenia. *Sustainability, 9* (1), 122. DOI:10.3390/su9010122

Gupta, R. & Gregg, M. (2012). Using UK climate change projections to adapt existing English homes for a warming climate. *Building and Environment, 55*, 20-42. https://doi.org/10.1016/j.buildenv.2012.01.014

Guy, S. & Moore, S. A. (2005). Introduction: The Paradoxes of Sustainable Architecture. In: S. Guy, S. & S.A. Moore (Eds.), *Sustainable Architectures: Critical Explorations of Green Building Practice in Europe and North America* (pp. 1-12). New York: Spon Press.

Hallegatte, S. (2009). Strategies to adapt to an uncertain climate change. *Global Environmental Change, 19* (2), 240-247. https://doi.org/10.1016/j.gloenvcha.2008.12.003

Hodgson, D., McDonald, L.J. & Hosken, J.D. (2015). What do you mean, 'resilient'? *Trends in Ecology & Evolution, 30* (9), 503-506. https://doi.org/10.1016/j.tree.2015.06.010

Intergovernmental Panel on Climate Change. (2014). Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: IPCC. Retrieved from https://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

Kendrick, C., Odgen, R., Wang, X. & Baiche, B. (2012). Thermal mass in new build UK housing: A comparison of structural systems in a future weather scenario. *Energy and Buildings, 48*, 40-49. https://doi.org/10.1016/j.enbuild.2012.01.009

Kharseh, M. & Altorkmany, L. (2012). How global warming and building envelope will change building energy use in central Europe. *Applied Energy*, *97*, 999-1004. https://doi.org/10.1016/j.apenergy.2012.03.023

Kohler, M. (2012). Aerial architecture. In: C. Davidson & F. Roche (Eds.), *Log 25: Reclaim resi[lience]stance* (pp. 25-32). New York: Anyone Corporation.

Kosanović, S. (2009). *Ekološki ispravne zgrade – uvod u planiranje i projektovanje*. Beograd: Zadužbina Andrejević.

Kosanović, S. & Folić, B. (2014). Reviewing the sustainability in students' design work. In: A. Fikfak (Ed.), *Book of Proceedings of Scientific Meeting on the topic of Urbanism "Smart Urbanism" - Teaching Sustainability, Ljubljana, University of Ljubljana, Faculty of Architecture, 19-21.06.2014* (pp. 117-126). Ljubljana: Faculty of Architecture.

Levin, H. (2003). Designing for People: What Do Building Occupants Really Want? Keynote Lecture, *'Healthy Buildings 2003', Singapore, December 7-11, 2003*. Retrieved from https://www.researchgate.net/

Lomas, K.J. & Ji, Y. (2009). Resilience of naturally ventilated buildings to climate change: Advanced natural ventilation and hospital wards. *Energy and Buildings*, *41*, 629-653. https://doi.org/10.1016/j.enbuild.2009.01.001

Loonen, R.C.G.M., Trčka, M., Cóstola, D. & Hensen, J.L.M. (2013). Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews, 25*, 483-493. http://dx.doi.org/10.1016/j.rser.2013.04.016

Marjaba, G.E. & Chidiac, S.E. (2016). Sustainability and resiliency metrics for buildings – Critical review. *Building and Environment, 101*, 116-125. https://doi.org/10.1016/j.buildenv.2016.03.002

Matthews, E.C., Friedland, C.J. & Orooji, F. (2016). Integrated environmental sustainability and resilience assessment model for coastal flood hazards. *Journal of Building Engineering, 8*, 141-151. http://dx.doi.org/10.1016/j.jobe.2016.08.002

Mavrogianni, A., Wilkinson, P., Davis, M., Biddulph, P. & Oikonomou, E. (2012). Building Characteristics as Determinants of Propensity to High Indoor Summer Temperatures in London Dwellings. *Building and Environment*, *55*, 117-130. https://doi.org/10.1016/j.buildenv.2011.12.003

O'Brien, K., Pelling, M., Patwardhan, A., Hallegatte, S., Maskrey, A., Oki, T., Oswald-Spring, U., Wilbanks, T. & Yanda, P.Z. (2012). Toward a sustainable and resilient future. In: C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, & P.M. Midgley (Eds.). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)* (pp. 437-486). Cambridge: Cambridge University Press.

Pacheco-Torgal, F. (2014). Eco-efficient construction and building materials research under the EU Framework Programme Horizon 2020. *Construction and Building Materials, 51*, 151-162. http://dx.doi.org/10.1016/j.conbuildmat.2013.10.058

Pawley, M. (1990). *Theory and design in the second machine age*. Oxford: Blackwell Publishers.

Robert, A. & Kummert, M. (2012). Designing net-zero energy buildings for future climate, not for the past. *Building and Environment, 55*, 150-158. https://doi.org/10.1016/j.buildenv.2011.12.014

Roche, F. (2012). Reclaim resi[lience]stance. In: C. Davidson & F. Roche (Eds.), *Log 25: Reclaim resi[lience]stance* (pp. 1-7). New York: Anyone Corporation.

Shouler, M. (2016) Design buildings for the future. 21 March 2016. Retrieved from http://thoughts.arup.com/post/details/533/design-buildings-for-the-future

Sterner, S. C. (2010). Designing Resilience: Sustainable Design from a Complex Systems Perspective. In: A. Parr & M. Zaretsky (Eds.), *New Directions in Sustainable Design* (pp. 152-170). Routledge.

United Nations Educational, Scientific and Cultural Organization (UNESCO). (2005). United Nations Decade of Education for Sustainable Development 2005–2014: Draft International Implementation Scheme. Retrieved from http://unesdoc.unesco.org/images/0013/001399/139937e.pdf

United Nations Environmental Programme. (2007). Buildings and climate change: Status, challenges and opportunities. Retrieved from http://www.unep.fr/scp/publications/details.asp?id=DTI/0916/PA

Wang, X., Chen, D. & Ren, Z. (2010). Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. *Building and Environment, 45*, 1663-1682. https://doi.org/10.1016/j.buildenv.2010.01.022

Wilson, E. & Piper, J. (2010). *Spatial planning and climate change*. Abingdon: Routledge.

Yeang, K. (2000). *The green skyscraper: The basis for designing sustainable intensive buildings.* Prestel.

Zolli, A. (2012, November 2). Learning to bounce back. *The New York Times*. Retrieved from http://www.nytimes.com/2012/11/03/opinion/forget-sustainability-its-about-resilience.html

Zolli, A. & Healy, A.M. (2013). *Resilience: Why things bounce back*. New York: Simon & Schuster.

Building Certification Systems and Processes

Maike Klein[1*], Tanja Osterhage[2], Dirk Müller[3], Saja Kosanović[4] and Linda Hildebrand[5]

* Corresponding Author
1 E.ON ERC, Institute for Energy Efficient Buildings and Indoor Climate, RWTH Aachen University, Aachen, e-mail: mklein@eonerc.rwth-aachen.de
2 E.ON ERC, Institute for Energy Efficient Buildings and Indoor Climate, RWTH Aachen University, Aachen, e-mail: tosterhage@eonerc.rwth-aachen.de
3 E.ON ERC, Institute for Energy Efficient Buildings and Indoor Climate, RWTH Aachen University, Aachen, e-mail: dmueller@eonerc.rwth-aachen.de
4 Faculty of Technical Sciences – Architecture Department, University of Priština in Kosovska Mitrovica, e-mail: saja.kosanovic@pr.ac.rs
5 Faculty of Architecture, RWTH Aachen University, Aachen, e-mail: lhildebrand@rb.arch.rwth-aachen.de

ABSTRACT **Multiple recognised benefits of sustainable buildings are effectively communicated through assessment models. In order to use existing certification models or to engage in the development of new schemes, it is necessary to build knowledge about their character, organisation, and procedures. Having regarded that the assessment methodology is undergoing a continuous process of development, this paper aims to discuss the core features and components of building certification, from the time of the emergence of initial models to the future horizons, thus drawing a holistic picture about this instrument that is relevant for the achievement of sustainability of buildings.**

The paper consists of five parts. The first part presents the background of building certification models. Furthermore, their key characteristics are discussed, from the assessment of environmental quality of buildings, to the typological variations, to territorial applicability, to the connection with the regulations, to the scope of economic and social issues encompassed by the assessment. The system of assessment models is analysed in the third section, and the comparison of hierarchical organisation of several well-known models is given. The fourth part of the paper presents different examples of the assessment process, from the registration for certification to the certificate awarding. Finally, the fifth section summarises the main observations regarding development trends, current status, and possible directions of future advancement of certification models in the function of their increased use.

KEYWORDS certification model, system and process, building typology, territorial boundaries

1 Introduction

Since the development of the first versions, the certification models have highlighted the importance of considering the sustainability of buildings of various types and sizes. The certification contributes to the improvement of the quality of buildings, integrates life cycle approach with the design, supports the implementation and the development of regulations, and encourages the orientation of the construction industry towards the goals of sustainable development.

All rating models have a common goal to assess and verify the level of achieved quality of a building by providing a certificate that:

- proves that the reduction of the negative impacts of a building on the environment has been achieved, while at the same time the technical, economic, social, and functional requirements have been respected or upgraded through holistic sustainability considerations;
- promotes sustainable building design and construction among different actors and stakeholders;
- increases the value of a certified building in real estate market (e.g., Eichholtz, Kok, & Quigley, 2010).

By reviewing the characteristics of different well-known models for building certification, their development paths and the established systems and processes, and by comparing specific models with the general objectives of building ratings, this paper analyses potentials and limitations regarding sustainability assessment of buildings from the present perspective, and reflects possible directions for further advancement in the field.

1.1 Development of Certification Models

The first energy labelling systems – energy passes – were introduced in Europe during the 1980s as a reaction to the previously occurred energy crises. With the rise in awareness of environmental impact, the need for a more comprehensive consideration of the quality of buildings started to increase, and expanding assessment boundaries were ultimately determined by the Life Cycle Assessment (LCA) method. This opened a path to the development of databases of building materials and furthermore brought environmental aspects closer to the building industry. Subsequently, efforts to integrate energy issues, performance of building materials, and other building-related environmental topics, to quantify quality, and to allow for comparability of obtained results led to the formation of models for comprehensive building assessment. The best-known building certification models today are BREEAM (Building Research Establishment's Environmental Assessment Methodology), LEED (Leadership in Energy and Environmental Design), and DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)).

In 1990, the UK based organisation Building Research Establishment (BRE) launched its first BREEAM building certificate. BREEAM is labelled as the first real attempt to establish a comprehensive methodology for the assessment of a broad range of environmental issues of buildings (Haapio, 2008, p. 7), the first assessment method that was integrated into regulations, and the first certificate that included the environmental performance of materials (Anderson & Shiers, 2009). Nowadays, BREEAM is a widespread, recognised, and comprehensive platform that offers rating schemes for new infrastructure projects, developments at the neighbourhood scale, new-build domestic and non-domestic buildings, existing non-domestic buildings in-use, and domestic and non-domestic building fit-outs and refurbishments.

In 1998, the US Green Building Council launched its first LEED certificate that dealt with the assessment of energy savings, water efficiency, reduction of carbon dioxide emissions, improvement of indoor environmental quality, and stewardship of resources and sensitivity to their impact. Because of a checklist-based system that was easy to apply, the LEED label gained international publicity within a short period. Gradually, the scope of the LEED framework has enlarged to finally include: different schemes for the assessment of building design and construction; interior design and construction; building operation and maintenance; neighbourhood development; and homes. Just like other developed models, the LEED platform and its different schemes are continually being revised and upgraded. LEED Version 4, for example, offers improvements in terms of environmental outcomes, flexibility to different project types and regional context, etc. (US Green Building Council, 2013b).

In 2009, the German Sustainable Building Council and the German Federal Ministry of Traffic, Construction and Urban Development together released an initial scheme for the evaluation of office buildings, known as BMVBS (abbr. Bundesministerium für Verkehr, Bau und Stadtentwicklung (Federal Ministry of Traffic, Construction and Urban Development)), but later continued their work separately. While the application of BMVBS became mandatory for newly constructed federal office buildings, the developed DGNB certification model, although based on German standards, is voluntary. Nowadays, DGNB is an internationally adaptable certification system with the ability to assess various building types and districts (DGNB, 2017). Compared to the other two assessment models – BREEAM and LEED – the DGNB model is more thorough and complex.

Today, national green building councils worldwide are joined into a global network called the World Green Building Council (WGBC) that administers different national models (like Japanese CASBEE – Comprehensive Assessment System for Built Environment Efficiency, Spanish 'Verde', or Korean Green Building Certification – KGBC), adjusts large international platforms such as the LEED, BREEAM, DGNB, and Australian Green Star to different national conditions (e.g., BREEAM-NOR for Norway, Green Star SA for South Africa, etc.), and engages in the development of new models.

2 Key Characteristics of Certification Models

Every building certificate has several key characteristics that define its structure and content, in particular referring to:

- the environmental dimension of sustainability, i.e. the environmental quality of buildings;
- social and economic dimensions of sustainability;
- building typology;
- regulative grounds; and
- territory for which a certification model is intended.

2.1 Environmental Quality of Buildings

Following the review of different models developed internationally, it can be concluded that the assessment of the environmental quality of buildings continues to represent their key objective. Basically, most of the negative environmental effects of buildings originate from the use of natural resources: energy, water, land, and raw materials i.e. the products obtained from these raw materials (Table 2.1).

The Table 2.1 shows that:

- the use of different types of natural resources can lead to the same type of environmental effects on the environment;
- the use of any type of natural resources in activities connected with the buildings generates multiple types of environmental effects;
- the use of any type of natural resource generates effects that further make new effects, based on the principle of chain reaction;
- the largest number of effects caused by the use of natural resources finally result in negative impacts on the living world, and to human health and wellbeing;
- some environmental implications of the use of natural resources make a reversible impact on causative activities and states, e.g., depletion of energy resources influences the possibility to obtain useful forms of energy; and
- the effects listed according to the type of used natural resources do not correspond to the life cycle of buildings, i.e. they occur during different life cycle phases, which means that the sole consideration of the use of resources is not sufficient to comprehensively assess the environmental quality of buildings.

Besides environmental impact of resource use, there also exists the impacts that depend on the way a building is set as functional materialised structure, i.e. the way in which occupants use a building. Pollution through artificial light, noise, municipal waste generation, microclimate changes caused by the physical structure of a building, and the disturbance of natural mechanisms by the same cause, etc. are some examples of environmental impacts that cannot be assessed by using only the resource use-based approach without applying the Life Cycle Assessment (LCA) method.

TYPE OF USED RESOURCES	ENVIRONMENTAL EFFECTS			
ENERGY USE	Air pollution	Oxygen content		Effects on the living world
		Smog		
		Acid rain		
		Global warming	Sea level rise	
			Climate change	
	Water pollution			
	Soil pollution			
	Depletion of energy resources			
MATERIALS USE	Direct effects on human health			
	Air pollution	Smog		Effects on the living world
		Acid rains		
	Water pollution			
	Waste generation and soil pollution			
	Visual pollution			
	Pollution with noise and vibrations (during installation and decommissioning)			
	Effects connected with energy use			
	Effects connected with water use			
	Effects connected with land use			
	Microclimate changes			
	Disturbance of natural mechanisms			
	Depletion of raw materials resources			
WATER USE	Lack of fresh water			Effects on the living world
	Water pollution	Eutrophication		
		Soil pollution		
LAND USE	Soil pollution	Water and air pollution		Effects on the living world
		Degradation of natural values		
	Changes in land cover, soil composition and relief morphology	Erosion		
		Degradation of natural values		
		Desertification		
		Changes in the watercourses		
	Microclimate changes			
	Deforestation	Erosion		
		Reduced oxygen content		
		Global warming		
	Reduced areas of free land			

TABLE 2.1 Environmental effects of use of natural resources in activities connected with the buildings

To assess the performance of buildings more holistically, developed certification models today combine both mentioned approaches. Nevertheless, the issues found in the overlap zone of the life cycle of a building and the life cycle of used materials require particular attention during the assessment, in order to reduce the probability of overlooking some important environmental items. For example, the assessment of land use is given more significance in the life cycle of buildings (e.g., during the site preparation, construction, or use), than in the life cycle of building materials. On the other hand, energy issues are addressed through both the material and the building LCAs, as evidenced by the criteria and indicators established in building assessment models and their supporting tools and databases. Recently, different research challenges and opportunities for successful integration of various LCA-related issues into the building assessment models have been identified (e.g., Anand & Amor, 2017).

2.2 Typological Variations

Typology plays an important role when it comes to the environmental impact of buildings. For example, different types of buildings have particular thermal comfort requirements that have varying energy demands. While the first assessment models referred only to offices and residential buildings, a broad variety of typological variations have become available in the meantime. Today, unified and flexible platforms offer various assessment schemes for residential buildings, offices, laboratories, manufacturing facilities, schools, hospitals, etc. For example, in the frames of one of its five different schemes – Building Design and Construction (BD+C), LEED offers assessment possibilities for the following building typologies: new construction and major renovation; core & shell development; schools; retail; data centres; warehouses and distribution centres; hospitality; healthcare; and multifamily housing. BREEAM International New Construction 2016 includes an even greater variety of typologies, from single and multiple residential dwellings, to residential institutions for short- or long-term stay, to offices, industrial units, and retail buildings, to education buildings (from preschool to higher education institutions), and finally to a variety of non-standard building types (like prisons, museums, libraries, etc.). At present, the DGNB model offers national schemes for the following building typologies: new offices; existing offices; residential buildings; dwellings; healthcare; education facilities; hotels; retail; assembly buildings; industrial; and tenant fit-out.

Unlike large platforms that allow for the evaluation of different building types from a common base, there are also those models that refer to the assessment of only one type of buildings, e.g., single family dwellings (LEED for Homes, CASBEE for Detached Houses (New Construction), or BRE's Home Quality Mark). It is certain that the models developed for one specific type of buildings can give more precise results in some segments. In addition to the typological characteristics that reflect on the characteristics of the life cycle and, therefore, on the definition of a model, the responsiveness to the characteristics of a territory for which a model is intended is equally important.

2.3 Territorial Applicability

As sustainable buildings are place-responsive by definition, the certification models must be well-suited to the intended territory. In the ideal case, an assessment model would tackle local issues in the most comprehensive way, because of a range of local specificities regarding climate, state of the environment, construction practice, typological characteristics, energy issues, water supply, land use, regulations, etc. However, the development or use of locally applicable certification models are currently rare. The majority of existing models are either intended for national use or are applicable to different national/regional conditions by virtue of the differentiation between the universal and the territory-specific assessment items. In the DGBN model, for example, international projects are certified under the DGNB CORE 14 scheme that adapts to national standards and requirements. BREEAM International New Construction 2016 distinguishes between 'fixed' assessment items with universal significance and 'variable' assessment items that are variable locally, and foresees that a first project registered for a BREEAM rating in a country or a region will undergo a special review process that aims to determine the territorial significance (weight) of assessment criteria. All projects subsequently registered for the BREEAM certification in the same country/region will be assessed on the basis of the weightings adopted for that territory (BREEAM, 2017, p. 22). Nevertheless, there is an ongoing debate about the efficacy of international assessment tools in measuring the building performance outside their country of origin, or even within the country of origin, if variable climate and topographic conditions exist (Banani, Vahdati, Shahrestani, & Clements-Croome, 2016; Suzer, 2015).

2.4 Regulations

Building certification models contain different legally prescribed norms. Through the system of criteria and indicators, the prescribed minimums are further upgraded and classified into several grades of archived sustainability quality. Given that the certification models set voluntary targets that are stricter than the valid legal requirements, or establish new norms in the segments that are not legally defined, they may be considered as a driving force for the development of regulations.

The development of models on the basis of national regulations that differ in their scope and strictness from one country to another causes a lack of consistency in baseline assumptions (Reed, Wilkinson, Bilos, & Schulte, 2011). To overcome this constraint, different proposals for the development of a global certification system and globally applicable building regulations have been given. Further standardisation, with the aim of allowing for the establishment of comparable thresholds of building quality and to enable the comparison of results obtained by using different models, represents a necessary development direction.

In general, the application of building rating systems is still voluntary. Currently, this represents one of the major constraints in the spreading of sustainable building practice.

2.5 Rating Scope: From Environmental to Sustainability Assessment

Early versions of rating models were commonly criticised for neglecting broader sustainability aspects (e.g., Cole, 1998; Cooper, 1999; Guy, 2005). Besides the environmental (Section 2.1), certification models today encompass different economic and social assessment items. The principal economic considerations in existing rating models are related to cost monitoring, economic efficiency calculations, and the life cycle cost analysis. Because of the complexity of the social dimension, some certification models distinguish between technical, social, and functional aspects and processes.

CASBEE and DGNB platforms comprehensively integrate different segments of sustainability into their certification systems (IBEC, 2014; DGNB, 2017). Additionally, DGNB version 2018 links assessment criteria with the following wider objectives: People First; Circular Economy; Design and Cultural Quality of Construction; Implementation of Sustainable Development Goals/Agenda 2030; EU-conformity; and Innovation. The positive evaluation of criteria that support the achievement of these objectives will be rewarded with bonuses (DGNB, n.d.).

Increased research interest in holistic sustainability assessment over the last decade has resulted in different proposals that extend beyond the building boundaries, like the integrated building-urban evaluation approach (Conte & Monno, 2012), or the approach that combines the active participation of stakeholders, and the common organisational hierarchy of the assessment system and spatial hierarchy of assessment subjects, thereby linking building sustainability with the concept of sustainable communities (Kosanović, Jovanović Popović, & Stanković, 2014).

3 System Organisation

Most of the certification models are organised as vertical branched systems consisting of a range of assessment items – criteria – that are grouped into categories (and optional subcategories). The scope of assessment items, their organisation within the categories, and the weight assigned to them are informed by the building typology to which a model is applied. For illustration, the platform BREEAM International New Construction 2016, which contains 57 individual assessment issues grouped into nine different categories (plus the category of Innovation), applies to a broad variety of building types, including residential buildings. Nonetheless, BREEAM distinguishes between building types by defining differing criteria and benchmarks for some assessment issues, and several criteria in this universal platform relate only to residential buildings. The model further elaborates on the requirements regarding the rating of residential types by offering four different classification routes, two of which relate to single dwellings (BREEAM, 2017, p. 402). Following the same principle, some criteria in the universal platform, LEED v4 for Building Design and Construction (US Green Building Council, 2017), like Design for Flexibility, or Furniture and Medical Furnishing (both of which are found in the category Materials and Resources) apply only to healthcare buildings (Table 3.1).

BREEAM INTERNATIONAL NEW CONSTRUCTION 2016	LEED V4 FOR BUILDING DESIGN AND CONSTRUCTION	DGNB SCHEME FOR NEW CONSTRUCTION
Health and Wellbeing Visual comfort; indoor air quality; safe containment in laboratories; thermal comfort; acoustic performance; accessibility; hazards; private space; water quality. **Land Use and Ecology** Site selection; ecological value of site and protection of ecological features; minimising impact on existing site ecology; enhancing site ecology; long term impact on biodiversity. **Pollution** Impact of refrigerants; NOx emissions; surface water run-off; reduction of night time light pollution; reduction of noise pollution. **Transport** Public transport accessibility; proximity to amenities; alternative modes of transport; maximum car parking capacity; travel plan; home office. **Water** Water consumption; water monitoring; water leak detection and prevention; water efficient equipment. **Materials** Life cycle impacts; hard landscaping and boundary protection; responsible sourcing of construction products; designing for durability and resilience; material efficiency. **Waste** Construction waste management; recycled aggregates; operational waste; speculative floor and ceiling finishes; adaptation to climate change; functional adaptability. **Energy** Reduction of energy use and carbon emissions; energy monitoring; external lighting; low carbon design; energy efficient cold storage; energy efficient transport systems; energy efficient laboratory systems; energy efficient equipment; drying space. **Innovation** Up to 10 points for recognised additional sustainability related benefits. **Management** Project brief and design; life cycle costs and service life planning; responsible construction practices; commissioning and handover; aftercare.	**Indoor Environmental Quality** Minimum indoor air quality performance; environmental tobacco smoke control; minimum acoustic performance; enhanced indoor air quality strategies; low-emitting materials; construction indoor air quality assessment; thermal comfort; interior lighting; daylight; quality views; acoustic performance. **Sustainable Sites** Construction activity pollution prevention; environmental site assessment; site assessment, site development – protect or restore habitat; open space; rainwater management; heat island reduction; light pollution reduction; site masterplan; tenant design and construction guidelines; places of respite; direct exterior access; joint use facilities. **Location and Transportation** Neighbourhood development location; sensitive land protection; high-priority site; surrounding density and diverse uses; access to quality transit; bicycle facilities; reduced parking footprint; green vehicles. **Water Efficiency** Outdoor water use reduction; indoor water use reduction; building-level water metering; cooling tower water use; water metering. **Materials and Resources** Storage and collection of recyclables; construction and demolition waste management planning; building life-cycle impact reduction; environmental product declarations; sourcing of raw materials; material ingredients; PBT source reduction – mercury, lead, cadmium, and copper; furniture and medical furnishing; design for flexibility; construction and demolition waste management. **Energy and Atmosphere** Fundamental commissioning and verification; minimum energy performance; building level energy metering; fundamental refrigerant management; enhanced commissioning; optimise energy metering; demand response; renewable energy production; enhanced refrigerating management; green power; carbon offsets. **Innovation** Innovation; Accredited Professional. **Regional Priority** No defined criteria but credit points are awarded.	**Sociocultural and Functional Quality** Thermal comfort; air quality; acoustic comfort; view out; user control / possibility of influence; indoor and outdoor environmental quality; security; accessibility. **Site Quality** Micro-site; influence on neighbourhood; connection to transport systems; distance to relevant objects and facilities for the user. **Ecological Quality** Life cycle assessment of the building; risks to the local environment; responsible resource procurement; biodiversity at the location; drinking water demand; wastewater volumes; land use. **Technical Quality** Noise protection; quality of building envelope; use and integration of building technology; ease of cleaning; ease of deconstruction and recycling; protection against emission; mobility. **Economic Quality** Life cycle costs; flexibility and usability; commercial viability. **Process Quality** Quality of project preparation; securing sustainability aspects in tendering and assignment; documentation for a sustainable management; procedures for urban development and design; construction site/construction process; quality of the construction work; orderly commissioning; user communication; consideration of facility management.

TABLE 3.1 Comparative overview of categories and criteria in the following models: BREEAM International New Construction 2016; LEED v4 for Building Design and Construction; and DGNB Scheme for New Construction

On the other hand, the Code for Sustainable Homes (Department of Communities and Local Government, 2010) model offers a set of criteria (grouped into nine categories) that is tailored for residential units and hence better adjusted to typological specificities, similar to the LEED for Homes (which contains eight categories) (US Green Building Council, (2013), and CASBEE for Detached Houses (New Construction) (with six categories) (Murakami, Iwamura, & Cole, 2014) models. By analysing different models that are designed for the same building type (Table 3.2), it can be concluded that the vertical hierarchical organisation and the scope of assessment items vary; consequently, the models do not allow for the comparison of results between them, and the lack of a standardised basis is currently perceived as a constraint.

CODE FOR SUSTAINABLE HOMES	LEED FOR HOMES V4	CASBEE FOR DETACHED HOUSES (NEW CONSTRUCTION)
– Energy and CO2 emissions – Water – Materials – Surface Water Run-off – Waste – Pollution – Health and Wellbeing – Management – Ecology	– Energy and Atmosphere – Water Efficiency – Materials and Resources – Sustainable Sites – Regional Priority – Innovation – Indoor Environmental Quality – Location and Transportation	– Comfortable, healthy and safe indoor environment – Durability for long-term use – Consideration for the townscape and ecosystem – Energy and water conservation – Conservation of resources and reduction of waste – Consideration for the global, local and surrounding environment

TABLE 3.2 Comparative overview of categories in the Code for Sustainable Homes; LEED for Homes; and CASBEE for Detached Houses (New Construction) models.

Nevertheless, when comparing large assessment platforms, some common characteristics regarding categories, criteria, indicators, and weighting may be drawn. In every model, the categories are formed according to sustainability aspects, such as:

- ecological quality, e.g. energy performance of building, lifecycle impact of building materials, waste management, water consumption efficiency, pollution, land use, etc.;
- economical quality, e.g., life cycle costs; and
- sociocultural and functional quality, e.g., management of the planning and building process, location, transport, mobility, indoor environment quality, comfort, etc.

All models evaluate sustainability quality over mandatory criteria – prerequisites, and voluntary criteria. The most relevant criteria, defined as minimum necessary requirements, are mandatory. If mandatory criteria are not fulfilled, a certificate cannot be issued. Besides obligatory or voluntary fulfilment, the relevance of criteria is additionally defined by weight and assigned points. Each system has an individual rating and weighting method; accordingly, similar assessment topics can be given different priorities in different models. Generally, weighting enables distribution of the points and understanding of the relationship between prerequisites, credits, and specific outcomes (Pyke, McMahon, Larsen, Rajkovich, & Rohloff, 2012).

3.1 Indicators

The indicators are used to express the value of certain quality. For example, thermal comfort can be expressed by people's satisfaction with the indoor air quality (predicted mean vote). To provide comparability, assessment systems use both quantitative and qualitative, i.e. descriptive indicators. Most of the indicators relate to international standards issued by the International Standards Organisation (ISO) and the European Committee for Standardisation (CEN). In addition, LEED platforms refer to the standards of the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), DGNB platform to the German Institute for Standardisation (DIN) and the Society of German Engineers (VDI), and the BREEAM model refers to the standards of the Chartered Institution of Building Services Engineers (CIBSE). While DGNB and BREEAM define the unit and the indicator, LEED allows for variety in providing proof of performance, e.g., for the criterion Thermal Comfort, the project team can choose between two options: to meet the requirements of the American ASHRAE standard or to meet the requirements of the ISO and CEN standards that are more commonly used in Europe.

The indicators of ecological quality within the models are approached differently. While some models express the ecological impact caused by building services or a material, others use LCA results (like DGNB), or rate the impact from environmentally friendly to harming (e.g., BREEAM). Furthermore, BREEAM includes total carbon dioxide emissions for production and building operation, total net water consumption (m^3) and transport-related carbon dioxide emissions. The benchmark can be defined by a limit of a certain indicator (e.g., for global warming potential); in other cases, a specific share of materials from a category must be met, or an energy standard must be fulfilled. Again, some models encourage the use of renewable or local materials and reward the fulfilment of this criteria with points.

The indicators to assess economic aspects can include space efficiency as it contributes to the economic efficiency. The most common indicator for this group is life cycle cost.

The indicators used to indicate social and functional quality relate to a broad range of items regarding mobility (e.g., accessibility to public transport, availability of recharging points for e-bikes and e-cars, availability of bike racks, proximity to local supplies), comfort (visual, acoustic, thermal), etc. To that purpose, both qualitative and quantitative indicators are applied, e.g., the average daylight factor or illuminance measured in Lux to indicate the visual comfort, or the concentration of volatile organic compounds (VOC) to indicate the indoor air quality. In the building design phase, comfort can be assessed by using simulations.

4 Certification Process

Building certification process involves different actors such as certification institute, owners, designers, and other professionals, and in some cases the building users. In addition, some certification models require the engagement of a professional who is licenced by the corresponding certification institute (e.g., LEED accredited professional, or BREEAM assessor). In an optimal process, the client and a professional assessor together discuss certification goals and set target values early in the design stage.

Every model has a particular rating process, for which reason the number of process steps, their organisation and synchronisation with the life cycle phases of a building, the types of issued certificates (e.g., preliminary certificate that is based on plans and intentions, or the final i.e. the full certificate issued according to the real state of realised projects), the expiration of issued certificate, etc. differ from one certification scheme to another.

For example, the CASBEE for Detached Houses model foresees a certification process that focuses on verification after building completion. The rating process in the BRE's model Home Quality Mark extends from the design phase (with interim assessment and certificate) to the post-construction stage, when the final certification occurs (BRE Global Ltd, 2016). In LEED for Homes, the certification process starts with registration, continues through the on-site verification throughout the design (when the preliminary rating is done) and construction (including mid-construction and final construction verification visits), the review of documentation that is submitted after the project has been completed, and ends with the award of the certificate (US Green Building Council, n.d.). In the LEED v4 commercial platform, the rating process consists of the following major steps:

– **registration**, prior to which the minimum programme requirements were checked, and the roles of project team members (owner, agent, and project administrator) were defined;

– **application**. Here, LEED credits that will be pursued are already identified, assigned to project team members, and followed by the submission of completed project material into the online portal;

– **review** carried out by the certification body. The exact review procedure and the deadline for submitting for review depend on the LEED scheme for which the project is applying (e.g., standard review, precertification review, or split review that includes both design and construction); and

– **certification** of completed project (US Green Building Council, 2017b).

In BREEAM International New Construction 2016, the assessment and certification process is aligned with the Royal Institute of British Architects (RIBA) Plan of Work, and consists of five stages: pre-assessment; design stage assessment; interim (design) certification;

construction stage assessment/review; and final (post-construction) certification (BREEAM, 2017). For other certification schemes, like BREEAM In-Use, the certification process is adapted to the corresponding planning process. Assessment and certification is guided by the independent, trained, and licenced assessor. Upon successful completion of the procedure, a certificate indicating the level of achieved quality of a building is issued.

The DGNB model provides a full certificate after the project realisation. Prior to that, a pre-check that sets the targeted level of quality and a preliminary certificate can be given. The assessment process is led by the DGNB accredited accessor who reports the project to the certification institute and advises individual stakeholders through all assessment stages – from concept development to project realisation. Together with the client and the participating planners, the assessor sets target values for agreed sustainability objectives and reviews them during the process. Once the project has been completed, the documents are submitted to the certification institute, which evaluates them and subsequently awards the certificate.

4.1 Certification Result

The result of certification process is expressed as a whole number or a percentage of earned credit points, accompanied by hierarchical description. In the BREEAM International New Construction 2016 model, for example, the total achieved credit points in each category are multiplied by weighting factors and translated into a scale ranging from Unclassified (< 30%), Pass (30-44%), Good (45-54%), Very Good (55-69%); Excellent (70-84%), to Outstanding (≥85%) (BREEAM, 2017). In each of the six DGNB assessment categories, the achieved credit points are multiplied by a weighting factor to calculate the degree of fulfilment. The total degree of fulfilment is first calculated by weighting the results from all categories, and then translated into a scale (by respecting minimum performance) ranging from Bronze (with a total performance index from 35% and minimum performance index of 0%), to Silver, to Gold, to Platinum (with total performance index from 80% and minimum performance index of 65%). To confirm successful completion of the rating procedure, the LEED version 4 platform uses a four-stage rating scale: Certified (40-49 points), Silver (50-59 credit points), Gold (60-79 points), and Platinum (80-110 points).

5 Discussion and Conclusions

Over the past three decades, certification models have informed the discussion about the environmental impacts of buildings and the possibilities for their reduction. Even with the recognised relevance and offered benefits, however, the application of certification models is still insufficient. Some reasons for the infrequent use of building rating models are their voluntary character, complex assessment process, and economic barriers.

The comparison between different building certification models is common nowadays (e.g., Doan et al., 2017; Ebert, Eßig, & Hauser, 2012; Nguyen & Altan, 2011; Rogmans & Ghunaim, 2016). The analysis of different versions of several well-known certification models shows that there exist certain development tendencies, such as the expansion from predominantly environmental to the more comprehensive sustainability evaluations. In addition, some new models or new versions of existing certification models have deepened assessments of resilience, e.g., the Home Quality Mark has introduced a subcategory entitiled Safety and Resilience (BRE Global Ltd, 2016), and BREEAM International New Construction 2016 has introduced the criterion Adaptation to Climate Change (BREEAM, 2017). Still, a more profound consideration of building resilience aspects is necessary (e.g., Champagne & Aktas, 2016). In principle, resilience-related items may be embodied into certification models either though the modification of sustainability criteria (e.g., by using climate change predictions to determine energy performance of buildings), or through the introduction of new criteria defined according to the territorial characteristics.

Furthermore, it has been noticed that certification models like LEED and BREEAM have been transformed over time into comprehensive unified platforms applicable to different types of buildings and different territories. The adjustment to conditions of a specific territory in universal models is solved by the modification of weightings (e.g., BREEAM International New Construction 2016) or by assigning additional points for applied regionally relevant measures (e.g., LEED v4 for Building Design and Construction). Although the widespread application of the same models enables the comparison of results, the extent to which universal platforms respond to varying local/regional peculiarities (e.g., regarding environmental conditions, building practice, regulations, etc.) has not been sufficiently analysed to-date. Therefore, the development and use of certification models whose structure, content, and assessment process are tailored according to the conditions existing within the defined spatial boundaries remain to be proven relevant. The acknowledged pertinence is additionally justified by the fact that existing models offer different assessment methodologies and different labels, which may create doubts in terms of the selection of an acceptable certification model.

To that end, one of the possible directions for the further development of certification models could concern the establishment of platforms intended for a particular building typology and territory, adjustable to building state (new construction, existing, or undergoing refurbishment). In that way, the specificities of the examined building type would be more profoundly addressed, having regarded that the life cycle impact of buildings is narrowly connected with their typology. Furthermore, territorial specificities at the local level could be managed by distinguishing a generic model from its local variants, i.e. by modifying criteria and indicators, or by introducing more comprehensive changes in generic structure where necessary.

The model intended for a particular building typology and territory, and adjustable to a building state, can be developed by the vertical (hierarchical) structuring of the assessment system (comprising categories, subcategories, criteria, and indicators) and the horizontal layering of the assessment process (comprising several different groups of activities) (Kosanović, 2012). The layers should be understood as independent and at the same time compatible and transparent segments of the rating process, defined in a way to allow for overlapping. The overlapping of layers would help to better distinguish between the newly built, the existing, and the buildings undergoing renovation, all belonging to the same type, and, further, to better address the user factor and to fully integrate the certification and design processes. The amalgamation of assessment layers with the life cycle of buildings, on the one hand, and the assessment system on the other, is vital for the successful transformation of the use of certification models into sustainable building practice.

References

Anand, C.K., & Amor, B. (2017). Recent developments, future challenges and new research directions in LCA of buildings: A critical review. *Renewable and Sustainable Energy Reviews, 67*, 408-416. https://doi.org/10.1016/j.rser.2016.09.058

Anderson, J., & Shiers, D. (2009). *The Green Guide to Specification* (4th Ed.). Hoboken: Wiley-Blackwell.

Banani, R., Vahdati, M. M., Shahrestani, M., & Clements-Croome, D. (2016). The development of building assessment criteria framework for sustainable non-residential buildings in Saudi Arabia. *Sustainable Cities and Society, 26*, 289-305. https://doi.org/10.1016/j.scs.2016.07.007

BRE Global Ltd. (2016). *Home Quality Mark*. Technical manual, SD232:1.0 (Beta England) – 2015. Retrieved from http://www.homequalitymark.com/filelibrary/HQM-Beta--England--2015_SD232_r1.0.pdf

BREEAM – Building Research Establishment's Environmental Assessment Method. (2017). *BREEAM International New Construction 2016. Technical manual SD233 version 2.0*. BRE Global Ltd. Retrieved from https://tools.breeam.com/filelibrary/Technical%20Manuals/BREEAM_International_NC_2016_Technical_Manual_2.0.pdf

Champagne, L.C. & Aktas, B.C. (2016). Assessing the resilience of LEED certified green buildings. *Procedia Engineering, 145*, 380-387. https://doi.org/10.1016/j.proeng.2016.04.095

Cole, R. J. (1998). Emerging trends in building environmental assessment methods. *Building Research & Information, 26*(1), 3-16. https://doi.org/10.1080/096132198370065

Conte, E. & Monno, V. (2012). Beyond the *buildingcentric* approach: A vision for an integrated evaluation of sustainable buildings. *Environmental Impact Assessment Review, 34,* 31-40. https://doi.org/10.1016/j.eiar.2011.12.003

Cooper, I. (1999). Which focus for building assessment methods – environmental performance or sustainability? *Building Research & Information, 27*(4-5), 321-331. https://doi.org/10.1080/096132199369435

Department of Communities and Local Government. (2010). *Code for Sustainable Homes*. Technical Guide, November 2010. Retrieved from http://webarchive.nationalarchives.gov.uk/20150728184956/https://www.planningportal.gov.uk/buildingregulations/greenerbuildings/sustainablehomes/technicalguide

DGNB – Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council). (n.d.). *DGNB system version 2018*. Retrieved from http://www.dgnb-system.de/en/system/version2018/?pk_campaign=sysloop_en_version2017

DGNB – Deutsche Gesellschaft für Nachhaltiges Bauen [German Sustainable Building Council]. (2017). *DGNB system – Kriterienkatalog Gebäude Neubau* [Catalogue of criteria for new construction], Version 2017. Retrieved from http://www.dgnb-system.de/fileadmin/de/dgnb_system/version2018/DGNB_System_Kriterienkatalog_Gebaeude_Neubau_Vorschau-Version_12.09.2017.pdf

Doan, D. T., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Ghaffarianhoseini, A., & Tookey, J. (2017). A critical comparison of green building rating systems. *Building and Environment, 123* (Supplement C), 243-260. https://doi.org/10.1016/j.buildenv.2017.07.007

Ebert, T., Eßig, N., & Hauser, G. (2012). Green building certification systems. Assessing sustainability - International system comparison - Economic impact of certifications. DETAIL Green Books.

Eichholtz, P., Kok, N., & Quigley, J. B. (2010). Doing well by doing good? Green office buildings. *American Economic Review, 100*, 2494-2511. Retrieved from http://urbanpolicy.berkeley.edu/pdf/aer_revised_proof_101910.pdf

Guy, S. (2005). Exploring sustainable architectures. In S. Guy & and S. Moore (Eds.), *Sustainable architectures: cultures and natures in Europe and North America*, pp.112. New York: Spon Press.

Haapio, A. (2008). *Environmental assessment of buildings* (Abstract of doctoral dissertation). Helsinki: Helsinki University of Technology. Retrieved from http://lib.tkk.fi/Diss/2008/isbn9789512295043/isbn9789512295043.pdf

IBEC – Institute for Building Environment and Energy Conservation. (2014). *CASBEE for Building (New Construction),* Technical manual (2014 edition). IBEC. Retrieved from http://www.ibec.or.jp/CASBEE/english/downloadE.htm

Kosanović, S. (2012). *Model za ocenu ekološke ispravnosti kuća za individualno stanovanje na području Beograda* [*Model for the environmental assessment of single family houses in Belgrade area*]. Doktorska disertacija [Doctoral Dissertation]. Beograd: Arhitektonski fakultet.

Kosanović, S., Jovanović Popović, M., & Stanković, B. (2014). Assessment of multi-family residential buildings in Serbia: a proposal for system development. *Proceedings of the World Sustainable Building Conference-WSB2014, Barcelona, Spain, 28-30. October 2014*, Volume 5, pp. 209-215. Green Building Council España (GBCe).

Murakami, S., Iwamura, K., & Cole, R. (2014). *CASBEE: A decade of development and application of an environmental assessment system for the built environment*. Tokyo: Institute for Building Environment and Energy Conservation.

Nguyen, B. K., & Altan, H. (2011). Comparative Review of Five Sustainable Rating Systems. *Procedia Engineering, 21*(Supplement C), 376-386. https://doi.org/10.1016/j.proeng.2011.11.2029

Pyke, P.C., McMahon, S., Larsen, L., Rajkovich, B. N., & Rohloff, A. (2012). Development and analysis of climate sensitivity and climate adaptation opportunities indices for buildings. *Building and Environment, 55*, 141-149. https://doi.org/10.1016/j.buildenv.2012.02.020

Reed, R., Wilkinson, S., Bilos, A., & Schulte, K-W. (2011). A comparison of international sustainable building tools – an update. *The 17th Annual Pacific Rim Real Estate Society Conference, Gold Coast, 16-19 January 2011*. Retrieved from http://www.prres.net/papers/Reed_International_Rating_Tools.pdf

Rogmans, T., & Ghunaim, M. (2016). A framework for evaluating sustainability indicators in the real estate industry. *Ecological Indicators, 66* (Supplement C), 603-611. https://doi.org/10.1016/j.ecolind.2016.01.058

Suzer, O. (2015). A comparative review of environmental concert prioritization: LEED vs other major certification systems. *Journal of Environmental Management, 154*, 266-283. https://doi.org/10.1016/j.jenvman.2015.02.029

US Green Building Council. (n.d.). *Guide to certification: homes*. Retrieved from https://new.usgbc.org/cert-guide/homes

US Green Building Council. (2013). *LEED v4 for homes design and construction*. Retrieved from https://www.usgbc.org/sites/default/files/LEED%20v4%20ballot%20version%20(Homes)%20-%2013%2011%2013.pdf

US Green Building Council. (2013b). *LEED v4 user guide*. Retrieved from http://www.cabrillo.edu/~msoik/3/LEED%20v4%20guide.pdf

US Green Building Council. (2017). *LEED v4 for building design and construction*. Retrieved from https://www.usgbc.org/resources/leed-v4-building-design-and-construction-current-version

US Green Building Council. (2017b). *Guide to LEED certification: commercial*. Retrieved from https://new.usgbc.org/cert-guide/commercial

Risk Management and Risk Assessment Methods

Aleksandra KokićArsić[1*] and Milan Mišić[2]

* Corresponding Author
1 Higher Technical Professional School in Zvečan, e-mail: akokicster@gmail.com
2 Higher Technical Professional School in Zvečan, e-mail: m.misic@vts-zvecan.edu.rs

ABSTRACT **This paper outlines the basis and the meaning of risk, as well as the risk management system. The aim is to present facts, which allow the identification of potential risks, the anticipation of their occurrence, and the implementation of appropriate measures to mitigate or eliminate risks. As a part of the management, key activities of the risk management process, as well as their main phases, are given. Different visual, auxiliary, and statistical risk assessment methods and tools are reviewed and emphasised using examples of fire risks in the workplace. These same methods and tools are nonetheless applicable to various other risk assessment domains in the fields of architecture and engineering.**

KEYWORDS risk picture, risk management, risk assessment methods and tools, fire

1 Introduction

A key fact when it comes to risk is that a comprehensive definition is not known (Ball & Ball-King, 2011). Different perceptions and applications have resulted in a variety of interpretations of risk in literature. The concept of risk can be framed by (Arsovski, Kokić Arsić, Rajković, & Savović, 2013):

- probability of loss;
- uncertainty; or
- probability of any outcome that is not anticipated.

Uncertainty and loss are common to all definitions of risks. The uncertainty occurs when the outcome of a particular activity is not sure. When the risk exists, there must be at least two possible outcomes of which at least one must be undesirable.

In general, the risk of any activity can be defined as a function of probability and impact (Fig. 1.1).

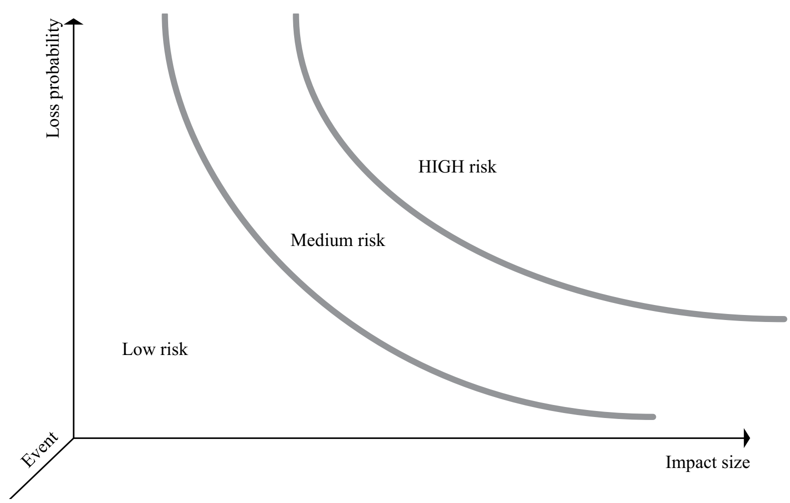


FIG. 1.1 Function of risk *(Arsovski et al., 2013)*

Risks represent a function of time, i.e. they change over time. This fact is relevant for monitoring the risk assessment dynamics in modern business-production systems exposed to constant changes. The research of risks, their consequences, and, in particular, the possibilities for their occurrence, are necessary for full understanding, raising, and strengthening of the level of knowledge and proper implementation of the risk management concept, and especially for its integral risk assessment process (Rausand, 2011).

Risks appear in many different forms and in various segments of industry. Professional risks, for instance, represent risks in the workplace. According to Bischoff (2008), these risks are within the limits of the norm, i.e. they are considered acceptable if they meet certain conditions:

- slight uncertainty regarding the likelihood of consequences;

- relatively low overall probability of injury;
- low or medium probability, low durability;
- inability to create the same, or repeated unwanted and unplanned activities;
- slight deviations between the assumed potential injuries and the likelihood of occurrence; and
- low level of risk related to social anxiety and potential dissatisfaction.

Risks are also very complex. Complexity is reflected in the assessment of a business-production system where the risks are identified, analysed, and evaluated systemically, not individually. Individual risk observation could have consequences for other activities, processes, or individuals within a system. In other words, individual risks that are considered acceptable, without taking into account their interdependence with other risks, may result in hazardous developments in another part of that system. To avoid this, a very good knowledge of hazards and harmfulness, that is, the nature of the risks that arise, is needed.

Organisations encounter a variety of risks that can influence the accomplishment of goals assigned to a range of activities. Actually, all activities of an organisation include risks. Expected results of an organisation's planned future activities are, by definition, unknown and uncertain, and thus vague. In the context of future activities, risk and uncertainty are therefore the most often mentioned. They may imply a possibility of failing to achieve the expected goals, of achieving poor results, or of losing the invested funds. Risk management is helpful in an organisation's decision-making process, taking into account uncertainty and impact on goal achievement. As such, risk management is the inherent part of organisation, overall management, management, process, policy, philosophy and culture (Đapan, 2014).

The most common interpretation and understanding of the objective of risk management concept is to reduce the risk by applying prescribed measures as a prerequisite for protection of people, environment, or property from the consequences of unwanted and unplanned activities. The essence of risk management is the willingness to accept a certain level of risk. Target is to create the balance between safety functioning of the system and avoiding losses and unplanned events and catastrophe. (Aven, 2008).

2 Risk Management Principles and Standards

Successful and sustainable risk management is embedded in a company and supported by its management. A risk management system aims to help a company to efficiently manage risks at different levels and in specific contexts, and to ensure that any risk information is used as a basis for decision-making at all relevant organisational levels.

Organisations should adhere to the principles of effective risk management. According to Arsovski et al. (2013), risk management

TOC

creates values; it represents an integral part of an organisation's decision-making processes, and takes into account the human factor. Furthermore, effective risk management explicitly addresses uncertainties, in a systematic and structured way. As such, it is based on the best available information and tailored to the specificities of an organisation. Finally, effective risk management is transparent, comprehensive, dynamic, iterative, and responsive to changes, all of which facilitate the continuous improvement and enhancement of an organisation (Arsovski et al., 2013).

Among numerous international standards on risk management, the following may be distinguished: Australian–New Zealand Risk Management Standard – AS/NZS 4360:2004; Canadian Risk Management Guide CAN/CSA-Q850-97(R2009); British Standard – BS 6079-3:2000; ISO 31000 – Risk Management – Principles and Guidelines; and ISO 31010:2009 – Risk Management – Risk Assessment Techniques. The Australian – New Zealand Risk Management Standard – AS/NZS 4360:2004 provided a general framework for establishing the risk management process and outlined procedures that can be applied to risk identification, assessment, analysis, and communication. The Canadian Risk Management Guide CAN/CSA-Q850-97(R2009) provides guidelines for decision-makers. The British Standard – BS 6079-3:2000, as a convention, includes past and present practices in risk management, but does not offer ways of managing risks in the future. The ISO 31000:2009 provides principles and guidelines for risk management implementation, and primarily focuses on company risk management. According to ISO 31010:2009, when carrying out the risk assessment procedure, it is necessary to consider:

- vision and goals of the organisation;
- type and level of risks that are acceptable, as well as how to deal with risks that are not acceptable;
- how the risk assessment process is integrated into the organisation's processes;
- methods and techniques used in the risk assessment process as an integral part of the risk management concept;
- responsibility for the implementation of risk assessment process;
- resources and needs for the implementation of risk assessment process; and
- how to report and review risk assessment processes.

3 Risk Picture

Risk assessment includes the most important phases in the risk management process (Fig 3.1): risk identification, risk analysis, and risk assessment.

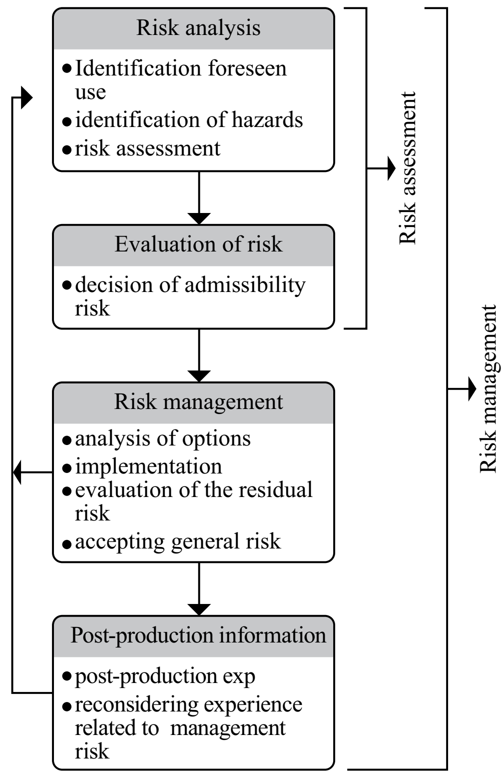


FIG. 3.1 Risk management processes
(Arsovski et al., 2013)

According to Aven (2008), risk picture is a platform that contains certain constituent risk components. Protection system first considers implementation of risk analysis and risk assessment, then definition of barriers, all in sense to identify accident and implement continuos improvement. Aven and Vinnem (2007) identify two key risk management tasks that are to establish risk picture for different alternatives of decisions, and to use this risk picture in decision-making.

According to Ericson (2005), the hazard consists of the following components: element of the hazard, the initiating mechanism, and goal and threat. Hazards exist because they are inevitable (elements of hazards must be used in a system), and caused by inadequate safety considerations. Leveson (2011) defines a hazard as a condition that, together with the worst set of environmental conditions, will lead to an accident (loss).

The occurrence of unwanted activities can be caused by different internal and external factors, such as: problems in equipment and material, wrong procedures, human error, lack of adequate training, management problems, etc. Organisational mistakes are often at the root of engineering system failures. However, when it comes to defining a risk management strategy, engineers often tend to focus on technical solutions, partly because of the ways in which risks and failures were traditionally analysed in the past.

Haimes (2015) identifies four sources of system failures: software, hardware, human, and organisational, and highlights the twofold importance of their consideration; they are comprehensive and include all aspects of the system life cycle (planning, design, construction, use, and management), and require full involvement of all persons at all levels of the organisational hierarchy in the risk assessment process.

The visually receptive concept developed by James Reason, subsequently called the "Swiss cheese model" (Fig. 3.2), illustrates how accidents arise from holes in multiple barriers caused by active failures and latent conditions (Reason, Carthey, & de Leval, 2001; Mannan, 2012).

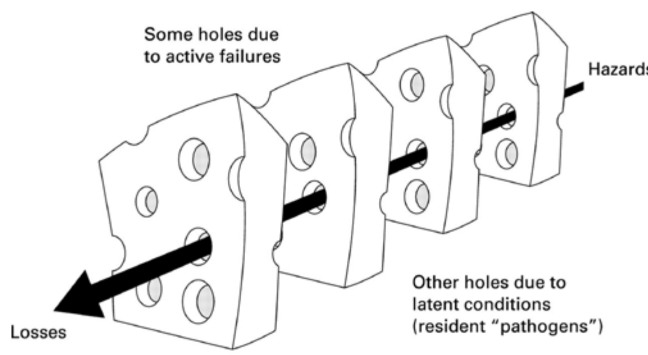


FIG. 3.2 "Swiss Cheese" model
(Reason, Carthey & de Leval, 2001)

3.1 Example: Fire Risk Picture

The assessment of the risk of fire is primarily an empirical decision-making process based on knowledge and experience, and is aimed at increasing fire safety. The specificity of the observed problem requires knowledge of the technological process of work, equipment, and the characteristics of the building. By looking at the "risk picture" (Aven, 2008), consideration is, after hazards and cause, directed to the barriers. In this context, barriers are elements located between initial and central elements of the "risk picture" on one side, and the final elements on the other. In general, barriers may be understood as tools used to protect certain values from some hazards.

Barriers are the key elements of protection system management. A fire protection system based on the barrier model comprises:

- danger analysis and fire threat assessment;
- defining and applying barriers;
- defining the barrier performance criteria;
- performance verification; and
- continuous enhancement.

According to Ware (2009), the following three groups of barriers can be defined: Buildings and Technologies; Processes; and Human Resources.

Building and Technologies

The group Building and Technologies relates to building, technologies, and technical protection systems and fire extinguishing equipment (stable detection systems, alarms, extinguishing and cooling systems, hydrant network with accessory equipment, and fire extinguishers). Threat analysis and risk assessment for buildings and technologies are carried out in the design, construction, and exploitation phases. An internal documentation audit during the design and construction phases aims to verify compliance with fire protection standards, whereas the external verification is done before exploitation in the form of a technical acceptance check.

Processes

Processes include: maintenance (keeping, inspection, and testing of all building elements, technologies, and systems relevant for fire protection); inspections and tests of equipment and assets belonging to the organisation's fire brigades; system of work permits for high-risk work activities and the management of contractors and third parties regarding industrial, ecological, and occupational safety and health, including fire protection; and fire and evacuation actions. In the event of a fire, every *trained* employee is obliged to participate in extinguishing it, and to assess the safe ways of doing so; otherwise, the employee is obliged to inform fire-fighting units immediately, to act in accordance with the appropriate instructions, if possible, and to evacuate. The fire-fighting units shall act in accordance with the operational fire extinguishing plans, fire protection plans, and recovery plans. The evacuation shall be carried out in accordance with the *evacuation plan*. The elimination of the consequences caused by the fire is done according to the *recovery plan*.

Human resources

Training and drills for human resources encompass trainings in fire protection as well as the fire-fighting drills, including evacuation.

4 Fire Risk Management

The management on the example of fire protection is a cyclical process applied in all phases of the life cycle of buildings and technologies (Fig. 4.1). It encompasses risk assessment and appropriate measures of preventive and repressive fire protection.

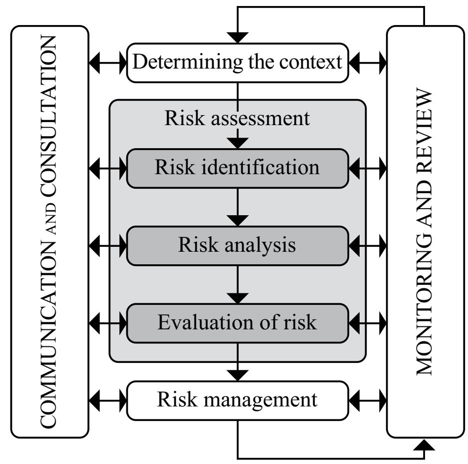


FIG. 4.1 Model of the fire protection management *(according to ISO 31000:2009)*

The risk of fire can be considered as a function of frequency and consequence. It is usually measured by the number of casualties, as well as the material and financial losses. Risk management represents identification, measurement, and risk control. Risk control depends on the priority of risk and implies the introduction of measures aimed at reducing the risk to an acceptable level.

In the context of responsibility for fire protection management, it is carried out on two levels. The first level consists of fire-fighting, and the second of preventive activities.

4.1 Fire Risk Assessment

Fire risk assessment includes identification, assessment, and management of risks arising from the occurrence of a fire. Simply put, fire risk assessment is a tool used to identify hazards and the risks arising from them, i.e. an organised methodological procedure for analysing workplace activities that can pose a risk of fire, likelihood of a fire, and an estimate of the damage caused by the fire. The objectives of the fire risk assessment in the workplace are to (Nikolić & Ružić-Dimitrijević, 2009):

– identify fire hazards;
– reduce the risk of noticed hazards by reducing the operational damage to the admissible; and
– apply technical and organisational preventive and repressive fire protection measures in order to protect the persons present.

There is no comprehensive risk assessment method. The procedure is to be conducted in a practical and systematic way, from design, construction, and finally to the exploitation of a building. Hazard analysis and threat assessment are used to obtain information on the types of hazards and the levels of threat, as a basis for defining the organisation of fire protection, barriers, performance standards, and the verification methods. In the design and construction phases, hazard analysis and threat assessment are done through the documents arising from legal and other requirements. The results of threat analysis and assessment are incorporated in project documentation, and subsequently in *fire protection rules*, *fire protection plan*, *recovery plan*, *training program*, as well as in normative methodological documents referring to the protection against fire.

4.2 Assessment Procedure

The assessment of fire risks must include workplace, wider working environment (such as the parts of building that are rarely used), and outdoor space. Recognition and identification of fire hazards at the workplace are done on the basis of the data collected from available documentation, by monitoring the work process, obtaining the necessary information from employees and other sources, and by sorting the collected data and the possible hazards indicated by these data. Fig. 4.2 shows the course of the *Action Plan* for risk assessment.

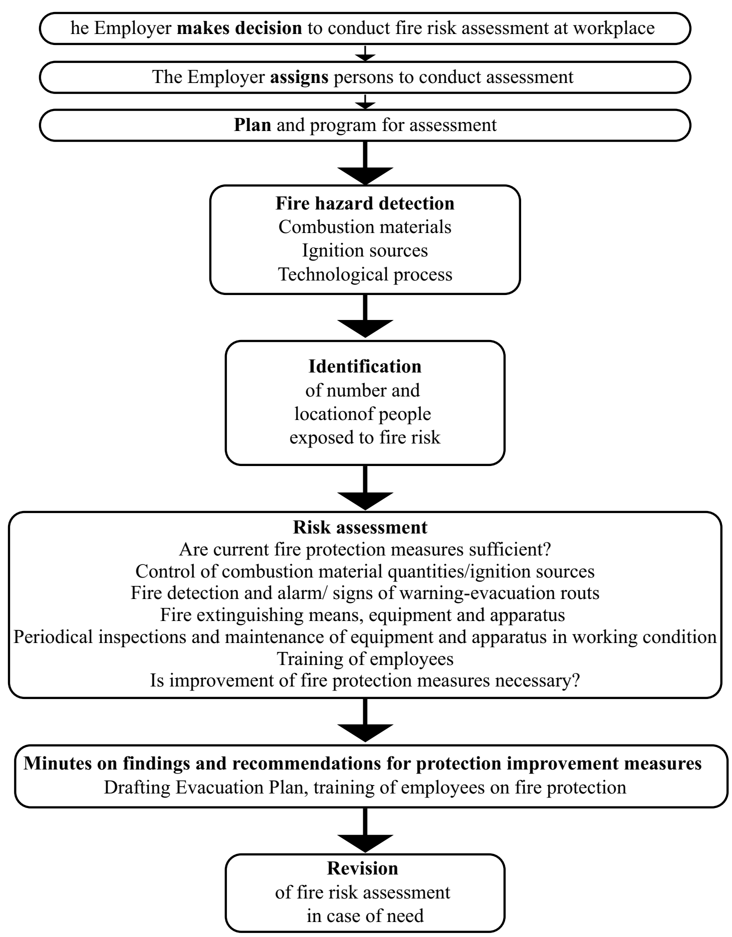


FIG. 4.2 Course of Action Plan for Risk Assessment

The first step in the assessment procedure foresees the identification of all fire hazards, including all sources of ignition (e.g. open flame, electrical energy, static electricity, sparks, etc.). It is also necessary to record the conditions that contribute to the rapid spread of fire, such as inadequate division of the building into fire compartments, presence of stairs and elevators, low fire resistance of building construction elements, etc.

The second step foresees the identification of the number of persons who are exposed to the immediate risk in the event of a fire and those who are in close proximity. Identification should consider the permanent location of the workplaces, as well as occasional locations across the building. It is especially necessary to consider those persons who work independently and/or in isolated areas, persons with special needs who are not able to react quickly in the event of fire, as well as visitors who are not familiar with the evacuation routes.

After identifying the hazard and the individuals endangered by the fire, it is necessary to assess the fire risk. The analysis of existing measures of preventive fire protection represents the next assessment phase. Fire detection devices (e.g. manual detectors, fire detectors, sirens, telephone etc.) are assessed depending on the size and complexity of the workplace. The possibility of abandoning the workplace in the shortest possible time should be analysed. Evacuation routes and exits must be permanently passable, clearly marked, and illuminated. The assessment of the amount and conditions of existing devices, equipment, and the hazard analysis, as well as the existing measures, determine if the present level of protection is sufficient or if it should be upgraded.

Further assessment includes the categorisation into high, medium, or low risks. The fourth phase consists of making a record of detected fire hazards and taking measures to reduce or eliminate them. A plan to prevent fire occurrence and to carry out safe evacuation in the event of fire must be made. This phase also requires the adequate training of employees in the field of fire protection. Fire risk assessment documentation should be revised with the occurrence of new hazards and changes in the level of fire risk.

4.3 Key Indicators of Process Success

The *availability coefficient* is "equal to the probability of finding the system in the operational state at the needed moment of time" (Ushakov, 2016, 95). In relation to fire protection, it refers to technical protection systems and fire extinguishers, and their external and internal inspections. Internal and external checks of the availability of technical protection systems, fire extinguishers, and equipment, are determined by special instruction. At the organisational level, the additional indicators of the process success are collected, processed and analysed. The result of the verification represents the corrective and practical measures arising from inspection and audit, the investigation of events and consideration of performance indicators, all of which are defined in action plans (Kokić Arsić, Arsovski, Kanjevac Milovanović, Bojić, & Savović, 2013).

5 Methods and Tools for Risk Assessment

The concept of risk management implies that a balance should be found between providing secure functioning, and avoiding unexpected and unwanted events, so that it can be said that risk management is practically based on risk control. Since it is clear that risks cannot be eliminated, the primary objective of risk management is to provide a level of risk below the minimum allowable value.

Risk assessment is primarily the empirical process of making engineering decisions based on knowledge and experience in order to enhance safety and health at work by using selected, well-known and recognised methods. There are numerous recognised risk assessment methods established by various associations and associations worldwide. Nonetheless, none of these risk assessment methods prescribes a choice of preventive measures to reduce, eliminate, or prevent risks. Rarely is there only one "real" tool, method, or risk analysis model to provide a "correct" analysis to support decision-making. The proper choice of risk assessment methods will allow for the adequate application of measures to achieve a safer workplace and work environment, with less probability of work-related illnesses and injuries to employees.

The risk assessment methods presented in this study are based on the standard ISO 31010 and divided into visual, auxiliary, and statistical methods. For every method presented, a note of the benefits and limitations of their use is given. The methods are classified into logical units, and the work indicates in which part of the risk assessment process their utilisation is optimal. The utilisation of risk assessment methods (including tools), as presented here, is demonstrated primarily in the example of fire protection. These same methods and tools are nonetheless also applicable to various other risk assessment domains in the fields of architecture, construction, and engineering.

5.1 Visual Methods

Check list

A check list is a simple written form used to identify basic groups of risks for which the assessment is carried out (Table 5.1). After the basic hazards are defined, the identification of the minor, individual threats within the groups is done. Check lists are easy to use and, if precisely designed, they represent a significant tool for identifying risks. On the other hand, the weakness of this method is that the identification of certain hazards could be omitted due to their nature, origin, or interaction with other hazards.

1.	DOES YOUR ORGANISATION HAVE A FIRE PROTECTION POLICY?	YES	NO	NOTE
2.	Did your organisation establish and document action procedures in case of fire?			
3.	Are security fire protection procedures carried out regularly?			
4.	Are employees informed on fire protection procedures?			
5.	Are employees informed on current hazards that can occur in their workplace?			
6.	Is there a reaction plan in case of major fire?			
7.	Is there an authorised person dealing with fire protection in your organisation?			
8.	Has the authorised person for fire protection been appropriately trained and does he/ she have the required certification?			
9.	Is contact with fire-fighting units possible both during and after working time?			

TABLE 5.1 Example of a check list for fire risk detection

Preliminary Hazard Analysis – PHA

Preliminary Hazard Analysis – PHA is a method for qualitative risk assessment used to identify possible accidents in a building. The goal is achieved by conducting tests in the following order: examining the sequence of events that can potentially turn into an accident; relating these unfortunate cases to the given hazard class; and, finally, considering measures to remove the hazard. PHA is most commonly used, at the earliest stage, for predicting potential problems in cases where only a small amount of information is available. However, this method provides only preliminary information, without detailed analysis or prevention measures. An example of the PHA method used for detection of the fire risk and hazard classes is given in Tables 5.2 and 5.3.

PART OF EQUIPMENT OR FUNCTION	HAZARDOUS ELEMENT	HAZARDOUS ACTION	HAZARDOUS STATE	DIRECT CAUSE	HAZARD CLASS	PREVENTION MEASURES
Gas container	Gas pressure	Leaking caused by container leaking	Free gas	Spark, flame, static electricity	I or II	Extinguishing system installed

TABLE 5.2 Example of PHA methods for fire risk identification

HAZARD CLASS I	CATASTROPHIC CONSEQUENCES - ONE OR MORE DEATHS AND COMPLETE BUILDING DAMAGE
Hazard class II	Critical consequences - serious injuries, building damage and complete cessation of production
Hazard class III	Marginal consequences - less damage and damage to the building, moderate production decrease
Hazard class IV	Negligible consequences - no injuries and no damage to the building

TABLE 5.3 Illustration of hazard classes and consequences

5.2 Auxiliary Methods

Interviews and brainstorming

Interviews and brainstorming are used for gathering the widest possible range of ideas that precede the risk assessment process. The benefits of these methods are that they help identify new risks and new situations arising from their identification. Furthermore, in terms of time, these methods are quick to organise and implement, and do not require significant prior preparation. They also enable good communication among all involved parties. The limitations are the lack of experience and of necessary knowledge, whereas the inclusion of different types of personality in the implementation of these activities is highly unlikely to take into account all potential risks.

Delphi Technique

Delphi Technique is an independent analysis based on the opinions of experts. Its aim is to use knowledge, experience and intuition of processes and sub-processes in a rational and systematic way to secure realistic outlook (Arsovski, Vujović, Mišić, Nestić, & Gvozdenović, 2013). The Delphi technique belongs to the group of decision-making processes based on reaching a consensus among decision-makers. This technique can be applied at any stage of a risk management process in which an expert opinion is required. The advantages are that it gives a range of independent and anonymous opinions of the same rank and the same importance, and time efficiency. The limitations are that it requires constant participation of the employees, as well as the fact that the participants have to express their opinions correctly and completely in a written form (Kiral & Kural, 2014).

"What-if" Technique

A structured "What-if" Technique is applied in cases of emergency risk identification, with a very strong connection between the analysis and risk assessment (Golfareli & Rizzi, 2008.) This technique can be applied to different types of business-production systems. It takes very little time effort to prepare for its implementation. The "What-if" technique is relatively fast and the main risks are identified quickly. Here, the response of a system to the deviations is observed, while the consequences are not examined. Therefore, the technique can be used to identify improvements, and the results are used as input information for quantitative analysis. However, it should be noted that the identification of some risks and hazards requires expertise and preparations, and can be time-consuming. Regardless of the level of precision of this technique, there is a possibility to omit some more complex causes.

Human Reliability Analysis

Human Reliability Analysis evaluates the impact of a human being on a system and is used to evaluate human error. The results can be presented quantitatively or qualitatively. As shown in Fig. 5.1, human activity is introduced at all levels of the risk assessment, and individuals play a very important role here. Consideration of the human error as an influencing factor can reduce the probability of error occurrence. Human Reliability Analysis can include:

- task analysis;
- error identification (ways they in which can appear);
- presentation (determining cause-effect relationships between human-related events, software, hardware, environment, etc., in a logical and measurable manner);
- quantification (evaluation of error);
- reducing the error by preventive actions (probability of occurrence or its effect); and

TOC

– quality assurance and documentation (verification that evaluations are valid and can be used to inform future design or for another purpose).

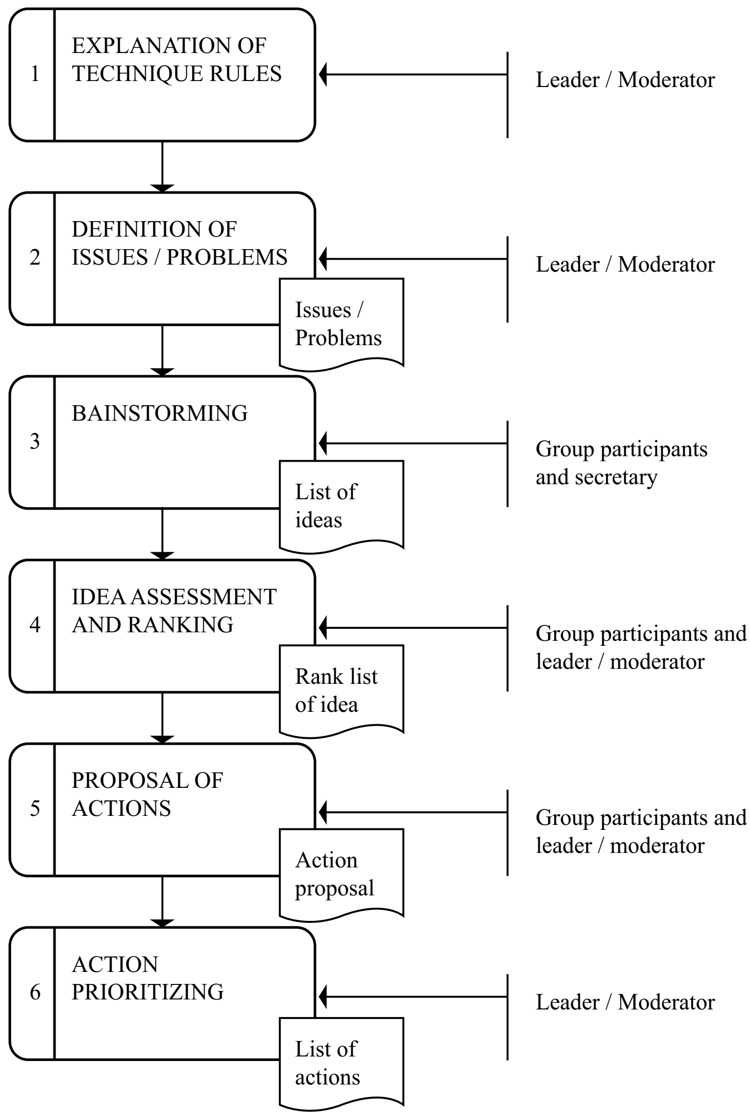


FIG. 5.1 Risk Assessment Action Plan flow *(Lazić, 2006)*

Root Cause Analysis

Root Cause Analysis deals with current errors and their fundamental causes (and not with obvious causes of errors) in order to improve the system and avoid similar future losses (Vorley, 2008). This analysis can be used in a large number of areas. The advantages are the participation of adequate and experienced experts in the team, structured analysis, consideration of all possible assumptions, documenting the results, and provision of recommendations for improvement. The limitations relate to difficulty in engaging experts at a given moment; potential inaccessibility or destruction of the main pieces of evidence during the occurrence of the error; inability to provide the team with sufficient resources for situation assessing; and inability to implement the recommendations.

Scenario Analysis

Scenario Analysis is a method of assuming future possible consequences based on present data and extrapolation tools. It is built mainly on descriptive models and used to identify the emergence of possible risks and their impacts. On the basis of the forecast, the future situation that may, though does not necessarily, have a trend similar to the one in the past, is assumed. This is very important for a system that contains very little knowledge on which a forecast can be based, or for systems where risk assessment is necessary over a longer period of time. Nonetheless, some of the scenarios offered may be unrealistic and are without adequate basis for the forecast, especially when there is a lack of data. The concept of the Scenario Analysis Method given in Fig. 5.2 indicates that a thorough understanding of the company situation requires the identification of internal and external factors, as well as their interactions, anticipated discontinuity, and transfer of the anticipated scenario outcomes into alternative business strategies.

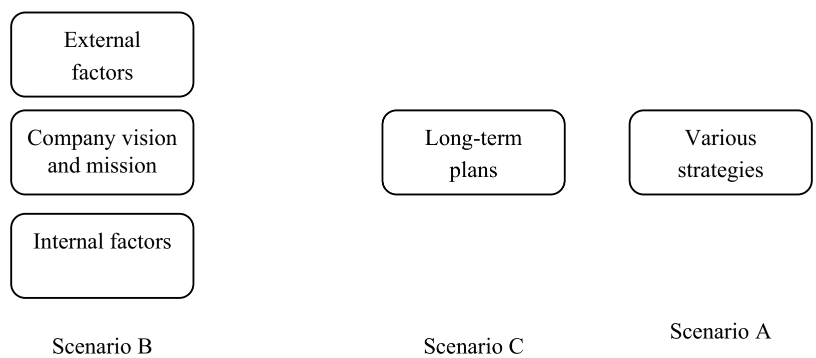


FIG. 5.2 The concept of the Scenario Analysis Method

Business Impact Analysis

Business Impact Analysis is also known as an impact assessment on business. It provides an analysis of how the key risks affect the systems functioning, as well as the possibilities of identification and quantification in the management of these systems. The advantages of this method are the facilitated understanding of critical systems and processes, and the possibility to redefine system processes, whereas the disadvantages relate to over-simplified or over-optimistic expectations, and the difficulties in the full and adequate understanding of systems processes and activities (Charters, 2011).

Fault Tree Analysis

Fault Tree Analysis is a technique for identifying and analysing factors that lead to an unwanted and unplanned event. It aims to determine, reduce, and eliminate potential causes / sources by using graphical representation of the logical diagram or tree. The advantages of this method are that it provides a very systematic approach to the problem, flexible analysis, a top-down approach, and usefulness of the analysis of more complex systems. The graphical representation, in many ways, facilitates system understanding and behaviour, as well as the factors that affect it. Its limitations relate to a possible high level of uncertainty during analysis, if the system is not sufficiently known. In some cases, the interaction of factors is not always possible, and the fault tree is a statically time-independent model. As the fault tree manipulates only with two outputs - "with or without consequences", the human factor can neither be easily included in the analysis nor in the consequent cancellation and domino effect.

Cause-Consequence Analysis
Cause-Consequence Analysis represents a combination of the Fault Tree and the Event Tree. Here, the causes and consequences of the initial event are taken into account. The advantage of this method is that it combines two methods for improved results. As it is possible to overcome certain constraints by analysing events that develop after a certain period of time, this analysis gives a wider picture of the whole system. On the other hand, the level of analysis complexity is significantly higher than in separate Fault Tree or Event Tree analyses.

Cause-and-Effect Analysis
Cause-and-Effect Analysis is a structured method for identifying possible causes of an unwanted and unplanned event (Fig. 5.3). Influential factors are divided into categories where all possible assumptions are taken into consideration, but as such do not determine the real causes. This type of analysis is organised in the form of a so-called Ishikawa Diagram (Fishbone Diagram). The advantages of the method include participation of adequate and experienced experts in the team, consideration of all possible assumptions, structured analysis, and its graphic representation. Limitations refer to the possible lack of necessary knowledge and experience, and the exclusion of the ultimate concept of analysis from representation; for that reason, this method needs to be a part of some other more comprehensive analysis, such as Root Cause Analysis.

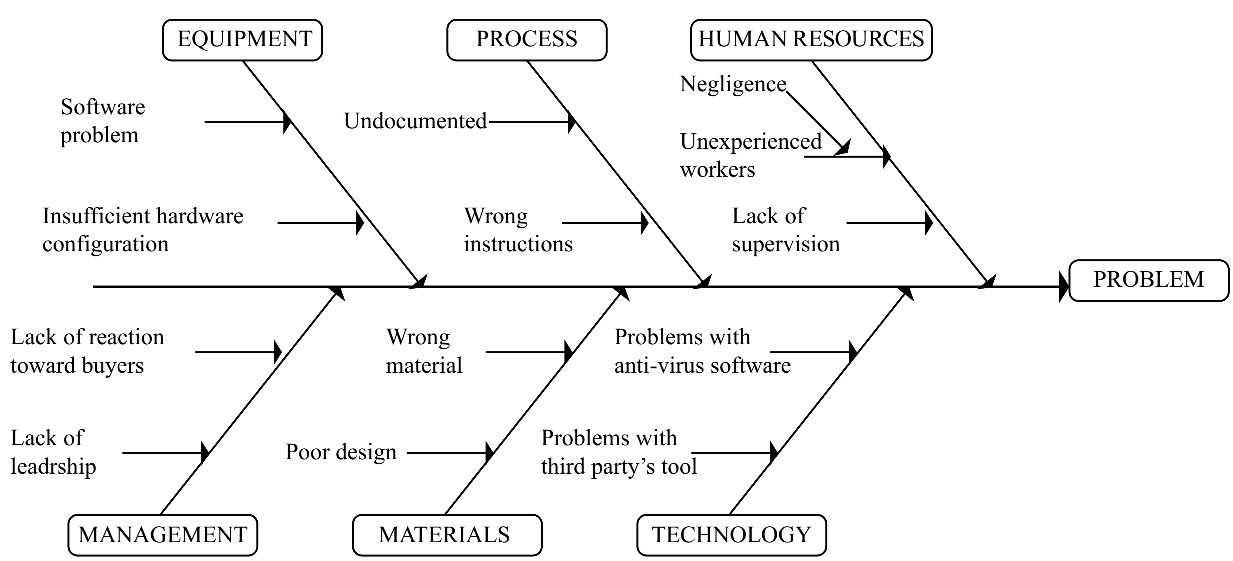


FIG. 5.3 Ishikawa Diagram *(Ishikawa, 1976)*

Failure Modes and Effects Analysis – FMEA

Failure Modes and Effects Analysis – FMEA identifies how components, elements, systems, and processes will fail to fulfil their projected function. In this case, all potential failures of each individual part of the entire system are identified. The goals of the FMEA method are to detect and localise potential errors in a timely manner; avoid or mitigate project risks; prevent costs of possible revocation due to the occurrence of an error; and prevent loss of reputation on the market.

The implementation of the FMEA goes through the following stages:

- making a decision on FMEA;
- appointment of the FMEA team;
- preparation for analysis;
- analysis;
- assessment of the current situation;
- control of FMEA; and
- implementation of corrective measures and assessment of the results of corrective measures.

Function	**Project design FMEA**		☐ New component or new use ☐ Improvement of current	Product	Sketch number
	Responsible person	Organizational unit/supplier	Plant / supplier	Type/system/function	Date of project design
				FMEA date	Page/s

Name of component / system	Class	Failure			Current state					Correction measures			Improved state			
		Type	Causes	Consequences	Control measures	R1	R2	R3	**RPC**	Recommend correction measures	Implementation responsibilities and dynamics	Undertaken correction measures	R1	R2	R3	**RPC**

Error /failure probability R1		Error / failure importance (severity) R2		Error /failure identification probability R2		Risk priority coefficient RPC		FMEA team	
Score	points	Score	points	Score	points	RPC = R1 R2 R3		Participants	Function
Negligible	1	Negligible	1	Negligible	1	Score	points		
Minor	2-3	Minor	2-3	Minor	2-3	Minor	1-50		
Medium	4-6	Medium	4-6	Medium	4-6	Medium	50-100		
High	7-8	High	7-8	High	7-8	High	100-200		
Critical	9-10	Critical	9-10	Critical	9-10	Critical	200-1000		

FIG. 5.4 FMEA form

In the first stage, the FMEA team answers the question: What possible mistakes (defects) can occur? Finding answers and determining the likelihood of defects is based on previous knowledge, testing, and experience. The second stage is the identification of potential errors (severity – weight of defects). The team analyses and identifies the possible consequences for each potential error. The third stage is to identify the cause of the fault (defects) and the possibilities of their detection. For each error, one or more causes are identified. The fourth stage involves an analysis of the system control and testing. The analysis determines to what extent the applied methods, control, and testing means ensure the timely detection of the cause of errors and prevent the occurrence of errors. The fifth stage is to determine the probability of occurrence of an error for any possible cause of error. A record of possible errors, causes, and consequences is achieved by using the

FMEA form (Fig. 5.4) which lists all activities of the FMEA team and represents the basis for conclusion-making.

Reliability Centred Maintenance

Reliability Centred Maintenance identifies guidelines that need to be implemented to better manage failures and thus to effectively achieve the required security, availability, and cost-effectiveness of the system.

Sneak Analysis and Sneak Circuit Analysis

Sneak Analysis and Sneak Circuit Analysis deal with the "sneak" or "hidden" conditions of the design phase. A "hidden" condition is any condition that can lead to an unwanted and unplanned event. It does not allow the desired event to proceed smoothly, but is not caused by the failure of some of the components.

DEVIATION	CAUSES	CONSEQUENCES	PRECAUTION MEASURES	COMMENTS, RECOMMENDATIONS
High flow	Failure of safety valve in open position	High level in reactor with potential overfilling	FI567 (local) LIT987 (remote indicator)	(R) FIT (remote) with alarm for high level alert
High level	Failure of either safety (open) valve or valve (closed)	Potential overfilling	LIT (remote indicator)	(C) Verify if an error in LIT triggers an error signal according to DCS, the last time the value was not maintained (R) Provide LAH, LAHH from the LIT signal (R) Secure LHHS from the independent level of the transmitter to the supply pump

TABLE 5.4 Illustration of HAZOP template

HAZOP – Hazard and Operability Study

HAZOP – Hazard and Operability Study deals with deviations from expected characteristics (Table 5.4). As a result, solutions for risk processing are expected. The benefits of this method are a systematic approach to testing systems, processes, or procedures, provision of results and activities for risk processing, applicability to a large number of systems, processes and procedures, and the provision of explicit access to consideration of causes and consequences of human error. Nonetheless, detailed analysis can be very demanding, both in terms of financial resources and time; it may require high-level criteria for documenting the methodology and is often aimed at finding a solution to complex problems rather than some fundamental assumptions.

Hazard Analysis and Critical Control Points – HACCP

Hazard Analysis and Critical Control Points – HACCP is a systematic and proactive approach to ensuring quality, reliability, and security of the process by monitoring and measuring selected parameters. The aim is to reduce the risk during the process and not to control the final product. HACCP requires detection of hazards, identification of risks and their importance, determination of critical control points, and undertaking the necessary measures when control parameters exceed limit values.

TOC

Layers of Protection Analysis – LOPA

Layers of Protection Analysis – LOPA is often referred to as a barrier analysis that enables the assessment of the control process effectiveness. It requires significantly less time and resources in comparison with, for example, the Analysis of the Failure Tree or Quantitative Risk Assessment. LOPA helps to identify and to direct resources to the most critical levels of protection, and identifies operations, systems, and processes that need the utmost protection (Dowell & Hendershot, 2002).

"Bow tie" Analysis

"Bow tie" Analysis represents a simple graphic solution for describing and analysing the risk spreading, ranging from hazard detection to control. It can be viewed as a combination of thinking, cause analyses, fault tree, and an analysis of the consequences with the event tree. The basic "bow tie" steps include: the timely detection and localisation of potential errors; avoiding or mitigating project risks; prevention of costs of possible revocation due to error occurrence; and prevention of the loss of reputation on the market.

5.3 Statistical Methods

Markov Analysis

Markov Analysis a probabilistic technique used when the state or behaviour of the system depends only on the current state and not on any state or behaviour in the past. It is most commonly used for systems that can come out of a state of failure and which can survive in multiple states.

Monte Carlo Analysis

Monte Carlo Analysis is applied in very complex systems when it is very difficult to understand certain situations and solve problems using analytical methods.

Bayesian Analysis

Bayesian Analysis is a statistical procedure that combines previously known information with the latter, in order to determine the overall probability.

Multi-Criterion Decision Analysis - MCDA

Multi-Criterion Decision Analysis - MCDA is an analysis that uses a set of criteria to objectively evaluate the value of a range of alternatives. Generally, this type of analysis allows the ranking of the offered or existing alternatives.

6 Conclusion

Numerous risk definitions refer to probability, opportunity, chance, or expected outcome, and may also relate to uncertainty, unwanted and unplanned activities, and hazards. In order to eliminate the occurrence of unwanted and unplanned events, it is necessary to understand these events and their consequences. Knowing the nature of the consequences represents the basis of their reduction and of the contined desire for their complete elimination.

In addition to the most common types of risk assessment used in the context of risk management, it is also necessary to define the framework of the risk assessment process, depending on the problem type and complexity, and to select appropriate:

- variables (parameters, factors); and
- techniques (methods, tools) for modelling.

The risk assessment process has been given a key role by the European Directive 89/391/EEC. In non-member states, for example in the Republic of Serbia, and in the fire protection context used in this work to concretise the topics of risk assessment and risk management, the basic binding guidelines that employers have to respect, apply, and implement are given through the Labour Law and the Occupational Health and Safety Act. Every organisation has the obligation to provide every worker with such work conditions that don't endanger life and health. When risk management activities are carried out in an appropriate and prescribed manner, it is a sure sign that workplace safety is enhanced.

There are many types of variables and methods that can serve as a stable basis for an adequate risk assessment. All methods and tools for risk assessment are conceived and adapted to reducing risks. The decision on selection is made on the basis of sufficient information on the type and characteristics of the workplace, the likelihood of occurrence of unwanted and unplanned events, possible consequences, etc. Therefore, it is necessary to choose the method that best suits and determines the real state for the observed workplace.

References

Arsovski, S., Kokić Arsić, A., Rajković, D. & Savović, I. (2013). Struktura standardizovanih sistema menadžmenta [Standardize Management System Structure]. In: S. Arsovski (Ed.). *Integrisani sistemi menadžmenta* [Integrated Management System] (2nd ed.) (pp. 169-317). Kragujevac: FIN Kragujevac, Centar za kvalitet.

Arsovski, S., Vujović, A., Mišić, M., Nestić, S. & Gvozdenović T. (2013). Merenje i praćenje [Monitoring and Measurement] performansi IMS-a. In: S. Arsovski (Ed.). *Integrisani sistemi menadžmenta* [Integrated Management System] (2nd ed.) (pp. 375-450). Kragujevac: FIN Kragujevac, Centar za kvalitet.

Aven, T. (2008). *Risk Analysis*. Chichester: John Wiley & Sons, Ltd.

Aven, T. & Vinnem J.-E. (2007). *Risk management* (2nd ed.). Netherlands: Springer.

Bischoff, H.J. (2008). Risk profiles in modern work life. In: H.J. Bischoff (Ed.). *Risks in modern society – Topics in safety, risk, reliability and quality* (pp. 11-16). Netherlands: Springer.

Ball, D. & Ball-King L. (2011). *Public safety and risk assessment: Improving decision making* (2nd ed.). London: Routledge.

Charters, I. (2011). *A practical approach to business impact analyses, Undestanding the organisation through continuity management*. BSI British Standards Institution.

Dowell, A. & Hendershot, D. (2002). *Simplified risk analysis layer of protection analysis*, AIChE, 281a, 16-20.

Đapan, M. (2014). *Unapređenje modela za procenu rizika na radnom mestu primenom teorije fazi skupova i prognostike* [Improvement of model for risk assessement on work place using theory of fuzzy sets] (Theses). Kragujevac: FIN Kragujevac.

Ericson, A. (2005). *Hazard analysis techniques for system safety*. Chichester: John Wiley & Sons, Inc.

Golfareli, M. & Rizzi S.(2008). UML-based modeling for what-if analysis. In: IY. Song, J. Eder & T.M. Nguyen (eds.). *Data Warehousing and Knowledge Discovery. DaWaK 2008. Lecture Notes in Computer Science*, vol. 5182. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-540-85836-2_1

Haimes, Y.Y. (2015). *Risk modeling assessment and management* (4th ed.). NJ: John Wiley & Sons.

International Organisation for Standardization, International Trade Centre & United Nations Organisation for Industrial Development. (2015). *ISO 31000*: *Risk management – A practical guide for SMEs*. Switzerland: ISO. Retrieved from: https://www.iso.org/files/live/sites/isoorg/files/archive/pdf/en/iso_31000_for_smes.pdf

Ishikawa, K. (1976). *Guide to quality control*. Asian Productivity Organisation.

ISO – International Organisation for Standardization. (2009). *ISO 31000:2009 Risk Management – Principles and guidelines.*

ISO – International Organisation for Standardization. (2009). *ISO/IEC 31010:2009 Risk management – Risk assessment techniques.*

Kiral, I.A. & Kural, Z. (2014). Risk identification in construction projects: Using the Delphi method. *11th International Congress on Advances in Civil Engineering, 21-25 October 2014, Istanbul Technical University, Istanbul, Turkey.*

Kokić Arsić A., Arsovski S., Kanjevac Milovanović K., Bojić B. & Savović I. (2013). The management decision for competitiveness improvement. In: *Technics Technologies Education management*. Sarajevo: Society for development of teaching and business processes in new net environment in B&H.

Kosow, H. & Gaßner, R. (2008). *Methods of future and scenario analysis – Overview, assessment, and selection criteria.* Bonn: German Development Institute. Retrieved from: https://www.die-gdi.de/uploads/media/Studies_39.2008.pdf

Lazić, M. (2006). *Alati, metode i tehnike unapređenja kvaliteta [Tools, methods and techniques for quality improvement].* Kragujevac: Mašinski fakultet u Kragujevcu.

Leveson, N. (2011). *Engineering a Safer World: Systems Thinking Applied to Safety.* MIT Press.

MS/2. (2000). *British Standard BS 6079-3:2000, Project management – Part 3: Guide to the management of bussines related project risk*. BSI.

Mannan, S. (2012). *Lees' loss prevention in the process industries: Hazard identification, assessment and control.* Volume 1. (4nd ed.). Amsterdam: Elsevier.

Nikolić, B. & Ružić-Dimitrijević, Lj. (2009). Risk assessment of information technology system. *Issues in Informing Science and Information Technology*, 6, 21-22.

Rausand, M. (2011). *Risk assessment theory, methods, and applications*. NY: Wiley.

Reason, T.J., Carthey, J. & de Leval, M.R. (2001). Diagnosing "vulnerable system syndrome": an essential prerequisite to effective risk management. *Quality in Health Care*, 10 (Suppl II), 21–25. Retrieved from: http://qualitysafety.bmj.com/content/qhc/10/suppl_2/ii21.full.pdf

Standards Australia. (2004). *AS/NZS 4360:2004 Risk Management.*

Standard Councils of Canada. (2009). *CAN/CSA-Q850-97(R2009) Risk Management: Guideline for Decision-Makers.*

The Council of the European Communities. (1989). Council Directive 89/391/EEC of 12 June 1989 on the introduction of measures to encourage improvements in the safety and health of workers at work. *Official Journal of the European Union,* L 183, 29/06/1989, 0001 – 0008.

Ushakov, I. (2016). Avaliability. In: S. Gass & M. Fu. (Eds.) *Encyclopaedia of Operations Research and Management Science*. Volume 1. (3rd ed.) (p. 95). Springer US. Retreived from: https://link.springer.com/referenceworkentry/10.1007%2F978-1-4419-1153-7_46

Vorley, G. (2008). *Mini guide to route causes analysis*. UK: Quality Management & Training (Publications) Ltd. Retrieved from: http://www.root-cause-analysis.co.uk/images/Green%20RCA%20mini%20guide%20v5%20small.pdf

Ware, J. (2009). *A systematic analysis to identify, mitigate, quantify, and measure risk factors contributing to falls in nasa ground support operations* (Doctoral Dissertation). Florida: University of Central Florida. Retrieved from: http://stars.library.ucf.edu/cgi/viewcontent.cgi?article=4909&context=etd

Methodology for Assessing Environmental Quality of Materials and Construction

Linda Hildebrand[1*] and Alexander Hollberg[2]

* Corresponding Author
1 Faculty of Architecture, RWTH Aachen University, Aachen, e-mail: lhildebrand@rb.arch.rwth-aachen.de
2 Institute of Construction and Infrastructure Management, ETH Zürich, e-mail: hollberg@ibi.baug.ethz.ch

ABSTRACT **As architects and engineers work at different scales, the ecological impact generated within the scope of their professional activities can be differentiated between material, component, building, and city levels. By focusing on the material and component levels, this chapter introduces and gives a detailed analysis of the structure of the life cycle assessment (LCA) method used for quantifying environmental impact. The review encompasses the following issues: LCA goal and scope, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and results interpretation. Subsequently, the scope of LCA data is discussed and the criteria to be sought when working with LCA data are proposed and described. Finally, the chapter considers the application of the LCA data, especially in formats such as Environmental Product Declaration (EPDs) and LCA databases, provides relevant examples, and thus concludes the presentation of the facts necessary for the application of life cycle assessment methodology in different design and engineering contexts.**

KEYWORDS ecological assessment, environmental impact, evaluation criteria, LCA, material

TOC

1 Introduction

The development of reliable methods to quantify ecological impact was initiated in the 1970s. Since then, the tendency to reduce impact on nature resulting from the anthropogenic behaviour has been gaining relevance in political discussion and marketing. Simultaneously, companies started to advertise characteristics of products and processes in order to highlight the ecologically-friendly approach, but the content and quality of the given information represented mixed facts, often referred to as greenwashing. In the 1990s, the methods for quantifying ecological impacts were introduced to the building sector. At that time, only a small number of professionals who understood the methods of calculating environmental impact were able to draw guidance from results.

Although the methods for ecological impact qualification evolved over time (Table 1.1), their primary concept, based on a list of resources and emissions used for a life cycle phases analyses (input and output analyses), has been preserved.

ACRONYM	TITLE	INSTITUTE	WEBPAGE
C2C	Cradle to Cradle	Braungart and McDonough	www.c2ccertified.org
-	Ecological Footprint	Global Footprint Network 2009	www.eea.europa.eu
-	Faktor X	Aachener Stiftung Kathy Beys, UBA	www.umweltbundesamt.de
MFA	Material Flow Analysis	Wassily Leontief	-
MIPS	Material Input per Service	Wuppertal Institute	www.wupperinst.org/en/a/wi/a/s/ad/141/
LCA	Life Cycle Assessment	Various	Various
PEF	Product Environmental Footprint	Environment and Sustainability of the European Commission	www.ec.europa.eu/environment/eussd/smgp/policy_footprint.htm

TABLE 1.1 Methods to calculate environmental impact

In the last decade, the number and intensity of impact quantification methods used in the building sector have increased (Hollberg, 2016). Today, different approaches can be found, but the most common and documented method is the *Life Cycle Assessment (LCA)*. LCA calculates resources and emissions assigned to a particular defined service or product.

1.1 Development of LCA

Although the LCA emerged as a narrow concept, its meaning has been made significantly more complex over time. A method for systematic screening of energy and material flows, developed by biologist and economist Geddes in 1884, accounts for one of the first documented approaches leading to what is today defined as 'life cycle assessment' (Frischknecht, 2006; Geddes, 1884). Having determined that every production inevitably implies energy utilisation, the starting point of any product assessment was, and still is, energy.

TOC

Over the last 50 years, LCA methodology has evolved internationally. Following the oil crises in the 1970s, different institutes started researching the possibilities of enhance efficiency in energy generation, and additionally to reduce waste, e.g. by comparing the life cycle of glass bottles versus cans. One of the first mentioned pieces of research in the field of LCA was a study carried out for the Coca Cola Company by the Midwest Research Institute (MRI) in 1969, where resource consumption for beverage containers was compared to environmental releases (Guinée et al., 2011; Jensen, Hoffman, Møller, & Schmidt, 1997). Boustead explained the application of the method for quantifying the amount of energy used in beverage cans production, and the publication *Handbook of Industrial Energy Analysis* (Boustead & Hancock, 1979) enabled the spread of the method for quantifying energy on a physical basis into other disciplines in the UK. The term *Life Cycle Assessmen*t was coined by the Institute Eidgenössische Materialprüfanstalt in St. Gallen in 1978 (Kümmel, 2000), followed by the introduction of the term *Grey Energy* referring to the quantified expression of primary energy used for a service or product as an indicator for environmental impact (Spreng & Doka, 1995). The period from 1970-1990 is the *Decades of Conception* of basic LCA concepts, and the period from 1990-2000 the *Decade of Standardisation* (Guinée et al., 2011). During the last decade of the 20th century, several institutes dealing with the LCA standardisation were founded. Following the initiative of the Nordic Council of Ministers, the Nordic Guidelines for LCA were formulated in 1991. The results of two LCA coordinating workshops organised by the Society of Environmental Toxicology and Chemistry (SETAC) in 1992, which formed the *Guidelines for life-cycle assessment*, i.e. the *Code of Practice* published in 1993 (Consoli et al., 1993), marked a notable progress in the harmonisation of LCA methods. In 1992, the *Environmental Life Cycle Assessment of Products*, often referred to as *The Guide*, was published (Heijungs at al., 1992). To meet the need for standardisation, the first *ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework* was published in 1997. In 2002, the United Nations Development Programme and SETAC together founded the *Life Cycle Initiative,* thus offering a networking platform for engaging in life cycle thinking (Hildebrand, 2014). In the *Decade of Elaboration* (Guinée et al., 2011), LCA as a method of quantifying the ecological impact is applied in different fields and disciplines, from energy generating industry to process technology.

2 LCA Structure

Life cycle assessment began with listing and quantifying the ecological impact of energy sources, where the data related to raw material extraction and transportation were based on information provided by the industry. The information on one process is called flow. Several flows form one module or product. Several products constitute a system. Hierarchy enables the provision of sufficient data for the building sector. In this logic, products add up a building.

As a method for ecological impact quantification, LCA can be applied to materials, buildings, and neighbourhoods. This section describes fundamental facts and specificities of the LCA method used for material and component evaluation.

Matthews, Hendrickson, and Matthews (2015) provide an easy-to-understand introduction to the LCA and a comprehensive overview of different approaches. The procedure itself is regulated by standards ISO 14040:2006 and ISO 14044:2006. While ISO 14040 describes the framework, more detailed information regarding the LCA implementation can be found in ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines (Hildebrand, 2014). As defined in ISO 14040 (2006), LCA is the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". Inputs can be resources, energy, pre-products or auxiliary material. Outputs are usually emissions into the air, water or earth, waste and side-products.

Standards ISO 14040 and ISO 14044 regulate four phases in the procedure of environmental impact measurement (Fig. 2.1): a) Goal and scope definition; b) Life cycle inventory analysis (LCI); c) Life cycle impact assessment (LCIA); and d) Interpretation. LCA consists of mandatory (a, b, c) parts and optional (d) part, which can be adjusted to specific requirements (Hildebrand, 2014).

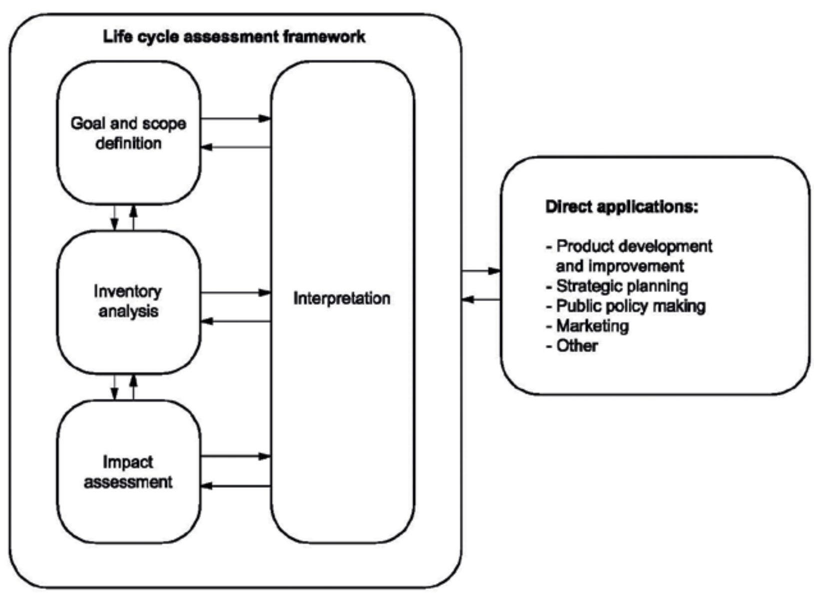


FIG. 2.1 The structure of LCA according to ISO 14040

2.1 Goal and Scope

Precise definition and description of the goal and scope account for the first stage in LCA. Intended application should be specified concerning motivation, audience, and context of the study (Hildebrand, 2014). The goal and scope are defined within the following dimensions: Functional units; Life cycle phases; and System borders.

2.1.1 Functional Unit

The description of an object of evaluation (product, service, or company), called functional unit, needs to be precisely specified. Here, a functional description explaining in detail the performance of an object of ecological evaluation by using a range of physical numbers is required (for example, ten square meter exterior wall with a certain thermal resistance).

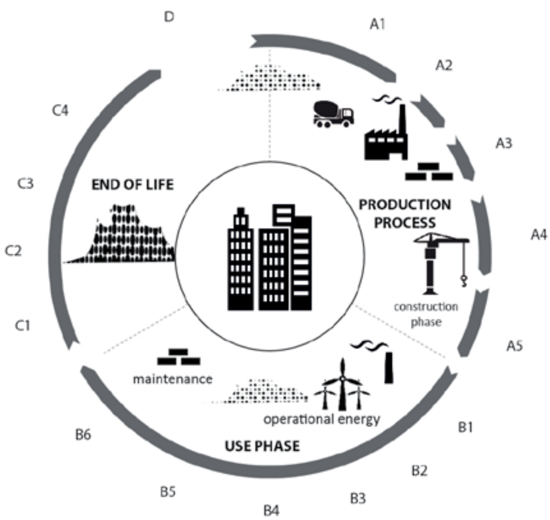
2.1.2 Life Cycle Phases

From one aspect, the scope of evaluation is described by life cycle phases. The life cycle phases of a product can be subdivided into production, usage, and end of life phase (Hildebrand, 2014). When comparing different products, all framework parameters should be aligned, especially the life cycle phases.

If the objective is to evaluate only production of a material or a component, then the included scope is called *from cradle to gate*: the cradle refers to excavation of resources and the gate to factory. When the complete cycle until the end of the usage phase is included, the scope is *from cradle to grave*. A LCA can consider the phases from cradle-to-gate (upstream processes), from gate-to-gate (manufacturing processes), from gate-to-grave (downstream processes), or include all phases in a cradle-to-grave consideration (Hildebrand, 2014) (Fig. 2.2; Table 2.1). BS EN 15804:2012 defines the phases in more detail (DIN, 2012).

The cycle is applied to both materials and buildings. The cycle of a building material and the cycle of a building differ specifically in the phase of utilisation. For comparison, while building utilisation relates to the significant energy consumption, the usage phase for materials only includes energy needed for material maintenance, replacement, or reparation.

The most prevailing segments in the LCA of a material are (mandatory) production and the end-of-life. The following text reviews the most significant steps of a LCA developed on the basis of the BS EN 15804:2012 (DIN, 2012).



A1	RAW MATERIAL SUPPLY
A2	Transport
A3	Manufacturing
A4	Transport
A5	Construction/ installation process
B1	Use
B2	Maintenance including transport
B3	Repair and transport
B4	Replacement including transport
B5	Refurbishment including transport
B6	Operational energy use
B7	Operational water use
C1	De-construction demolition
C2	Transport
C3	Waste processing
C4	Disposal
D	Re-use recovery and recycling potential

FIG. 2.2 Life cycle of building materials in phases *(Hildebrand, 2014)*;
TABLE 2.1 List of phases according to EN 15804

Production stage (A1-A3)

The life of any product starts with resources depletion. It is then followed by the transportation of raw material to processing facilities and production. The distance from source to factory and the mode of transportation together influence the strength of environmental impact caused by transport. During the production process, utilisation of energy accounts for the main environmental burden, and the amounts of accompanying generated emissions depend on the primary energy resource. For example, 1 MJ from a brown coal power station releases significantly more emission than 1 MJ from wind energy (Hildebrand, 2014).

Transport and construction stage (A4-A5)

The energy and emissions related to transportation depend on the distance between the construction site and the manufacturer's plant. In the studies published by Kellenberger & Althaus (2009), transportation accounted for 5-8% of the total primary energy demand. However, the data for building material are not available, which most commonly leads to an exclusion of this stage. In the phase of construction, all efforts on the site and between manufacturing facilities are calculated. Therefore, gathering the data on this life cycle phase requires sufficient detailing.

Usage stage (B1-B7)

The utilisation of building materials starts when a building is completed and its operating system begins to provide useful forms of energy. In terms of materials and components, building operation is not relevant, but the flows related to their repair, replacement, and maintenance are. Rarely, building elements require energy supply for their performance, e.g. permanently inflated foil cushions. The extent of ecological impact in usage stage highly depends on the building context, its exposure to weather and other forces, as well as on material content.

End-of-life stage (C1-C4, D)
End-of-life starts when an item has lost its function. The actual processes cannot be foreseen, and so the end-of-life scenarios are simplified and their accuracy accordingly questioned. Generic scenarios cover the flows for most building material. The generic end-of-life scenarios are: Building rubble procession; Recycling; Energetic recycling; and Landfill (Hildebrand, 2014).

2.1.3 System Border

The border of a system undergoing life cycle assessment identifies included and excluded parameters. In addition to the life cycle phases, the flows included and excluded from the calculation are mentioned.

Only significant processes should be included in assessment in order to balance complexity in gathering the data. The significance is defined by a certain percentage of contribution of individual product to the whole system, based on mass, energy, or ecological significance (DIN EN ISO 14044, 2006). The percentage and the units should be documented under this category.

LCA method can be classified as comparative or descriptive. The assessment of variants and the delivery of decision-basing data represent the scope of comparative LCA. On the other hand, descriptive LCA analyses the distribution of different components of an assessed product or service (Hildebrand, 2014).

2.2 Life Cycle Inventory Analysis (LCI)

All relevant processes are defined within the life cycle inventory analysis (LCI). Usually, this is the most resource-intensive evaluation stage and an iterative process (Klöpffer & Grahl, 2014). In the inventory, all flows are quantified and categorised as input or output flows. Elementary flows are resource consumption and emission. Inputs and outputs are categorised as follows: Energy inputs, raw material inputs, ancillary inputs, other physical inputs; Products, co-products and waste; Releases to air, water and soil; and Other environmental aspects (Hildebrand, 2014).

A special relevance in the process of data collection is given to the following factors: time, geographic origin, and data consistency. Validation in terms of comprehensiveness and plausibility and proper data documentation are mandatory. Accompanying sensitivity analysis, as a part of the LCI, enables confirmation and an adjustment where necessary.

Most industrial processes have more than one product as output. When co-products occur in the process of an investigated product, input and output flows have to be partitioned. The ISO 14044 (2006) standard defines this action as "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems". Due to variability found in functional units, the so-called allocation becomes intricate and should, as such, be avoided. Division of inputs and outputs should be done according to the weight, volume, or monetary value.

2.3 Life Cycle Impact Assessment (LCIA)

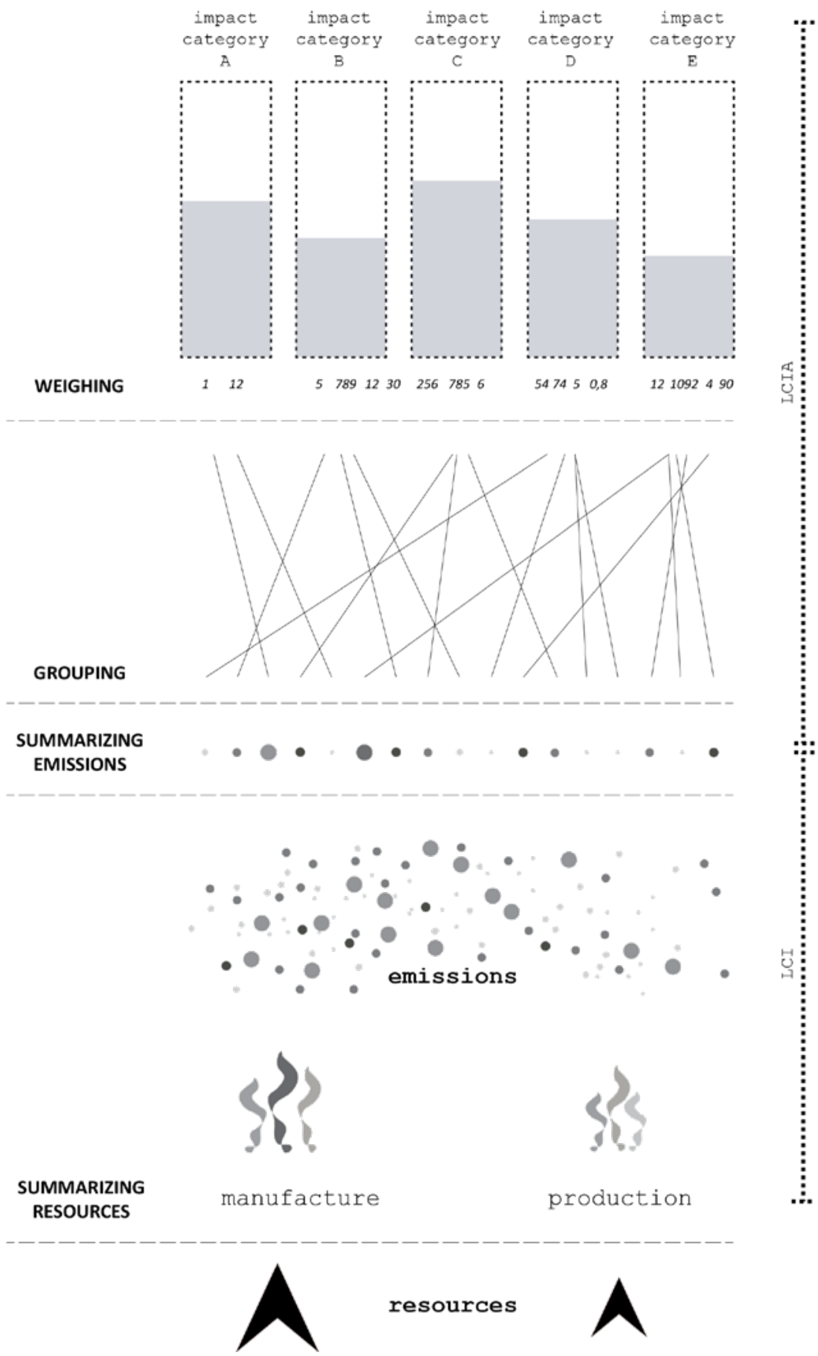


FIG. 2.3 LCI and LCIA built up on one another *(Hildebrand, 2014)*

LCIA is the quantification of all input and output flows related to a functional unit. Emissions (impact indicators) with different levels of harmfulness are taken into account in one category group by weighting (Fig. 2.3) (Hildebrand, 2014). The results are sorted into impact categories on the basis of ecological effects. LCIA stage is, according to the ISO 14040, divided into three mandatory steps: 1) Selection of impact categories, category indicators and characterisation models; 2) Classification: Assigning the LCI results to impact categories; and 3) Characterisation: Calculation of the category indicator results.

2.3.1 Characterisation Models

In comparison with the emissions that can be monitored and calculated, the measurement of environmental impact related to a process is more complex. Different methods for translating emissions into ecological impairment were developed to estimate the harm on nature. Ecological protection targets are defined and all emissions affecting them are listed in a target or impact category. Within a group, the weight of emissions is defined on the basis of their environmental harm. For example, both carbon dioxide and methane contribute to global warming potential. However, since methane has a higher environmental impact than carbon dioxide, a factor is applied to compensate for this difference. When a common denominator is found, the two emissions can be expressed using the same unit (category indicator, in LCA terms) (Hildebrand, 2014).

IMPACT ASSESSMENT METHODS	PUBLISHER /DEVELOPER	COUNTRY CODE
BEES	National Institute of Standards and Technology (U.S. Department of Commerce)	USA
CML-IA	University of Leiden CML	NL
Eco-indicator 99	PRé Consultants bv	NL
EDIP 2000/ EDIP 2003	Institute for Product Development (IPU)	DK
EPS 2000	Swedish Environmental Research Institute (IVL)	SE
Impact 2002+	Risk Science Center	USA
Ecological Scarcity (UBP Method)	Öbu/ FOEN	
ReCiPe	RIVM, CML , PRé Consultants, Radboud Universiteit Nijmegen and CE Delft.	NL
Traci 2	U.S. Environmental Protection Agency	USA
TWIN2010	NIBE/ Stichting Bouwkwaliteit	NL
USEtox	UNEP-SETAC	USA

TABLE 2.2 International characterisation models *(Hildebrand, 2014)*

An overview of different developed characterisation models is provided in Table 2.2. Every model contains protection targets expressed by impact categories, category indicator, and a list of emissions that belong to the impact category, and the factor by which these emissions need to be quantified. Impact indicators address target on midpoint or endpoint level. For example, while midpoint level addresses ozone depletion potential, the endpoint would express contribution to cancer.

(For further information: Bare, 2002; Finnveden et al., 2009; Guinée et al., 2011; Heijungs et al., 1992; Matthews et al., 2015; Ministry of Housing, Spatial Planning and the Environment, 2000)

Most characterisation models offer a weighting for normalisation, thus describing the method by which to calculate one of the several indicators. ISO 14040 names three optional steps: 1) Normalisation: Calculation of the magnitude of category indicator results relative to a reference; 2) Grouping: Sorting and ranking of impact categories; and 3) Weighting: Multiplication of indicator results.

For the normalisation, indicator results are divided by a selected reference value, for example, the results for global warming potential (GWP) are divided by whole annual GWP of Europe. The aim is to reveal which indicator contributes more to the overall problem area (Lützkendorf, 2009).

Grouping defines a hierarchy of categories based on value-choices (Klöpffer & Grahl, 2014).

Weighting accumulates different indicators into a holistic one to provide a clearer suggestion and avoid contradictions (Crawford, 2011). This complex process is comprehensively discussed in the research sphere. Wegener Sleeswijka, van Oersc, Guinée, Struijsd and Huijbregtsb (2007) describe the constraints in merging different factors into a single value, and present an overview of applied normalisation methods. In the building sector, this action seldom finds its application due to constrained traceability. Green building certificates try to meet the demand by displaying a variety of indicators and calculating them into one grade.

2.3.2 Indicators

The characterisation is, as explained, organised in impact categories. These count as indicators for quantifying the environmental impact. The most common indicators are introduced below.

Embodied or *grey energy* describes the amount of energy used to produce, maintain, and demolish or deconstruct a building. In contrast to operational energy, this type is not visible on one bill, but has to be calculated from different process steps. Primary energy (PE) consists of primary energy from renewable and from non-renewable resources. Since primary energy from non-renewable resources has a more harmful impact on nature, this indicator finds a broader application. Non-renewable primary energy PE(nr) originates from fossil and nuclear energy sources. Renewable primary energy PE(r) contains energy generated by wind, water, solar radiation, and biomass. PE is typically measured in megajoules (MJ), or less often in kilowatt hours (kWh) (Hildebrand, 2014).

Embodied energy (EE) is not defined by standards. In literature, the examples in which EE expresses other emission indicators can be found. In Eco-Devis, for example, 2g of a solvent account for 1 MJ of primary energy (Pestalozzi, 2014). This mixture of parameters leads to incomparable indicators. In order to counteract such complications, the *cumulated energy demand* (CED) was developed by Kasser (2003), and elaborated upon by Frischknecht (2006). CED defines energy categories and excludes any other factors. It is regulated by the VDI standard 4600 (2012): Cumulative energy demand (CED) - Terms, definitions, methods of calculation (VDI, 2012). CED includes the expenditure of primary energy for production (CEDH), use (CEDN) and the end of life phase (CEDE) of a product or service similar to the EN 15804. VDI 4600 (2012) distinguishes between primary energy from non-renewable energy sources (KNAR) and from renewable resources (KAR). Both are included in the CED indicator (Hildebrand, 2014).

Besides embodied energy, the *embodied emissions* represent the common set of indicators used to quantify the environmental impact of a product or a service. In this group, the following indicators are found:

- Global Warming Potential (GWP 100);
- Ozone Depletion Potential (ODP);
- Acidification Potential (AP);
- Eutrophication Potential (EP);
- Photochemical Ozone Creation Potential (POCP); and
- Abiotic resource depletion potential (material) (ADP element) / Abiotic resource depletion potential (ADP energy) (fossil).

Global Warming Potential (GWP 100)

The increase of greenhouse gases in the atmosphere causes temperature increases, which further affect poles and advances the depletion of their ice volume, resulting in the rising sea level. Global warming provokes climate change and intensifies the occurrence of extreme weather events. Due to the awareness of these interdependencies, the *Global Warming Potential (GWP 100)* indicator is the most commonly used. Being the most common greenhouse gas, carbon dioxide (CO_2) is used as a reference for this impact category (CO_2-equivalent). Other emissions contributing to greenhouse effect are factored in as explained earlier.

Ozone Depletion Potential (ODP)

With the depletion of the protective ozone layer, ultraviolet (UV) radiation penetrates the filter, enhances air warming and potentially causes harm to human health and living organisms. In the past, the main contributor to ozone depletion was Chlorofluorocarbon (CFC), which is often used as freezing agent. With the CFC/Halon prohibition ordinances (OzonAction Programme, 2000), depletion decreased significantly but the effects that had already been generated will remain. Trichlorofluoromethane (R11) is used as an equivalent within this emission category.

Acidification Potential (AP)

The conversion of emissions of some harmful substances that reduce the pH value (such as sulphur dioxide and nitric oxides) can provoke the occurrence of acid rains which further affect water and soil, and cause forest die-back. *Acidification Potential (AP)* is indicated in sulphur dioxide equivalents (SO_2 equivalent).

Eutrophication Potential (EP)

As a response of the water ecosystem to increased presence of fertilisers, eutrophication describes the growth of algae in surface water. Newly-formed algae cover blocks the penetration of sunlight into deeper water layers, decreases photosynthesis, and reduces oxygen levels. Consequently, fish and plants lose the fundamental requirements of existence and die. The *Eutrophication Potential (EP)* is expressed in phosphate equivalent (PO_4- equivalent).

Photochemical Ozone Creation Potential

High ozone concentration is toxic for humans as it can lead to breathing difficulties. In addition, it is suspected to be responsible for damage to vegetation and material. A high concentration of ozone in the troposphere occurs under high summer temperatures accompanied by low humidity and the absence of air movement. A typical example of a photochemical ozone occurrence in late summer is in an enclosed area of a highway with a high traffic load. Photochemical ozone develops in a complicated chemical process, when CO_2 and SO_4 are emitted with high intensity. The *Photochemical Ozone Creation Potential (POCP)* is measured in ethene equivalent (C_2H_4-equivalent).

Abiotic Resource Depletion Potential (material) (ADPe), and Abiotic Resource Depletion Potential (fossil energy) (ADPf)

Abiotic depletion relates to the extraction of minerals and fossil fuels. It considers the amount of global reserves that can be exploited economically. Annual extraction is divided by the reserves squared. Hence, the amount of abiotic resources for a process, in relation to the global amount of this resource, defines the abiotic resource depletion potential (Hildebrand, 2014). According to Oers, Koning, Guinée, and Huppes (2002, p. 29), the "abiotic resource depletion is the decrease of availability of functions of resources, both in the environment and the economy". ADPe result is related to the reference element antimony (Sb). By including the annual extraction rate, the current importance of a given resource is captured (JRC, n.d.). ADPf is calculated analogously, with the difference being that the lower heating value of the fossil fuel is used instead of material mass. Therefore, the unit is Mega Joule (MJ).

2.4 Interpretation

The interpretation after LCI or LCIA is aimed at identifying the achievement of significant results in line with defined items in goals and scope. According to ISO 14044 (2006), significant results can be "inventory data, such as energy, emissions, discharges, waste, impact categories, such as resource use, climate change, and significant contributions from life cycle stages to LCI or LCIA results, such as individual unit processes or groups of processes like transportation and energy production". By controlling compatibility with aims and scope, interpretation verifies requirements fulfilment.

3 The Scope of LCA Data: Evaluation Criteria

Scale defines the potential to influence the ecological quality of a planned object. For materials and components, the scale can be differentiated from small to large. Buildings and urban or neighbourhood scales, on the other hand, build up on smaller units.

On the urban scale, energy supply and mobility associated with the location of the site predefine the ecological impact. For new developments, the increased share of renewable energy and the integration into a network (e.g. smart grid, or smart city) reduce (non-renewable) energy demand and thereby emissions, as compared to conventional supply. The decision about the location of a new development will impact the energy needed for transportation. While in rural areas individual transport is required, re-densification can include options for public transportation. On the building level, the decisions are similar. Site limitations and potentials shape the options for energy supply and mobility types, and passive properties such as orientation and heat insulation, as well as the active energy systems, influence the ecological dimension.

Building material is the smallest module of a building. To that end, ecological analysis on the material scale provides a generic comprehension of the impact that building fabric makes on environment. The motivation to calculate or measure the ecological impact of a service or product is informed by the need to make a responsible decision. Not just on material scale, it is therefore necessary to have different options evaluated against each other. As explained within the section *Goal and Scope* of this work, these options are called 'functional units' in LCA-terms. On the material scale, functional unit is one unit of weight or volume or sometimes area. The most common scenario in which to use LCA data on a material level is to compare two or more different products with equal functional characteristics.

The increasing amount of standardised LCA information has improved communication between stakeholders (companies, planner, and client). LCA information that is available for building materials ranges from various database sheets to environmental product declarations (EPDs), and from concise to very detailed presentations. Categories to express LCA results need be comprehensible and practical at the same time. To support readability, Hildebrand (2014) recommended the following criteria to be sought when working with the LCA data:

- Evaluation goal;
- Data source;
- Generic and specific LCA data and its validity;
- System borders;
- Reference unit;
- Life cycle phases;
- Considered time span; and
- Indicator.

Evaluation goal: What is the purpose of evaluation?
If only one item is assessed, the purpose of evaluation could be to present ecological impact of a function, product or service. More likely, the goal of evaluation is the comparison of different products or services. Both the evaluation (with at least two items included) and the LCA goal (one item) relate to quantification, i.e. to the definition of ecological dimension by using numbers. On the basis of comparison, the evaluation most frequently aims at finding the solution with the lowest ecological impact. With the identification of detailed (research) questions, evaluation is deepened. Other possible evaluation goals could be the comparison of generic and specific data or the variation with regard to changeable durability (Hildebrand, 2014).

Data source: Where does the data come from and is it complete?
Firstly, the source of all data needs to be traceable, meaning that the documents of data's origin should be accessible. All included impact categories must be explained and the life cycle phases shown. When relevant, it might also be useful to include the information on pre-chains.

Consistency represents the key to data selection. Selected data should correspond to the evaluation scope and goal and should as such be documented. When applying more than one database, their belonging to the same framework needs to be secured. Third party document review is preferred over the manufacture information on products.

Generic and specific LCA data: Does the information base on an average value or a specific product?
Generic data is obtained by averaging the values from different published sources. For certain products, generic information is the only provided as manufacture did not include the LCA. Specific or product-related data are suggested rather than general data. The specification additionally affects data validity. According to the EN 15978 (CEN, 2011), generic data should not be older than ten years, as this is the assumed period of time during which the general processing line will not undergo significant changes, and any small change will not affect the average values considerably. On the other hand, specific data should

be derived within the last five years, as any change introduced to the production process could potentially reflect on ecological impact.

System borders: Which boundary conditions are included?
Like stated earlier, system borders define the information that is significant for assessment. Here, the recycling approach presented by displaying life cycle phases is relevant.

Reference unit: What unit is the basis for comparison?
The reference unit for a building material relates to a mass (1 kg), volume (1 m^2) or an area (1 m^2). These units are applicable to general comparison and simplified approach. A typical illustrative question could be: What material embodies more GHGs – steel or aluminium?

While material comparison only represents the starting point, the inclusion of functionality increases information value. The inclusion of load-bearing capacity, cost or heat transmission characteristics therefore indicate a more complex evaluation goal.

Life cycle phases: Which phases are included?
Life cycle phases included in a LCA are based on the EN 15804 description. On material level, production and partly end-of-life phases are the most common. Depending on the life span, replacement cycles can be added. The energy used for building operation is included on building level.

Considered time span: For how long is function provided?
In ecological evaluation, time dimension is used in three different ways. For describing scenarios and expressing the expected number of year of a function, the *life span*, also called the *duration*, is often used. Life span may refer to a certain aspect of performance such as technical where the time during which an object functions as initially expected is defined. L*ife time* describes the period of existence of an object. To express emissions contributing to a certain effect, the term *time span* used. It is defined per indicator group in which the effect of one emission is accounted. For example, the effect of CO_2 in the atmosphere is assessed for the period of hundred years as it is believed that the impact is traceable within this time span (Hildebrand, 2014). The life span of materials differs, and combinations and connections impact the exchange cycles.

Indicator
Indicator is chosen within the LCA scope and goal. Most commonly, global warming potential and primary energy (non-renewable) will be displayed.

4 Application of LCA Data

In building industry, LCA data are available as generic or product based information. In order to provide fact-based alternatives to the so-called greenwashing information, data were gathered and made

TOC

publicly available. Another attempt was the introduction of a third-party review certificate, i.e. the Environmental Product Declaration (EPDs).

Online portals today enable the acquirement of information about building materials through *databases*. Every database is referring to different assessment terms. Some well-known databases include Ecoinvent (http://www.ecoinvent.org), Inventory of Carbon and Energy (http://opus.bath.ac.uk/12382/), Ökobau.dat (http://www.oekobaudat.de/en.html), and Wecobis (https://www.wecobis.de, available in German language).

The aim of an *Environmental Product Declaration* is to "present quantified environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function" (Belavicqua, Ciarapica & Giacchetta, 2012, p. 349). All products subjected to comparison need to be assessed under equal circumstances. Product Category Rules (PCR) were developed to regulate parameters such as life cycle phases, in- and excluded process or allocated products for each product category group. While ISO 14025 (2006) defines the PCR structure, the content is filled by institutes issuing certificates in collaboration with industry partners. The introduction of the PCR essentially helps to build objective comparison, and therefore enhances LCA data acceptance.

Among others, Swedish Environdec and German Institute for Construction and Environment have to-date issued EPDs in more than 20 categories within the construction sector (IBU, n.d). Usually, it is the company that approaches an institute with the request for EPD. If a PCR is available, a LCA consultancy can conduct the calculations. In the opposite case, PCR will be developed. According to the ISO 14025, an external professional will be asked to verify accordance with the ISO 14040 standard and the PCR.

EPD based on standard ISO 14025 contributes to the integration of life cycling into practice and the trustworthy and clear presentation of ecological information. The introduction of EPDs and the availability of databases prepared the foundations for LCA data utilisation in building industry. Today, green building certification systems like LEED and DGNB require LCA in order to reach the highest standard.

4.1 Material Evaluation and Comparison

The application of ecological information is no longer reserved for LCA professionals as the data are freely accessible. Still, a fundamental understanding of the LCA is needed among architects and engineers working with sustainability. To that end, it seems helpful to have an overview of the LCA material data.

Hildebrand (2014) carried out the evaluation of all five basic types of materials: minerals, wood, metal, synthetics and insulation materials, grouped according to the ecological impact.

In total, eighty materials from the open access data base *Ökobau.dat* were analysed regarding the primary not renewable energy (embodied energy, EE) and GWP for the production of one kilogram of material. To compare the ecological qualities on material level, one kilogram is isolated from its functional context and the primary energy embed in different materials could be compared. The results of research are presented below.

Embodied energy (EE) ranges from 0 to 200 MJ for 1 kg and from 0 to 900,000 MJ for 1 m^3, for all material groups. Mineral materials show value from 0.5-9 MJ per kilogram except the glass with approximately 18 MJ/kg. Aggregates have the lowest values with 0.5 MJ (gypsum stone). The maximum values of embodied energy are found in natural stone. For cementous products, EE raises with the percentage value of steel reinforcement. This is also true for growing amounts of cement sinter, while blast furnace slag, aggregates cement or other recycled content help to reduce the impact.

Wood based products embody a range from 5- 21 MJ/kg of energy. Primary renewable energy is even higher, from 8-53 MJ/kg, having regarded that this material captures CO_2 in the growing phase and releases it when rots or burnt. The longer the carbon is stored in the building context, the later it can function as GHG. Installing a wood product in a building, as compared to letting it rot in the forest, helps extend the storage period and postpones the moment of release (Walz, Taverna & Stöckli, 2010), and additionally prevents the use of fossil resources for building materials.

EE for metals varies from 14 MJ/kg for copper (bronze) to 149 MJ/kg for aluminium casting. Steel products vary from 20-30 MJ; only the stainless steel is higher with 61 MJ/kg. Aluminium marks the highest values with 130-150 MJ/kg. Compared to other material groups, metal has the highest potential for material recycling. Up to 90% of EE can be saved when using recycled aluminium instead of a virgin material.

EE value for synthetic materials is from 30-150 MJ/kg. The least value of embodied energy is found in linoleum. On the other hand, materials that are more transparent embed the highest amounts of energy. Obtained values can be compared with those valid for primary aluminium. The main reason for the high value of EE is the nature of production chain (from raw material to final product) which is consisted of many steps. Regarding recycling, material purity determines to a large extent the achievement of level of quality as compared to the first-time produced material.

4.2 Functional Unit in the Building Context

Ecologic values introduced in the previous section aim at gaining a profound understanding of the evaluation comparing LCA results on the basis of mass. Nonetheless, this type of material consideration is isolated from building context because it doesn't include functionality.

A material can perform different tasks; only when placed in functional context, a fair comparison between different materials can be made.

When functional unit is defined, LCA uses it as a base for comparing multiple solutions. The function of a unit is ideally described numerically. As isolated functions are described more easily, LCA evaluation on material and component levels is recommended. For insulation material, for example, the function can be determined according to one property that is heat conductivity (Fig 4.1).

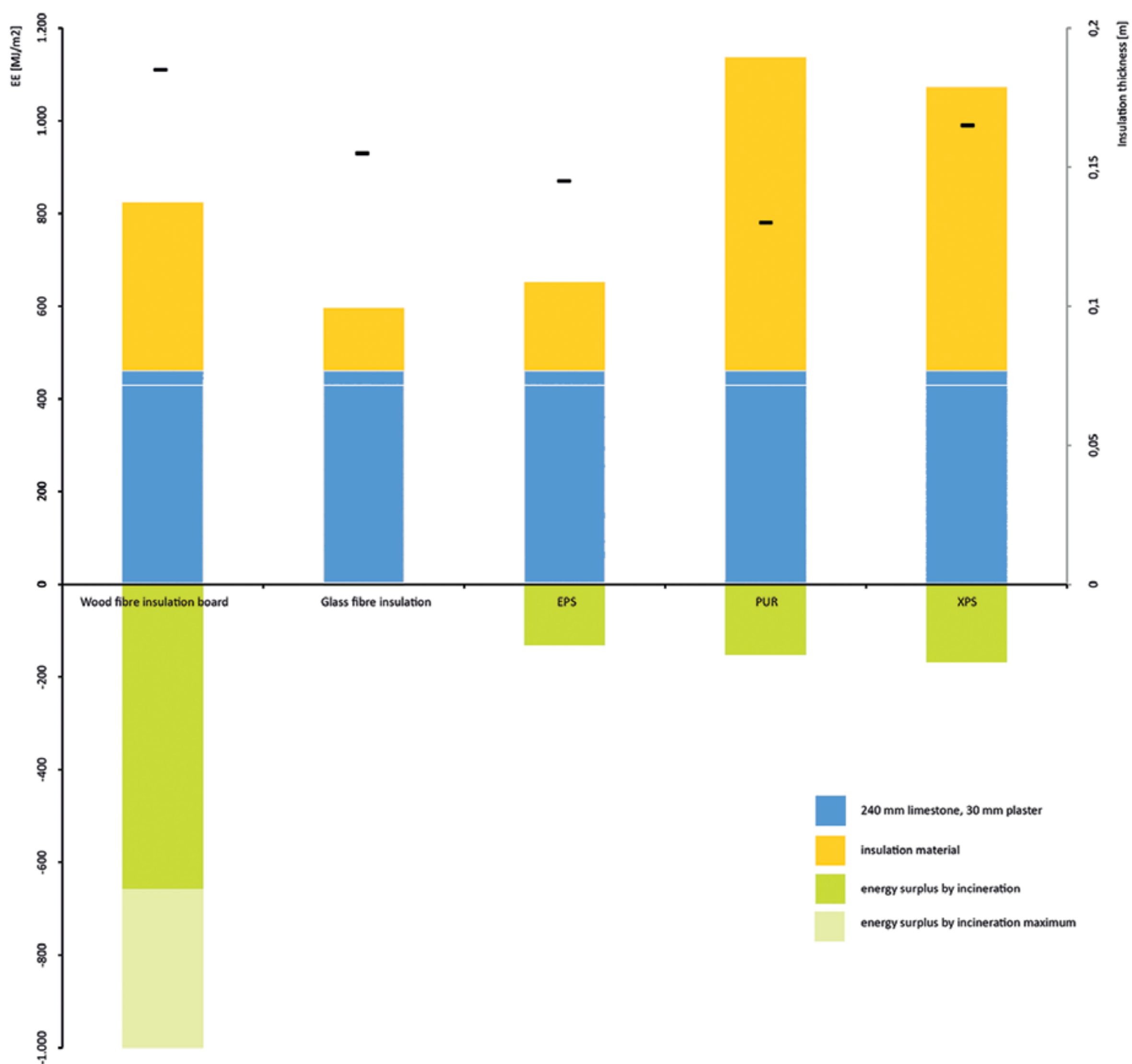


FIG. 4.1 Comparison of different insulation material (0,2 W/sqmK, 240 mm limestone, 30 mm plaster) *(Hildebrand, 2014)*

Here, LCA application can be demonstrated by example where the task is to identify insulation material with the least environmental burden. The function to be performed is heat resistance of 0,2 W/m²K. For that objective, a limestone wall with five different insulation material types is compared based on EE and GWP. To fulfil functional requirement and keep the same thermal resistance of compared materials, insulation thickness varies from 155mm for glass fibre insulation to 145mm for expanded polystyrene (EPS). The EE varies from 134- 190 MJ/m^2. Even it is thinner, synthetic insulation material requires more energy in production. When end-of-life scenario is included, the intensity is more accentuated (Hildebrand, 2014).

Although calorific value of synthetic materials leads to improved performance regarding embodied energy, an extensive separable demolition represents the precondition of this end-of-life scenario. The same interdependency applies to wood fibre insulation. To draw end-of-life scenario, the connectivity of materials and hence the potential for reuse and recycling are defined on construction level. When the type of construction and the simplified end-of-life scenario are aliened, LCA becomes a method to compare different planning solutions against each other and to quantify the ecological dimension of each of them.

5 Discussion and Conclusions

5.1 Potential and Constraints of the LCA

The purpose of the paper is to stimulate awareness about ecological impact of building materials and to provide an overview of the method which supports design decision-making process.

Progressive application of the LCA data in building sector is supported by the availability of different types of third party review certificates (EPDs) used by companies to promote products. Especially in Western Europe, the increasing product evaluation leads to data availability, where results are gathered and updated in databases. In Germany, UK and Netherlands, LCA is often accessible free of charge.

While positive marketing aspect in some countries improved the data situation, the application as a decision-making basis cannot be documented due to its voluntary nature. According to the environmental relevance of materials, which will grow with the reduced (not renewable) energy needed for building operation, LCA data should be included in building permits. For this to happen, the conditions need to be developed on political level and to include not only the display but also the benchmarks for embodied energy and emissions. In existing green certificates, different benchmarking approaches can be found. For example, Swiss model assigns to every inhabitant 1 ton of carbon dioxide per year based on the planetary boundaries. Such models are needed to bring climate goals into practice, like agreed by the Paris Agreement.

The iterative process of developing solution, assessing operational and embodied energy and emissions, and comparing results against an alternative can be simplified and accelerated by using the tools. To that end, the number of tools integrating LCA data as a decision basis in the planning phase is growing, just like the open access tools for comparing alternatives on component or building levels.

Especially in early design phase, working with LCA data as decision basis requires the definition of assumptions regarding cubature and choice of products. Nonetheless, the studies have shown that the uncertainty related to these assumptions does not impact result essentially. The relevance of information for the LCA grows with the level of detail.

The choice regarding end-of-life scenario accounts for a highly uncertain subject due to the time span from planning to demolition, as economic background, technical developments, legislation and user requirements can change significantly in a period from 50-100 years. In all cases, decision about the end-of-life scenario must be such as to secure the protection of material value.

- The challenges in reducing the ecological impact of building materials can be summed up as:
- Gathering of sufficient national data, as a prerequisite;
- Development of legal background including benchmarks;
- Access to the tools that support integration on material and building level;
- Addressing the uncertainty in order to define the scope;
- Inclusion of the end-of-life scenario in construction.

5.2 Outlook

The general trend of growing complexity of data in the building context points at the need to improve data management systems that support decision-making in all planning stages: in design phase, the selection of the best material and construction type; in operational phase – provision of information on exchange cycles; and in the end-of-life – informing about the designated reuse and recycling scenario.

One of the greatest challenges in the field is transition between life cycles. The potential for re-integration of materials and products for further use on component (reuse) or substantial (recycling) level needs to be enhanced in many aspects. On practical level, the legal issues must be solved, the provision of secondary resources needs to be decentralized and, most of all, planners and clients need to demonstrate the willingness to use products with recognisable traces from the former usage phase or/and the products that do not communicate sustainable attitude only by visible marks.

In the context of the LCA, methods are needed to reflect the value of material after its first usage phase. Ecological benefits of reusing and recycling, or the preparation for reuse and recycling need to be quantified. Only then the sensible solution can be implemented and the purpose of the LCA, which is to support the design option with the best environmental performance, can be fulfilled.

References

Bare, J. C. (2002). *Developing a consistent decision-making framework by using the U.S. EPA's TRACI*. Cincinnati, OH: National Risk Management Research Laboratory, US Environmental Protection Agency. Retrieved from: https://clu-in.org/conf/tio/lcia_092309/AICHE2002paper.pdf

Belavicqua, M., Ciarapica, F. E. & Giacchetta, G. (2012). *Design for environment as a tool for the development of a sustainable supply chain*. London: Springer-Verlag.

Boustead, I. (1996). LCA- How it came about. The beginning in the UK. *International Journal of Life Cycle Assessment*, 1(3), 147-150.

Boustead, I. and Hancock, G.F. (1979). *Handbook of industrial energy analysis*. New York: John Wiley & Sons.

CEN – European Committee for Standardization. (2011). EN 15978. *Sustainability of construction works -Assessment of environmental performance of buildings - Calculation method*.

Consoli, F. et al. (Eds.). (1993). *Guidelines for life-cycle assessment: A 'Code of Practice' from the workshop held at Sesimbra, Portugal, 31 March - 3 April 1993, Society of Environmental Toxicology and Chemistry (SETAC).* Pensacola, FL: Society of Environmental Toxicology and Chemistry (SETAC).

Crawford, R. H. (2011). *Life cycle assessment in the built environment*. Abingdon, UK: Routledge.

DIN – Deutsches Institut für Normung. (2012). *Nachhaltigkeit von Bauwerken – Umweltproduktdeklarationen Grundregeln für die Produktkategorie Bauprodukte; Deutsche Fassung EN 15804:2012*. (Vol. 15804:2012). Berlin: DIN Deutsches Institut für Normung e. V.

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. & Suh, S. (2009). Recent developments in life cycle assessment. *Journal of Environmental Management*, 91 (1), 1-21. https://doi.org/10.1016/j.jenvman.2009.06.018

Frischknecht, R. (2006). *Umweltverträgliche Technologien: Analyse und Beurteilung. Teil 2: Ökobilanzen*. Zürich: ETH. Retrieved from: http://esu-services.ch/fileadmin/download/frischknecht-2006-skript-LCA.pdf

Geddes, P. (1884). An analysis of the principles of economics. *Proceedings of the Royal Society of Edinburgh*, Vol. XII, 943-980.

Guinée, J., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T. & Rydberg, T. (2011). Life cycle assessment: Past, present, and future. *Environmental Science & Technology*, 45(1), 90-96. DOI: 10.1021/es101316v

Heijungs, R., Guinée, J.B., Huppes, G., Lankreijer, R.M., Udo de Haes, H.A., Wegener Sleeswijk, A., Ansems, A.M.M., Eggels, P.G., Duin, R. van, & Goede, H.P. de. (1992). *Environmental life cycle assessment of products. Guide and backgrounds (Part 1).* Leiden: CML. Retrieved from: https://openaccess.leidenuniv.nl/handle/1887/8061

Hildebrand, L. (2014). *Strategic investment of embodied energy during the architectural planning process*. Doctoral Disseration. Rotterdam: Delft University of Technology.

Hollberg, A. (2016). *Parametric life cycle assessment*. Doctoral Dissertation. Weimar: Bauhaus Universität Weimar.

IBU – Institut Bauen und Umwelt e.V. (n.d.). Veröffentlichte EPDs. Retrieved from: http://bau-umwelt.de/hp346/Impressum.htm

ISO – International Organization for Standardization. (2006). *ISO 14044:2006 – Environmental management-Life cycle assessment-Requirements and guidelines*; (German and English version EN ISO 14044:2006 [Vol. DIN EN ISO 14044:2006]).

JRC – Joint Research Centre of the European Commission. (n.d.). LCA Resources Directory. Retrieved from: http://eplca.jrc.ec.europa.eu/ResourceDirectory/

Jensen, A. A., Hoffman, L., Møller, B. T. & Schmidt, A. (1998). Life cycle assessment – A guide to approaches, experiences and information sources. Enviromental Issues Report No 6. European Environment Agency. Retrieved from: https://www.eea.europa.eu/publications/GH-07-97-595-EN-C

Kellenberger, D. & Althaus, H-J. (2009). Relevance of simplifications in LCA of building components. *Building and Environment*, 44(4), 818–825. https://doi.org/10.1016/j.buildenv.2008.06.002

Klöpffer, W. & Grahl, B. (2014). *Life cycle assessment (LCA) - A Guide to best practice*. Weinheim: Wiley-VCH Verlag GmbH & Co. KgaA.

Kümmel, J. (2000). *Ökobilanzierung von Baustoffen am Beispiel des Recyclings von Konstruktionsleichtbeton*. Doctoral Dissertation. Stuttgart: Universität Stuttgart.

Lützkendorf, T. (2009). Nachhaltige Gebäude – beschreiben, beurteilen, bewerten: die Situation in Deutschland. In: *Nachhaltig Bauen und Bewerten: vom Energie- zum Nachhaltigkeitsausweis; Tagungsband; Kongress, Messezentrum Wien, 19-20. Februar 2009. Hrsg.: B. Bauer* (27-36). Wien: IBO.

Matthews, H. S., Hendrickson, C. T. & Matthews, D. (2015). *Life cycle assessment: Quantitative approach for decisions that matter*. Retrieved from: http://www.lcatextbook.com

Ministry of Housing, Spatial Planning and the Environment (2000). *The Eco-Indicator 99 - A damage oriented method for Life Cycle Impact Assessment*. Manual for Designers. Retrieved from: https://www.pre-sustainability.com/download/EI99_Manual.pdf

Nordic Council of Ministers. (1992). *Product life cycle assessment - principles and methodology.* Copenhagen: Nordic Council of Ministers.

Oers, L. v., Koning, A. d., Guinée, J.B. & Huppes, G. (2002). *Abiotic resource depletion in LCA.* Road and Hidraulic Engineering Institute. Retrieved from: http://media.leidenuniv.nl/legacy/report%20abiotic%20resource%20depletion.pdf

OzonAction Programme. (2000). *Regulations to control ozone depleting substances: A guidebook.* UNEP/Earthprint.

Pestalozzi, C. (Ed.). (2014). *Eco-devis. Wichtigste Ergebnisse in Kürze*. Zürich: Geschäftsstelle eco-bau. Retrieved from: http://www.crb.ch/crbOnline/CRB-Standards/Anwendungshilfen/eco-devis.html

Spreng, D. & Doka, G. (1995). *Graue Energie – Energiebilanzen von Energysytemen.* Zürich: Hochschulverlag AG an der ETH Zürich.

VDI – Verein Deutscher Ingenieure (2012). *Kumulierter Energieaufwand (KEA) Begriffe, Berechnungsmethoden – VDI 4600.* Berlin: Beuth Verlag.

Walz, A., Taverna, R. & Stöckli, V. (2010). Holz nutzen ist wirksamer als Vorräte anhäufen. *Wald und Holz*, 4/10, 37-40.

Wegener Sleeswijka, A., van Oersc, L. F. C. M., Guinée, J., Struijsd, J. & Huijbregtsb, M. A. J. (2007). Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000. *Science of The Total Environment*, 390 (1), 227-240. https://doi.org/10.1016/j.scitotenv.2007.09.040

A Comparative Overview of Tools for Environmental Assessment of Materials, Components and Buildings

Rebecca Bach[1] and Linda Hildebrand[2*]

* Corresponding Author
1 Faculty of Architecture, RWTH Aachen University, Aachen, e-mail: rbach@rb.arch.rwth-aachen.de
2 Faculty of Architecture, RWTH Aachen University, Aachen, e-mail: lhildebrand@rb.arch.rwth-aachen.de

ABSTRACT **Tools for the assessment of environmental performance of materials, components, and buildings are found in the form of software programs and databases. This chapter deals with the identification and analysis of assessment tools on an international level. The work is structured in four parts. The first part provides background information and introduces the topic. In the second, the categories that determine the character of software products are introduced and described. Accordingly, 26 software products are identified and listed, and ten of these are analysed in more detail. The third part of the work focuses on databases for the environmental assessment of materials, components, and buildings. Similarly to the software comparison, the categories of database features are firstly derived. Out of 21 identified and listed databases, six are subsequently analysed in more detail. The conclusions outline the life cycle assessment potentials and limitations in the architectural planning process.**

The aim of this chapter is to provide the knowledge necessary for understanding the scope of tools for ecological evaluation. Derived categories can be used to characterise any software or database product. Furthermore, the work demonstrates that presented software programs and databases can be used to assess the environmental impact of construction alternatives. Thus, the work builds the relevant facts that apply to the choice of appropriate programs and suitable databases, helps the integration of ecological aspects in the architectural planning process, and, by doing so, assists in reducing the impact of the built environment on the natural environment.

KEYWORDS environmental assessment, software, databases, characterisation, comparison

1 Introduction

Environmental assessment in the building context began after the oil crisis, when calculations of the amount of energy needed for building operation became more common. Within the last three decades, the number of green building certificates grew and with it the awareness of different life cycle phases. The production phase of building fabrics and the end-of-life scenario of a building were included in sustainability assessments and received increasing attention. Today, different methods for environmental impact quantification are available, and the life cycle assessment (LCA) represents the most common and the best regulated method in the building context (Klöpffer & Grahl, 2009).

LCA is used to assess different environmental impacts of products, processes, or services called functional units. The method compiles input and output flows and summarises resources and emissions associated with a specific functional unit. Databases and software programs are used mainly in the second phase of the LCA – the life cycle inventory, in which input and output flows are calculated. The resources and emissions are grouped with a characterisation model in the life cycle impact assessment (LCIA). According to this, the environmental impact is displayed using different indicators.

Software programs support the calculation on material, component, and building levels, as large amounts of data are involved. The first LCA flows (in the 1960s) were calculated for the depletion of resources and the generation of energy. (Guinée et al., 2011; Jensen et al., 1998) Meanwhile, a broad variety of data on building materials became available. Product related information is provided by the Environmental Product Declaration (EPD) according to the ISO standard 14025 (DIN, 2011). The variety of databases and software programs allows suitable application according to the planning phase.

For calculation on component and building levels, LCA material flows are connected to the building mass. In the first step of the LCA, that is the definition of goal and scope, the data required for creation of the life cycle inventory (LCI), as well as the materials' origin, i.e. the sources from which they are obtained, are determined. The data are collected according to the processes and are to be considered during the LCI.

2 Development of Software and Databases for Environmental Assessment

In the framework of sustainable construction and, more specifically, the growing application of LCA in the building context, impact assessment started with manual calculation and spreadsheet programs that can be considered as the first tools.

The first software product used to assess environmental impact in the building context was made in 1985 by expanding the database of a spreadsheet program of the Swiss Federal Laboratories for Materials Science and Technology EMPA, which specifically dealt with life cycle assessment (Spreng, 1995). As a result, developed LCA software products, such as Simapro, PIUSoecos and the Boustead Model, were project-specific and limited to a company's in-house use (Müller-Beilschmidt, 1996).

Against the background of the political objectives to reduce environmental impact, and the growing complexity in production processes, large amounts of data were produced, increasing the need for LCA-specific software to handle the extensive calculations (Lüdemann & Feig, 2014).

A large number of software programs for specific applications have been developed in the last 30 years. In addition to the building context, computer programs focused on the city map e.g. the NEST (Yepez-Salmon, 2011), road construction e.g. the ROAD-RES tool (Birgisdóttir, 2005), and many other industrial areas. The European Platform on Life Cycle Assessment was developed by the European Commission's Joint Research Centre (n.d.) to provide an overview of both databases and LCA software programs.

LCA software programs can be divided into 3 levels (Fig. 2.1):

- Level 1 - material,
- Level 2 - component, and
- Level 3 - building.

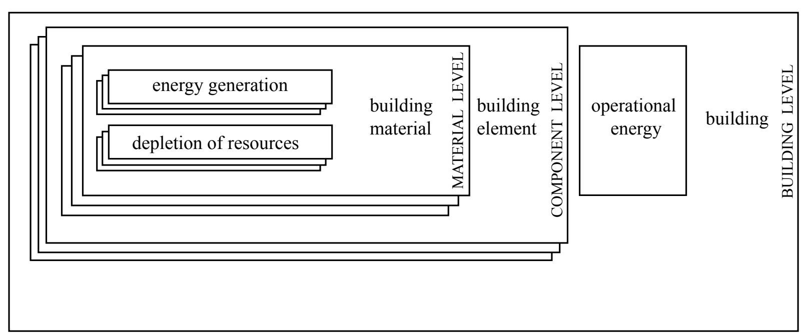


FIG. 2.1 Levels describing the scope of LCA software and databases

LCA on the material level calculates the energy and emissions related to the depletion of resources, the generation of energy, and the steps of production. The results are indicators per material, which can be used to compare different products. Computer programs like GaBi (DE), SimaPro (NL), Umberto (DE), and OpenLCA (DE) are suitable for this purpose and will be introduced later in this text (Sections 3 and 4).

The second level accumulates different materials for a building element. Different planning solutions within a product can be compared against each other. Bauteileditor (DE) represents an example of a product suitable for this purpose.

On the building level, LCA software products can contain two categories of energy; the effort to provide indoor air comfort and electricity is summed up as the operational energy for which (primary) energy and emissions can be calculated with LCA. The second category refers to the building substance and includes all building materials and components that form structure, building envelope, and all interior elements.

LCA software programs can be confused with the tools used for green building certificates. A LCA tool can be a *part* of a green building certificate but does not cover all aspects of it. According to the three pillars of sustainability, economic and social aspects also need to be evaluated for this purpose.

3 Software Programs for Environmental Assessment

For an architect or a planner, computer aided design (CAD) software products serve to provide documents that communicate the design/planning concept. The use of tools for specific application depends on the size of a project. As small projects with repetitive elements (components) are more easily presented, the level of complexity is sufficiently covered by the two-dimensional drawings. In this case, the LCA can be done with an external spreadsheet. For complex building design representations, three-dimensional modelling is more suitable and different types of information (for example, the costs) can be referred to the building volume. Ideally, the LCA is integrated in the design, construction, and detailing phases, and is developed in tandem with the project, by using ongoing internal calculations.

LCA software programs are used to calculate the environmental impact of products and services. LCA data can be applied at different stages of the architectural planning process. In the design phase, for example, LCA can be included as an optimisation parameter. Here, LCA software can be used to determine the optimal characteristics of a building, i.e. to compare different design alternatives, for example in terms of the energy needed for building operation and the energy used to produce the building's materials. In the later stages, LCA data can help to compare finalised products.

Early software products used to determine environmental impact encompassed LCA data for a single product. Today, most products compile LCA for a building volume or mass, but not all of them are able to perform the assessment in the proper sense. According to Fig.2.1, software products that conduct strict life cycle assessments work on the material level.

3.1 Software Characterisation

To characterise and compare different software programs for environmental assessment, eight categories have been identified and introduced in this work: 1) origin, 2) data source, 3) required user's knowledge, 4) accessibility, 5) entry format, 6) level, 7) default settings, and 8) life cycle phases. Characterisation aims to provide the understanding of general calculation concepts employed in software development.

Origin

NAME (COUNTRY)	PUBLISHER/DEVELOPER	WEBSOURCE
360 optimi (FI) (released in 2015)	Bionova Ltd	www.oneclicklca.com/sustainability-metrics-software
Athena (CA) (released in 2002)	Athena Institute International	www.athenasmi.org/our-software-data/impact-estimator
BeCost (FI)	VTT Technical Research Centre	www.virtual.vtt.fi/virtual/proj6/environ/ohjelmat_e.html
Building for Environmental & Economic Sustainability, BEES (US) (released in 1997)	NIST – National Institute of Standards and Technology	www.nist.gov/services-resources/software/bees
Caala (DE) (released in 2016)	Bauhaus University Weimar	www.caala.de/en
Eco Balance Assessment Tool, ECO-BAT 4.0 (CH)	Laboratory of solar energetics and building physics (LESBAT) of the HES-SO of Yverdon-Les-Bains (HEIG-VD)	www.eco-bat.ch
EcoEffect (SE)	Royal Institute of Technology (KTH)	www.ecoeffect.se
Economic Software, ECO-Soft (AT)	ECO-Soft GmbH	www.eco-soft.at/web
e-DEA (FR, DE)	EVEA and GreenDelta	www.edea-software.com
Environmental Improvement Made Easy, EIME (BE, FR)	Bureau Veritas CODDE	www.bureauveritas.com/home/about-us/our-business/cps/our-services/information-services-tools/eime
Economic Input-Output Life Cycle Assessment, EIO-LCA (US)	Green Design Institute at Carnegie Mellon University	www.eiolca.net
eLCA (DE) (released in 2013)	BBSR- BundesinstitutfürBau-, Stadt- und Raumforschung	www.bauteileditor.de
Elodie (FR)	CSTB- Centre Scientifique et Technique du Bâtiment	www.elodie-cstb.fr
Envest (UK)	BRE sustainable consulting	http://envest2.bre.co.uk/detailsLCA.jsp
Ganzheitliche Bilanzierung, GaBi (DE) (released in 1991)	PE International	www.gabi-software.com
Legep (DE) (released in 2005)	Holger König	https://legep.de
Lesosai (CH)	Solar Energy and Building Physics Laboratory (LESO-PB) of Ecole polytechniquefédérale de Lausanne (EPFL)	www.lesosai.com/de
NovaEQUER (FR)	IZUBA énergies	www.izuba.fr/logiciel/equer
OneClick LCA (FR)	Bionova Ltd	www.oneclicklca.com/green-building-software
OpenLCA (DE)	GreenDelta	www.openlca.org
REGIS (CH)	Sinum	www.sinum.com/index.php?id=30
Sustainable Buildings Specifier, SBS Building Sustainability (DE)	Fraunhofer IBP, PE International	www.sbs-onlinetool.com
Simapro (NL) (released in 1990)	PRé Sustainability	https://simapro.com
Tally (US) (released in 2008)	KT Innovations, Thinkstep and Autodesk	www.choosetally.com
Team (FR)	PwC Ecobilan Experts	https://ecobilan.pwc.fr/en/boite-a-outils/team.html
Umberto NXL (DE) (released in 1994)	Ifu Hamburg	www.ifu.com/en/umberto

TABLE 3.1 An overview of software programs for environmental assessment

Today, a broad variety of LCA software programs are available. Some software solutions were developed for a specific assessment purpose, while several others were also upgraded with an assessment function. The national background and the context of the development of the software (e.g. for business or research purpose) provide the initial picture regarding its scope and accessibility. The year of release can be an indication to measure how up-to-date or complete a program is. New programs that operate in beta-phase can be included in the optimisation process, while incorporating the latest research results. Programs that have been available for some time might have gone through optimisation and adaption to current research results (by means of updates and new version releases). The criteria aimed at describing the software program origin include *the name of a program, the country in which a program was developed, the year of release, the name of a publisher/developer*, and *the web source*.

Table 3.1 presents the overview of 26 software programs for environmental assessment that have been developed on international scale. The selection was made on the basis of online research and information from LCA experts. The detailed comparison of 10 software programs (marked in Table 3.1) was done according to the categories described below, and the results are presented in Table 3.2 and Fig. 3.1.

Data Source

Each software program for environmental assessment uses databases. The relation between software programs and databases can be described as both active and passive. A software program uses the information stored in databases and calculates the results. In a database, the data relating to a particular product or service are collected. Data source refers to either a single piece of data or the database used. While some software programs are open to different data sources, other are limited to default databases. Databases are described in more detail in Section 4 of this chapter.

Required User's Knowledge

Software programs work on different knowledge levels. The precise determination of boundary conditions allow the utilisation of software by users with limited experience. Users access a program under adjusted framework conditions. Generally, software programs developed for research institutes or consulting firms require a higher level of expertise than the programs designed for planners and decision-makers. The main levels used to describe a user's knowledge of LCA methodology are *expert*, *basic knowledge,* and *no prior knowledge*.

Accessibility

Software programs can be distinguished as those with *free access*, *conditional access*, and *paid access*. Some developers offer free access for educational purposes and paid access for professional use. Some of the software programs collect data in exchange for free use.

Entry Format

According to the input format, software programs can be divided into *based on spreadsheet* or *geometric-based* programs.

Spreadsheet-based programs offer a broad variety in relation to default settings. Some are almost blank, and therefore offer individual assessment, which requires an elaborate process, while others provide default settings and consequently obtain faster results. The input information about a material is based on mass or volume, and the boundary conditions are preset. A program associates building mass or volume with databases and the calculation is carried out automatically.

Geometric programs use 3D information to derive material volume and then connect to databases. LCA information for a building or a building element can be provided via the export of a spreadsheet.

Level
Software products can be conceived at different levels. According to Fig. 2.1, a distinction is made between *material*, *component,* and *building* levels.

Default Settings
In some programs, defaults settings are introduced to simplify and speed up the execution of the LCA. The adaptability of default settings is variable. While some products enable the user to input default settings, others predefine them without the possibility of participation or intervention on the user's part.

Relevant approaches to default settings include:

- Lifecycle phases. This approach is applied when life cycle phases cannot be evaluated separately or when only the production phase can be considered;
- Life cycle duration. The time span describing usage duration varies and thus affects the results significantly. The typical default value (often 50 years) needs to be in line with the aim of the assessment;
- Data basis. Some software products have different options for databases. In general, a suitable product would reflect its national context.

Life Cycle Phases
Standard EN 15804 (DIN, 2012) defines 16 life cycle phases: A1 – Raw material supply; A2 – Transport (to the manufacturing facility); A3 – Manufacturing; A4 – Transport (to the construction site); A5 – Construction/ installation process; B1 – Use; B2 - Maintenance including transport; B3 – Repair and transport; B4 – Replacement including transport; B6 – Refurbishment including transport; B6 – Operational energy use; B7 – Operational water use; C1 – De-construction demolition; C2 – Transport; C3 – Waste processing; C4 – Disposal; and D – Re-use recovery and recycling potential. Nonetheless, only a few software programs for environmental assessment support differentiation in this detail. For this category, each phase included in software (and available thanks to the linked database) is listed in Table 3.2.

3.2 A Comparative Overview of Software Programs

The first software solutions were used to assess simple products and energy generation processes. The German **Ganzheitliche Bilanzierung** (Holistic Assessment) and the Dutch **Simapro** programs were introduced in the early '90s. Today, GaBi, Simapro and **Umberto** have evolved into expert tools based on very detailed information, and are used mainly to assess products (Environmental Products Declarations). The use by architects (at building level) has been limited due to the extensive processing time. The focus of the German software **Legep**, released in 2005, is on building materials; the entry format is spreadsheet based and oriented according to the design stages. At the same time, **Athena**, established in Canada, is focused on material selection, by using the US units of building materials.

SOFTWARE	DATA SOURCE	REQUIRED USER'S KNOWLEDGE	ACCESS	ENTRY FORMAT	LEVEL	DEFAULT SETTINGS AND ADAPTABILITY	LIFE CYCLE PHASES
Athena (Impact Estimator for buildings)	Athena Database Details	Basic (tutorials)	Free (registration needed)	Spreadsheet	Material; Component	Default setting partly adaptable	A1-A3; A4-A5; B1-B7; C1-C2; C3; C4; D
Bauteileditor eLCA	Ökobau.dat	No prior knowledge	Free (registration needed)	Values entered in default spreadsheet	Component	Default setting not adaptable	A1-A3; C3; C4; D
BEES	Environ. Perform. Score; Econ. Perform. Score	Basic; Expert	Free (no registration)	Spreadsheet	Component	Default setting partly adaptable	A1-A3
Caala	Ökobau.dat	No prior knowledge	Beta Version is free	3D geometrical	Building	Default setting partly adaptable	A1-A3; C3; C4; D
Ganzheitliche Bilanzierung	GaBi Database; Ökobau.dat	Expert (tutorials and manuals)	Conditional access (30 days trial); Paid access (license needed)	Spreadsheet with graphical elements	Material; Component; Add on "Built-it"	No default setting	A1-A3; A4-A5; C3; C4; D
Legep	Ecoinvent; Ökobau.dat	No prior knowl-edge; Basic; Expert	Paid access (license needed)	Spreadsheet	Component; Building	Default setting adaptable; Default setting partly adaptable	A1-A3; C3; C4; D
Umberto	GaBi Database; Ecoinvent	Expert (no tutorials or manuals)	Limited access (14 days free trial); Paid access (license needed)	Spreadsheet	Material; Component	Default setting adaptable	A1-A3; C3; C4; D
Simapro	Various	Basic; Expert	Conditional access; Paid access (license needed)	Values are en-tered in default spreadsheet	Component; Building	Default setting adaptable	A1-A3; C3; C4; D
Tally	-	-	Conditional access	3D Geometrical	Building	Default setting partly adaptable	A1-A3; C3; C4; D
360 optimi	Various, for example Ökobau. dat, EPD	No prior knowledge	Free access (registration part access); Conditional access	3D Geometrical	Building	Default setting partly adaptable	A1-A3; C3; C4; D

TABLE 3.2 Comparison of a selection of software products for environmental assessment in the building context

At the beginning of the millennium, the building sector showed a growing interest in LCA data and the spreadsheet program structure was brought closer to architects. For example, GaBi developed the "Built-it" interface that organises building elements according to the DIN 276 (DIN, 2017) with iterative optimisation steps. To increase the number of users, the **Open LCA** program provided free access and included a broad variety of databases. The spreadsheet entry format was illustrated with graphical elements, but framework conditions (for example durability of elements, time span, reference unit) needed to be set by the user. Complex details supported the LCA as a niche application used by experts. The growing number of green building certificates motivated the use of LCA and defined the framework conditions and benchmarks.

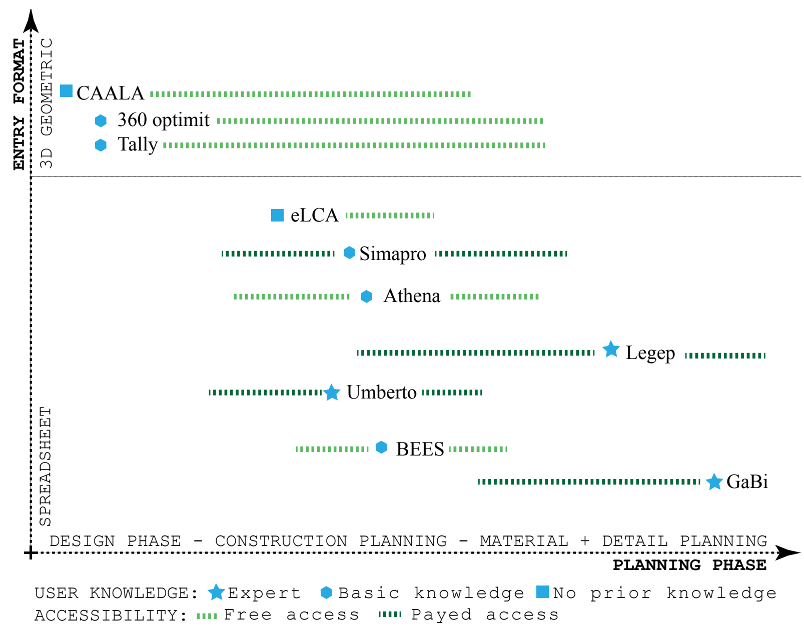


FIG. 3.1 Planning phases, user knowledge, and accessibility of software products

The spreadsheet-based tool Bauteileditior **eLCA** (Building Element Editor) limited the entry mask and provided a large amount of default settings, which allowed for easy calculation at the building element level. eLCA is able to compare planning alternatives to strengthen the application as a basis for decisions, rather than documenting the results. This free tool motivated the integration of LCA for the German context. Against the background of the increasing amount of information linked to building volume, 3D tools that provide reference points between information and building materials are increasingly more common (building information modelling – BIM). This offers the chance to connect ecological data and include it in the early design stage rather than in the phase of construction when the scope of intervention regarding environmental impact reduction is limited. **Tally** and **360 optimi** provide the link between 3D data and different LCA databases. **Caala** connects to Ökobau.dat and includes an optimisation feature, which assesses the ecological impact from the building fabric and relates it to a simplified (operational) energy calculation. In comparison, this computer program, which is currently in the Beta phase, shows the greatest number default settings that are currently non-exchangeable. In this way, design decisions regarding the cubature *and* material choice can be optimised and the LCA methodology can help to reduce the environmental impact of a building. A growing number of add-ons for computer programs like Revit (Autodesk) or Rhinoceros (McNeel) are available.

It can be stated that LCA tools were essentially developed for experts able to model framework conditions. However, built-in default settings simplified the entry format and helped to increase of the number of users.

4 Databases for Environmental Assessment

In the LCA framework, databases serve to store data for a particular flow that can, for example, refer to material resource extraction. Companies can be holders of particular LCA data, expressing the ecological characteristics of a product. Framework conditions are the key to a comparable LCA. In Europe, the comparability is most commonly achieved by compliance with the ISO 14025 that regulates the data as type III certificates (DIN, 2011) – the Environmental Product Declaration (EPD). This includes certain framework conditions for each material group and a third-party review. In the last three decades, the number of LCAs in the built environment increased and the collection of data was developed to make it easily accessible to planners and decision makers. All of the data from one base set are expected to have the same framework conditions, as a prerequisite for fair comparison. In addition to collections of particular LCA data by companies, a number of databases with generic data sets are available. These include average values of industrial data. The associations, such as World Steel, which represents more than 160 steel producers, collect the data and share them as average industrial or generic data.

Databases include LCA information on material or component levels, which are used to compare different alternatives or to calculate the environmental impact of components or buildings in order to meet a benchmark. Most software products allow all types of databases to be imported. Most of the databases provide an export in spreadsheet format. While single data can be opened with common tools like a web browser, PDF reader, or Excel, the database (the multitude of data) requires software products.

4.1 Databases Characterisation

To characterise and compare databases for environmental assessment in the building context, seven categories have been identified and introduced in this work: 1) origin, 2) validity, 3) data source, 4) accessibility, 5) reference unit, 6) referent level, and 7) geographical reference.

Origin
Most databases were initiated by the experts who conducted the LCA at the product level for companies. At some point, literature information and the data obtained by experts formed a collection that was of interest for others. The relevance of the origin and background for database formation can be illustrated on the following example:

TOC

Depletion of resources for the production of electricity is reflected in all flows that are relevant in the building industry, as they all include the electricity. The ratio of non-renewable to renewable sources varies among the countries and so do the emissions related to a product. Additionally, the transport distances from one production site to another vary between countries (Khasreen, Banfill, & Menzies, 2009). Transferability is limited and the country for which the LCA data was calculated is important in judging its scope.

Table 4.1 presents an overview of 21 databases for environmental assessment developed on an international scale. The selection was made on the basis of online research and other available information. Furthermore, six commonly used databases (highlighted in Table 4.1) were compared in detail, according to the categories described below, and the results are presented in Table 4.2.

NAME (COUNTRY)	PUBLISHER/DEVELOPER	WEBSOURCE
Agribalyse (FR)	French Environment and Energy Management Agency (ADEME)	www.ademe.fr/agribalyse
AusLCI (AU)	ALCAS (Australian Life Cycle Assessment Society)	www.auslci.com.au
DEAM TM Data for Environmental Analsys and Management (UK)	Ecobilane	www.ecobilan.com/uk_deam01_02.php
Ecoinvent (CH) (released in 2003)	Ecoinvent centre	www.ecoinvent.org
ELCD (EU) (released in 2006)	JRC (Joint Research Centre)	http://eplca.jrc.ec.europa.eu/ELCD3/
ESU World Food (EU)	ESU-services Ltd.	http://esu-services.ch/data/fooddata
EuGeos' 15804-IA (UK)	EuGeos	-
Exiobase (NL)	EXIOBASE Consortium	http://exiobase.eu
GaBi (DE) (released in 1991)	Thinkstep	www.gabi-software.com/databases/gabi-databases
Gemis Database (DE)	IINAS (International Institute for Sustainability Analysis and Strategy)	http://iinas.org/database.html
The Inventory of Carbon and Energy, ICE (UK)	University of Bath. Sustainable Energy Research Team	www.bath.ac.uk/mech-eng/research/sert/index.html
IO Database for Denmark 1999 (DK)	Who we are 2.-0 LCA consultants	-
New Energy Externalities Developments for Sustainability, NEEDS (EU) (released in 2009)	The NEEDS Project	www.needs-project.org/needswebdb
Ökobau.dat (DE) (released in 2009)	BMUB (Bundesministeriumfür Umwelt, Naturschutz, Bau und Reaktorsicherheit)	http://oekobaudat.de/datenbank/browser-oekobaudat.html
Pharos Project Database (US)	Healthy Building Network	www.pharosproject.net
ProBas (DE)	Umwelt Bundesamt	www.probas.umweltbundesamt.de/php/index.php
PSILCA (DE)	Green Delta	-
Quartz (US, DE)	The Quartz Project	http://quartzproject.org
U.S. LCI (US)	NREL (National Renewable Energy Laboratory)	www.nrel.gov/lci
USDA (US)	United States Department of Agriculture (USDA)	-
Wecobis (DE)	BMUB	www.wecobis.de/#&slider1=5

TABLE 4.1 An overview of databases for environmental assessment

Validity

LCA data have limited validity. Over time, framework conditions change and influence the results. Therefore, updates are needed to track relevant changes and to adapt the values if necessary. For this reason, the criteria to distinguish different levels of validity are *Regular updates*, *Validity is shown*, and *Validity is not shown*.

Data Source

Data sources can be distinguished as primary or *specific* data and *generic* data. Primary data are determined by the quality of a product, while generic data refer to the average data. When possible, primary data should be preferred over generic data (Prox, 2016). However, to provide a basis for decision-making in the early planning phase where the products have not yet been defined, the use of generic data is appropriate (for example, as an argument for a type of construction). Generic data sets are also suitable for research projects where few to no primary data records are available, as well as for closing the gaps in primary data sets.

Mixing databases should be avoided. Lasvaux, Habert, Peuportier, and Chevalier (2015) compared primary data with French EPD, generic data, and Ecoinvent flows, and noted a significant deviation of up to 100%.

Additionally, generic records differ within different databases (Frischknecht, 2006; Peereboom, Kleijn, Lemkowitz, & Lundie, 1998). In the literature, the LCI of a single product is carried out using different databases, in order to compare the data records. Although the numerical calculations differ greatly, the results are nevertheless comparable with respect to their relations (Takano, Winter, Hughes, & Linkosalmi, 2014).

Accessibility

In relation to accessibility, the databases for environmental assessment can be characterised as those with *Free access*, *Conditional access* and *Paid access*.

Reference unit

Relevant flows in the building context refer to either *mass*, *volume,* or surface *area*. Technically, indicators could also refer to services like one hour electricity with 1000 Watts. However, services are not investigated here, as the complex functions of materials or components do not occur in databases.

Referent level

According to the characterisation of software products, the referent levels are distinguished as *material*, *component,* and *building*.

Geographical reference

As mentioned earlier, the geographical reference is relevant in describing the scope of LCA data. It is common practise that countries without sufficient databases for construction materials use foreign data, for example, Danish architects use German data for a project in Denmark.

As this includes uncertainty, a safety margin is added for compensation. This is the best choice, but the safety margin nonetheless weakens the accuracy of results. In any case, the scope of data needs to be specified. The criteria to mark geographical references are distinguished as *national*, *European*, *international,* and *no reference*.

4.2 A Comparative Overview of Databases

The interest in LCA data for building products grew during the 1980s. At that time, Swiss, German, British and Austrian institutes started to collect data from individual products. Values calculated for specific products were mixed with the information from literature (Ecoinvent, n.d.).

DATABASE	VALIDITY	DATA SOURCE	ACCESS	REFERENCE UNIT FORMAT	LEVEL	GEOGRAPHICAL REFERENCE
Ecoinvent	Regular updates (ecoinvent 2/ 3.0, / 3.1/ 3.2/ 3.3, current version 2017); Validity is shown	Generic, specific	Paid access	Volume; Mass	Material; Component	National (Switzerland, Austria, Germany); European
European Life Cycle Database (ELCD)	Validity is shown	Generic, specific	Free access	Volume; Mass	Material; Component	European
Ganzheitliche Bilanzierung GaBi Database	Regular (annual) updates; Validity is shown	Generic, specific	Paid access	Volume; Mass	Material	No reference
Inventory of Carbon & Energy, ICE	Validity not shown	Generic	Free access	Volume; Mass	Material	National (UK); No reference
New Energy Externalities Development for Sustainability NEEDS	Validity not shown	Generic	Free access	Volume; Mass	Material	National (Switzerland, Austria, Germany)
Ökobau.dat	Regular updates; Validity is shown	Generic, specific	Free access	Volume; Mass	Material	National (Switzerland, Austria, Germany)

TABLE 4.2 Comparison of six databases for environmental assessment in the building context

All databases collect input and output flows but they vary with regard to focus and indicators. In the beginning, data sets showed differences in the time span, life cycle phases, energy supply, and other parameters. Comparability became relevant at the beginning of the 21st century and the developers of **GaBi**, **Ecoinvent** and other databases cooperated in order to develop a consistent framework format - the **European Life Cycle Database** (ELCD). Here, not only a format to display LCA results was developed, but, in addition, processes at the European level were provided with free access. At the same time, the free database **US Life Cycle Inventory** was released in the US.

At the beginning of the 2010s decade, databases were assigned a specialised focus, for example agricultural (like **Agri-footprint**), or social (like **PSILCA database**). In the building industry, national databases **Ökobau.dat** and **WECOBIS** (both in Germany), and the **Inventory of Carbon and Energy**, ICE (UK) were released. The Ökobau.

dat that originates from GaBi data was sold to the German government, which later published the free-access dataset with both generic and specific information from EPDs. The **NEEDS** database, released in 2009, included different future scenarios for energy supply (optimistic, realistic, and pessimistic).

A variety of databases are available today (Table 4.1). Giving preference to one of them depends on the national context, as the data refer to the energy generation context and the scope of assessment. While years ago, a choice about software program was defined by the type of databases, OpenLCA now enables a free choice.

5 Conclusions

In order to explore the potential of LCA, it is important not only to carry out the ecological assessment of a building, but also to include the results as support for decision-making during the early stages of the planning process, and thus to choose a solution with the least ecological impact. For this purpose, a wide range of software programs are developed, continually optimised, and adapted to meet the current state of research, user needs, and changing data.

Software products can be used in any national context. It is the database that embodies the regional reference. However, the lack of national LCA databases does not necessarily have to be an obstacle for LCA application. For example, in the US context, no open comprehensive database is available and yet the studies are conducted by researching single assessments. This is controversial with regard to the framework conditions, but it can be a first approach if no other solution is available.

Until recently, LCA tools, for the most part, did not consider the connectivity of materials, which consequently led to a choice of materials that caused ecological problems at the end of the use phase. Currently, some tools are being upgraded in terms of reintroducing the material in the life cycle (e.g., the eLCA).

Nonetheless, an integrated approach to negative environmental impact reduction should, alongside the LCA, include the considerations of operational energy, as well as the utilisation of other natural resources, such as water and free land.

References

Birgisdóttir, H. (2005). *Life cycle assessment model for road construction and use of residues from waste incineration* (Doctoral dissertation). Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.566.8489&rep=rep1&type=pdf

DIN (2011). *DIN EN ISO 14025 Environmental labels and declarations - Type III environmental declarations - Principles and procedures (ISO 14025:2006);* . Berlin: Normenausschuss Grundlagen des Umweltschutzes (NAGUS) im DIN [Standards Committee principles of environmental protection (NAGUS) at DIN].

DIN. (2017). *Building costs* (Vol. 276). Berlin: Beuth.

DIN (2012). *Sustainability of Structures - Environmental Product Declarations Basic Rules for the Product Category Construction Products; EN 15804:2012* (Vol. 15804:2012). Berlin: DIN Deutsches Institut für Normung e. V.[German Institute for Standardization]

Ecoinvent. (n.d.). *History*. Retrieved from http://www.ecoinvent.org/about/history/history.html

Frischknecht, R. (2006). Notions on the Design and Use of an Ideal Regional or Global LCA Database. *The International Journal of Life Cycle Assessment, 11*(1), 40-48. DOI:10.1065/lca2006.04.010

Guinée, J., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R, Ekvall, T., Rydberg, T. (2011). Life Cycle Assessment: Past, Present, and Future. *Environmental Science & Technology, 45*(1), 90-96. DOI: 10.1021/es101316v

Jensen, A. A., Hoffman, L., Møller, B. T., Schmidt, A, (1998). *Life Cycle Assessment - A guide to approaches, experiences and information sources*. Copenhagen, DK: European Environment Agency. Retrieved from https://www.eea.europa.eu/publications/GH-07-97-595-EN-C

Joint Research Centre of the European Commision. (n.d.). *European platform on life cycle assessment*. Retrieved from http://eplca.jrc.ec.europa.eu

Khasreen, M., Banfill, P. F., & Menzies, G. (2009). Life-cycle assessment and the environmental impact of buildings: A review. *Sustainability, 1*(3), 674-701. DOI:10.3390/su1030674

Klöpffer, W., & Grahl, B. (2009). Einleitung. In *Ökobilanz (LCA): Ein Leitfaden für Ausbildung und Beruf* [In LCA: Guidelines Education and Profession] (pp. 1-26). Weinheim, DE: Wiley-VCH Verlag GmbH & Co. KGaA. DOI: 10.1002/9783527627158.ch1

Lasvaux, S., Habert, G., Peuportier, B., & Chevalier, J. (2015). Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. *The International Journal of Life Cycle Assessment, 20*(11), 1473-1490. DOI:10.1007/s11367-015-0938-z

Lüdemann, L., & Feig, K. (2014). Comparison of software solutions for Life Cycle Assessment (LCA)– a software ergonomic analysis, *Logistics Journal*. DOI: 10.2195/lj_NotRev_luedemann_de_201409_0. Retrieved from https://www.logistics-journal.de/not-reviewed/2014/09/3991/luedemann_2014.pdf

Müller-Beilschmidt, P. (1996). Software zur Unterstützung der Okobilanzierung- ein Überblick [Software to support Life Cycle Assessment-an overview]. In M. Schmidt & A. Häuslein (Eds.), *Ökobilanzierung mit Computerunterstützung* [Computer aided LCA] (pp. 3-10). Berlin: Springer.

Peereboom, E. C., Kleijn, R., Lemkowitz, S., & Lundie, S. (1998). Influence of inventory data sets on life-cycle assessment results: a case study on PVC. *Journal of Industrial Ecology, 2*(3), 109-130. DOI:10.1162/jiec.1998.2.3.109

Prox, M. (2016, April 19). *Erfolgsfaktor für Ökobilanzen (Life Cycle Assessment, LCA): Daten, Daten und nochmals Daten* [Data, data and data again]. Retrieved from https://www.ifu.com/knowtheflow/2016/erfolgsfaktoren-fur-okobilanzen-life-cycle-assessment-lca-daten-daten-und-nochmals-daten/

Spreng, D. (1995). *Graue Energie-Energiebilanzen von Energysytemen* [Embodied Energy- Energy assessment in energy generation systems]. Zürich, CH: Hochschulverlag AG an der ETH Zürich, B.G. Teubner Stuttgart.

Takano, A., Winter, S., Hughes, M., & Linkosalmi, L. (2014). Comparison of life cycle assessment databases: A case study on building assessment. *Building and Environment, 79*(Supplement C), 20-30. https://doi.org/10.1016/j.buildenv.2014.04.025

Yepez-Salmon, G. (2011). *Construction d'un outil d'evaluation environnementale des ecoquartiers: vers une méthode systémique de mise en œuvre de la ville durable* [Construction of an environmental assessment tool for ecoquartiers: towards a systematic approch to implement the sustainable city] (Doctoral Dissertation). Retrieved from http://ori-oai.u-bordeaux1.fr/pdf/2011/YEPEZ_SALMON_GRACE_2011.pdf

Impact of Climate and Pollution on Resilience of Some Conventional Building Materials

Merima Šahinagić – Isović[1*], Marko Ćećez[2] and Rada Radulović[3]

* Corresponding Author
1 Faculty of Civil Engineering, University "Džemal Bijedić" of Mostar, e-mail: merima.sahinagic@unmo.ba
2 Faculty of Civil Engineering, University "Džemal Bijedić" of Mostar, e-mail: marko.cecez@unmo.ba
3 Faculty of Technical Sciences – Civil Engineering Department, University of Priština in Kosovska Mitrovica, e-mail: rada.radulovic@pr.ac.rs

ABSTRACT **The influence of climatic conditions on building materials represents an important field of study, having regarded that it is directly linked to the properties and behaviour of the overall built structures. Since the beginning of the 21st century, when climate change became widely accepted as a source of impact on the built environment, research dealing with material resilience is gaining additional importance.**

Construction design and utilisation of materials have traditionally been based on the inputs related to environmental conditions, among others. Most of the materials used for construction are environmentally sensitive; their properties change depending on climate conditions. Resilience is defined as the ability of a material to absorb and withstand changes and external influences without destruction. It is clear that the resilience of materials is closely related to their durability, and considering one without the other is ineffective. Depending on the character and level of aggression for each structure, the measures should be foreseen to ensure durability of constructions.

The most significant impacts of climate and pollution are observed in this chapter through the effects of temperature changes, moisture, and air pollution. Resilience of several commonly used building materials: stone, concrete, wood, and ceramic, subjected to the listed effects, will be studied and presented.

KEYWORDS resilience, deterioration, stone, wood, concrete, ceramic materials

1 Introduction

Today, human influence on Earth's systems is obvious. Because of economic and population growth, anthropogenic greenhouse gas emissions have been constantly increasing from the beginning of the industrialisation period. Consequently, atmospheric concentrations of carbon dioxide, methane, and nitrous oxide are higher. The effects of changes in atmospheric conditions have been detected throughout the climate system and are extremely likely to have been the dominant cause of observed warming since the mid-20th century (Qiao, Casey, Kuna, Kelly, Mei, & MacGregor, 2017).

Reports show that climate change alters current conditions regarding temperature, precipitation, sea level or river water levels, and causes damage to various built infrastructures (Zame & Assomo, 2015).

Since 1850, the global average surface temperature has increased by 0.74 °C. Meanwhile, global average sea level has risen by 100 mm in the past 130 years. Eastern parts of North and South America and Northern Europe experienced an increase in precipitation, while, oppositely, precipitations have decreased in other parts of the planet, such as the Mediterranean and the regions in Southern Asia (IPCC, 2007).

Surface temperature is projected to rise over the 21st century. Some studies indicate an increase in air temperature of about 3°C over the next 50 years in Southeast Europe, with about 20% less precipitation (Bruci, 2008). Rising sea levels and increasing average temperatures lead to significant regional and local climatic variations. For example, the intensity of rainfall will increase as wind speeds increase. This means more aggressive water penetration into building materials (Inkpen, 2004).

Construction design and usage of materials in most parts of the world has traditionally been based on the use of inputs of environmental conditions, among others. Most of the materials used for construction are environmentally sensitive; their properties change depending on climate conditions (Qiao, Casey, Kuna, Kelly, Mei, & MacGregor, 2017). To identify the cause of destruction and to build resilience, it is necessary to consider climate factors and investigate related changes in used materials.

High performance and low maintenance of constructions are a key objective of any building sector worldwide. To this end, understanding the resilience of the building materials used is a most crucial matter. To achieve sustainability, it is important to assess the resilience to climate change of used materials, to adapt and to mitigate negative effects (Qiao, Casey, Kuna, Kelly, Mei, & MacGregor, 2017).

Resilience is a term closely related to material durability and to consider one without the other is fruitless. Material resilience is the ability to absorb and resist changes and external influences without decay. In sustainable and resilient buildings, besides mechanical actions, material resilience to external (atmospheric) actions is of great importance.

Climate change encompasses concurrent consideration of (changed) environmental impacts, some of which are taken into account in the design process, while some others are beyond the scope of activity at building level. The most significant climatic and environmental impacts representing the subject of researchers' interest nowadays are related to temperature, moisture, ice, and pollution effect (e.g. carbonisation) (Radić, 2010).

While researching material resiliency and durability, all of the impacts listed above are considered individually. Recent investigations, however, suggest that, for material decay, the combination of impacts is significantly more harmful to a material than individual effects. This means that the life-cycle prediction of a construction, and of the materials applied on it, may be misdiagnosed, even if one of the aforementioned effects is isolated from the combined group (Giordano et al., 2011; Yao et al., 2012). In this paper, the resilience of stone, concrete, wood, and ceramic will be discussed in relation to the effects of climate and pollution.

2 Temperature Impact

When subjected to a certain temperature, materials behave differently. Performance is also compounded by rapid and drastic temperature changes as typical climate change manifestations. Due to the exposure to temperature changes, the dimensions of a material are being modified. In most cases, these fluctuations are not anticipated in advance, but reports nonetheless show that the temperature range constantly increases (Bruci, 2008). For example, in certain parts of the Southeast Europe, according to the climate change statistics and predictions, a building can be exposed to temperature variations from -20°C to +40°C (with additional possible temperature deviations because of the micro-location), which puts any material incorporated in that building at the risk of deformation (Radić, 2010). Resilience to temperature impact is defined through physical properties, such as thermal conductivity, thermal conductance, thermal resistance, and thermal mass (Muravljov, 2007).

Thermal conductivity is the property of a material that relates to its ability to conduct heat (Muravljov, 2007). Every material is characterised by a distinctive heat flow. The faster the heat passes through a material, the more conductive it is. Thermal conductivity (λ) depends on temperature changes (ΔT) at boundary surfaces of the element (S) and the element thickness (a).

For building materials, *thermal conductance* Λ (conductivity) is usually defined for specific layer thickness (a), and it is calculated as $\Lambda = \lambda / a$ (W/m^2 °C). This parameter is also known as *U-value*, and often the heat resistance representing a reciprocal value of U is used.

The decrease of the U-value shows that the insulation properties of a material are improving.

In a realistic multi-layered element exposed to different temperatures on surfaces, *thermal resistance* R is defined as the sum of individual U-values (Muravljov, 2007). In addition, the coefficients representing transfer of temperature from the environment to exterior (e) and interior (i) wall surfaces need to be considered. They are determined depending on heat flow direction. A higher value of R factor means that the observed element is a better insulator.

Thermal mass is the resistance of a material to temperature change, considering the increase or decrease, and it represents a key factor in dynamic heat transfer interactions within a building.

A material's *linear coefficient of thermal expansion* (α_T) is one of the most important parameters in the analysis of temperature effects. It represents the dilatation at a temperature change of 1°C. The values of a linear coefficient for some commonly used building materials are presented in the Table 2.1.

ALUMINIUM	$23{,}80 \times 10^{-6}$	LIMESTONE	$9 - 10 \times 10^{-6}$
Cement mortar	$10 - 12 \times 10^{-6}$	Marble	$5 - 10 \times 10^{-6}$
Concrete	$8 - 12 \times 10^{-6}$	Brick	$4{,}50 \times 10^{-6}$
Steel	$10 - 13 \times 10^{-6}$	Sandstone	$12{,}40 \times 10^{-6}$
Wood	$3 - 6\times 10^{-6}$	Glass	$8{,}50 - 9 \times 10^{-6}$
Granite	$8{,}10 \times 10^{-6}$	Schist	$10{,}1 \times 10^{-6}$
Copper	17×10^{-6}	Polyethylene	200×10^{-6}
Polypropylene	110×10^{-6}	PVC	$90 - 150 \times 10^{-6}$

TABLE 2.1 Values of linear coefficient of thermal expansion *(Muravljov, 2007)*

In the following sections, the review of behaviour and resilience to long-term temperature changes of several conventional building materials: stone, concrete, wood, and ceramic, is given. The effect of high temperatures (fire) will not be considered. However, related literature has been provided for further reading (e.g. Điđić, 2015; Domone & Illston, 2010).

2.1 Impact of Temperature on Stone Properties

Stone is a natural and durable material that has long been considered as resistant to temperature changes. However, even relatively small daily or seasonal temperature variations can be damaging. When stone is exposed to a temperature change, small inner tension stress is being created (Čaušević & Rustempašić, 2014). This stress will not cause structural damage, but it can create microcracks. It should be noted that tension stress is only concentrated at the surface of a stone material (Doehne & Price, 2010). The stresses are then accumulated as a result of contraction and expansion of minerals that form the stone, due to cyclical changes in temperature and depending on the coefficient of thermal expansion of minerals (Stefanović, 2010). As a consequence, changes in microstructure and the microcracks formed due to tension stress lead to expansion of existing cracks. Ultimately, the path is opened for the penetration of water, gases, salts and other agents, which can destroy natural stone and deteriorate its resilience.

Limestone, one of the most widespread types of stone in the Southeast Europe, is considered a durable and resilient material. However, when subjected to temperature changes, especially in combination with moisture, limestone decays rapidly. In the research of Al-Omari et al. (2014), limestone material incorporated in a building structure and subjected to daily variations in temperature and humidity was investigated. Here, tension stress ranging from 0.23-0.40 MPa was observed. Occurred stresses are sufficient to cause microcracks and/or the expansion of existing cracks in cases of long-term exposure to temperature changes.

Marble, often used for decorative purposes and commonly found in historic buildings, is one of the most weather-resistant types of stone. However, when exposed to several heating and cooling cycles, the porosity of marble increases due to the thermal behaviour of constituent crystals (calcium carbonate) that are expanding and shrinking. The grains that constitute marble not only change their size but also their shape, which ultimately results in the formation of micro-cracks on the edges (Scherer, 2006). The process is relatively slow, but inevitable during the years of exposure to temperature changes.

The decay processes that are explained above refer to the alternating influence of elevated temperatures and cooling effect in a short period (e.g. daily or weekly). The presence of salt only intensifies the decay. For example, sodium chloride expands at approximately five times the rate of calcite at surface temperature, creating inner tension stress and ultimately the cracks (Doehne & Price, 2010). This is how residual salt on limestone can precipitate its deterioration. However, the effect of low temperatures in combination with water is far more destructive. The degree of damage due to low temperatures depends on the lowest temperature, number of cycles of freezing and thawing, cooling rate, material properties such as water absorption, and the size and arrangement of pores, as well as others. The determination of resilience to frost action is an indispensable part of any laboratory stone test. The European standard *EN 12371 - Determination of frost resistance* explains the testing procedure. Fracture mechanism is relatively simple. Penetrating the stone (absorption), water molecules pass through the pores and cracks. When subjected to low temperatures, liquid water molecules are changed to solid state. Water in a solid state increases its volume by 9% and forms a crystal lattice that pressurises and mechanically damages stone (Stefanović, 2010). After a number of freezing and thawing cycles, the result is complete material destruction. Resilience to frost action depends on the stone type and its porosity, but it should be borne in mind that no stone used in construction is immune to the effect of frost. Examples of stone damage due to low temperature effect are given in Fig. 2.1 and 2.2.

A B

FIG. 2.1 Marble damaged by the effects of low temperatures *(Stefanović, 2010)*

FIG. 2.2 A+B: Limestone damaged by the effects of low temperatures *(Čaušević & Rustempašić, 2014)*

In the construction industry, stone is also used as a component in concrete or mortar, where both natural aggregate or crushed stone material are used. Resilience of the aggregate, making up 70-80% of the concrete mass, is the primary function of the type of particular rock material. Limestone, marble, and granite can have substantially different values of thermal dilatation coefficients (α_t), when considered as a ratio to the cement stone. In the case of the application of such rock-based aggregates, there is a potential danger of temperature change-related destruction of concrete.

The incompatibility of values α_t for rock materials and cement stone must not be ignored. With temperature changes, in the case of aggregate-based concrete, high flexural strength in the mass is created, which initially causes small, and later large, cracks. If temperature changes are repeated in several cycles, the use of such aggregates may cause complete degradation of the physical and mechanical properties of concrete.

Biological impact (bio-deterioration) on stone durability should not be neglected either. Increased temperatures in combination with the constant presence of moisture leads to the formation of living organisms (such as fungi, lichens, algae, etc.) on stone surface. Their presence not only degrades the appearance of the stone but also leads to its decay. The damage made by these organisms can be chemical and physical. Mechanical damage is caused by hyphae penetration into the stone. Chemical damage depends on the organism type, and it is common for lichens (Doehne & Price, 2010).

2.2 Concrete and Temperature Effect

Artificial stone – concrete is the most used material in the contemporary construction industry. For a long time, concrete was considered a material with an unlimited lifetime, resilient to all external effects. However, practical experience and numerous studies have shown that this assumption was wrong. Today, special attention in the design of concrete mixtures is given to durability and resilience to external effects.

Concrete properties are the function of a large number of influential factors: characteristics of component materials and their quantitative ratio, production method for concrete elements, technological factors,

TOC

and the exploitation conditions. It was found that most of the properties of concrete depend on the final structure and the conditions under which the forming takes place. Thus, environmental parameters such as weather, temperature, and humidity significantly influence the formation of concrete structures. The interdependence between 'composition - structure - concrete properties', representing the basis of the so-called structuralistic concept of concrete theory and technology is shown schematically in Fig. 2.3.

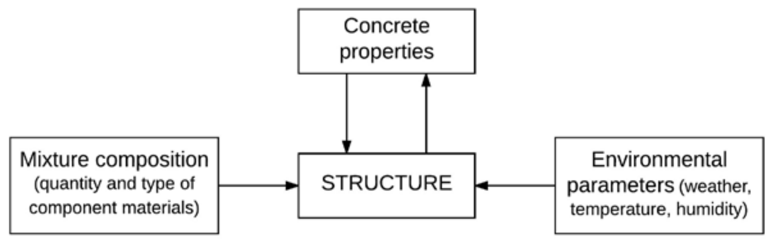


FIG. 2.3 Interdependences between the factors influencing concrete structure *(Jevtić, 2012)*

The concrete is exposed to temperature impact from the moment of installation until the end of building's lifespan. The most significant temperature effect on concrete is shrinkage. In general, shrinkage is a complex phenomenon inevitable in concrete structures, developing immediately after the installation (such as plastic shrinkage), during the binding process (e.g. chemical and autogenous shrinkage), and after hardening (drying shrinkage, thermal, i.e. temperature shrinkage, or carbonation shrinkage) (Šahinagić-Isović, Markovski & Ćećez, 2012). Although external temperatures influence all shrinkage types, the shrinkages during installation and binding process can be ignored when considering the exposure to long – term temperature change, because they terminate relatively quickly.

Drying shrinkage is a result of long-term impact of temperature and humidity, i.e. drying of concrete surfaces. Its influence on concrete is particularly significant in environments with elevated temperatures and low humidity. Here, the thickness of a concrete element represents a very important factor. For elements approximately 15 cm thick, drying process lasts about 10 years, and for elements approximately 50 cm thick about 100 years. Drying shrinkage varies between 2 and $6x10^{-4}$ (Šahinagić-Isović, Markovski & Ćećez, 2012; Yang, Li, Deng, & Liu, 2014). Low water – cement ratio and low permeability of high strength concrete play a significant role in drying shrinkage. When water – cement ratio is so low that almost all water is consumed during the hydration process and relative humidity inside concrete falls below 80%, then practically there is no moisture exchange between the concrete and the external environment.

Besides, concrete is sensitive to temperature differences that occur inside the construction, as a consequence of weathering conditions or because of heating certain parts of construction. These differences in temperature lead to uneven expansion and contraction and further cause the occurrence of cracks. The elements that are subject to cracks usually have dimensions larger than 50 cm in cross section (e.g. columns, beams, slabs, and foundations). In the research of Chen and Wen (2003), concrete slabs were exposed to a temperature difference of 30°C, by heating one end of the element and cooling the other end over a period of 20 days. Registered stresses of about 1.50 MPa had led to the creation of 0.50 mm wide cracks, which is more than current standards allow. Therefore, special attention should be paid to the design of concrete constructions exposed to uneven temperature effects. While a drop in temperature may result in cracking in the exposed element, a temperature increase may cause cracking in the protected portion of structure (Chen & Wen, 2003).

Similarly to stone, continuous low temperatures are also harmful also to concrete. Fracture mechanism is basically the same. By transforming into ice, water in concrete pores increases its volume by 9%, which leads to the expansion of cracks and to construction destruction, after the process is repeated numerous times. The testing of concrete resilience to low temperatures (freeze – thaw cycles) is done according to the European norms *CEN/TS 12390-9 – Testing hardened concrete - Freeze-thaw resistance*. Since concrete is very sensitive to low temperatures, the constructions (and concrete mixtures) exposed to this effect must be designed carefully. Many authors have published research on this topic: Auberg & Setzer (1997); Bjegović & Širmer (2015); Boos & Giergiczny (2010); and Pigeon, Marchand, & Pleau (1996) are recommended for further reading.

If it is assumed that the destruction of concrete at low temperatures takes place according to the mechanism of ice expansion, and not due to incompatibility of the coefficients of thermal dilatation of cement stone and aggregate grain, then concrete resistance to frost can be increased by:

- Producing a concrete of lower porosity;
- Using the air entraining admixtures; or
- Disabling the entry of water into the capillary pores of cement stone.

2.3 Impact of Temperature Variations on Wood Material

The use of wood in construction is widespread. Its intended purpose is closely related to the type of this material that is selected. Wood resilience depends on what conditions it is exposed to during its use. If environmental conditions are optimal, wood may perform as a quite resilient and long-lasting material, with a durability of over a hundred years. On the other hand, wood material exposed to changing environmental conditions shows a significantly lower performance.

Wood is sensitive to temperature changes, but not in the same way as some other materials. When heated, wood expands, and when cooled, it shrinks. Warping may also occur. The degree of deformation depends on the type of material, fibre direction, and temperature change. However, wood is characterised by a naturally developed defence mechanism against temperature changes, as it is has been exposed to this effect from the growing phase. The extent of resilience to temperature changes depends on the type of wood.

In comparison to some other conventional building materials, the thermal conductivity coefficient of wood is much lower. The expansion of wood, occurring with temperature increases, appears to be linear over a wide temperature range. Slight differences in expansion, occurring between radial and tangential planes, are usually ignored, and the coefficients are averaged to provide a transverse value (Domone & Illston, 2010). Changes in the dimensions of timber elements exposed to temperature changes are usually much less pronounced than those occurring under the influence of moisture (Section 3.3).

Ultraviolet sunlight instigates the aging of natural wood by destroying its content, i.e. the lignin. In addition, the presence of water (moisture) enhances this effect by washing the lignin away (Radić, 2010). It is common that only the surface layer of the wood is impacted, meaning that the properties are damaged only at the surface where the wood also loses its natural colour and gets greyish shade (Skadsen, 2007) (Fig. 2.4). Therefore, wood that is used externally is less resilient and has a shorter life span than wood protected from direct sunlight (Andrady, Hamid, Hu, & Torikai, 1998).

FIG. 2.4 Illustration of natural aging of wood *(Čaušević & Rustempašić, 2014)*

2.4 Ceramic Materials: Corrosion and Impact of Temperature Changes

The multitude of preserved structures, and the remains of built heritage that is thousands of years old, testify to the stability and durability of ceramic material and ceramic construction elements. There are two dominant ways in which ceramic material deteriorates due to environmental factors: corrosive and erosive (Vasić & Janjić, 1986). The term "corrosion" implies the deterioration of ceramic material caused by the factors in surrounding environment, while the term 'erosion' refers to the deterioration caused by mechanical action, which is not the subject of this paper.

Different models that were developed to describe the mechanisms of the corrosion of ceramic construction materials can be found in literature (e.g. Cauley, 2004). In real environmental systems in which different processes concurrently take place, a general model that would describe all cases of corrosion of ceramic construction materials cannot be established. Ceramic material reacts differently in contact with different environments and hence there is no single explanation for occurring corrosion (Vasić, Radojević, & Vasić, 2007).

The manufacturing process and mineralogical composition of raw materials significantly influence the production of ceramic materials and consequently their resistance to corrosion due to environmental effects. Basically, the corrosion of ceramic materials depends on structural characteristics. Compact materials with stronger bonded particles have a higher corrosion resistance. For illustration, durability characteristics of blocks made of baked clay are directly related to the formed structure, which is primarily a consequence of the applied baking regime. Obtained characteristics of ceramic blocks further directly influence the durability of a brick wall structure. Ceramic products obtained by baking at higher temperatures have better mechanical properties and lower porosity.

The damage to ceramic materials, considering manufacturing technology of brick products, mainly occurs at low temperatures. Negative effects of low temperatures on ceramic materials manifest when the water in capillary pores freezes. The damage occurs when the fulfillment of capillaries with water is greater than the critical value of saturation (91.7 %). The exact degree of damage caused by frost effect will depend on: water absorption; size, shape and arrangement of the pores; moisture content; cooling speed; the lowest temperature; and the number of freeze-thaw cycles. Hollow bricks are more susceptible to frost damage than solid products.

The deterioration of brick walls exposed to increased temperatures occurs due to the impacts of heat and sunlight on bonding materials in the wall structure, in particular ultraviolet and infrared rays.

3 Moisture Impact

The previous section dealt with the impact of temperature on building materials from the beginning of construction process to the end of building life cycle. The same time frame is relevant for moisture effect, and it should be borne in mind that most materials degrade more quickly when they are exposed to temperature and moisture effects simultaneously. The penetration of moisture inside constructions causes direct damage to applied building materials. Increased moisture content stimulates the growth of micro-organisms such as moulds, algae, or mosses. Water vapour permeability and water resistance are two main factors that determine corrosion rate in building materials impacted by moisture (Muravljov, Ukrainčik, Bjegović, Jevtić, & Denić, 1988).

Moisture affects materials through atmospheric humidity, precipitation (rain and snow), and unpredictable events (such as floods, or damaged pipes). The most significant effect of precipitations on materials is indirect, and has occurred because of the evaporation of precipitation water. When a material is colder than its environment, evaporated water will be retained on the surface (e.g. wall surface), representing a constant threat. Relative humidity is a term used to indicate the percentage level of saturation of the atmosphere with moisture, where normal relative humidity ranges from 40 – 60%. Unpredictable weather events, such as extreme precipitations or storms, indicate shorter or longer exposure of construction elements and materials to water.

The presence of moisture in building materials also can result from the presence of water in soil (due to flooding, snow melting, tides, or elevated underground water levels), damage in flume and roof installations, incorrectly placed envelope openings with the wrong inclination, failures in water supply, sewage and hot water systems, and others.

3.1 Stone and Moisture

All stone types are sensitive to the effects of moisture, especially in conditions of long-lasting exposure. Air humidity, i.e. atmospheric moisture, comes into contact with stone surface, transforms into a fluid state due to differences between surface and air temperatures, and finally reaches inner parts of the material through capillary pores or cracks.

The destructive effect of water (moisture) that transforms into ice inside the stone at low temperatures is described in a previous section. Nonetheless, the water in liquid state can cause stone destruction by chemical bonding. Although a large quantity of water evaporates from stone surface after precipitation, a certain amount is still absorbed through the pores. Absorbed and retained water then reacts with the stone material. Namely, when water molecules come into contact with the molecules of stone minerals, they chemically bind by 'pulling out' minerals from their crystalline lattice. This dissolution process (Stefanović, 2010) is intensified when water contains salt, which is often the case around the urban streets in winter conditions. Here,

TOC

walkways and lower parts of building facades are more likely to be damaged, particularly when they constitute carbonate sedimentary rocks (limestone, dolomite), sandstone, and marble. For example, if limestone comes into contact with water and carbon dioxide, the following chemical reaction occurs:

$CaCO_3+CO_2+H_2O=Ca(HCO_3)_2$.

Formed calcium bicarbonate is easily dissolved in water. The acidity of rain, i.e. acid rain, which is a probable phenomenon in polluted built-up areas, only accelerates the dissolution effect. After precipitation and evaporation of water from the surface of the stone, efflorescence occurs, and the salts remain on surface (Fig. 3.1). In addition, water can react with sulphur dioxide or sulphur trioxide from polluted air to produce sulphurous and sulfuric acids, which destroy stone. This effect is particularly harmful to sandstone types, where the inner material binder is usually being destroyed. Decay processes are explained in the following sections.

FIG. 3.1 Efflorescence of stone wall *(Stefanović, 2010)*

FIG. 3.2 Example of alkali reaction *(Bjegović & Štirmer, 2015)*

Porous stone types have an increased sensitivity to moisture effects because of their high absorption potential. Nevertheless, simple processing and good economic prices keep them in the market's favour and often justify the utilisation. The resilience of porous stone types can be improved by reducing surface porosity. For this purpose, various types of surface coatings are used.

3.2 Impact of Moisture on Concrete

When concrete is exposed to moisture and water, damages to both cement stone and steel reinforcement occur. There are three possible cases describing concrete exposure to water: concrete submerged under water; concrete that occasionally moisturises; and concrete unilaterally exposed to water (e.g. in swimming pools). The practice has shown that the second case is the most damaging for concrete material.

If concrete is exposed to elevated moisture (over 80%), and if its aggregate contains silicate compounds, then there is a high probability of an alkaline reaction occurring between aggregate and cement constituents Na_2O and K_2O (sodium and potassium oxide), which react chemically with water to form sodium and potassium hydroxide (Shimomura, Maruyama, Nakarai, & Sato 2008). The continuous presence of water in material leads to the enlargement of existing and the formation of new cracks, as well as to chipping of concrete parts, but intermittent drying and wetting of concrete surfaces can be even more damaging. Alkaline reaction can be prevented with the use of certain cement types and additives, such as cement with mineral additives, or low alkali cement (Bjegović & Štirmer, 2015). An example of alkali reaction is shown in Fig. 3.2.

If concrete humidity amounts to more than 30% and less than 100% (concrete submerged under water), there is a high probability of carbonation. The by-product of cement hydration (binding) is lime (calcium hydroxide $Ca(OH)_2$), which reacts with carbon dioxide from air and forms calcium carbonate (CaCO3) and water:

$$Ca(OH)_2+CO_2=CaCO_3+H_2O.$$

Since calcium carbonate has greater volume than calcium hydroxide (cement), it expands with chemical reaction and as a result produces cracks in concrete (Bjegović & Štirmer, 2015). At the same time, the alkalinity of concrete is reduced, thus meeting conditions for the initiation of corrosion in reinforcement (Jevtić, 2008). Although the presence of carbon dioxide represents the main reason for carbonation, if the environment is too dry the carbonation will not occur, as this process requires water for dissolving carbon dioxide. Carbon dioxide dissolved in water forms carbonic acid (H_2CO_3) which can penetrate into concrete.

Penetration of chlorides is equally important as carbonation for initiating the corrosion of concrete reinforcement. The transport medium for chlorides is water, which means that there must be a sufficient percentage of humidity for corrosion to occur. The chlorides that come in contact with concrete most commonly originate from sea salt or from salting the roads against freezing. Once the critical chloride ion and hydroxide concentration is reached, the corrosion process begins (Bjegović & Štirmer, 2015).

The processes described above are quite slow, and it takes years, sometimes decades, to see their devastating effect. However, the corrosion rate over the last 20 years is more intensive than in the past 300 years. Normally, concrete protects the reinforcement with its standard 25 mm thick cover layer and a high pH value (in regular conditions more than 12). With increased air pollution, the occurrence of acid rainwater penetrating beyond the protective cover layer, and leading to the loss of concrete alkalinity and consequently to the reinforcement corrosion, is significantly more probable. The corrosion process requires the presence of air and moisture to advance. In addition, it creates the so-called rust which has a greater volume and leads to the formation of cracks and chipping of the parts of concrete elements. Structurally, corrosion reduces the bearing capacity of the construction, as it reduces the cross section of the reinforcement. At the surface, corrosion is manifested in the form of cracks and/or brown stains, although in some cases there is a complete absence of surface signs. An example of corrosion and its effect on concrete is shown in Fig. 3.3.

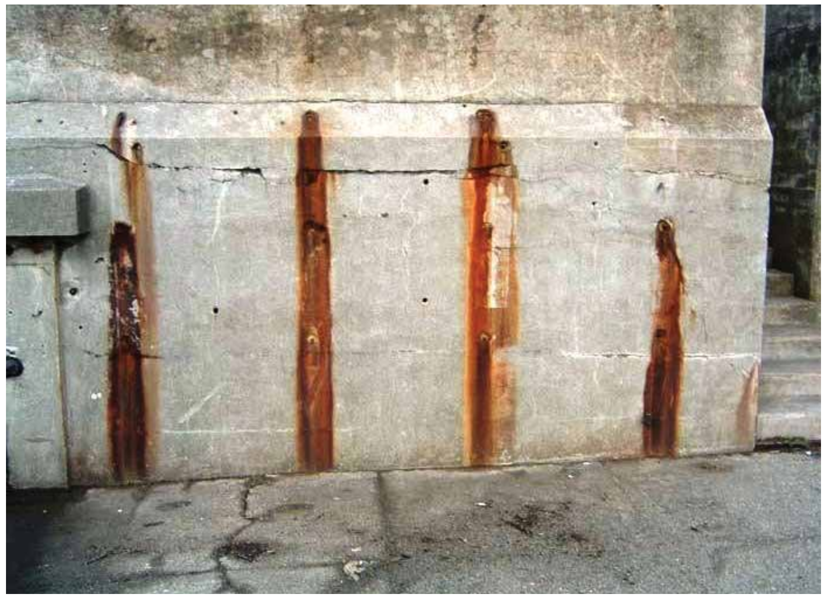


FIG. 3.3 Example of corrosion in concrete constructions *(Bjegović & Štirmer, 2010)*

Concrete corrosion caused by so-called 'soft waters' may be successfully eliminated with the cements having a reduced content of clinker minerals C_3S (below 50%) and the cements containing more than 30% of pozzolanic supplement. The utilisation of metallurgical and pozzolanic cements, as well as high alumina cement, is recommended.

The risk of corrosion from sea water, underground water, or industrial wastewater can be successfully overcome by using cements with low content of C_3S mineral such as sulphate resistant Portland cement, sulphate-resistant metallurgical cement, aluminous cement, and super-sulphate cement.

The presence of moisture and certain air temperatures provide a basis for the development of various micro-organisms, i.e. for the biological impact on concrete. Most commonly, cement stone is attacked by bacteria and fungi, thus reducing concrete resilience (Bjegović & Štirmer, 2015).

3.3 Wood and Moisture Effect

Wood displays excellent properties in dry environments, or when submerged in water. On the other hand, it shows low durability when used in a humid environment or when alternately saturated and dried. A humid environment is suitable for the development of various types of fungi and microorganisms that eventually cause wood rotting. The most resilient and durable types of wood in the southeast part of Europe are oak and pine (Muravljov, 2007).

Changes in moisture content, especially after rainwater exposure and drying, intensify stress and accelerate the natural aging of a wood material (Radić, 2010).

In conditions of low environmental humidity (below 20%), the risk from fungi occurrence in wood is practically removed. When humidity is higher, and at the same time air temperature amounts to 20 – 30°C, fungi development is likely. These microorganisms destroy lignin and cellulose, cause rotting, and finally reduce wood properties.

Wood resilience can be maintained to a certain level by proper protection, including impregnation, application of coatings, and chemical change of wood structure (Radić, 2010). To prevent fungi development, the optimal measure is avoidance of wood utilisation in environmental conditions suitable for their growth. Furthermore, it is necessary to secure a dry environment and natural ventilation for constructions with applied wood elements. When environmental conditions are satisfactory, wood material shows significant resilience. It is also worth noting that all protective solutions are temporary and that they lose their function over time. Therefore, regular maintenance of any wood element or structure is needed.

3.4 Impact of Moisture on Ceramic Materials

On the one hand, the porosity of ceramic materials (e.g. bricks and blocks) is beneficial for mortar connections, but on the other hand it represents a weakness due to which deterioration in the presence of moisture occurs.

The causes of deterioration of wet ceramic products can be divided into three groups:

- Physical causes (e.g. temperature fluctuations, frost, crystallisation of salts);
- Biological causes (such as microorganisms, algae, fungi, or lichens); and
- Chemical causes (formation and rinsing of easily soluble compounds).

Humidity – the most influential factor in compromising the durability of ceramic materials – may appear in the following ways:

- as hygroscopic moisture, by absorbing atmospheric moisture;
- due to the condensation of water vapour, as a result of water vapour diffusion;
- as capillary absorption, where ceramic material is in direct contact with water.

Hygroscopicity is the ability of a capillary (porous) material to absorb water vapour from humid air, even without direct contact with water.

The hygroscopicity increases considerably if a ceramic material contains soluble hygroscopic salts in its structure. These salts are more hygroscopic than ceramic material, for example bricks; the increase of moisture in a construction element (e.g. wall) is proportionate with salt content and the amount of air moisture (Radonjanin & Malešev, 2010).

The diffusion of water vapour implies the movement of water vapour molecules from a location with a higher concentration to a location with a lower concentration in order to establish balance. Walls made of ceramic bricks are more or less permeable to water vapour. The difference in concentrations of water vapour on two sides of a wall causes movement through this construction element.

When the temperature of a brick wall is lower than ambient temperature, a humidifying phenomenon known as *condensation of water vapour* occurs in the form of drops of water on the material's surface. Porous ceramic material then absorbs condensed water. As a result, moisture content in the inner part of wall element is increased. This means that condensation may also occur inside the brick wall.

Capillary absorption is a common mode of water absorption. The height to which water rises in capillary-porous materials such as ceramics may be very large, up to 15m (Oberknežev, 2004). For this reason, moisture in many buildings appears far above the point of contact with water (Radonjanin & Malešev, 2010).

When ceramic material is exposed to constant or intermittent contact with water containing significant amounts of dissolved salts, the damage induced by salts crystallisation occurs. The penetration of water into material is associated with the occurrence of chemical reactions between water and ceramic constituents, as well as with the appearance of stresses within the ceramic material. In the first case, there is a selective dissolution of one or several ceramic constituents and in the second, there is an emergence of pressures on the walls of the pores of the ceramic building material.

The efflorescence of soluble salts, as a specific type of corrosion of ceramic building materials and masonry structures, implies the occurrence of white, pale yellow, or coloured powdery deposits or stains on surfaces (Vasić & Janjić, 1986). This phenomenon occurs when:

- brick, mortar, or water used for mortar preparation contain soluble salts in significant amounts; and
- humidification of ceramic material, binding agent, or masonry element is enabled to the extent at which the dissolution of present salts develops.

The content of soluble salts that can cause efflorescence usually ranges in promilles (‰) compared to the mass of building material. For this reason, the control of harmful content in the mass production of bricks is difficult.

TOC

Efflorescence of soluble salts is, to a significant degree, dependent on the surrounding environment, i.e. on climatic conditions to which ceramic materials are exposed during their use. As the relative humidity of air changes with temperature, the crystals formed in porous materials alternately transform from a crystalline to an amorphous form. Crystallisation of salts is followed by volume changes and consequent generation of heavy pressures which, due to exceeding the tensile strength, cause damage and cracking.

To reduce corrosion of ceramic materials to the smallest possible extent, it is necessary to:

- use compact ceramic materials baked at higher temperatures;
- prevent the penetration of water or other liquid agents from surrounding environment;
- improve the physical properties (such as water tightness and resistance to frost) in cases where it is necessary, by using hydrophobic silicone-based protection coating.

FIG. 3.4 Brick decomposition caused by hydration and crystallising pressures *(Vasić & Janjić, 1986)*

4 Pollution Impact

The pollution brought into relation with climate change mainly refers to the increase of emissions of certain gases, primarily carbon dioxide (CO_2). In the last 20 years, carbon dioxide emissions have increased by about 24% (World Bank, n.d.). Particularly high concentrations of CO_2 are registered in locations close to industrial facilities and major roads (Šahinagić-Isović, Markovski & Ćećez, 2012). In addition to CO_2, increased concentrations of sulphur dioxide (SO_2) are registered near industrial facilities, coal-fired plants (thermal power plants), and oil and gas power plants. Both carbon dioxide and sulphur dioxide cause significant decay of building materials. Therefore, these effects should be taken into consideration when designing a building in an environment exposed to air pollution.

4.1 Pollution Impact on Stone Properties

A high concentration of CO_2 is very harmful for stone in general. Carbon dioxide reacts with water in the air, generating carbonic acid (H_2CO_3) compound, which reacts with limestone to produce calcium bicarbonate:

$H_2CO_3+CaCO_3=Ca(HCO_3)_2$.

Produced calcium bicarbonate easily dissolves in water and eventually washes the stone away. Besides limestone, sandstone material is also sensitive to carbonic acid. It dissolves the binder (usually clay or limestone) and causes the formation of pores and voids, so that the sandstone gradually loses its properties.

If limestone is used in an environment with a high concentration of sulphur dioxide, the following chemical reaction will occur:

$CaCO_3+SO_2+H_2O+O=CaSO_4+H_2CO_3$.

In the presence of water (e.g. acid rain), the subsequent reaction is:

$CaSO_4+2H_2O=CaSO_4\bullet 2H_2O$.

The result is, in fact, the gypsum ($CaSO_4\bullet 2H_2O$). The crystallisation then increases the volume of this substance and finally causes damage to the stone (Muravljov, 2007).

4.2 Effects of Concrete Exposure to Pollution

The effect of carbon dioxide on concrete is reflected in the carbonation process, and carbonation cracking. The process takes place in hardened concrete. Carbonic acid (formed by the reaction of carbon dioxide and water), reacts with calcium hydroxide in a cementitious stone, creating calcium carbonate and water:

$Ca(OH)_2+CO_2=CaCO_3+H_2O$.

Since the volume of calcium carbonate is greater than that of calcium hydroxide, this chemical reaction is followed by the formation of cracks. The speed of cementitious stone corrosion depends on the structure of the pores and, more, on their water content (Šahinagić-Isović, Markovski & Ćećez, 2012). If pores are filled with water (submerged construction), the progress of carbonation will be the slowest. On the other hand, if water is not present, there will be no chemical reaction. This means that the presence of a certain percentage of water is a precondition for carbonation. The research of Talukdar, Banthia, and Grace (2012) shows that the carbonation process progresses rapidly when cracks exist in the concrete. In addition, the depth of carbonation depends on the size of cracks. It is interesting that concrete's compressive strength slightly increases after the carbonation process (Chi, Huang, & Yang, 2002). Calcium carbonate produced in the carbonation process occupies a larger area than calcium hydroxide, thus increasing the compressive strength. However, this effect is local because it depends on the layout of the cracks.

Destructive effect of sulphates on concrete is a consequence of reaction with calcium and aluminum ions. The reaction causes expansion and cracking, which accelerates the degradation process by allowing further penetration of sulphates. The sulphates most seriously attack concrete that is based on Portland cement (Bjegović & Štirmer, 2015). Attack intensity depends on many factors, such as the type and concentration of sulphates. In extreme cases, sulphates can completely destroy the concrete. Relative wide-spreading and serious damages that may occur due to the aggressive effect of sulphates give great significance to this occurrence (Radić, 2010).

In contact with the water, sulphur dioxide forms sulphuric acid, i.e. acid rain (H_2SO_4). In this process, other expected reactions of sulphur dioxide, water, sulphurous acid, and sulfuric acid with calcium hydroxide free ($Ca(OH)_2$), calcium oxide (CaO), dicalcium silicate ($2CaO \bullet SiO_2$) and tricalcium aluminate ($3CaO \bullet Al_2O_3$) result in the formation of crystals or precipitates in concrete matrix with volumes from 5-30 times greater than the initial volumes of these crystals (Mainier, de Almeida, Nani, Fernandes, & dos Reis, 2015). Mentioned reactions include gypsum formation, and ettringite formation or decalcification, and they all lead to crack development or expansion. The resilience of concrete in a sulphate rich environment depends on sulphate concentration and concrete structure. The application of Portland cement with granulated slag is more suitable for sulphate resistant concrete (Bjegović & Štirmer, 2015).

4.3 Wood and Polluting Agents

If wood is exposed to the joint effects of sunlight and acid rain, the decay process is accelerated, as sulphur dioxide destroys the cellulose and sunlight destroy the lignin. In addition, the coatings for wood protection react with SO_2 to which they are sensitive. If wood is exposed to acid rain effects over a long period of time, the coating peels and wastes away (Williams, 1986). This is one more reason why regular maintenance of wood structures is needed.

4.4 Pollution Impact on Ceramic Materials

Due to the significantly higher concentration of gases, the susceptibility of ceramic materials to pollution impact is especially noticeable in urban areas. The chemical reaction between calcium carbonate ($CaCO_3$) and water (rainwater), which contains dissolved carbon dioxide (CO_2), sulfur (SO_3), hydrogen chloride (HCl), etc., causes the corrosion of these materials.

In recent years, the destruction of brick products due to the presence of acid gases in the atmosphere is becoming more apparent. Previously, the study of ceramic tiles exposed to the effects of atmosphere with a high content of SO_2 has shown an increased content of soluble salts, reduction of bending strength and an increase of water absorption (Vasić & Janjić, 1986). Under the influence of acid rain, calcium carbonate ($CaCO_3$) present in the pores of brick products can be converted into calcium sulfate ($CaSO_4$), where the volume of newly formed salt increases almost twice. The occurrence of hydration pressures in pores of ceramic material is caused by changes in relative humidity and ambient temperature, where, in all cases, present salt crystallises, thus forming other salts with various degrees of hydration.

Some harmful effects caused by the influence of the surrounding environment on ceramic bricks are more visible. Such is the case with efflorescence, which occurs due to the impact of polluted atmosphere, usually in proximity to manufacturing complexes (such as factories for fertilisers, sulfuric acid, etc.). Under the influence of sulfuric gases from the air, calcium sulphate formed at the surface of the bricks disrupts their aesthetic appearance.

Brick walls can also be attacked by different microorganisms: algae, fungi, lichen, and moss. The lichens that develop in the form of green, black, and pink circular stains have the most destructive effect on bricks. These damages have both chemical and mechanical sides. Chemical damages occur due to the reaction of CO_2 from the air and the mucus, which is a metabolic product of lichens. Because of the high mechanical absorbability of lichens, they act as 'pegs' on material.

5 Resilience Building Measures

Deterioration seems inevitable for all of the studied building materials subjected to climate effects and air pollution. These harmful impacts manifest through long-term exposure rather than immediately. The initial durability of materials therefore decreases over time. To keep materials resilient to the effects of climate (change), planning and acting in accordance with the preventative and/or rehabilitation measures are necessary. In order to foresee the effects of specific measures, the characteristics of given environment should be fully determined and the function of resistance to material corrosion should be mastered. Analytical prediction of material resilience-related behaviour is based on the processes of degradation in corrosive environments, divided according to the levels of exposure, and the type and character of damage. A mathematical life-cycle model, which includes all relevant factors (from user needs to causes of degradation, mechanisms of effect, previous tests, and exposure and assessment) can be created with considerable accuracy.

Durability of structures in practice is always the result of several factors, including design solution, applied materials, construction method and quality control, as well as the strategy for management and maintenance. Unfortunately, apart from the usual calculations primarily related to the static stability, the procedures dealing with the resistance of structures to other influences are not applied. The most commonly applied procedure is tantamount to prescribing quality conditions established on the basis of laboratory tests and practical sustainability criteria.

After construction completion, the most important step in assuring resilience is maintenance. With adequate maintenance, the level of initial performance and usability over a long lifespan can be kept. Maintenance is the result of regular and timely construction inspections that allow data relating to the condition of the construction to be obtained and thus inform decisions regarding future actions (e.g. rehabilitation, repair, reconstruction, etc.) (Radić, 2010).

It is never too early to think about corrosion, meaning that protection against it should be initiated in design stage. Through practical examples, students and engineers from different disciplines are able to acquire the knowledge needed for solving problems related to the deterioration of materials.

6 Materials with Enhanced Properties: Fibre Reinforced Concrete and Mortar

There is a constant effort to develop new, and innovate existing, building materials in order to improve their properties. In most cases, existing building materials are improved by adding or subtracting ingredients. Such is the case with the Fibre Reinforced Concrete (FRC), briefly reviewed in this section. FRC is not a new material; initial research on it dates back to the 1960s. Up until now, however, FRC has only found its application in some special constructions.

The basic idea in FRC development is to add artificial or natural fibres to an ordinary concrete mixture and improve several material properties. The most commonly used artificial fibres are steel, carbon, glass, and polymeric fibres, and the natural fibres are flax, hemp, jute, agave, etc. (Šahinagić-Isović, 2015) Besides concrete, the fibres can be successfully applied to mortars. Having regarded that mortar is a composite material made of the same components as concrete (with the difference that only fine aggregate is used), and that it behaves in a way similar to concrete, the application of fibres can improve physical-mechanical and deformation characteristics just as for concrete.

Concrete has great compressive, but low tensile strength. In addition, it is characterised as a brittle material. For this reason, reinforcement is added to concrete structures when needed. The main goal of adding fibres to a concrete mixture is to increase tensile strength and toughness. As positive side effects of increased toughness, some other concrete properties like bending strength, modulus of elasticity, impact resistance, fatigue resistance, shrinkage and occurring crack width are also improved. Usually, the fibres do not affect compressive strength noticeably (Šahinagić-Isović, 2015).

The type and percentage of fibres added to a mixture are very important. Namely, adding fibres is only justified to a certain limit. Hence, only a small percentage of fibres is usually added, e.g. 0.25 – 2.0% of steel fibres, and max 1.0% of polymer fibres (Šahinagić-Isović, 2015). A higher percentage of fibres does not include linear improvement of material properties.

As already stated, fibres considerably improve concrete properties. Here, shrinkage and cracking are explained in the context of FRC resilience to climate impacts. The case study including drying shrinkage, autogenous shrinkage and crack width analyses of FRC (for ordinary and high strength concrete) with 0.45% of steel fibres is firstly discussed.

Drying shrinkage and autogenous shrinkage represent very important parameters regarding long-term exposure to temperature and moisture effects. For concrete without fibres, drying shrinkage can be up to $6x10^{-4}$. The major portion of autogenous shrinkage takes place in the first days of binding and it can reach $3x10^{-4}$. The intensity is important because it is added to the final shrinkage value. Fibre application will not prevent shrinkage, but it can reduce the final value. Reported drying shrinkage of FRC with 0.45% steel fibres in the research by Šahinagić-Isović (2015) is $5.07x10^{-4}$ for ordinary strength concrete, and $3.9x10^{-4}$ for high strength concrete. Both results are about 6% lower compared to concrete without fibres. FRC with 0.45% steel fibres has shown $0.82x10^{-4}$ autogenous shrinkage for ordinary strength concrete, and $2.2x10^{-4}$ for high strength concrete. Ordinary strength FRC had 36% lower autogenous shrinkage than concrete without fibres, and high strength FRC had 19% lower autogenous shrinkage.

In terms of resilience to climate-related impacts, it is crucial to prevent crack increase. The fibres will not prevent cracking, but they can reduce crack width and reduce its occurrence. The study of Ćećez (2015) showed that crack width of ordinary FRC beams with 0.45% of steel fibres is 36% lower compared to the beams without fibres. For high strength FRC beams, crack width is lower than for beams without fibres by about 43%.

The application of polypropylene fibres to thin concrete elements (i.e. mortars) brings improvement to physical-mechanical properties. The results of an experimental programme conducted by Radulović, Jevtić, and Radonjanin (2016), in order to examine shrinkage of mortars with added polypropylene fibres, indicate a decrease of shrinkage for only 1.5% on the 126th day of testing, while in earlier stages (4th day) the shrinkage was 26.2% less in comparison with the etalon. This can be explained by the fact that polypropylene fibres are very effective in the earliest stage, while their elastic modulus is lower than the modulus of concrete elasticity, so that the cracking and shrinkage are prolonged for the subsequent period when material strength is greater.

FRC is successfully applied in industrial floors, tunnels' primary and secondary lining, various prefabricated elements, and rehabilitation of existing structures. The application in building construction is, however, unjustifiably omitted. As presented, both shrinkage and crack width are reduced in FRC, thus increasing resilience and mitigating negative climate effects on material properties.

7 Conclusion

The most important environmental impacts on building materials originate from the effects of temperature, moisture and pollution. In this work, the influence of high and low temperatures, consequences of moisture presence, physical and chemical forms of material abrasion, and other related issues have been analysed using examples of commonly used building materials: stone, concrete, wood, and ceramic.

Temperature changes, as described here, produce significant negative effects on examined building materials. Fluctuations in temperature lead to the gradual destruction of studied materials: stone, concrete, and ceramics, primarily through the series of shrinking and expanding cycles. Destruction is reflected through the occurrence of micro-cracks, which further evolve into eye-visible cracks, thus reducing material resilience. These cracks represent an open path to the water penetrating into material. At low temperatures, water is transformed into ice, and additional cracking and chipping are likely to appear. The effect of temperature changes on wood is manifested through warping and accelerated natural aging when this material is exposed to ultraviolet sunlight.

The effects of moisture on the materials studied are closely related to those of temperature. Moisture reaches materials in several ways, and the most common mode of moisture penetration is through capillary water. Once the water is inside the material, it causes damage by transforming into ice (when material is subjected to low temperatures), by chemical reaction with material content, or by provoking biological destruction, i.e. the growth of harmful microorganisms under favourable temperature conditions. The sensitivity of concrete to moisture is doubled; moisture destroys both cement stone and steel reinforcement. Similarly, moisture represents the most significant cause of reduced resilience in wood material.

Air pollution affects building materials through various gaseous agents, primarily carbon dioxide (CO_2) and sulphur oxide (SO_2). When these gases react chemically with materials' constituents, various compounds that initiate the process of material degradation and accordingly reduce resilience are produced.

TOC

This study has shown that resilience can be retained or even enhanced during the service life of a material. On the other hand, new materials with improved resilience to climate and pollution effects are continuously developing. At the same time, the properties of conventional building materials are improved. One example is Fibre Reinforced Concrete (FRC), an innovated resilient material that represents a step forward for the construction industry.

References

Andrady, A.L., Hamid, S.H., Hu, X. & Torikai, A. (1998). Effects of increased solar ultraviolet radiation on materials. *Journal of Photochemistry and Photobiology B: Biology*, 46 (1–3), 96-103. doi.org/10.1016/S1011-1344(98)00188-2

Al-Omari, A., Brunetaud, X., Beck, K. & Al-Mukhtar, M. (2014). Effect of thermal stress, condensation and freezing–thawing action on the degradation of stones on the Castle of Chambord, France. *Environmental Earth Sciences*, 71, 3977–3989. DOI 10.1007/s12665-013-2782-4

Auberg, R. & Setzer, M.J. (Eds.) (1997). Frost resistance of concrete. In: *Proceedings of the International RILEM Workshop*. Taylor & Francis. ISBN 9780419229001.

Bjegović, D. & Štirmer, N. (2015). *Teorija i tehnologija betona.* [Theory and technology of concrete]. University of Zagreb, Faculty of Civil Engineering. ISBN 978-953-6272-77-8.

Boos, P. & Giergiczny, Z. (2010). Testing the frost resistance of concrete with different cement types – experience from laboratory and practice. *Architecture, Civil Engineering and Environment (ACEE)*, 2/2010, 41-52. Retrieved from: http://acee-journal.pl/1,7,15,Issues.html

Bruci, E. (2008). Climate change projection for South Eastern Europe. Presented at the First Session of *South-Eastern Europe Climate Outlook Forum (SEECOF-1), 11 - 12 June 2008, Zagreb, Croatia*. Retrieved from: http://meteo.hr/SEECOF08/day2/2-4.pdf

Cauley, R. A. (2004). *Corrosion of ceramic and composite materials book.* New Jersey: Marcel Dekker. ISBN 0824753666

Chen, B. & Wen, Z. (2003). Research on cracking and waterproof techniques for concrete structure of subway station. In: Y. Yuan, S.P. Shah & H. Lü (Eds.) *International conference on Advances in Concrete and Structure ICACS 2003, Xuzhou, Jiangsu, China, 17-19 September 2003*. RILEM Publications S.A.R.L., 621 – 627. ISBN: 2-912143-41-1.

Chi, J. M., Huang, R., & Yang, C.C. (2002). Effects of carbonation on mechanical properties and durability of concrete using accelerated testing method. *Journal of Marine Science and Technology*, 10(1), 14-20. Retrieved from http://jmst.ntou.edu.tw/marine/10-1/14-20.pdf

Čaušević, A. & Rustempašić N. (2014). *Rekonstrukcije zidanih objekata visokogradnje* (Reconstruction of masonry buildings). University of Sarajevo, Faculty of Architecture. ISBN 978-9958-691-33.

Ćećez, M. (2015). *Granično stanje upotrebljivosti kod mikroarmiranih betona.* [Ultimate limit state for Fiber reinforced concrete]. (Master thesis). Univesity „Džemal Bijedić" of Mostar, Faculty of Civil Engineering.

Doehne, E. & Price, C. A. (2010). *Stone conservation: An overview of current research.* (2nd ed.). Los Angeles: The Getty Conservation Institute.

Domone, P. & Illston, J. (2010). *Construction materials. Their nature and behaviour.* (4th ed.). Taylor & Francis. ISBN 0-203-92757-5.

Džidić, S. (2015). *Otpornost betonskih konstrukcija na požar*. [Resistance of concrete structures to fire]. Srajevo: International Burch University Sarajevo. ISBN 978-9958-834-47-9.

Giordano, L., Mancini, G. & Tondolo, F. (2011). Durability of R/C Structures under mechanical and environmental action. *Key Engineering Materials*, 462-463, 949-954. Retrieved from 10.4028/www.scientific.net/KEM.462-463.949

Grdić, Z. & Đorđević, S. (1994). The influence of admixture on cement paste texture changes. *Facta Universitatis, Series Architecture and Civil Engineering*, 1 (1). University of Niš.

Inkpen, R. (2004). Atmospheric pollution, climate change and historic buildings. *Building Conservation Directory*. Retrieved from http://www.buildingconservation.com/articles/atmospheric/atmospheric.htm

IPCC. (2007). Climate change 2007: Synthesis report. *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC. Retrieved from https://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_full_report.pdf

Jevtić, D. (2008). Mogućnost modeliranja svojstava betona u funkciji povećanja trajnosti [Modelling possibility of concrete properties in order to increase its durability]. *Materijali i konstrukcije [Materials and Constructions]*, 51(1), 18-31. UDK: 666.972.5.001.575:691.32 = 861

Jevtić, D. (2012). Korozija i trajnost betona i betonskih konstrukcija [Corrosion and durability of concrete and concrete structures]. In: Z. Gulišija & Č. Lačnjevac (Eds.) *Korozija i zaštita materijala [Corrosion and protection of materials]*. Beograd: Inženjersko društvo za koroziju i Institut za tehnologiju nuklearnih i drugih mineralnih sirovina [The engineering society for corrosion and the institute for technology of nuclear and other mineral raw materials]. 261-296.

Mainier, F.B., de Almeida, P.C.F., Nani, B., Fernandes, L.H. & dos Reis, M.F. (2015). Corrosion caused by sulfur dioxide in reinforced concrete. *Open Journal of Civil Engineering*, 5, 379-389. Retrieved from http://dx.doi.org/10.4236/ojce.2015.54038

Muravljov, M. (2007). *Građevinski materijali* [Building materials]. (6th Eds.). Beograd: Građevinska knjiga. ISBN 978-86-395-0512-7.

Muravljov, M., Ukrainčik, V., Bjegović, D., Jevtić, D. & Denić N. (1988). Korozija i zaštita materijala [Corrosion and protection of materials]. *Građevinski calendar [Construction calendar].* Beograd: DGIJ.

Oberknežev, S. (2004). Vlaga i transfer kapilarne vlage kroz porozan građevinski materijal u starim građevinskim objektima - spomenicima kulture [Moisture and transfer of capillary moisture through porous building material in old building objects-cultural monuments]. In: Z. Vapa (Ed.) *Proceedings of the Scientific and Professional Conference on Methods of Determining and Treating the Adverse Effects of Humidity and Dampness on Structures and Items of Cultural Heritage, Novi Sad, 21-22 October 2004*. 47-60.

Pigeon, M., Marchand, J. & Pleau R. (1996). Frost resistant concrete. *Construction and Building Materials*, 10(5), 339-348. doi.org/10.1016/0950-0618(95)00067-4

Qiao, Y., Casey, D.B., Kuna, K.K., Kelly, K., Mei, B. & MacGregor, I.D. (2015). Climate resilience of flexible pavement highways: Assessment of current practice. *Journal of Pavement Engineering and Asphalt Technology*, 18 (1), 31-43. Retrieved from https://www.researchgate.net/profile/Yaning_Qiao/publication/318203459_Climate_Resilience_of_Highways_Assessment_of_Current_Practice/data/595c50b40f7e9bf415b4b217/Manuscript-170-Revision.pdf

Radić, J. (2010). *Trajnost konstrukcija I* [Construction durability I]. Zagreb: University of Zagreb, Faculty of Civil Engineering. ISBN 978-953-169-213-7.

Radonjanin, V. & Malešev, M. (2010). Uzroci i mehanizmi deterioracije zidanih zgrada [Causes and mechanisms of deterioration of masonry buildings]. In: V. Radonjanin (Ed.) *Konferencija "Zidane konstrukcije-nosivost, trajnost i energetska efikasnost"* [Conference: Masonry structures - load capacity, durability and energy efficiency] Beograd: DIMK Serbia, 15-28.

Radulović, R., Jevtić, D. & Radonjanin, V. (2016). Svojstva cementnih košuljica sa dodatkom polipropilenskih vlakana i kompezatora skupljanja [The properties of cement screed with the addition of polypropilene fibres and the shrinkage-reducing admixture]. *Građevinski materijali i konstrukcije [Building materials and structures],* 59, 17-35. UDK: 691.54 666.94.

Scherer, G.W. (2006). Internal stress and cracking in stone and masonry. In: M. S. Konsta-Gdoutos (Ed.). *Measuring, Monitoring and Modelling Concrete Properties*. SpringerLink, 633-641. DOI: 10.1007/978-1-4020-5104-3_77

Shimomura, T., Maruyama, I., Nakarai, K., & Sato, R. (2008). Durability mechanics of concrete and concrete structures - Re-definition and a new approach. In R. Sato, K. Maekawa, T. Tanabe, K. Sakata, H. Nakamura & H. Mihashi (Eds.). *Creep, Shrinkage and Durability Mechanics of Concrete and Concrete Structures*. Taylor & Francis, 1073–1098. DOI: 10.1201/9780203882955.pt9

Skadsen, E.N. (2007). Basic wood anatomy and behavior. Retrieved from http://www.organicjewelry.com/woodanatomy.html

Stefanović, S. (2012). Uticaj atmosferilija na kamen i zaštita kamena [The effect of weathering on the stone and stone protection]. In: Z. Gulišija & Č. Lačnjevac (Eds.) *Korozija i zaštita materijala [*Corrosion and protection of materials]. Beograd: Inženjersko društvo za koroziju i Institut za tehnologiju nuklearnih i drugih mineralnih sirovina [The engineering society for corrosion and the institute for technology of nuclear and other mineral raw materials], 333-347.

Šahinagić – Isović, M. (2015). *Posebne vrste betona: Mikroarmirani betoni*. [Special types of concrete: Fiber reinforced concrete]. University „Džemal Bijedić" of Mostar, Faculty of Civil Engineering. ISBN 978-9958-604-87-4

Šahinagić – Isović, M., Markovski, G. & Ćećez M. (2012). Shrinkage strains of concrete - causes and types. *Građevinar*, 64(9), 727-734. UDK: 666.97.03.001.8

Talukdar, S., Banthia, N. & Grace, J.R. (2012). The effects of structural cracking on carbonation progress in reinforced concrete: Is climate change a concern? In: B.J. Magee (Ed.) *Proceedings of the 3rd International Conference on the Durability of Concrete Structures, Queen's University Belfast, 17-19th September 2012.* ISBN 978-1-909131-04-0

Vasić, R. & Janjić, O. (1986). Oštećenja fasadnih površina od opeka izazvana dejstvom rastvornih soli i mraza [Damage to the brick façade surfaces caused by the use of soluble salt and frost]. *II Jugoslovensko savetovanje o sanaciji zgrada [II Yugoslav Council on Building Restoration], Maribor,* 46-55.

Vasić, R., Radojević, Z. & Vasić, M. (2007). Korozija građevinskih konstrukcionih keramičkih materijala [Corrosion of constructional ceramic materials]. *Zaštita materijala [Protection of materials],* 48(3), 21-27. Retrieved from http://idk.org.rs/wp-content/uploads/2016/10/ZM_48_3_21.pdf

Williams, R.S. (1986). Effects of acid rain on painted wood surfaces: importance of the substrate. *Materials Degradation Caused by Acid Rain*, 318 (22), 310–331. DOI: 10.1021/bk-1986-0318.ch022

World Bank (n.d.). CO2 Emission. Retrieved from http://data.worldbank.org/indicator/EN.ATM.CO2E.PC?end=2013&start=1990

Yang, Y. Z., Li, M. G., Deng, H. W. & Liu, Q. (2014). Effects of temperature on drying shrinkage of concrete. *Applied Mechanics and Materials*, 584-586, 1176-1181. DOI 10.4028/www.scientific.net/AMM.584-586.1176

Yao, Y., Wang, Z. & Wang L. (2012). Durability of concrete under combined mechanical load and environmental actions: a review. *Journal of Sustainable Cement-Based Materials*, 1(1-2), 2-15. dx.doi.org/10.1080/21650373.2012.732917

Zame P.Z. & Assomo P.S. (2015). The influence of climate factors on the stability of infrastructures: case of forest ecosystem in southern Cameroon. *International Journal of Geosciences*, 6, 1317-1322. dx.doi.org/10.4236/ijg.2015.612104

Natural and Regionally Available Materials for a Sustainable Future _
Reviving Tradition in Contemporary Construction

Maja Popovac[1*], Manja Kitek Kuzman[2] and Ljubomir Miščević[3]

* Corresponding Author
1 Faculty of Civil Engineering, "Džemal Bijedić" University of Mostar, e-mail: maja.popovac@unmo.ba
2 Biotechnical Faculty, University of Ljubljana, e-mail: manja.kuzman@bf.uni-lj.si
3 Faculty of Architecture, University of Zagreb, e-mail: lmiscev@arhitekt.hr

ABSTRACT **Energy issues, environmental impact and circularity are key words in the building industry today. Recent practice introduced many artificial materials, regardless of their origin, impact on health, local economy, or life cycle characteristics. Increased resource consumption and carbon dioxide emission, on the one hand, and waste generation on the other hand, have caused significant environmental problems. The globalisation of the building materials market, the huge amounts of energy used for their mass production and transportation, and the inclination away from traditional materials and crafts caused the building industry to become a major environmental polluter.**

There is great potential for renewable, natural and locally grown, and extracted and manufactured materials all over Europe. Before the wars of the 1990s, the building industry in ex-Yugoslav countries relied on "Krivaja", "Šipad", "Marles" and other manufacturing companies that fully based their programmes on renewable materials from local sources, and on know-hows about traditional crafts. Nowadays, by focusing on the performance of building materials, new environmentally friendly technologies, and new approaches to traditional buildings and settlements, architects, designers, and engineers are challenged to create a new sustainable and resilient environment.

This chapter will introduce traditional, natural, locally produced and recyclable materials – wood, stone, clay, and alternative natural and regionally available materials – sheep wool and straw, as potentials to develop new building practices, keep old crafts alive, boost local economy, improve health, and decrease negative impacts on the living environment.

KEYWORDS natural materials, stone, wood, clay, alternative materials

1 Introduction

Along with their first intentions to settle in a certain location, humans started to explore the ways of using locally available materials for building shelters. Wood, stone, clay, animal skin, and different plants offered many possibilities, and so prehistoric man started to experiment, with the aim of finding the best solution for his micro-location.

From the end of the 18^{th} century, global ecological picture started to change rapidly. The Industrial Revolution fomented the development of new manufacturing technologies. Available technologies introduced new materials, or improved the quality of existing ones. Developed transportation took on a significant role in various processes, from the delivery of raw materials, final product distribution, to the flow of working labour. During the 20^{th} century, houses became machines, equipped with cables, pipes, elevators, heating systems, and other sophisticated technologies.

The increased consumption of all natural goods, utilisation of artificial substances, and developed transportation jeopardised the quality of living environments, and made buildings and cities among the most significant consumers and polluters.

By learning from traditional architecture, carefully considering the life cycle of materials and buildings, cultivating traditional skills and encouraging circular economy, it is possible to improve the quality of life and of environment, boost local economy and tourism, and create trends with developed countries and their agendas for sustainable and resilient future (Roso Popovac, Šahinagić-Isović, Šarančić-Logo, & Ćećez, 2017).

Natural and regionally available materials are the optimal choice for contemporary sustainable and efficient construction. These materials do not require complex processing or long transportation, and may later be easily re-used, recycled, or left to decompose, without harmful impact on the environment. Traditionally, natural materials were used in the best possible way: they were adaptive to the site, climate, needs and opportunities, and developed through the adequate crafts and architectural techniques.

Research carried out in Libya has showed that 600-year-old houses, when the outside temperature is around 44°C, maintain an average inside temperature of 26°C, compared to 38°C in new non-air-conditioned houses (Kamal & Al Shehab, 2014). When coupled with traditional techniques like passive cooling, traditional materials sustain indoor comfort for many years and, for that reason, are continuously used in different parts of the world.

In contrast to the artificial, natural materials generally have better attributes when it comes to human health considerations, not only in the phase of use and maintenance, but throughout the whole life cycle. For example, natural (and naturally treated) wood has been proven to be an exceptionally healthy building material. However, it is also true that natural products originating from the ground can possibly contain measurable amounts of radiation. Stone, minerals, sand, and clay all may have the trace amounts of radioactive elements commonly called the NORMs (Naturally Occurring Radioactive Minerals). Nonetheless, the most significant sources of radiation are not materials, but the ground soils.

At the end of service life, natural materials may be re-used, recycled, or biologically decomposed. For example, wood material and components may be reused in another building or recycled into a source of thermal energy. Previously used wool and straw can be reused in agriculture to keep the moisture around the plants. Today, there are many interesting initiatives and projects for circular design and recycling of existing materials, among them the EU funded project *BAMB* (Buildings as Material Banks) which aims to develop the strategy for eliminating construction waste and to link material circularity with a circular economy. Another example is the *Harvest map* (https://www.harvestmap.org), a marketplace for professional 'upcyclers'' from the Netherlands, i.e. a platform for easy, accessible trade with previously used materials of different kinds.

To intensify the utilisation of natural and regionally available materials, local community and stakeholders need wider knowledge, more information, and a positive attitude. After the introduction and spread of the use of artificial materials over the last 50 years, a lot of effort is now needed to break prejudices like 'wood is not fire-resistant', 'straw is going to provide shelter to rodents and insects', 'sheep wool has a bad smell', among others. As the price of natural materials is often slightly higher in comparison to conventional materials, the economically driven decisions of investors with regard to initial investment should be re-defined to support their application.

This chapter reviews several most common natural and regionally available building materials: stone, wood, and clay. Environmental qualities, traditional application, and possibilities for utilisation of these materials in contemporary terms are analysed, and the examples, followed by an adequate argument, are presented. The work also considers some alternative natural and regionally available materials whose utilisation today could be intensified.

2 Stone

In past times, stone material was used for load-bearing constructions. Typically, thick stone walls in traditional multi-storey buildings mainly consisted of two outside layers of masonry work with crushed stone and mortar infills. Although the construction process was generally slow and demanded masonry skills, the structural stability, regenerative powers of lime mortar, and easy rebuilding and reconstruction gave 'eternal life' to many stone structures.

TOC

The Balkan region is rich with various stone types. Some Balkan quarries were the sources of material for ancient Greek and Roman settlements along the coast and islands of the Adriatic Sea, and in inland areas. Among the best-known quarries of that time were Istria, Pućišta on Brač island, Mukoša near Mostar, and Jablanica.

The stone structures are durable, reusable, and recyclable. In fact, stone is one of the few building materials that rarely demands any additional processing after the extraction (at the beginning of the life cycle) and remodelling of its original size and shape (before first and every subsequent installation).

The examples of reuse of stone material previously incorporated into other built structures are numerous and various. Sometimes, ready-to-use building material was found at the location where an original building had previously existed. In other cases, the demolition of original stone structures was related to the symbolic demonstration of domination of new conquerors over a previous culture. In these circumstances, previously used material was often incorporated into the foundations of new structure.

The traces of Roman basilicas, temples, and other obsolete building types may be found in existing structures throughout Europe and Asia (Fig. 2.1).

FIG. 2.1 Cathedral in Pula made of stone from Roman temple

FIG. 2.2 Stone blocks from Austro-Hungarian fortification incorporated into fence wall, Mostar

In ex-Yugoslav countries, many built cultural-historic monuments were destroyed during the wars of the 1990s. Due to the lack of awareness about the value of cultural heritage (Roso Popovac, 2015), the purpose of devastation in some cases was no greater than to supply the stone blocks. The parts of stone bridges, fortifications, houses, and sacral objects were so embedded into new structures that they left no trace of their existence at the original location (Fig. 2.2).

Although stone belongs to the group of materials with low health hazards for users, its extraction and processing can jeopardise workers' health with some serious conditions like pneumoconiosis or dermatoses. Stone dust can contain iron, zinc, cadmium, nickel, lead, chromium, barium, beryllium, and aluminium (Ugbogu, Ohakwe, & Foltescu, 2009). However, the impact generated with stone extraction is in contrast with its potential for continual re-use and re-cycling.

With technological advancement, stone processing is transforming into an automatised process, providing a huge scale of products of different sizes and shapes. Stone processing and adjustment do not generate waste material, because even the smallest particles can be used (as gravel, for artificial stone or concrete production, etc.).

The main constraints related to stone utilisation are its price, which can exceed the price of other building materials by several times, the costs for skilled workers, and the duration of construction works. Nevertheless, quality, durability, and other performance characteristics justify the increment of initial investment.

Nature provides three types of stone:

- **Volcanic (Igneous)**, made mainly of magma that cools under the surface, with crystallised mineral gasses that cause crystalline formations (e.g. granite and basalt);
- **Sedimentary**, where sediments of organic particles from glaciers, rivers, plants, wind, and soil together form the stone under pressure, heat, and other conditions (e.g. limestone, sandstone, travertine);
- **Metamorphic** mixture of various existing natural stone types formed by exposure to pressure, heat, and minerals (such as marble, serpentine).

Stone types are often named after the location in which they are found. A typical example is the famous *Carrara marble*, a light grey-blue stone of excellent quality. Many famous ancient and contemporary buildings like the Pantheon, Trajan's Column, the Peace Monument in Washington D.C., as well as the Michelangelo's famous sculpture David, and many others, were made of Carrara marble. The old bridge of Mostar is made from *Tenelija* limestone found only in Mukoša quarry near Mostar in Bosnia and Herzegovina. Another famous limestone, so called *Bath stone,* has been used in many buildings throughout South England.

Although stone has been used in on-site terrazzo floor production for decades, a fourth, prefabricated type, man-made or engineered stone, is available on the market today. With its price and availability, artificial stone is a great competitor of natural stone types. It is obtained mainly from marble and quartz (over 93-97%) with the addition of polymer resin (lately, of popular geopolymer).

When it comes to stone selection, its specific purpose, type of structure, and climate conditions need to be considered. For example, porous stone laid horizontally in exterior construction can cause additional loads that influence construction stability and result in a spectre of damages, leading to deterioration, and finally destruction.

Stone is also one of the most widely used raw materials in the world. It is used in production of lime, cement, man-made stone, concrete, and other artificial materials. As the requirements for improvement of stone characteristics are becoming increasingly demanding, the number of chemical agents involved in production, maintenance and preservation of stone, from slip and fire protection coats to nanotechnologies in monument protection, are growing. Some of these materials can, however, lower the ecological quality of natural stone. Chemical treatment can be a source of harmful substances for humans and nature, and might not provide the same bonding for different materials (for example in production of concrete), which influences the quality of final product.

When it comes to radiation issues, one of the most notorious stone types is granite. Nevertheless, the general claim regarding the radioactivity of stone is very vague, having regarded that the concentrations of radioactive elements depend on the location from which the stone material was taken, and that they vary from one sample to another, or even within the same stone element.

2.1 Stone in Contemporary Design

One of the most interesting contemporary examples of stone utilisation in Bosnia and Herzegovina is the estate of six homes in Bijača village, owned by the Stanić family. Design studio "2 Arhitekta" (Tomislav Ćurković and Zoran Zidarić) developed the project that combines traditional materials, shapes, and forms through modern architectural expression.

A

B

FIG. 2.3 A+B: Stanić family house in Bijača

The houses are made of traditional stone visible on the façade, with a 50cm wide stone trim and oversized asymmetric concrete window frames, which are reminiscent of the old houses and their white stone window frames. The material used for these structures is typical, local limestone cut in blocks, and the masonry work revives the traditional way of local building.

TOC

The entire property is covered with vineyards and green plots supported with a kilometres-long drywall, a typical stone structure in Herzegovina, Istria, Dalmatia, and other karst areas. Traditionally, there were three main reasons for building the drywalls. The first was to provide the boundary between different owners' plots and a protective barrier to animals and intruders. The second reason was to create plots with level ground on steep terrain, whereby the drywall was used as a support structure. The third reason was to clear the plot of stones, as people were trying to increase the area of fertile soil for their gardens by day-to-day stone collection.

The entire complex in the village of Bijača was built in one year. The construction process was, in fact, a perfect workshop for young stone cutters who practiced and learned old crafts. Because of the chosen materials, orientation, and knowledge from the past, the durability of the complex in Bijača will undoubtedly exceed the houses made of contemporary materials.

2.2 Lime

Besides its most common use as a building block, stone can be used as sticking and adhering material – component of lime mortar.

Hydraulic lime is a traditional building material that was used for thousands of years by Egyptians, Greeks, Romans, and other ancient cultures. Traditionally, lime is not only used as a component of mortar, but also as a plastering and coating material. Until recently, lime was the main material used as a disinfectant for annual indoor and outdoor wall painting, water purification, fruit trees painting to prevent sun scald, toilet space sanitisation, etc. For these reasons, it was common in ex-Yugoslav countries to have a pit in the household yard, in which lime was hydrated for generations.

Buildings constructed before 1920 were mostly made with hydraulic or hydrated lime. Today, lime is mostly used as an addition to cement mortars, for reconstruction of historical buildings and monuments, and for production of ready-to-use mortars. Due to the use of artificial paints and chemicals against insects and for disinfection, lime is very rarely used nowadays. The tradition of burning lime is still alive, but significantly reduced due to the industrial production of powdered lime for mortars. As the awareness about the healthy living environment is (re)entering ex-Yugoslav countries, together with the revival of traditional techniques, it is possible that the demands for natural lime will increase in future.

In the European Standard EN 459-1:2015, lime is defined as: "calcium oxide and/or hydroxide, and calcium-magnesium oxide and/or hydroxide produced by the thermal decomposition (calcination) of naturally occurring calcium carbonate (for example limestone, chalk, shells) or naturally occurring calcium magnesium carbonate (for example dolomitic limestone, dolomite)". Same standard (EN 459-1:2015) introduces two families of lime: "air lime and lime with hydraulic properties, used in applications or materials for construction, building and civil engineering."

3 Wood

Wood is the ultimate renewable material. It possesses qualities that have made it a material of choice for millennia, and these qualities are further enhanced by its recognised ability to sequestrate carbon, while the polymeric components of wood and its porous structure confer on it a noble, versatile, and general-purpose character and a faculty for transformation exceeding that of all other materials. Trees and their derivative products, nowadays known as engineered wood products, have been used around the world for thousands of years. The contemporary construction of tall buildings has recently been particularly challenged with the potential use of timber as a major structural element (Ramage et al., 2017). The unique advantages of this material, its widespread availability, sustainable renewal, favourable ecological performance, and flexibility of implementation grant it a status of "nobility" in the eyes of scientists and engineers. In the eyes of architects, however, the simplicity and beauty of wood as a new aesthetic are not just visual experiences - architects even try to integrate the smell, texture, and tangibility of wood into the architectural built environment. Forests and timber are a unique ecological value chain with great potential for future uses.

The specificities of a natural and sustainable material from a local forest should be seen as a starting point for the new approaches to contemporary products that suit individual building types and are in harmony with regional building culture. Basic traditional architectural principles, linked with the economic position of each country, influence the development of sustainable contemporary architecture and new methodologies.

3.1 Cascade Use of Wood for Sustainability

Cascading is a strategy of using raw materials such as wood or other bio-based materials in chronologically sequential steps, as efficiently as possible, for new materials, or to recover energy when it no longer is economical or technically possible to renew the use (Fig. 3.1). The use of the same unit of wood for multiple successive applications will result in a gradual reduction of quality and particle size (Meier, Streiff, Richter, & Sell, 1990).

In the forest products industry, waste hierarchy is presently underdeveloped and largely ignores the EU's preferred option of maximising the carbon storage potential of wooden materials through their reuse in solid form with the subsequent downcycling of reclaimed wood, in as many steps of a material cascade as possible (Leek, 2010).

TOC

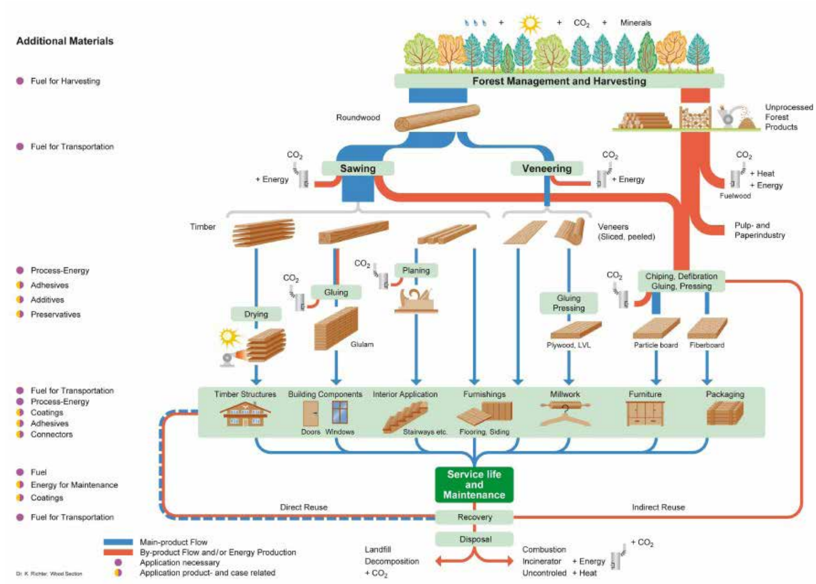


FIG. 3.1 Cascade use of wood *(Meier et al., 1990)*

3.2 Use of Wood in Slovenian Contemporary Architecture

Slovenia has a long tradition of sustainable forestry, industrial refining of the raw material provided by forestry, and historical continuum in the use of timber in construction. In spite of wood tradition (Fig. 3.2), architectural material development, and the technological potential and function-based building regulations introduced in Europe nearly three decades ago, Slovenia has chosen its own path to reach a modern and industrialised use of timber in construction that allows a diversity of architectural expression and design possibilities (Kitek Kuzman & Kutnar, 2014).

A *B*

FIG. 3.2 A+B: The House on Sv. Gregorij, Architecture: Jasna Starc, Arhitektura Starc *(Images by Blaž Zupančič, n.d.)*

The primary wood products used in timber construction in Slovenia range from sawn timber to various engineered wood products (EWPs). In mass-timber structures, glued laminated timber (glulam), cross-laminated timber (CLT), laminated-veneer lumber (LVL), and laminated strand lumber (LSL) are used for walls, floors, and roofs. In timber-frame structures, timber wall sections are assembled from studs and crossbars of various dimensions. For the exterior and interior surfaces, besides solid wood, various panel-based products are used, including drywall panels and gypsum board, particleboard, cement-bonded panels, fibreboard, oriented-strand boards (OSB), and LVL (Obućina, Kitek Kuzman, & Sandberg, 2017).

Although the production of CLT and its use in timber construction are increasing, the use of sawn timber has lost its historical dominance and has been replaced by a number of EWPs, which have made a significant contribution to the development of a new approach to contemporary architecture.

In Slovenia, several "techniques are available for the construction of buildings with supporting frameworks of timber. One way is to use structural wood members to form a frame which is covered by structural wood panels, where the foundations are generally of concrete. This building technology is often used in the construction of single-family houses but also in the construction of multi-storey buildings. Another technique uses CLT for the supporting framework, walls and joists, and the walls have to be insulated to give the building a high level of energy efficiency. The technique is well adapted to the construction of multi-storey buildings. A third technique is a system of columns and beams, where glulam is used to a large extent for the load-bearing structure." (Kitek Kuzman & Sandberg, 2016, p. 244)

FIG. 3.3 From the left: Prefabricated CLT elements are transported to the construction site and then assembled and erected manually – Waldorf School in Ljubljana, Slovenia.

The CLT products are expected to play an important role in the future for single- and multi-storey timber buildings in Slovenia – Vita Nova glass wooden house by Kager company. Timber offers great potential for the reconstruction and modernisation of existing buildings, mainly through additional storeys or roof extensions – Hotel Breza in Slovenia *(CBD d.o.o., Bruno Dujič, images by authors, n.d.).*

A contemporary Slovenian trend is "towards a higher degree of prefabrication, i.e. a greater part of the building work takes place at an industrial plant in a well-controlled environment with approved quality assurance. The actual on-site assembly of the building until the roof is laid takes only one or two days. The prefabrication can include various components such as wall and floor elements, roofs, trusses etc., but also modules, so called volumes. Both components and modules are prefabricated with insulation, installations, windows and doors. Prefabricated components of wood are relatively light in weight and can be erected to heights of several storeys using simple lifting equipment. With prefabricated wood modules, the total cost is up to 20-25% lower than to building on-site. This is partly due to a time saving of up to 80%. In Slovenia, most of the large house manufacturers offer off-site prefabrication houses." (Kitek Kuzman & Sandberg, 2016, p. 246)

TOC

3.3 Wooden Passive House in Croatia

The family house “ČV1” in the small settlement of Kupinečki Kraljevec near Zagreb (Fig. 3.4) is the first timber-constructed passive house in Croatia, built in 2003 with the use of brick and wood materials salvaged from a nearby traditional house. Experience in architectural heritage therefore represented one of the basic components of the new “culture-logical recycling” concept.

“ČV1” house is a great example of how to use a plot to favour the wider environment and energy efficiency, how to combine recycled materials from traditional architecture, and to fulfil requirements of the passive house standard at the same time. The south façade is open to the sun, while the north façade stays mostly closed. The house is two-storey, with open gallery space in the living room. The roof is single-pitched (to the north), and its overhang, together with the terrace in the second level, creates protection from summer sunshine while allowing winter sun to penetrate deeply into the house. One part of the roof is covered with vegetation.

FIG. 3.4 Family house “ČV1”in Kupinečki Kraljevec, Croatia *(Image by Ljubomir Miščević)*

The timber construction is made as a box-section (2x4”) with 30cm of thermal insulation. The façade and ground floor space of the staircase on the north façade side are bordered by 120-year-old brick. The facade of the first floor is covered with 150-year-old oak planks.

Another attribute of the house is its advanced energy efficient windows and façade doors with a very high level of thermal isolation and other physical characteristics suitable for large south facing surfaces, especially in climates with large amounts of solar radiation.

The envisaged values of thermal physics parameters meet the requirements for passive house. Installed active systems include a heat pump (air heat exchanger) and ventilation system. The roof accommodates solar thermal converters and photovoltaic converters (Miščević, 2012).

Experience from utilisation has so-far confirmed presumed efficiency, although the house does not yet have an operational ventilation system. Large glass surfaces facing south provide almost all thermal energy needs during the winter.

4 Clay

Bricks (mud bricks, sun-dried bricks, or adobe) are among the oldest man-made building materials. Approximately 6000 years ago, floods from the rivers Nile, Tigris, and Euphrates provided deposits of mud and silt which formed hard sun-dried cakes that were easy to remodel and incorporate into walls. In the absence of other locally available materials, ancient builders discovered that clay bricks can be very durable, especially when properly shaped, and started to use mostly wooden moulds to provide standard dimensions for easier and faster assembling. In the city of Ur in Mesopotamia, bonding material for sun-dried bricks was bitumen slime. Later, the potters discovered that partially dried bricks can be burned to provide better results. The first closed kilns were introduced around 2500 BC. The development of glazing techniques around 600 BC allowed the production of mosaic tiles.

Past civilisations used sun-dried (Fig.4.1) or fired bricks as the main building material for capital structures. The Great Wall of China, the Pantheon and the Colosseum in Rome, and the great proportion of historical buildings in Western Europe and South America (post-colonisation), were built from clay bricks.

FIG. 4.1 Sun-dried bricks *(production and images by Kristijan Zver, 2007)*

Depending on the type of clay, nowadays bricks are produced by firing at temperature ranging from 600°C – 1100°C. Energy-consuming production process, carbon footprint and the amount of radiation made contemporary brick producers rethink about sun-dried bricks.

Raw material used for brick-making can be grouped into three classes:

- clay found near the surface, mostly in riverbeds;
- shale – clay-rich sedimentary rock subjected to high geological pressure, with variable hardness;
- fire clay found at the greater depth.

Early Balkan cultures used clay for building and pottery-making, as evidenced in Vučedol, Vinča, Butmir, Hvar-Lisičići and other Neolithic archaeological sites positioned near rivers Sava and Danube. In Vučedol culture, made famous by bi-conical pottery with typical ornamentation (e.g. the Vučedol Dove), a typical house was square or cylindrical, made of wicker and coated with clay. The floor in a Vučedol house was made of burned clay. Roman and Ottoman builders continued to use brick made in a traditional way, while during the Austro-Hungarian period new technologies were introduced. Vernacular brick architecture in the Balkans is characterised by the use of sun-dried "ćerpič" bricks made of clay with the addition of straw. The clay was also used for adobe buildings and as a plastering material.

A

B

FIG. 4.2 A+B: Clay mortar plastering
(images by Kristijan Zver, 2007)

Recently, the Academy of Clay was established in village of Karanac in Slavonia (Croatia). Here, the entrants learn how to make and use sun-dried clay bricks in new construction and in reconstruction. By offering programs for children, social events and other activities that attract visitors and tourists, the Academy aims to preserve tradition for future generations, i.e. to revive the traditional use of clay. Similar contemporary initiatives are found in other parts of the Balkans region as well.

5 Other Natural, Regionally Available, and Traditional Materials

When it comes to utilisation of bio-based, natural, and regionally (locally) available building materials and techniques, the tradition of ex-Yugoslav and Balkan countries is rich, and still visible through crafts and heritage sites. In modern times, nonetheless, the utilisation of some traditional bio-based materials, e.g. hemp, red, straw and sheep wool, has been almost abandoned. Besides traditional healing benefits, hemp was used in the past for production of durable fabrics and ropes. Reed was the most common plaster base before contemporary suspended ceiling systems and methods for wall coating were introduced.

Today, many producers of sun-dried bricks are (re)considering hemp and straw as supplementary materials. Similarly, reed is regaining attention as an easy obtainable material. Traditional bio-based, natural, and easily available materials should be revived in both new construction and in reconstruction, as their benefits to human health, environment, and local (circular) economy are significant. In this section, the advantages of utilisation of sheep wool and straw are considered.

5.1 Straw

Straw is an agricultural waste material that can be installed straight from the crop field. It is a product of a one-year process of photosynthesis, comprising cellulose, lignin, and silicon. Even though the potential of this bio-based, natural, and easy-obtainable material is huge, straw is practically considered waste today, and only a small percentage of the total generated material is being used, mainly in agriculture and farming.

The oldest existing building made of straw is a church in Nebraska, USA, constructed in 1886 with only bales of straw as loadbearing and insulating material without additional construction (http://www.nebraskahistory.org). The applied low-cost building technique is now known as ‘Nebraska’ or ‘load bearing technique’, and the culmination of its application was in the period between 1915-1930. Although the technique initially emerged from the need to build temporary dwellings, it demonstrated that the straw-bale buildings are unexpectedly long lasting.

The first house made of straw bales in Europe is the French “Maison Feuillette” (http://cncp-feuillette.fr/) built in 1921. The engineer, Feuillette, proved with his project that it was possible to build good quality homes in the post-war period by using agricultural waste. This house, together with a complex of ancillary facilities, persists to this day as a stable and healthy structure. In the early 1970s, straw-bale construction was rediscovered in the United States, Canada, Australia, and some European countries. The increased number of publications dedicated to straw utilisation in construction built the foundations for the development of international ‘straw-bale movement’.


A


B

FIG. 5.1 A+B: Straw-bale house in Čikečka Vas, Slovenia *(images by Kristijan Zver, 2007)*

The house in Čikečka Vas in Slovenia (Fig. 5.1) was designed and constructed in 2007 by Kristijan Zver, one of the leading promoters of straw-bale design in the region. His cooperation with architect Alja Petrovič resulted in development of many new initiatives and accordingly in the increased number of straw-bale houses.

Generally, there are three main current techniques for building with straw. The most common way is to use wood or some other load bearing system with straw-bale infill. The other is the 'Nebraska' or 'load bearing' technique, where straw bales are the only loadbearing system. The third possibility is to use straw (in bales or free) as a part of prefabricated element (e.g. at https://www.modcell.com/).

Like timber, straw represents a material with immense potential to reduce annual emissions of carbon dioxide from material production, construction, maintenance, and building waste storage. By using straw bale and timber, in combination with other traditional or contemporary energy efficient technologies, buildings can become carbon neutral, thus achieving the essential feature of sustainability (Alcorn & Donn, 2010). Straw-bale construction results in higher net carbon storage (3.3 t of CO^2eq) than biochar production (0.9t of CO^2eq) (Mattila, Grönroos, Judl, & Korhonen, 2012).

The key to understanding straw as a building material is the new 'Factor 10' development concept that reduces the amounts of primary and operational energy by ten times. In other words, a house made of straw consumes ten times less energy than a conventional structure, according to the comparison of U-values (Glasnović, Horvat, & Omarić, 2008). Straw belongs to a group of materials that have excellent characteristics in the case of fire (Klarić, Džidić, & Roso Popovac, 2016). The lack of air in a properly packed straw-bale structure, especially when plastered with clay mortar, makes it almost non-flammable. Besides fire resistance, it is necessary to keep certain standards concerning humidity and density, and to ensure that there are no grains.

The main problem with persuading investors to use straw is a lack of knowledge and common ignorance about its durability. Even when used as an exposed roof cover, straw can last for decades, providing good thermal and water protection. When it comes to usual myths about insects, rodents, and fire, it should be noted that straw does not possess any nutritive value, and if it is dense enough and well plastered, insects and rodents make no threat to this material. That is why investors and the wider environment must be properly introduced to all benefits of this bio-based, natural, and local material. To that end, there are several free online courses that can provide a very deep understanding of all aspects of building with straw, as well as many books and manuals available online. With raised awareness about health, permaculture, and sustainable lifestyles, there is a hope that straw will become a more appreciated, and hence more commonly used, building material in contemporary, energy efficient, and cost-effective construction.

5.2 Sheep Wool

Sheep wool accounts for sustainable building material which comprises, on average, 60% of animal protein fibres, 15% moisture, 10% fat, 10% sheep sweat, and 5% impurities (Zach, Korjenić, Petránek, Hroudová & Bednar, 2012). Besides washing (preferably with ecological soaps) and production of either soft or hard blocks, or flakes for blowing-in, wool insulation does not need any additional energy for production. The durability of wool is practically better than in other insulation materials (for comparison, insulation made of expanded polystyrene foam lasts for approximately 20 years). Wool can also be mixed into clay sun-dried bricks or clay mortars as micro armature.

Zach et al. (2012) describe sheep wool as:

- clean and renewable natural material source;
- comfortable and easy to handle without potential risk to human health,
- easy to recycle and eco-friendly;
- self-extinguishing material, as the fibres do not support combustion, but char at high temperatures;
- consistent and durable material, as there is neither change in volume nor the loss of elasticity;
- highly hygroscopic – able to absorb moisture up to 35%, without U-value change;
- excellent thermal and sound insulation.

The potential for sheep wool insulation production in Western Balkan countries is high, and it can be considered as a material that could improve local economy (both farmers and industry). In Bosnia and Herzegovina, a small factory producing 4cm, 7cm, and 10 cm thick soft-wool insulation panels opened recently. The first measurements of temperature changes before and after applying 7cm thick sheep wool insulation panels on walls and roofs were done for the “Tree House” in Buna near Mostar (Fig. 5.2). Results showed that afternoon temperatures during the mid-summer period decreased for more than 10°C.

A

B

FIG. 5.2 A+B: Wool insulation (wool-line) for "Tree House" in Buna near Mostar

6 Conclusion

Natural materials are gradually coming out of the shadow, where they have been for last hundred years. The conciseness about sustainability, life cycle assessment, health issues, and environment has made the building industry of today rethink the way our homes are built.

Present trends in the building industry show that there is a growth in sustainability demands. The document *The World Green Building Trends 2016* (Jones, 2016), predicts a growth of 60% in green building by 2018. The most important fact for green building justification is the improvement of the quality of the environment and its transformation (Roso Popovac, Ćehajić, & Klarić, 2016). Historical buildings, materials, and crafts can provide valuable lessons that were forgotten during the last century.

Natural materials with low environmental impact, regionally available, durable, reusable, or easily decomposable are increasingly interesting to home-owners and to the market. Awareness about health issues caused by artificial or toxic materials in our homes and workplaces, and the problems associated with construction waste and energy consumption are turning natural, regionally (locally) available, and bio-based materials into desirable goods, and an increasing number of architects and engineers are promoting their benefits. Permaculture is becoming a way of life and a relevant philosophy.

Materials like stone, wood, clay, straw, or sheep wool are not just healthy, affordable, and energy efficient choices for stakeholders and the environment, but also hold potential to boost local economies. Circular economy, instead of linear, can turn small workshops and local industry into businesses that are more profitable and acceptable to local communities. With the utilisation of traditional materials, related emissions of carbon dioxide and other harmful gasses can be notably reduced.

The materials presented in this work are rarely used as sole materials for contemporary structures. But when their utilisation is intensified by smart combining with other, contemporary materials, the negative environmental impact of the overall buildings will be significantly reduced.

References

Alcorn, A., & Donn, M. (2010). Life cycle potential of strawbale and timber for carbon sequestration in house construction. In J. Zachar, P. Claisse, T.R. Naik & E. Ganjian (Eds.), *Proccedings from the Second International Conference on Sustainable Construction Materials and Technologies, 28-30 June, 2010, Universita Politecnica della Marche, Ancona, Italy*. ISBN 978-1-4507-1490-7. Retrieved from http://www.claisse.info/2010%20papers/m23.pdf

European Standards. (2015). *CSN EN 459-1 ed. 3. Building lime – Part 1: Definitions, specifications and conformity criteria.*

Glasnović, Z., Horvat, J., & Omarić, D. (2008). Slama kao superiorni gradevinski material. [Straw as superior building material], *Tehnoeko*, 3(2008), 14-17. Retrieved from https://www.fkit.unizg.hr/_news/31890/Tehnoeko%20-%20Slama.pdf

Jones, A.S. (Ed.). (2016). *The world green building trends 2016: Developing markets accelerate global green growth.* Smart market report. DODGE Data & Analytics. Retrieved from http://www.worldgbc.org/news-media/world-green-building-trends-2016

Kamal, M. A. & Al Shehab, T. (2014). Sustainability through natural cooling: Bioclimatic design and traditional architecture. *Study of Civil Engineering and Architecture (SCEA),* 3, 1-6. Retrieved from www.seipub.org/scea

Kitek Kuzman, M., & Kutnar, A. (2014). *Contemporary Slovenian timber architecture for sustainability.* London: Springer.

Kitek Kuzman, M., & Sandberg, D. (2016). Comparison of timber-house technologies in Slovenia and in Sweden. In S. LeVan-Green (Ed.), Forest Resources and Products: Moving Toward a Sustainable Future, Proceedings of the *59th International Convention of Society of Wood Science and Technology March 6-10, 2016, Curitiba, Brasil* (pp. 243-250).

Klarić, S., Džidić, S., & Roso Popovac, M. (2016). Slama – građevinski materijal historije i budućnosti, održive arhitekture i konstrukterskog inženjerstva [Straw – building material of past, future, sustainable architecture and construction engineering]. *3rd International Scientific Meeting E-GTZ , 2-4 June, 2016, Tuzla, BiH* (pp. 217-224). ISBN 978-9958-628-18-4.

Leek, N. (2010). Post-consumer wood. In *EU wood – Real potential for changes in growth and use of EU forests*. Final Report. Hamburg: EU Wood.

Mattila, T., Grönroos, J., Judl, J., & Korhonen, M.-R. (2012). Is biochar or straw-bale construction a better carbon storage from a life cycle perspective? *Process Safety and Environmental Protection,* 90(6), 452-458. https://doi.org/10.1016/j.psep.2012.10.006

Meier K., Streiff, H., Richter, K., & Sell, J. (1990). Zur ökologischen Bewertung des Bau- und Werkstoffs Holz [Ecological evaluation of timber constructions and materials], *Schweizer Ingenieur und Architekt, 24*, 689-695.

Miščević, Lj. (2012). The first ten realizations of Passive Houses in Croatia – experience in design, construction and financing. *16th International Passive House Conference 2012, Hannover* (pp. 241-246). Darmstadt: Passivhaus Institut. ISBN: 978-3-00-037720-4.

Obućina M., Kitek Kuzman M., & Sandberg D. (2017). *Use of sustainable wood building materials in Bosnia and Herzegovina, Slovenia and Sweden*. Sarajevo: Mašinski fakultet.

Ramage, H.M., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D.U., Wu G., YU L., Fleming P., Densley/ Tingley D., Allwood J., Dupree P., Linden P.F., Scherman O. (2017). The wood from the trees: The use of timber in construction. Renewable and Sustainable Energy Reviews, 68(1), 333–359. https://doi.org/10.1016/j.rser.2016.09.107

Roso Popovac, M. (2015). *One-span Ottoman bridges in Bosnia and Herzegovina*. Mostar, BA: Građevinski fakultet, Univerzitet Džemal Bijedić. ISBN 9958917084, 9789958917080.

Roso Popovac, M., Ćehajić, A., & Klarić, S. (2016). Odgovorni marketing kao sredstvo u poticaju i promociji zelene gradnje u BiH. *SFERA 2016: Oblikovanje i toplinska izolacija fasadnih zidova* [Design and thermal insulation of façade walls]*, Mostar, BiH* (pp. 106-111). ISBN 978-9926-8134-0-6.

Roso Popovac, M., Šahinagić-Isović, M., Šarančić-Logo A., & Ćećez, M. (2017). Sustainability and resilience in traditional Bosnian and Herzegovinian architecture - learning from tradition for better future. In Dž. Bijedić, A. Krstić-Furundžić & M. Zečević (Eds.). *Book of conference proceedings of the 4th International academic conference Places & Technologies 2017 – Keeping up with technologies in the context of urban and rural synergies, 8-9 June 2017, Sarajevo, Bosnia and Herzegovina* (pp. 563-571). Sarajevo: Faculty of Architecture of the University of Sarajevo.

Ugbogu, O. C., Ohakwe, J., & Foltescu, V. (2009). Occurrence of respiratory and skin problems among manual stone quarrying workers. *Mora: African Journal of resporatory Medicine,* March 2009, 23-26.

Zach, J., Korjenić, A., Petránek, V., Hroudová, J., & Bednar, T. (2012). Performance evaluation and research of alternative thermal insulations based on sheep wool. *Energy and Buildings,* 49, 246-253. https://doi.org/10.1016/j.enbuild.2012.02.014

Sustainable Refurbishment for an Adaptable Built Environment

Thaleia Konstantinou[1*] and Branka Dimitrijević[2]

* Corresponding Author
1 Architecture and the Built Environment, Delft University of Technology, Delft, e-mail: t.konstantinou@tudelft.nl
2 Department of Architecture, University of Strathclyde, Glasgow, e-mail: Branka.Dimitrijevic@strath.ac.uk

ABSTRACT **The reconsideration of the existing building stock is motivated by society's efforts towards sustainability and resilience. The building sector has a considerable role to play in doing so. The process of refurbishment is complex, since aspects such as design decisions, existing construction, energy efficiency, and user behaviour need to be considered. The motivation for refurbishing existing buildings is related to environmental, social, and economic aspects of their use or reuse, which are the three core aspects of sustainability. The key environmental motivation is to reduce energy consumption from fossil fuels and related greenhouse gases (GHG) emissions, and to include energy generation from renewables; the key economic motivation is to lessen the cost of energy used for heating, and the key social motivation is to reduce fuel poverty and improve the quality of life and well-being of the occupants.**

This chapter aims to explain the role of refurbishment of the building stock for sustainability and resilience. Firstly, definitions of the levels of building upgrades are given, and the motivations for refurbishment are discussed. Furthermore, the ecological, economic, and social aspects of refurbishment are deliberated on, together with the importance of the building stock for resilience. Finally, case studies of refurbishment projects are presented, providing insights into different aspects of refurbishment for sustainability and resilience.

KEYWORDS refurbishment, retrofit, existing buildings, sustainability, resilience

1 Introduction

The term 'sustainable development' was defined by the World Commission on Environment and Development (WCED, 1987) in its report 'Our Common Future'. The key principle of sustainable development is that it can only be achieved if socio-economic development is based on the responsible use, preservation, and renewal of the Earth's limited natural resources, and the use of renewable resources. Moreover, the report focused on global realities and recommended urgent action on eight key issues that ensure sustainable development. One of those key issues addressed by the WCED is energy (UNESCO, 2003).

The United Nations Conference on Environment and Development, held in Rio de Janeiro in June 1992, outlined the principles of future global sustainable development (UN, 1992). The principal output was Agenda 21, which determined priority actions and provided guidelines for their achievement. Agenda 21, a guiding philosophy for global sustainable development, served as the basis for subsequent international agreements related to global environmental, social, and economic problems.

More recently, in December 2015, the Paris agreement at the Climate Conference (FCCC/CP/2015/L.9, 2015) stressed the urgency to respond to the threat of climate change by keeping the global temperature rise less than 2 degrees Celsius above pre-industrial levels this century, and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. Within the scope of this agreement, stakeholders and authorities will need to further reduce their emissions and build resilience to decrease vulnerability to the effects of climate change (European Commission, 2015). This is in line with the long-term commitment of the European Commission (2013) to the decarbonisation path, with a target for the EU and other industrialised countries of 80 to 95% cuts in emissions by 2050.

The use of energy is the main source of greenhouse gases (GHG) (Eurostat, 2012, 2015). As the energy consumption of the building sector accounts for approximately 40% of final energy consumption in the EU (Eurostat, 2013), the importance of the building sector is recognised and addressed by institutions and legislative parties. Next to the energy use, the construction and operation of buildings have significant financial and social implications. Thus, a sustainable building should consider "design and construction using methods and materials that are resource efficient and that will not compromise the health of the environment or the associated health and well-being of the building's occupants, construction workers, the general public, or future generations" (Landman, 1999, p. 7).

The built environment is relevant to sustainability. The interest of legislative parties and the EU in particular, in the building sector confirms this importance. Together, the Energy Efficiency Directive (DIRECTIVE, 2012/27/EU) and the Energy Performance of Buildings Directive (EPBD) determine the framework for member states to promote the reduction of energy use in buildings (BPIE, 2013). Given the importance of existing buildings, sustainable refurbishment aims at achieving the goals of sustainable development by addressing environmental, social, and economic aspects. Research has shown that more energy conservation and other sustainable benefits can be achieved in the existing building stock compared to newly-built buildings (Itard & Meijer, 2008).

Refurbishment already represents a significant share of building construction practice with approximately half of the total turnover of major repairs (Thomsen, 2010; Genre, 1996; Flourentzou, Genre, & Roulet, 2001; McGraw-Hill Construction, 2011). The building industry, including architects, contractors, product suppliers etc., is already working on upgrading existing buildings. Nevertheless, sustainability benefits, such as energy savings, is rarely the sole motivation for refurbishment. Usually, the decisions are interconnected with other financial and social motivation. Whatever the motivation, the challenge for the design of the refurbishment strategy is to incorporate strategy measures that improve the sustainability and resilience of the refurbishment.

This chapter aims at explaining the role of the refurbishment of the building stock for sustainability and resilience. Firstly, definitions of the levels of building upgrades are given, and the motivations for refurbishment are discussed. In addition, the chapter deliberates on the ecological, economic, and social aspects of refurbishment. Finally, case studies of refurbishment projects are presented, providing insights into different aspects of refurbishment for sustainability and resilience.

2 Definitions of Refurbishment

Refurbishment as a term used in the building sector can cover a broad range of measures. Different terms may apply, depending on the degree and type of intervention, from repairs and maintenance to demolition and reconstruction. Fig. 2.1 summarises the various levels of intervention, from smaller to bigger interventions.

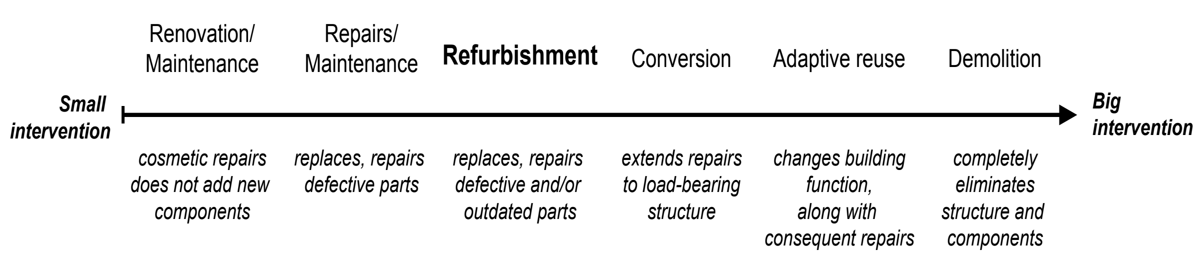


FIG. 2.1 Degrees of intervention on buildings *(Konstantinou, 2014)*

TOC

The refurbishment level ranges from repairs/maintenance to conversion. Maintenance is restricted to replacement or repair of defective components. Conversion would affect load-bearing building elements and interior layout. Refurbishment, on the other hand, does not include major changes in the load-bearing structure. In refurbishment, defective parts, as well as outdated components or surfaces, are repaired or replaced (Giebeler et al., 2009). Upgrade of fire protection, acoustics, and thermal performance can, therefore, be achieved through refurbishment. Additionally, during the refurbishment, buildings can be retrofitted with technologies for energy generation from renewable sources.

The Energy Performance of Buildings Directive (EPBD) applies the terminology of "major renovation". Existing buildings, building units and building elements that undergo major renovation need to reach specific requirements for the energy performance. EU Member States should define major renovation as measures in which the total cost of the renovation relating to the building envelope or the technical building systems is higher than 25% of the building value, or more than 25% of the surface of the building envelope undergoes renovation (DIRECTIVE, 2010/31/EU).

An interpretation of major renovation, which is related to sustainability and GHGs, is the term "deep renovation". The refurbishment depth is related to the level of savings on energy or greenhouse gas emission, specifying as "deep" such renovations that achieve energy savings of 60-90% (BPIE, 2011). Typically, a holistic approach that considers a package of measures is required to reach deep renovation savings. Superficial renovations with lower savings in energy consumption obstruct the climate targets fulfilment, as they can result in huge potential savings to remain untapped (Hermelink & Müller, 2011).

3 Sustainable Refurbishment

Motivations for refurbishing existing buildings are related to environmental, social, and economic aspects of their use or reuse, which are the three major categories of sustainability (Emad & David, 2012; Munasinghe, 2004; Nahmens & Ikuma, 2012). As refurbishing a building is a complex process that encompasses parameters such as the architectural design and construction, energy efficiency, socio-financial effects, and user behaviour, it is understandable that it can affect all different aspects simultaneously.

The key environmental motivation is to reduce energy consumption from fossil fuels and related greenhouse gases (GHG) emissions, and to include power generation from renewables; the key economic motivation is to reduce the cost of energy used for heating; the key social motivation is to reduce fuel poverty and improve quality of life and well-being of the inhabitants.

TOC

3.1 Environmental Aspects

Reduction of GHG emissions by improving energy efficiency of buildings
The building stock has been the central focus of policies for energy saving. The International Energy Agency (IEA) has identified the building sector as one of the most cost-effective sectors in the reduction of energy consumption, with an estimated possible energy saving of 1,509 million tonnes of oil equivalent (Mtoe) by 2050. Moreover, improving energy efficiency in buildings and, hence, reducing overall energy demand, can significantly reduce building-related carbon dioxide (CO2), translating to possible mitigation of 12.6 gigatons (Gt) of CO2 emissions by 2050 (IEA, 2010).

Energy efficiency of existing buildings can be achieved by applying one or more measures that increase the thermal resistance of the envelope and improve the performance of the building services. Such measures include the replacement of windows with new, state-of-the-art panes and frames, the addition of thermal insulation material to external walls and roof, and the replacement of existing heating systems with new ones with a higher coefficient of performance (COP), such as heat pumps. More details about passive and active measures and technologies can be found in Book 4 of this series.

Enabling generation of energy and hot water from renewable sources on refurbished buildings
Next to energy efficiency measures that reduce the energy demand and the related GHG, existing buildings can also act as power generators for electricity and hot water. The envelope of the existing building or its surroundings can be used to accommodate photovoltaic and solar panels, and retrofitted building services can use energy from renewable sources. More details about renewable energy technologies can be found in Book 4 of this series.

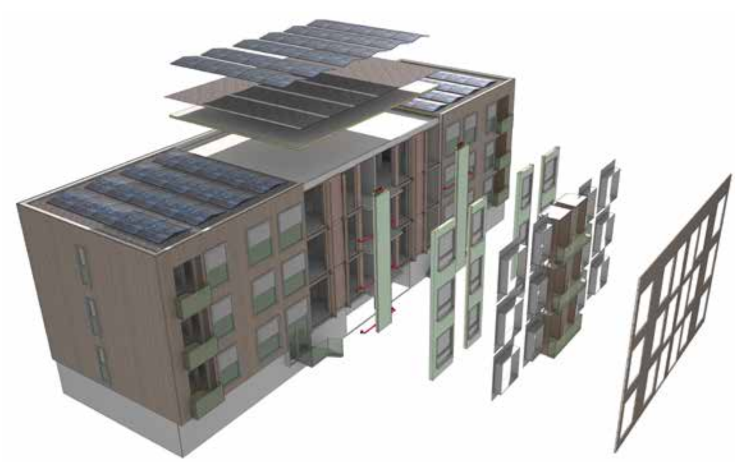


FIG. 3.1 Example of the 2ndSkinzero-energy refurbishment concept *(Konstantinou, Guerra-Santin, Azcarate-Aguerre, Klein, & Silvester, 2017)*

TOC

Combining measures to improve energy efficiency and generate energy has the potential to provide zero-energy refurbished buildings, such as in the approach presented in Fig. 3.1. The built environment can only be transformed to zero-emission by eliminating the buildings' consumption of energy generated from fossil fuels.

Saving natural resources by applying circular economy principles in refurbishment

To achieve strong energy performance in new constructions, which includes better insulation and efficient building services, new buildings require major energy, carbon, and wider environmental impacts, due to the demand in new materials (Power, 2008). Preserving and transforming existing buildings is more environmentally efficient than demolition and rebuilding, as natural resources are saved. The building process and the new materials used are energy intensive, while most of the building structure and building components in an existing property rarely need replacing. Consequently, new buildings require four to eight times more resources than an equivalent refurbishment (Itard & Klunder, 2007). Regarding broader environmental impact, demolition and building are a major source of landfill volume, accounting for around 30% (Power, 2008). Fig. 3.2 shows some examples of waste from building components. Therefore, the reduced availability of landfill sites also has implications for the scale of building and demolition, and limiting waste through reuse, refurbishment, and recycling is needed.

A

B

FIG. 3.2 (A) Waste from building components and (B) recycling plant of building components

3.2 Economic Aspects

Embodied energy and capital
Buildings also store capital, bound to the raw materials. While façades and building services may reach the end of their technical lifespan at the age of 30 years, the load-bearing structure can last for a century or more. Thus, demolition would not only be a waste of embodied energy and energy used for demolition, but also a waste of capital.

Reducing cost of energy consumed for heating and hot water
The operational cost of a building is strongly related to its energy consumption. The general trend is for energy prices to rise, despite some intermittent falls, which are often mitigated in the retail price by increasing related taxes (IEA, 2016; ITRE, 2015). The energy price rise directly leads to higher operational cost. Considering that tenants would accept higher rental rates if the operational costs were lower, refurbishment has a direct economic effect on improving energy efficiency and reducing the energy consumption of the building. The report "Europe's buildings under the microscope" (BPIE, 2011) estimated that deep renovation of the building stock to reach the 2050 targets may result in €380 billion savings for consumers, with direct positive effects on fuel poverty, as will be discussed in the following section as part of the social aspects.

Reducing cost by reusing existing building materials and components
From a financial point of view, demolition and new construction make sense if only minor renovation with little energy saving is possible, and if a building is in such bad state that extensive, cost-intensive, non-energy related measures are needed. In addition, the energy performance of a renovated building could be equal to that of a new building. Thus, the argument that the lifespan expectation and market position of a renovated building can be insufficient to justify the investment is not convincing (Thomsen & van der Flier, 2008).

Strengthening economic resilience by increasing the commercial value of refurbished buildings and their attractiveness to the market
The planning of a refurbishment project offers the opportunity to improve the performance and function of the building, as well as to increase the usable space by making the internal layout more efficient or by constructing additions and extensions to the building. The added usable space has an immediate result in the form of an increase in the commercial value of the building. Furthermore, high energy efficiency and sustainability features promote a green and renewed image of the property, which makes it more attractive to potential buyers and tenants.

Job creation
Finally, refurbishment activities can contribute to job creation. Particularly in the residential sector, employment gains are typically higher than in other sectors (Waide, Gurtler, & Smith, 2006). It is estimated that around 1 million jobs can be created annually throughout the period until 2050, as a result of deep renovation of the residential building stock (BPIE, 2011).

3.3 Social Aspects

Increasing social resilience
Demolition, as an alternative to renovation, is slow, costly, and unpopular. It provokes community opposition among the very people who are supposed to benefit from the measure (Power, 2008), as those living in locations targeted for demolition often have little say in the deposition of their neighbourhood and often face difficulty in finding replacement housing (Crump, 2012).

Reducing fuel poverty
Reduced energy demand results in lower energy bills for the people living in refurbished dwellings. With 10-25% of the total EU population estimated to be fuel poor, energy efficiency upgrade of residential buildings can provide the means for reducing fuel poverty as a result of lower energy bills following such renovations (BPIE, 2013).

Improving the quality of life of building occupants
Apart from the resulting savings in energy use and the consequent mitigation of climate change, an immediate effect of energy efficient refurbishment is improved comfort and increased building quality, both functionally and technically. Refurbishment can be decided on the grounds of reduction of noise or draught. Retrofitting of building services, replacement of windows, and restoration of damaged components are some measures to improve technical quality as well as the comfort in such spaces.

Functional shortcomings, such as small apartment size, inadequate space layout, and lack of accessibility for people who have temporary or long-term physical impairments, are also major issues that impair quality of life, and which refurbishment can address. Over the years, the average number of persons per dwelling has decreased from 5-6 in the early post-war years to 2.43 persons per dwelling in 2002 (Andeweg, Brunoro, & Verhoef, 2007). It is thus evident that updates in the layout and number of houses are necessary. Accessibility is also important, particularly with the shift in the age profile of the European population (BPIE, 2011). Housing built prior to the 1960s was not equipped with elevators, even in three or five-storey buildings. The refurbishment strategy can incorporate these functional improvements.

Preserving socio-cultural context of importance to the community
Refurbishment also serves to preserve the societal value of existing buildings, together with their cultural and historical value, while improving living conditions. When buildings today are in need of refurbishment, the task is to keep their history alive and preserve their value for society. In practice, this means that each project has to be valued for its qualities and potentials. Urban areas that are considered as important architectural and urban heritage may be designated as conservation areas in which only visually sensitive refurbishment is permitted, and demolition and rebuilding allowed only if it has been ascertained to be the only viable option. In urban areas that do not have exceptional architecture, good quality refurbishment can improve the

appearance of buildings and streets. Overall, refurbishment can preserve as well as promote the design qualities and socio-cultural values of a building, a street, or a neighbourhood atmosphere, as well as the heritage value of buildings and cities, as in the example shown in Fig. 3.3.

FIG. 3.3 Archipelbuurtdistrict in The Hague, NL. The district has preserved its original character.

Improving the appearance, attractiveness and safety of the built environment

Technical decay in buildings is related to social decay (Priemus, 1986). Strong socio-economic user groups leave buildings that are technically and functionally outdated, and weaker groups replace them. This process often results in a high turnover of tenants, vacancy, lack of control, and generally "unfavourable" living conditions. Refurbishment can, hence, stabilise an uncertain social environment, as the renovated buildings meet today's demands and provide a functional and attractive contribution to society. Such an example is the residential complexes in the Bijlmermeer district in Amsterdam (Fig. 3.4).

FIG. 3.4 Renovated ground floor apartments in the Bijlmermeerarea, Amsterdam, NL

4 Refurbishment Design for Future Adaptation

The study included surveying resilient design principles, and establishing building-related criteria (see Chapter 2 of this book). Grammenos and Russel (1997) define an adaptable building as one intentionally built so that changes in its use, expansion or contraction of space, or major changes to its systems and envelope can be accommodated with minimal waste of resources. The same principle should apply during the refurbishment of an existing building.

It is useful to make a distinction between the terms adaptability and flexibility of buildings. Designing for flexibility implies that a design brief requires building systems that can meet changing needs over time, both from minute-to-minute (as, for example, the building services respond to changes in the weather, internal heat gains, use, and occupant requirements), from day-to-day (with modifications in working patterns, space use, equipment, furniture etc.), and from time-to-time (with changes in organisational structures, requirements, tenancy and even function) (Bordass & Leaman, 1997). The first requirement implies that a building is highly serviced and may have sophisticated building management control systems. Complex building services systems that were initially intended to provide flexibility might themselves obstruct the change that is later found to be required. Harvey and Ashworth (1996) say that the more 'intelligent' the building, the more difficult it is to manage and reorganise because highly trained personnel are needed to carry out operations and replacement of systems. The alternative strategy may be to provide simpler, but potentially adaptable, buildings, which are easily altered as needs change, and to apply the same approach during the refurbishment of an existing building. If complexity is necessary, it should be isolated and managed by simple interfaces (Bordass & Leaman, 1997). Some buildings may not have such systems because they were not required for the initial buildings' uses. However, the design of adaptable buildings and refurbishment of existing buildings should provide a spatial capacity for the installation of additional services in the future.

In the design of more conventional buildings, which are envisaged as non-demountable and durable, but need to be adaptable, the main difficulty lies in predicting what types of space, structures, and services lend themselves to change. Although predictions are difficult, Ozbekhan (1969) points out the importance of being able to distinguish between what is constant and what is variable. Basic physical elements by which a traditional building can be defined are structure, enclosure, stairs, and services. The question is whether they are constant or variable. Some buildings have been planned with demountable structures, which may be considered as a variable feature. However, the structure of most buildings can be regarded as a constant until the end of the building life. Normally, enclosure and vertical circulations are designed as permanent features, intended to last throughout the building's life. Nevertheless, they can be and have been changed on some buildings. Design for Disassembly (DFD) is a trend in manufacturing that will introduce more variable features in building design. The need for services can be considered a constant, but their type and technological solutions not necessarily so.

Russell and Moffatt (2001) define three design strategies for adaptability: flexibility or enabling minor shifts in space planning; convertibility, or allowing for changes in use within the building; and expandability (alternatively shrinkability), or facilitating additions to the amount of space in a building. They provide a broad-brush description of desirable characteristics of foundations, superstructure, envelope, services, and interior spaces, which can enable easier adaptations. Langford, MacLeod, Dimitrijevic, and Maver (2002) developed the criteria for assessing a potential for adaptation of new and existing buildings. The criteria consider exterior spaces (building site); interior space (size of spaces/rooms, relations between them, and to the circulation routes in the layout); accessibility of the building site and existing infrastructure; spatial and structural characteristics; capacity of services, the possibility of enlargement of that capacity, and the space available for their maintenance and replacement.

According to Burns (1992), clients would like a structure that allows for flexibility and adaptability, but often are unwilling to spend additional money to achieve this in the initial design. However, they are beginning to expect adaptability to be part of the structural design of a building and refurbishment, given the greater uncertainty associated with the future property market (Burns, 1992). Kohler (1999) points out that instead of minimising the investment cost through low-cost highly customised solutions, an investment benefits from identifying the solution with the highest durability and reusability. An analysis of the investments for adaptations during the lifetime of buildings is needed to support design for adaptability. Grammenos and Russel (1997) refer to studies of hospital buildings that have shown that the capitalised costs of alterations over a typical ten-year period equalled the original capital cost.

The durability, adaptability, and energy conservation (DAEC) tool developed by Langford et al. (2002) enables the input of estimated costs of examined design features in the adaptability assessment. Two estimates for each design feature are provided: first, the initial costs, and second, the costs of providing the same features, if possible, after the building has been built. The comparison of the difference between the initial and later costs assists in deciding on the investment. Examining whether some design features could be provided at all after the building has been built may help in deciding if they need to be provided initially. Another aim of the comparisons is to assess whether the added costs for elevated adaptability can be justified on the basis of the avoided costs of alterations or demolition plus new construction (Grammenos & Russel, 1997).

TOC

5 Challenges and Barriers

Despite the motivation to continue using and renovating existing buildings, the EU average renovation rate is as low as 1%, and renovations are mainly minor. Barriers related to finances, institutional issues, awareness, advice and skills, and the separation of expenditure and benefit prevent or delay the uptake of renovation measures (BPIE, 2011).

Financial barriers are at the top of the list, as any renovation requires an investment. Deficiency of funds is the most reported reason that prevents investment in energy efficiency. Despite the fact that the measures are cost-effective in the long run, the initial investment cost is often an obstacle for the decision. Furthermore, energy cost is not a major concern for the majority of consumers. It represents a small share of household or company expenditure – an average of 3-4%, which can be higher in low-income households (BPIE, 2011; Drehobl & Ross, 2016) – and the payback period of the energy savings may exceed the occupancy period. In order to support decisions for energy upgrades, several financial instruments are necessary, such as grants, preferential loans, VAT reduction, penalties if minimum requirements are not met, and the financing of energy service companies. Alternative business models, e.g. the Product-Service System (PSS) for façade renovation proposed by Azcarate-Aguerre, Klein, and den Heijer (2016), also have the potential to tackle the high initial investment.

The lack of adequate advice and technical expertise is another concern that hinders renovation (BPIE, 2011). Existing building interventions require different skills than large-scale new construction regarding technical, social, and managerial craftsmanship, on top of different type, size, and organisation of the company. This observation applies to designers, developers, commissioners, and governments, whose knowledge about how and when to effectively maintain, adapt, transform, and redesign older stock still needs to improve (Thomsen, 2010). Even though energy savings are generally appreciated as a renovation effect, there remains a lack of understanding of the potential energy, cost, and carbon savings resulting from different measures.

Finally, a complex barrier is the separation of expenditure and benefit, also referred to as the “split incentives barrier” (BPIE, 2011).In cases when one party owns the building and is requested to invest in energy efficiency, while another – the tenant – benefits from the resulting energy saving, such split incentives occur. It is not easy to overcome this barrier. A combination of measures and policies is needed, such as regulatory instruments for energy efficiency standards for appliances and buildings, availability of reliable information about energy performance (IEA, 2007), as well as potential changes in the current transaction structure. These options are based on complex interactions, but may be combined into integrated policies that reduce energy-related emissions (Barrett, Lowe, Oreszczyn, & Steadman, 2008). Examples of such policies are the Green Deal in the UK, which spreads the costs of the energy efficiency improvements over the lifetime of the installed upgrade (Crawford, Johnson, Davies, Joo, & Bell, 2014), or the

TOC

Energy Performance Subsidy - Energieprestatievergoeding (EPV) in the Netherlands, which allows the landlord to ask for an additional amount of rent per m^2 for nearly zero energy buildings (RVO, 2016).

6 Best Practice

Despite the barriers discussed above, there are many successful examples that incorporate physical, aesthetic, and functional upgrades, while taking into account the occupants' needs and the architectural value of the building. Such concerns are necessary to address sustainability and resilience aspects.

This section presents three best practice refurbishment projects in different European countries. Each one had different concerns and objectives, but all resulted in solutions that improved the environmental, economic, and social value of the building.

6.1 Renovation and Transformation of a Residential Building in Klarenstraat, Amsterdam-Slotervaart, NL. Architect: Vanschagen Architecten

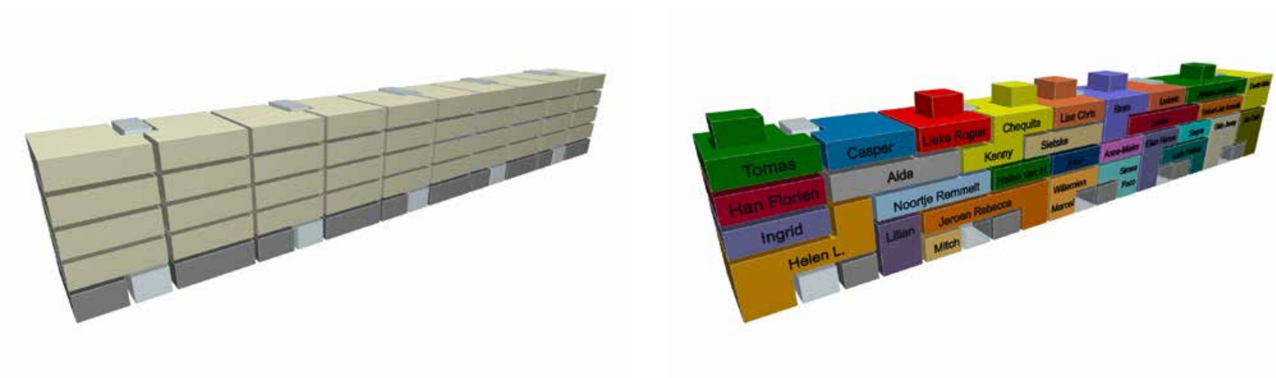
During the transformation of a tenement building in U.J. Klarenstraat, in the district of Amsterdam-Slotervaart, the buyers of the apartments, together with the architect and the housing association that owned the building originally, developed not only the architectural interventions but also the business model that made this project possible. In this way, the process illustrates a new role for the designer and the owner in renovation projects.

A

B

FIG. 6.1 The original (A) and the refurbished (B) apartment building in Klarenstraat *(Photo: courtesy Vanschagen Architecten)*

The original building was a typical example of a mid-rise, post-war, multi-family residential block, built in 1956 by architect Groosman (Fig. 6.1.a). It consisted of 40 identical apartments of 75m^2 each. On the ground floor, a storage and parking area was located. The transformation had a big effect on the occupants and ownership of the building on different levels. Firstly, the status was changed from moderate-rent apartments to individual owner occupied flats. As a result, the character of the apartment type was now adjusted to fit the needs of the new owners.



A *B*

FIG. 6.2 The layout of the renovated building. The 40 original identical apartments (A) were transformed into (B) 30 diverse apartments, ranging from 40 to 190 m^2 *(Photo: courtesy Vanschagen Architecten)*

The 40 original identical apartments were transformed into 30 diverse apartments, ranging from 40 to 190 m^2 (Fig. 6.2). Other improvements included the creation of private gardens on the ground floor, roof terraces, and new balconies, which were subject to owners' choice. Thus, the renovated building broke the prevailing pattern of the apartment blocks and complexes of the post-war period and demonstrated that it is possible to adapt to new standards of life and ownership.

Looking at the social aspects of the renovations, the new occupants' participation was critical for the transformation. Firstly, this was the first post-war tenement building renovation in the Netherlands that was assigned by a collective private client -collectiefparticulieropdrachgeverschap (CPO). Nowadays, this collective way of working has a positive effect on the way the building is inhabited as well as on the neighbourhood. Last but not least, the design process and the construction process were realised with the occupants' participation (Fig. 6.3). Once the general design layout and the basic structural interventions were completed, each owner could freely choose and construct the interior of their dwelling (Fig. 6.4).

Apart from the layout adaptations, the new owners had high ambitions in terms of energy efficiency. Even though each owner was given flexibility regarding the interior transformations, the building envelope insulation and the building services, including underfloor heating, were collectively upgraded to ensure high energy performance. Moreover, 250m^2 of photovoltaic panels were installed on the building. The interventions resulted in improving the energy label of the new dwellings from D/E to A, which constitutes a significant reduction in energy consumption (Rossem et al., 2017).

FIG. 6.3 The occupants involved in the renovation decision-making and participating in the construction work *(Photo: courtesy Vanschagen Architecten)*

FIG. 6.4 Interior of one of the apartments after renovation. Each apartment is different from the rest, not only in terms of size, but also due to the fact that the occupants made different design choices. *(Photo: courtesy Vanschagen Architecten)*

6.2 Transformation of 530 Dwellings, District Grand Parc, Bordeaux, FR. Anne Lacaton & Jean Philippe Vassal, Frédéric Druot, Christophe Hutin

The transformation of the three inhabited social housing buildings was the first phase of a renovation program of the 'Cité du Grand Parc' in Bordeaux. Built in the early 60s, this urban housing comprises more than 4,000 dwellings.

FIG. 6.5 The renovation process. The building exterior during the construction of the extension *(Photograph by Philippe Ruault)*

A *B*

FIG. 6.6 A+B: Construction phases of the new structure *(Photograph by Philippe Ruault)*

FIG. 6.7 Original and renovated apartment block G in the Grand Parc district *(Photograph by Philippe Ruault)*

FIG. 6.8 The interior after renovation and extension *(Photograph by Lacaton & Vassal – Druot)*

The starting point of the renovation was to improve the usable interior space of the apartments, which in the pre-renovation state were considered to be small, dysfunctional and dark. As the apartments would stay occupied during the renovation process, the main intervention was proposed for the exterior. The renovated apartments open onto large winter gardens and balconies and offer pleasant 3.80m deep outdoor spaces; wide enough to be fully functional. Including the winter gardens, balconies, and storage spaces, the area of each dwelling increased significantly (Lacaton & Vassal, 2016). Fig. 6.5 and Fig. 6.6 show the construction phase on the winter gardens and extensions, which were realised externally while the dwellings were in an occupied state.

Interior improvement interventions and restructuring of the bathrooms were also suggested. The gardens surrounding the buildings were improved to facilitate access and use. Overall, the project dealt with the global performance of the building envelope, the reconfiguration of vertical circulation routes and access halls. As a result, the three 10 to 15-storey-high buildings gained a renewed architectural expression and appeal (Fig. 6.7) and the 530 dwellings that make up the buildings, were transformed into beautiful dwellings with redefined qualities and comfort. The new winter gardens and balconies provided more daylight, flexibility in their use, and views (Fig. 6.8).

Apart from the increase in the usable space and the improved quality of living, the renovation resulted in significant energy saving. The energy consumption was reduced by 66%, mainly as a result of the reduced heating energy demand in the renovated dwellings, which in the renovated apartments accounts for 20 kWh/(m2.a), while it used to be 116 kWh/(m2.a).

Concerning financial aspects, the cost of the new construction and renovation per dwelling was calculated to be less than 1/3 of the cost of demolition and rebuilding, proving the transformation a sensible investment, which was possible with no rent increase for the occupants. Moreover, the renovation took place while the building remained occupied, which offered financial benefits for the housing association and preserved the social coherence of the compound.

6.3 The Redevelopment of the National Museum of Scotland, Chambers Street, Edinburgh

The former Edinburgh Museum of Science and Art, opened in Chambers Street in 1866, was amalgamated in 1985 with the National Museum of Antiquities to create the National Museums of Scotland, and later expanded into a new building in 1998 (National Museums Scotland, n.d.).The aim of the redevelopment (undertaken in 2006-2011) of the Grade A listed building built in 1866, was to improve access for all, enhance visitors' facilities, provide new areas for displaying the museum's exhibits and improve energy efficiency (Gibb, 2012). Along with the conservation work (Fig. 6.9), the vaulted cellar spaces, previously hidden from public view, were excavated to form a new entrance hall (Fig. 6.10).

The strategy for improving energy efficiency had to consider a potentially very high cost for enhancing the thermal performance or air-tightness of historic façades, which in many areas would be practically impossible. One of the strategic approaches was to assign functions to each space in a way that made the best use of energy, building form, and structure. This principle was applied by displaying more resilient items in the Grand Gallery and more sensitive ones in 'sealed' zones deep within the building plan, protected from daylight and controlled with new heat recovery air-conditioning systems (Gibb, 2012).

Heating distribution and control systems were updated so that heating circuits could be monitored and controlled individually to reduce overheating and energy use. The latest low-energy lighting technologies such as LEDs and high-efficiency fluorescent lamps, and a system for automatic lighting control, were installed. The centralised energy metering system enables monitoring and reduction of energy consumption in each of the galleries and the extended storage and support spaces (Gibb, 2012).

The redevelopment of the Grade A listed building, which forms part of the National Museums Scotland, shows that the decisions concerning interventions to improve the energy efficiency of historic buildings must consider how to preserve building authenticity and avoid unacceptable costs by assigning the most suitable functions to specific spaces.

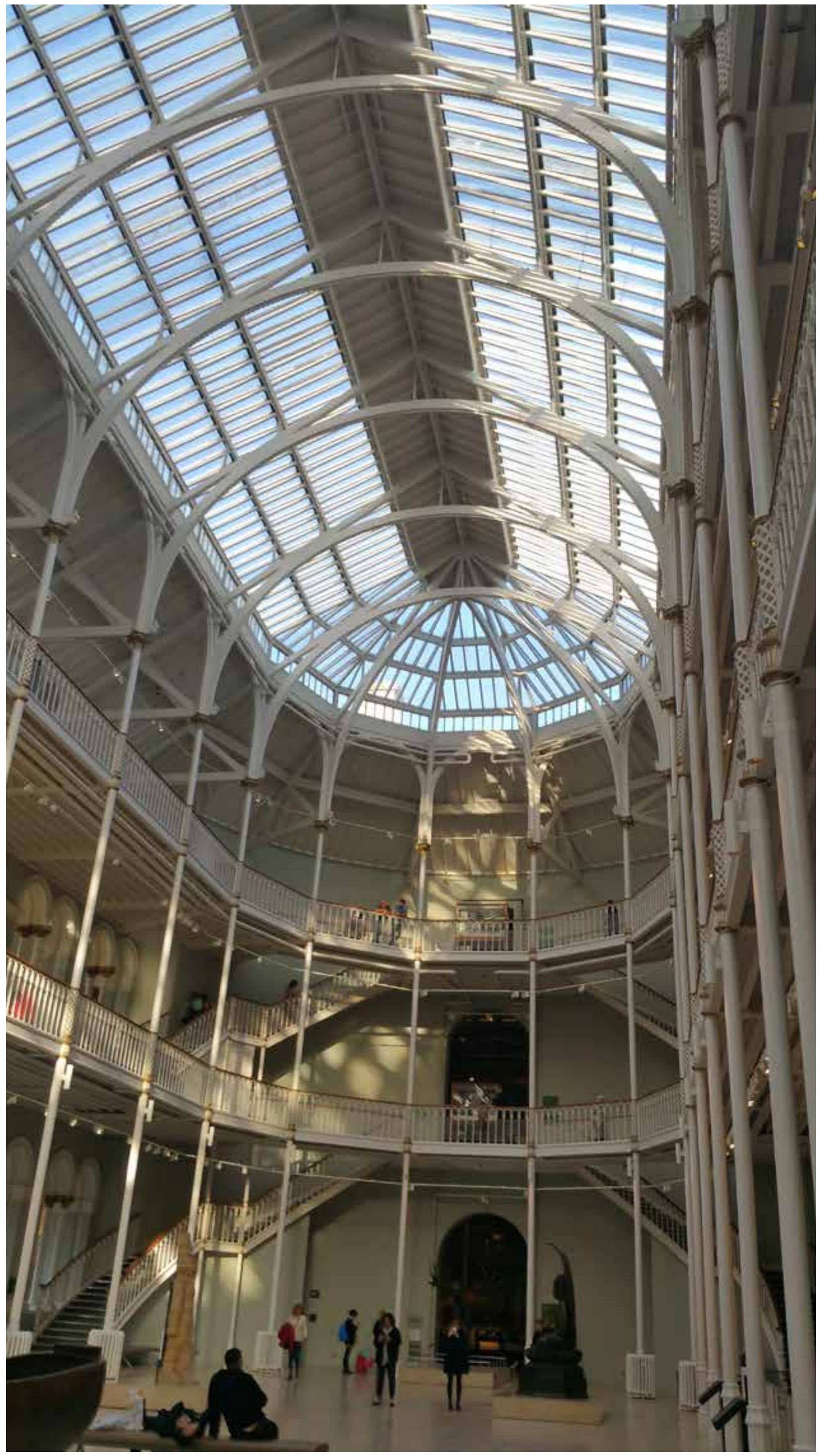


FIG. 6.9 Museum's Grand Gallery

This may mean that if the authenticity of a building (or some of its parts) is deemed more important than improving energy efficiency by adding thermal insulation (which can diminish a building's aesthetic qualities) or increasing air-tightness (which might be impossible or very expensive on some structures), such interventions will not be made. However, other energy efficiency interventions that do not have a negative impact on a building's aesthetics (e.g. more efficient lighting and control systems) should be considered.

FIG. 6.10 New entrance hall

7 Conclusions

Refurbishment is an integral part of buildings' life cycle, as components and functions become outdated or reach the end of their service life. Next to that, the upgrade of existing buildings presents an opportunity for achieving a more sustainable and resilient built environment. This chapter explained why refurbishment of existing buildings is related to sustainability and resilience, regarding the environmental, social, and economic effects it can have on the built environment and society in general.

The environmental aspects are primarily related to the reduction of energy demand and the resulting GHG emissions due to the improved energy performance of the building skin and services, as well as the possibility of integrating renewable energy sources in the refurbished building. Moreover, by reusing the existing building and extending its life, instead of demolishing it and building a new one, natural resources can be spared, which also offers financial benefits. Additional financial benefits are derived from the increase in the building value by the upgrade. Moreover, the improvement of the quality and the attractiveness of the buildings has, in turn, a positive effect on the quality of life and health of the occupants. The social and economic benefits extend as far as reducing fuel poverty, preserving the architectural and cultural heritage and creating jobs in the construction industry. Fig. 7.1 presents an overview of the sustainability aspects and the respective outcomes that sustainable refurbishment has.

It thus becomes evident that the benefits resulting from refurbishing the building stock cannot be strictly categorised in only one of the sustainability aspects, as they can be at multiple levels and the boundaries are blurred as the different aspects interact. Aspects of refurbishment are also demonstrated by the best practice examples, as well as multiple other examples of refurbishment practice, where the motivation and the result are never mono-dimensional.

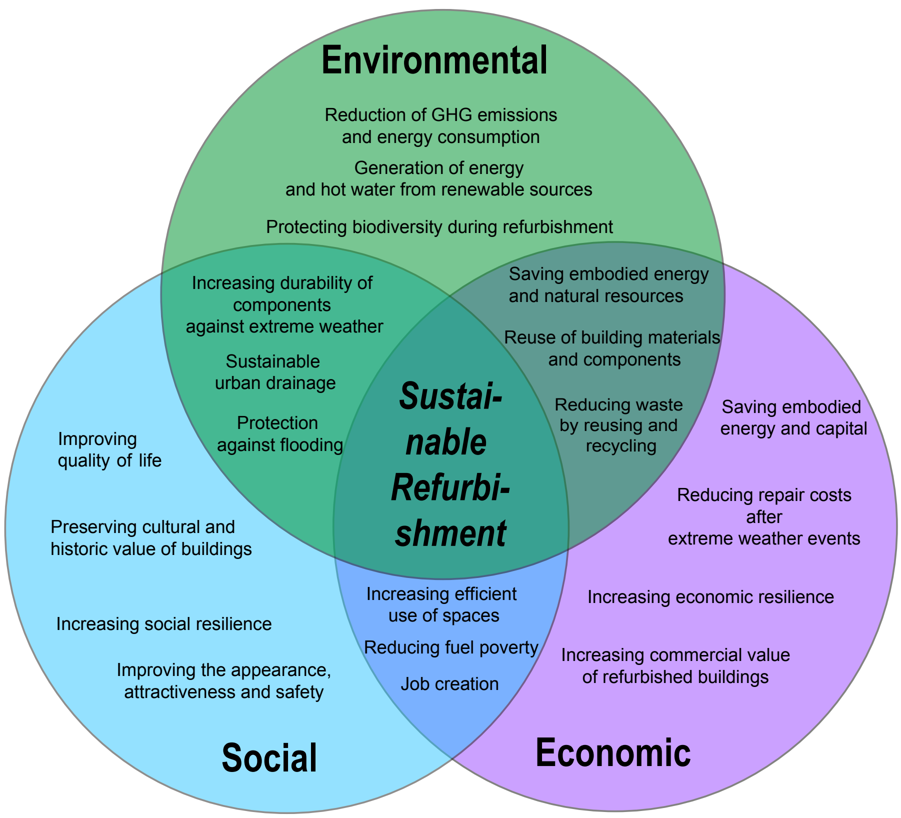


FIG. 7.1 Overview of refurbishment relevance to sustainability and resilience aspects

Taking into account all the positive aspects, it is understandable why refurbishment is a focal point in policies and directives. Overcoming the barriers to increase the rate and depth of renovation is a priority. Nevertheless, the key to the successful transformation towards a sustainable and resilient built environment lies within the building industry, and also depends on the architects, who should be aware of the challenges as well as the opportunities that the refurbishment of buildings presents, and who should make informed decisions towards their upgrade.

References

Andeweg, M. T., Brunoro, S., & Verhoef, L. G. W. (2007). Cost C16- Improving the quality of existing urban building envelopes: State of the art. IOS Press. Retrieved from http://books.google.nl/books?id=GPJXCZJGL40C.

Azcarate-Aguerre, J., Klein, T., & den Heijer, A. (2016, March). A business-oriented roadmap towards the implementation of circular integrated façades. Paper presented at the 9th International Conference on Improving Energy Efficiency in Commercial Buildings and Smart Communities., 16-18 March, Frankfurt am Main, Germany pp 463-473.

Barrett, M., Lowe, R., Oreszczyn, T., & Steadman, P. (2008). How to support growth with less energy. Energy Policy, 36(12), 4592-4599. Retrieved from doi:http://dx.doi.org/10.1016/j.enpol.2008.09.065

Bordass, W., & Leaman, A. (1997). Design for manageability. Building Research & Information, 25(3), 148-157. doi:10.1080/096132197370417

BPIE. (2011). Europe's buildings under the microscope. Brussels: Building Performance institute Europe. Retrieved from http://www.bpie.eu/eu_buildings_under_microscope.html.

BPIE. (2013). A Guide to Developing Strategies for Building Energy Renovation: Delivering the Energy Efficiency Directive Article 4. Brussels: Building Performance institute Europe. Retrieved from http://www.bpie.eu/renovation_strategy.html.

Burns, J. G. (1992). Design life of buildings: client expectations. In G. Somerville (Ed.), The Design Life of Structures (pp. 240-245). Glasgow: Blackie and Son Ltd.

Crawford, K., Johnson, C., Davies, F., Joo, S., & Bell, S. (2014). Demolition or Refurbishment of Social Housing? A review of the evidence. Retrieved from http://www.engineering.ucl.ac.uk/engineering-exchange/files/2014/10/Report-Refurbishment-Demolition-Social-Housing.pdf

Crump, J. (2012). Demolition. In J. S. Editor-in-Chief: Susan (Ed.), International Encyclopedia of Housing and Home (pp. 325-329). San Diego: Elsevier. doi: 10.1016/B978-0-08-047163-1.00525-7

DIRECTIVE. (2010/31/EU). on the energy performance of building. Brussels: THE EUROPEAN PARLIAMENT AND THE COUNCIL.

DIRECTIVE. (2012/27/EU). on the energy efficiency. Brussels: THE EUROPEAN PARLIAMENT AND THE COUNCIL.

Drehobl, A., & Ross, L. (2016). Lifting the High Energy Burdens in America's Largest Cities: How Energy Efficiency Can Improve Low-Income and Underserved Communities. Retrieved from http://energyefficiencyforall.org/sites/default/files/Lifting%20the%20High%20Energy%20Burden_0.pdf

Emad, S. B., & David, C. B. (2012). Developed Sustainable Scoring System for Structural Materials Evaluation. Journal of Construction Engineering and Management, 138(1). doi:10.1061/(ASCE)CO.1943-7862.0000412

European Commission. (2013). Multi-annual roadmap for the contractual PPP on Energy efficient Buildings under Horizon 2020. Luxemburg: Publications Office of the European Union. Retrieved from http://www.ectp.org/cws/params/ectp/download_files/36D2981v1_Eeb_cPPP_Roadmap_under.pdf

European Commission. (2015). Paris Agreement. Retrieved from https://ec.europa.eu/clima/policies/international/negotiations/paris_en

Eurostat. (2012). "Climate change statistics" - Statistics Explained. Retrieved from <http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Climate_change_statistics#>

Eurostat. (2013). "Consumption of energy" - Statistics Explained. Retrieved from http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Consumption_of_energy

Eurostat. (2015). Sustainable development - climate change and energy. Retrieved from http://ec.europa.eu/eurostat/statistics-explained/index.php/Sustainable_development_-_climate_change_and_energy

FCCC/CP/2015/L.9. (2015). ADOPTION OF THE PARIS AGREEMENT. Proposal by the President, Draft decision -/CP.21. Paris: Framework Convention on Climate Change.

Flourentzou, F., Genre, J.-L., & Roulet, C.-A. (2001). EPIQR-TOBUS: a new generation of refurbishment decision aid methods. In N. Maiellaro (Ed.), Towards Sustainable Building (Vol. 61, pp. 161-169). Dordrecht: Springer Science+Business Media. Retrieved from http://dx.doi.org/10.1007/978-94-017-3563-6_10

Genre, J. L. (1996). EPIQR - A New Refurbishment Concept: Planning the City of the future today. Paper presented at La città del futuro, Milano. Retrieved from https://www.cti2000.it/index.php?controller=pubblicazioni&action=show&id=5246.

Gibb, G. (2012). The redevelopment of the National Museum of Scotland, Chambers Street, Edinburgh. Innovation Review, 46-53. Retrieved from http://www.cicstart.org/newsletter/2012-03-Innovation_Review.pdf. .

Giebeler, G., Fisch, R., Krause, H., Musso, F., Petzinka, K.-H., & Rudolphi, A. (2009). Refurbishment manual: maintenance, conversions, extensions. Basel: Birkhäuser.

Grammenos, F., & Russel, P. (1997). Building Adaptability: A view from Future. Proceedings of the Second International Conference: Buildings and the Environment, June 9-12 1997, Paris. Vol. 2, pp 19-26.

Harvey, R. C., & Ashworth, A. (1996). The Construction Industry of Great Britain. Oxford: Newnes.

Hermelink, A., & Müller, A. (2011). Economics of deep renovation. Retrieved from http://www.eurima.org/uploads/ModuleXtender/Publications/51/Economics_of_Deep_Renovation_Ecofys_IX_Study_Design_FINAL_01_02_2011_Web_VERSION.pdf

IEA. (2007). Mind the Gap - Quantifying Principal-Agent Problems in Energy Efficiency. Retrieved from http://www.iea.org/publications/freepublications/publication/name,3886,en.html

IEA. (2010). Energy Performance Certification of Buildings: A policy tool to improve energy efficiency. Retrieved from https://www.iea.org/publications/freepublications/publication/buildings_certification.pdf

IEA. (2016). Key world energy statistics. Retrieved from http://www.iea.org/publications/freepublications/publication/KeyWorld2016.pdf

Itard, L., & Klunder, G. (2007). Comparing environmental impacts of renovated housing stock with new construction. Building Research & Information, 35(3), 252-267. doi:10.1080/09613210601068161

Itard, L., & Meijer, F. (2008). Towards a sustainable Northern European housing stock (Vol. 22). Amsterdam: IOS. Retrieved from https://www.arct.cam.ac.uk/Downloads/towards-a-sustainable-northern-european-housing.pdf.

ITRE. (2015). Recent Trends in Energy Prices. Brussels: E. Union. Retrieved from http://www.europarl.europa.eu/studies

Kohler, N. (1999). The relevance of Green Building Challenge: an observer's perspective. Building Research & Information, 27(4-5), 309-320. doi:10.1080/096132199369426

Konstantinou, T. (2014). Façade Refurbishment Toolbox: Supporting the Design of Residential Energy Upgrades. (Doctoral Dissertation: Delft University of Technology) Retrieved from http://abe.tudelft.nl/index.php/faculty-architecture/article/view/konstantiou

Konstantinou, T., Guerra-Santin, O., Azcarate-Aguerre, J., Klein, T., & Silvester, S. (2017). A zero-energy refurbishment solution for residential apartment buildings by applying an integrated, prefabricated façade module. Paper presented at the PowerSkin, Munich. Retrieved from https://books.bk.tudelft.nl/index.php/press/catalog/view/518/526/161-1.

Lacaton & Vassal. (2016). Transformation de 530 logements, bâtiments G, H, I, quartier du Grand Parc – Lacaton & Vassal, Druot, Hutin. Retrieved from https://www.lacatonvassal.com/index.php?idp=80#

Landman, M. (1999). Breaking Through the Barriers to Sustainable Building: Insights from Building Professionals on Government Initiatives to Promote Environmentally Sound Practices. Tufts University. Retrieved from https://books.google.nl/books?id=NjIkMgAACAAJ.

Langford, D. A., MacLeod, I., Dimitrijevic, B., & Mave, T. W. (2002). Durability, adaptability and energy conservation (DAEC) assessment tool. International Journal of Environmental Technology and Management, 2(1/2/3), 142-159. doi:http://dx.doi.org/10.1504/IJETM.2002.000783

McGraw-HillConstruction. (2011). Efficient Business Case for Energy Efficient Building Retrofit and Renovation. Retrieved from https://energy.gov/sites/prod/files/2013/12/f5/business_case_for_energy_efficiency_retrofit_renovation_smr_2011.pdf

Munasinghe, M. (2004). Sustainable Development: Basic Concepts and Application to Energy. In C. Cleveland (Ed.), Encyclopedia of Energy (pp. 789-808). New York: Elsevier. Retrieved from http://www.sciencedirect.com/science/article/pii/B012176480X004411.

National Museums Scotland (n.d.) History of National Museums Scotland. Retrieved from http://www.nms.ac.uk/about-us/history-of-national-museums-scotland/

Nahmens, I., & Ikuma, L. (2012). Effects of Lean Construction on Sustainability of Modular Homebuilding. Journal of Architectural Engineering, 18(2). doi:10.1061/(ASCE)AE.1943-5568.0000054

Noguchi, M., Nirmal, S. & Muneer, T. (2012) A 10kWp Photovoltaic facility for Fairfield Housing Co-operative. Retrieved from http://www.cicstart.org/userfiles/file/FS-35-REPORT.PDF

Ozbekhan, H. (1969). The Future as an Ethical Concept. In Proceedings of the 6th General Assembly and Congress, International Conference of Societies of Industrial Designers, September 1969, London

Power, A. (2008). Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability? Energy Policy, 36(12), 4487-4501. doi: 10.1016/j.enpol.2008.09.022

Priemus, H. (1986). Post-war public high-rise housing estates: what went wrong with housing policy, with the design and with management. Netherlands Journal of Housing and Environmental Research, 1(2).

Rossem, V. v., Ulzen, P. v., Vries, R. d., Gooijer, A., Gelinck, S., Hulten, F. v., & Schravesande, M. (2017). DIY KLARENSTRAAT: A new perspective on the post-war social housing block. In P. v. Ulzen, A. Buissink, & R. d. Vries (Eds.). Heijningen: JapSam Books.

Russell, P., & Moffatt, S. (2001). Assessing the Adaptability of Buildings, IEA Annex 31 Energy-Related Environmental Impact of Buildings. Retrieved from http://www.ecbcs.org/annexes/annex31.htm

RVO. (2016). Energieprestatievergoeding (EPV). Retrieved from https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/wetten-en-regels-gebouwen/bestaande-bouw/energieprestatievergoeding

Thomsen, A. (2010). Paradigm shift or choke? The future of the Western European housing stock. Paper presented at the Housing: the next 20 years - CCHPR Conference, 20-23 June, Amsterdam.

Thomsen, A. F., & van der Flier, C. L. (2008). Replacement or reuse? The choice between demolition and life cycle extension from a sustainable viewpoint. Shrinking Cities, Sprawling Suburbs, Changing Countrysides (Vol. 1). Centre for Housing Research, UCD.

UN. (1992). Agenda21. Paper presented at the United Nations Conference on Environment & Development, Rio de Janerio. Brazil. Retrieved from https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf.

UNESCO. (2003). What is sustainable development? Retrieved from http://portal.unesco.org/fr/ev.php-URL_ID=3994&URL_DO=DO_TOPIC&URL_SECTION=201.html

Waide, P., Gurtler, P., & Smith, W. (2006). High-Rise Refurbishment: The Energy-Efficient Upgrade of Multi-Story Residences in the European Union. EuroACE. Retrieved from https://www.iea.org/publications/freepublications/publication/pw_Highrise.pdf

WCED. (1987). Our common future. Oxford; New York: Oxford University Press.

Adaptive Socio-Technical Devices _
Social Inclusion as a Rehabilitation Tool

Francesca Guidolin[1]

1 Ph.D in Building Technology, Università Iuav di Venezia, Venice, e-mail: francesca.guidolin@iuav.it

ABSTRACT **The complexity of the contemporary city is determined by socio-economic and demographic changes and by new energy standards that bring us to consider the rehabilitation of the building stock as a crucial and complex issue. The concept of sustainability requires an adaptive "integrated rehabilitation", in order to upgrade buildings not only from a structural, energetic, and architectural point of view, but also from a functional and social one. The research considers one of the most outdated sectors: residential multifamily buildings of the post-war years, which are today at the centre of a debate on their functional, security, and typological obsolescence. The need for urgent refurbishment, while avoiding demolition, brings us to consider the importance of additive strategies for regeneration, which include social, management, and financial feasibility. Some of those strategies are recognisable as "socio-technical devices": artefacts in which technical issues are strictly related to social ones, for the efficiency of the whole system. *Socio-technical devices* in building technologies for refurbishment allow us to manage the complexity of a construction site *au milieu habité*, facing the problems related to residential functions in the rehabilitation of multi-storey buildings. Starting from the definition of this concept, the research investigates, through the analysis of European case studies, new scenarios for renewal processes to prevent the breaking point of the city as a system, for a more resilient, adaptive, and bottom-up intervention strategy.**

KEYWORDS integrated rehabilitation, socio-technical systems, resilient and adaptive innovation, social innovation

1 Introduction

In the last decades, new requirements were added to the necessity of structural and energy upgrading of the most obsolete building sector. Those requirements were determined by urgent issues at the urban and architectural scale, caused by demographic, social, and economic changes. The progressive ageing of the population and urbanisation caused by several factors, such as rural migration to urban areas, led to a disturbance of the equilibrium in housing demand and supply, which in turn led to a consequent unavoidable reflection on strategies and methods.

According to the current standards, in fact, the approach of sustainability in architecture, design, and construction considers the whole life-cycle of the building, not only from an environmental point of view, but also from social perspective. The ISO/DIS 15392 – *Sustainability in building construction – general principles*, prescribes a "holistic approach".

Across Europe, a large part of the existing multifamily residential stock is no longer acceptable for energetic, structural, architectural, and functional reasons.

Some data can be found in the Research TABULA, *Typology Approach for BUiLding stock energy Assessment*, part of the European Program *Intelligent Energy Europe*, that has highlighted potential energy saving through the refurbishment of the multi-family buildings (built from 1946 to 1960). The neighbourhoods built after the Second World War encompass the typical examples of high density residential buildings in which architecture is characterised by quantitative needs, instead of qualitative requirements: heavy prefabrication building systems like *tunnel*, or *banches et tables* systems, show different kinds of typological and functional deficiencies (Zaffagnini, 1982; De Vita, 1965). Some of their characteristics, such as rigid space organisation, low architectural distinction among parts, limited recognisability of functions, and uniformity of the façades are seen as a lack of architectural quality: the results are monolithic blocks, which, in most cases, are no longer acceptable.

An illustrative example of those problems that determine the absence of flexibility, incorrect space dimensioning, and inattention to the social consequences of the architectural design process can be found in the case of the American neighbourhood of Pruitt Igoe, in St. Louis (USA). The demolition of this block, conducted in 1972, was recorded as the moment in which "modern architecture died", in the words of the historian Charles Jencks, who recognised in the event the breaking point of the *modern* way to conceive buildings and design neighbourhoods that was typical of rationalism (Jencks, 1977). The case of Pruitt Igoe is a story of architectural degeneration that implied a social deterioration, and it is comparable to different cases across Europe.

In Italy, examples of this can be found in the neighbourhoods of "il Corviale" and "Tuscolano" in Rome, "Rozzol Melara" in Trieste, "Le

Vele" in Naples, the "Gallaratese" in Milan, the "Zen" in Palermo, the "Pilastro" in Bologna and the "Forte Quezzi" in Genoa. In those neighbourhoods, new regeneration projects and research tried to address social problems connected to an old architectural set-up, which was no longer sustainable for social and constructive reasons.

In these circumstances, the issues of flexibility and adaptability must be considered as important instruments to be taken into account in order to select and implement the right strategy for refurbishment, considering social benefits next to the material ones.

In the dichotomy between *demolition* and *refurbishment*, the principle of sustainability leads us to prefer the latter, which offers more advantages from an environmental and social point of view: reuse, recycling, and restoration allow the limited use of new materials; on the other hand, refurbishment allows us to keep the dwellers' "habitat" unaltered, thus the community of inhabitants of the building preserves its usual organisation and functioning.

Under these circumstances, the refurbishment challenge is to recognise the appropriate applicable strategy that could take into account exigencies and realise a performance upgrade, as requested by actual European standards.

Among the renewal strategies, the additive methods are the most used today in integrating new performances into old buildings. In particular, the *Exoskeleton System* seems to be the most high-performance mode to carry out a holistic refurbishment. This method can be classified as a three-dimensional additive strategy that consists of volumetric expansions, structurally independent from the building, that provide structural, energetic, functional, and social upgrade. This is possible thanks to the possibility to extend on top of existing roofs, and additions to façades.

The aim of this section is to investigate the potentialities of socio-technical devices, such as the Exoskeleton System, for their important role in extending the concept of refurbishment to also meet functional and social demands. To address this issue, the chapter will analyse the requirements of obsolete buildings in comparison to future social changes in order to highlight the importance of new design qualities for the renewal of residential buildings. Starting from the definition of the *socio-technical device*, this innovative approach will be illustrated in some case studies, such as the Exoskeleton System.

2 Household Changes

Different European studies show that there have been important changes from the '50s to the present day, and even more mutations are projected up to 2080.

Society in Europe is progressively ageing. The Report of *Eurostat 2015* shows that the median age of EU-28's population has risen from 36.2 in 1994 to 42.2 in 2014. The projection for 2080 predicts a rise in the number of people aged over 85, which corresponds with the range of people who live alone: 13.4 % of households in these countries in 2013 comprise a single person family aged over 65, according to the *EU statistics on income and living conditions* (EU-SILC).

The continuous ageing of people combined with the necessity for autonomy and independence proves the demand of functional upgrades for building stock in terms of accessibility, inclusion, security, and comfort. At the same time, research shows a *change of household habits*: family units are deeply transformed with the spread of single-parent families, singles, co-habiting people, and large immigrant families (Delera, 2009; Malighetti, 2004; Piaia, 2009).

All of this leads to new social and functional needs that existing residential buildings can no longer answer. It is necessary to consider possible adaptable scenarios for refurbishment, which consider the complexity of the problem and the integration of different aspects in terms of *flexibility of internal organisation* and the introduction of *adaptive spaces*.

Flexibility and adaptability must be considered in both the long term and the short term: on one hand, there is a rise of dynamism in the family's structures (e.g. increase in number of divorces), while on the other hand, more dwelling spaces adaptable to new uses are necessary (e.g. working at home, teleworking, co-housing, etc.). The heterogeneity of habits and cultures also requires the adaptation of spaces due to diversity of cultures and, therefore, different ways of living.

Such issues indicate that, although energy saving measures or structural safety are largely recognised as priorities, functional deficiencies must also be taken into account. Among the requested performances for adaptive reuse, refurbishment, or maintenance are:

- *flexibility* in space and functions distribution (Cellucci & Di Sivo, 2016);
- *adaptability* of different spaces or devices for several, and unprecedented, uses; (Montuori, 2014; Wong, 2016)
- *accessibility*, *security,* and *inclusion,* for living conditions and building fruition.

Those requirements consider not only the technical performances of the building or its parts, but the whole space design and building process. For this reason, the evaluation of these qualities requests a holistic approach that considers the various aspects of design and the proactive maintenance of achieved qualities over time.

3 Architectural Prosthesis

Today, several studies look at additional strategies for refurbishment (Marini, 2008; Scuderi, 2015; Arenghi & Pane, 2016), specifically in relation to their implications in the modification of the city as an "urban metabolism". This term was coined to describe the urban ecosystem as a living organism, subject to energy and material flows (Decker, Elliott, Smith, Blake & Sherwood Rowland, 2000). In this scenario, several strategies can be found, which can be divided into increasing density strategies, such as *volumetric additions*, *grafting*, *filling,* and *roof-topping* and decreasing density approaches, such as *emptying*, *digging,* or *remodelage* (Castro & Denissof, 2005).

This diversity of approaches leads to the recognition of the refurbishment practice as a highly creative act, in which architects and designers can express themselves even in already built contexts. This is also the reason why, in recent years, refurbishment methods through additional volumes have increased.

The additive approach, particularly in relation to accessibility and inclusion purposes, deserves specific mention. In this case, a high social and functional upgrade is linked to function restoring in the building: in most cases, barrier-free accessibility or inclusion systems are realised through additions to old buildings in which spaces and structural organisation preclude internal interventions: emergency stairwells, additional lifts or elevation systems, and galleries for circulation facilities are typical examples of these *functional prosthetic systems*.

The correlation between body and architecture prosthetics is not new (Wigley, 1991), and can be clarified in different functional and morphological homologies: external or internal, structural or functional, and temporary or permanent prostheses can be applied to buildings as to the human body. The concept of Exoskeleton itself, which is the main topic of this chapter, is an application of the homology between physical and functional issues of human and architectural bodies (Fig. 3.1).

FIG. 3.1 The Bionic Exoskeleton for human bio medical rehabilitation. Ekso Bionics *(Image copyright Ekso Bionics, 2011)*

The term "exoskeleton" was firstly used in the zoological science to indicate the tegument of some invertebrates with structural and chemical characteristics; in recent times, through a biomimetic approach, it has passed to the military field as a device to carry heavy loads and to biomedical practice as a technical suit for people with reduced mobility.

Referring to this correlation between body and architecture, most volumetric additions for accessibility and inclusion can be read as prosthetic devices: functional, regenerative structures that enable the building to restore its functionalities (Fig. 3.2).

FIG. 3.2 Examples of functional additions for accessibility and security: architectural prosthesis. From left: security stairwell in a historical building, Tolentini, Venice; external security stairs in New York *(Image by Lidia Savioli, 2015)*; external lift in Bolzano *(Image by Comune di Bolzano, 2014)*; external lift in the Reina Sofia Museum, Madrid *(Image by Valeria Tatano, 2014)*

As with the Exoskeleton System, functional prosthesis for accessibility can also be read as *socio-technical devices*, in which the addition of a technical apparatus allows the functional upgrade and the quality restoration of the building: a new functional programme for circulation.

However, their functionality is limited to the purely accessible, or internal flexibility improvement, whereas for the Exoskeleton, the complete and continuous morphology of the technical apparatus allows the whole reorganisation of the building structure, with improvements on many levels.

4 Rehabilitation Approaches

The adaptation for the multi-family residential typology has an additional challenge. This is due to the necessity for intervention in an inhabited environment. For this reason, key roles are played by the presence of communities, problems related to residential functions, construction site management, and the relocation of people during the implementation of the intervention.

Although the practice of demolition and new construction is possible, this "scrapping" solution (Micelli, 2011) is not always workable, firstly

TOC

for social reasons, but also for economic and environmental causes. As detected by the *Guidelines for the selection and use of fuels and raw materials in the cement manufacturing process* (WBCSD, 2005), the scale of value for the management of construction waste shows that prevention, reduction, reuse, and recycle are at the top of the range of priorities (Fig. 4.1). Moreover, construction waste is not environmentally friendly, due to its impact on the eco-system. Referring, for example, to the Italian context, construction waste is recognisable as "special waste", the treatment of which requires important economic expenditure (D.M. 152/2006, *Norme in materia ambientale, Art. 184, classificazione*).

According to recent research on construction in Europe (BPIE, 2011), the general obsolescence of the building stock requests a "mending operation" (Piano, 2014): a suitable urban renewal and architectural refurbishment that must be read in the context of *integrated rehabilitation* (Montuori, 2014), a holistic approach to the redevelopment process that combines energetic, structural, social, and economic strategies in an inhabited environment.

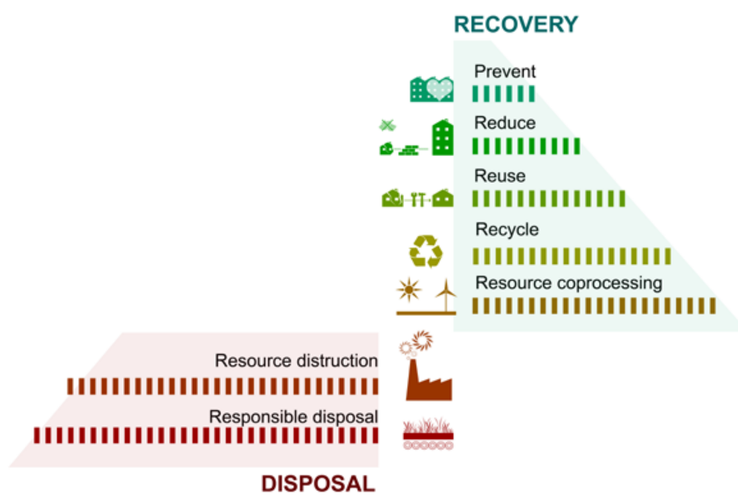


FIG. 4.1 Scale of sustainable treatment from disposal to recovery. Graphic diagram derived from WBCSD, 2005 *(Image by Francesca Guidolin, 2014)*

4.1 Functional and Social Upgrade: Strategies and Methods

As stated above, among the strategies for rehabilitation, a common method for functional upgrade can be recognised in the *additive strategy*. Several refurbishment interventions, carried out in Europe in the last two decades, have been considered and analysed, then classified throughout morphological and constructive parameters, with the aim of evaluating performances in terms of *integrated refurbishment*.

The definition of a "synoptic diagram" is based on the requirement/performance approach, and can be seen in the "taxonomy of refurbishment methods" (Fig. 4.2).

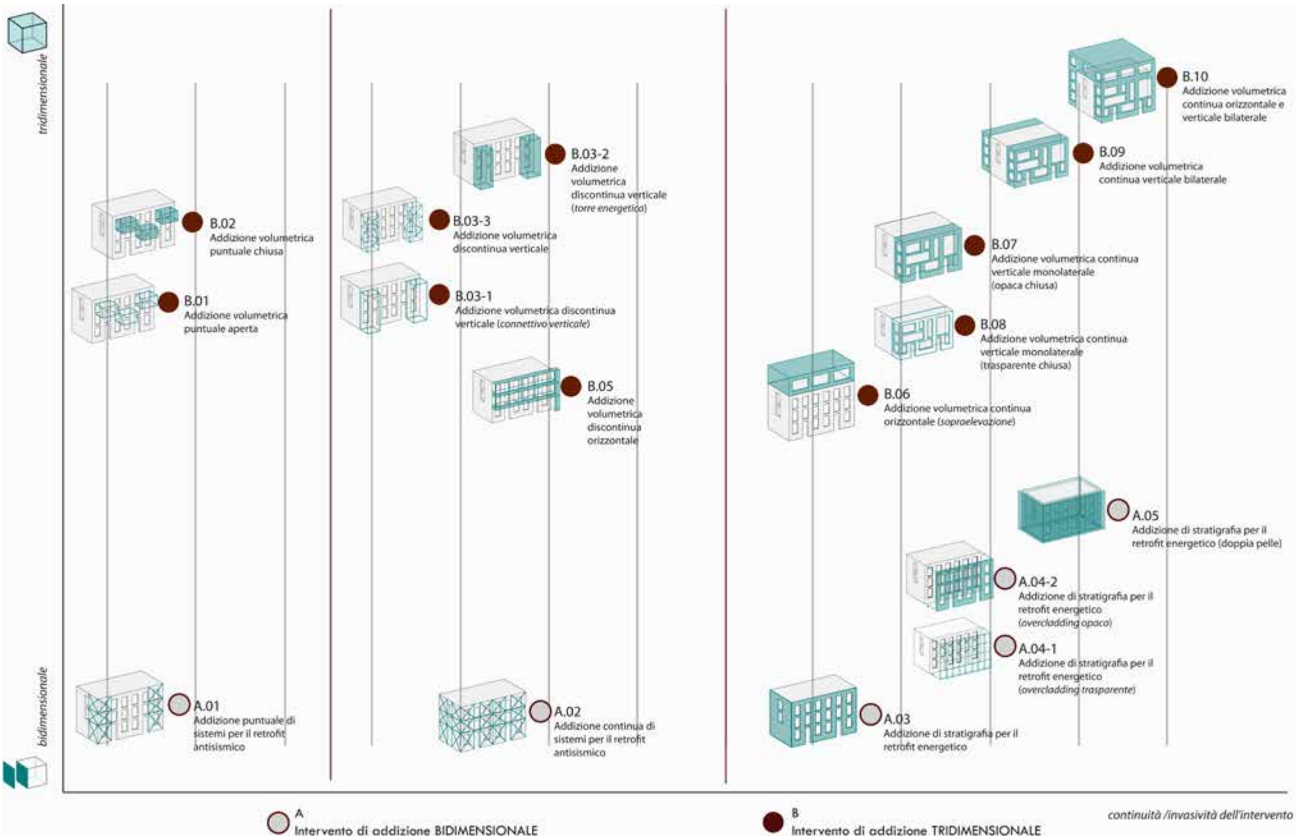


FIG. 4.2 Taxonomy of refurbishment methods, from two-dimensional to three-dimensional additive strategies *(Image by Francesca Guidolin, 2014)*

The synoptic diagram classifies on the abscissa the morphological parameters, from punctual (elements, boxes, towers) to continuous additions (both vertical, as lateral expansions, and horizontal, as roof-topping additions); whereas on the ordinate it classifies the constructive data, from two-dimensional (new high-performance layers), to three-dimensional additions (open or closed volumetric expansions).

The diagram can also be read as ranking intervention through three main types: *integration* of elements or systems; *substitution* of elements or systems with more qualitative ones; and *addition* of systems or spaces: the most relevant, as well as the most beneficial, renewal operation.

The practice of energetic and seismic rehabilitation shows the high impact of façade refurbishment: *seismic retrofit*, *overcladding*, *recladding,* and *refitting* (Trabucco & Fava, 2013; Zappa, 2011). Such integrations are added on the building envelope, or alter the envelope to create a more high-performance external shell.

The most effective solutions for functional upgrade are the additive ones, which can also improve the structure and the typological choices of buildings. Some of these actions result in punctual boxes, passive or circulation towers, and continuous and global volumes (Fig. 4.3).

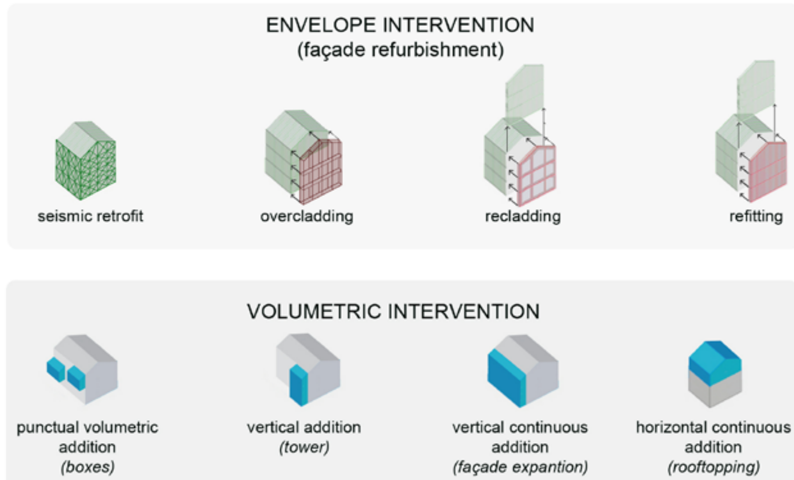


FIG. 4.3 Refurbishment methods: from façade refurbishment to volumetric additions *(Image by Francesca Guidolin, 2014)*

The results of this analysis reveal that the larger functional, energetic, and structural increase in performance lies in the area of the maximum ordinate and abscissa, where the three-dimensional construction technique intersects the volumetric addition strategies. This synoptic diagram, based on the taxonomy of rehabilitation strategies (Zambelli, 2004), finds a correlation in some European examples:

– the *Tour Bois le Prêtre* requalification by F. Druot, A. Lacaton and J.P. Vassal (Paris, 2008-2012);
– the *Villeneuve la Garenne* rehabilitation of "La Banane" by Groupe Arcane Architectes – Paris (Paris, 2009-2013);
– the *Westerpark* intervention by Van Hoogmoed Architecten (now PAN+ architectuur) (Tilburg, 2008);
– the *Leeuw Van Vlaanderen* intervention by Heren 5 Architecten (Amsterdam, 2007);
– the *Rathenow building renewal* by Klaus Sill and Jochen Keim (Rathenow, 1997);
– *Le Navi* rehabilitation by Ipostudio Architetti Firenze, a project for the European Research SuRE-Fit, 2006.

5 Towards the "Exoskeleton System"

The treatment of the envelope as a building skin can be found in recent strategies for climatic regulation, such as the introduction of shadings or skin envelope (OECD/IEA, 2013), but the possibility of integrating some volumetric additions in the envelope is an issue with high potential.

In fact, functional upgrades are realised through the addition of vertical and horizontal circulation spaces (stairs and lift, emergency exits, or emergency stairs), additional dwellings at the rooftop, private spaces inside the dwellings (additional or enlarged rooms), or collective (residential services, halls, community spaces), besides the energetic and structural improvements. Considering the more invasive intervention, that is, the global volumetric addition with a rooftop extension, it is possible to recognise the "Exoskeleton System" (Guidolin, 2016) (Fig. 5.1).Current research is investigating the adaptability potential of this device in terms of typological reshaping (Angi, 2016), as well as for its structural characteristics (Feroldi et al., 2014; Scuderi, 2015) and energetic possibilities.

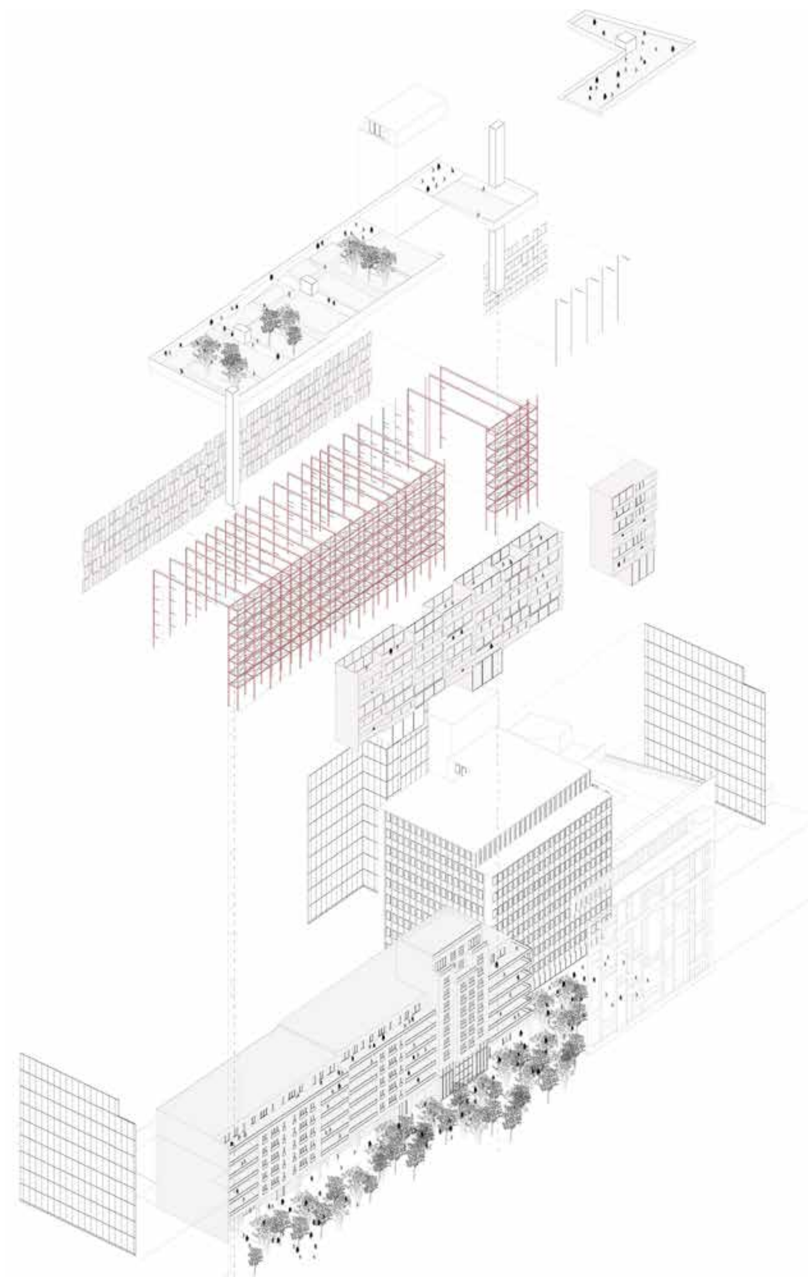


FIG. 5.1 The Exoskeleton System, image from the project "Pour une Réhabilitation Verte" *CAUE (Conseil d'Architecture Urbanisme et Environnement*) Paris International Challenge *(Image by Francesca Guidolin, Francesco Cauda, Mattia Chinellato, Francesco Messina, Enrico Robin, 2015)*

Exoskeleton structure, as can be seen in Fig. 5.2, is technologically composed of a structural system and cladding, two technological systems that can be totally designed and personalised. The standardisation of the grid with replicable modules can be customised to answer environmental and functional requirements.

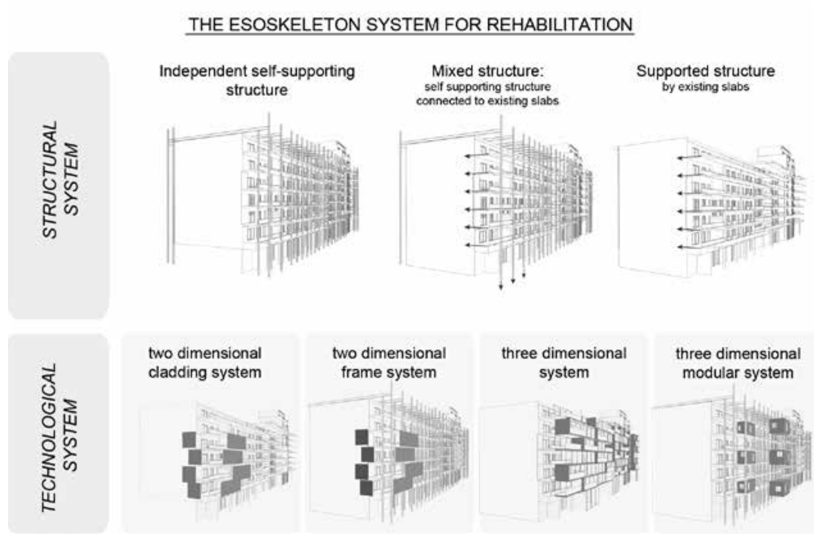


FIG. 5.2 The Exoskeleton System, structural and technological construction systems *(Image by Francesca Guidolin, 2014)*

Therefore, this additional envelope can include different private or collective spaces:

- *Winter gardens* and *greenhouses,* which, besides giving new functions, contribute to active micro-climate regulation and improvement for the dwellings, or the whole building in the case of towers. The adaptive characteristics of these new functions display their flexibility through the year, and are used seasonally and daily in different ways.
- At the same time, these spaces are used passively as buffer zones between the internal and external micro-climate, thus reducing transmittance.
- *Circulation towers*, containing stairwells, lifts, and collective spaces, that can also be used for energetic reasons such as solar chimneys, can stimulate the natural ventilation of the building, and of each dwelling if correctly designed.
- *New envelope claddings*: new windows frames are possible, by changing the old façade (which is now internal) and reconfiguring the balance between "empty and filled" space in the façade. This is achievable through a new combination of transparent or opaque cladding, realised with more insulating coatings.
- *Galleries and balconies,* which can simplify the accessibility of circulation, dwellings, and facilitate the organisation of internal space in each dwelling. In this case the building typology can be modified from a multi-level bar building to a bar building with balcony entrance. This modification enables the use of old circulation spaces as new collective spaces, or private spaces for each dwelling, or simply gives the possibility of a second fire exit for safety purposes.

The Exoskeleton System, as it relates to social characteristics, can be seen as a *socio-technical device* (Vermaas, Kroes, Van de Poel, Franssen, & Houkes, 2013). This definition was first given by Eric Trist and Ken Bamforth in 1951 (Trist & Labour, 1981) and it identifies an artefact that implies a relationship between technological issues and social ones, as well as the users' social behaviour in a place. In this respect, the use of an independent structure outside the original building is identifiable as a *socio-technical device* for four reasons:

- **Inclusion and accessibility**: being a strategy for functional upgrade in terms of accessibility could constitute a scenario for the renewal of the obsolete building stock, adapting it to ageing or disabled people, and increasing residential services and comfort.

- **Customisation, personalisation and decision-making inclusion**: a technological system allows each inhabitant to choose materials and uses: additional rooms, spaces, and technologies to improve the flexibility and adaptability of the dwellings (Reich, 1992; Wultz, 1986;).

- **Social innovation**: for multi-storey residential buildings, this is a functional issue for the activation of social participation in the development of the participative design process, from the initial phases (e.g. the mapping of needs) through to appropriate communication channels with the users.

- **Participative construction processes**: the importance of an external volumetric addition lies in the practical implications for the construction site, in particular the indirect costs of inhabitants' relocation for the management of the construction site *au milieu habité* or *en site occupé* (on a occupied site). The possibility to operate without interrupting the normal functioning of the building (e.g. avoiding the resettlement of inhabitants to other temporary dwellings) allows us to contain costs and to manage a less intrusive intervention.

These features are particularly interesting if we consider a building typology in which there is a "community" of inhabitants that has already defined its processes and rules. In such cases, the reasons that often lead to a slowdown of the refurbishment interventions result from disagreement on the inhabitants' part. Moreover, a heterogeneous social context and shared ownership (i.e. the coexistence of private and public owners) increase difficulties, highlighting different and often conflicting exigencies.

For these reasons, the establishment of programmes for public participation of communities and neighbourhoods in the decision-making processes could constitute the basis of a well-planned management structure, and for the resolution of many possible conflicts. Some recent examples apply technological devices to solve social problems during the participatory rehabilitation construction site, through the use of external structural additions such as Exoskeletons.

6 The Examples of Socio-Technical Devices for Refurbishment

The definition of a socio-technical device leads to the consideration of the Exoskeleton System as a technical artefact. In these kinds of devices, technical systems are strictly related to their social implications: it is possible to recognise a building as a closed *organisation,* in which existing rules, social relationships, and behaviours are already set up.

Thus, by introducing physical modifications to this apparatus, it is also possible to modify the pre-existing social conditions, as explained earlier (Par. 4): improving accessibility and inclusion, allowing the personalisation of technical solutions, and enabling social innovation and participation.

Recent refurbishment interventions carried out in the last decade in Europe, some of which are listed below, show how volumetric independent additions such as the Exoskeleton System can improve these qualities. Four examples from the refurbishment interventions studied in the research (Guidolin, 2017) are described here, selected for their illustrative characteristics as socio-technical devices.

6.1 « La Banane », Villeneuve la Garenne (FR)

In the "La Banane" refurbishment, realised in 2013 by Groupe Arcane Architectes – Paris, and the tenant agency *Coopération et Famille* in Villeneuve La Garenne (FR), the intervention concerned the expansion of the façades through the dismantling and substitution of claddings with the use of an external structure - a concrete exoskeleton. The construction site was not only realised "au milieu habité", but also without the need for the temporary displacement of inhabitants from their dwellings. To avoid the displacement of the dwellers, a technical solution was used in order to border the construction site for environmental and security reasons. This solution required the use of a well-suited building technology: a temporary partition was erected in each dwelling, in order to separate the construction site from the internal spaces (allowing also for asbestos removal), for a period of 3-4 weeks.

A participative process was carried out, to communicate the construction phases to the inhabitants, which included a series of meetings with the residents of the community to explain phases and results of the operation. Moreover, due to the complexity and the experimental nature of the intervention process, the construction agency, in conjunction with the architectural agency Groupe Arcane Architectes, produced some instruction manuals: a technical manual for the construction company and a communication manual for the inhabitants.

FIG. 6.1 The construction site of "La Banane" refurbishment in Villeneuve La Garenne, Groupe Arcane Architectes - Paris. *(Image by Groupe Arcane Architectes – Paris, 2013)*

This is an example of how technical tasks, if adapted and well communicated to the social players (the inhabitants) and stakeholders, can bring about the realisation of refurbishment interventions even if they are complex and difficult.

6.2 Westerpark Refurbishment in Tilburg (NL)

The refurbishment of the Westerpark neighbourhood in Tilburg, the Netherlands, in 2005, was carried out by the municipality and *TIWOS – Tilburgse Woonstichting*, with the support of the European Community in the SuRE-FIT project *(Sustainable Roof Extension Retrofit for High-Rise Social Housing in Europe*). A balance of cost-benefit ratio was carried out by Van Hoogmoed Architects (now PAN+ architectuur), demonstrating that costs related to the displacement of the inhabitants in the case of renewal can make the difference.

Three buildings were completely renovated in the Westerpark neighbourhood, by adding a floor on the rooftop and some spaces throughout the volumetric extension on the façades.The intervention was conducted simultaneously on all three buildings, forcing a substantial amount of displacement of residents (about 600,000 euros, according to the estimations of the architectural firm that conducted the intervention), which could have been reduced by dividing the operation into sections and phases (European Commission IEEA, 2010). The construction site organisation thus becomes a crucial point in managing the economy of the process, in which the inhabitant can play a non-marginal role.

FIG. 6.2 The construction site phases of the Westerpark intervention in Tilburg (NL), Van Hoogmoed Architecten (now PAN+ architectuur) *(Image by PAN+, 2005)*

6.3 Tour Bois le Prêtre (FR)

The organisation of a construction site through a participatory process was visible in the transformation of the *Tour Bois-Le-Prêtre* in Paris, by Fréderic Druot, Anne Lacaton, and Jean Philippe Vassal (2008-2012).

An architectural challenge launched by the Paris OPAC (*Office Public d'Aménagement et de Construction*) with the architect François Helene Jourda, did not allow this refurbishment as part of it, although some design characteristics had already been established. The challenge also excluded the demolition of the tower; in addition, the challenge requested the participation of dwellers in the definition of programmes from the beginning of the operation. Dwellers were also involved in the challenge programme, through a study of their requirements and needs (security, collective spaces renewal, new uses).

FIG. 6.3 The Tour Bois-le-Prêtre transformation, Frédéric Druot, Anne Lacaton, Jean-Philippe Vassal *(Images by Matteo Busa, 2014)*

The process started with the mapping of exigencies and the functional requirements for each residential unit. As in the *Villeneuve La Garenne* intervention, a single dwelling was first renovated to be used as a mock-up example for inhabitants. This action led the dwellers to understand what kind of intervention was going to take place, the construction site process, and the operations. According to Frédéric Druot, the construction site director was required to be present on site 60% of the time; moreover, a professional who took charge of relations with the inhabitants 100% of the time, during the construction stage carried out "au milieu habité" (PUCA, 2012).

In this case, an important improvement for accessibility was carried out thanks to volumetric additions: the existing stairwells and lifts were substituted with two transparent lifts, located at the north and south façades, with transparent materials, which allow the natural lighting of the halls of every floor. Also, fire security compartmentations were added, one for each floor, made up of transparent material too, for the same reason.

These examples show how the refurbishment device of the Exoskeleton System can be recognised as an application of a *socio-technical system* due to its ability to integrate purely technical and material aspects with social issues that this constructive device provides, not only in terms of functional upgrade (i.e. flexibility, adaptability and personalisation), but also in the feasibility of the intervention process, such as in the construction site management.The Exoskeleton System can avoid the interruption of indoor activities, thus being useful in cases in which the intervention process is inhibited by social reasons (for instance in hospitals, social housing, and multi-storey and heterogeneous property buildings).

In rehabilitation interventions, the possibility of avoiding inhabitant relocation is achievable through the introduction of rooftop extensions, which can be used as temporary dwellings for the users whose dwellings are being retrofitted. The rooftop expansion, which can be read as a *continuous horizontal addition* is possible due to the structural independence of the Exoskeleton System, which has independent foundations.

One of the justifications of this practice is the feasibility study carried out by Anna Delera and Paolo Carli (Polytechnic University of Milan) for the Quartiere Barzoni intervention, in which inhabitants are to be moved towards a new temporary construction during the intervention (Carli, 2012). In this feasibility study, there were three phases:

- The first phase, with the mobility inside of the four dwellings and external mobility of nine others;
- The second phase, with the internal mobility of fourteen dwellers in temporary rooftop houses, and six dwellers in external mobility;
- The third phase, with eighteen new dwellings on the rooftop and seven dwellers in external mobility.

The result was the construction of two towers in the north sector, the rooftop addition to other bars in the southern sectors with the relocation of as few dwellers as possible.

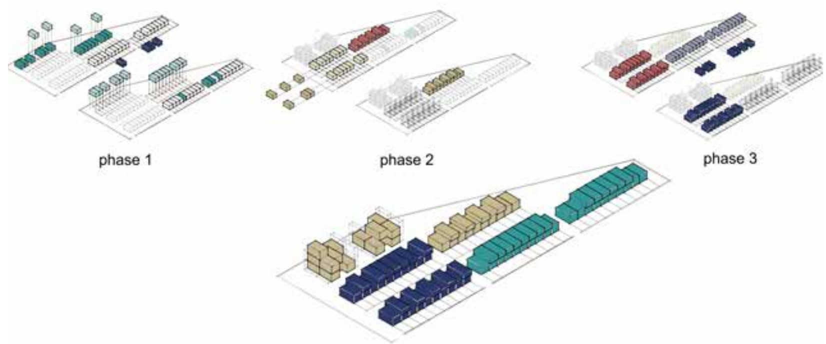


FIG. 6.4 The construction site planned for the feasibility study for Quartiere Barzoni, Milan. Anna Delera and Paolo Carli (2012) *(Image by Francesca Guidolin, 2015)*

7 Conclusion

The contemporary scenario for multi-storey residential buildings is complex from different points of view. The loss of quality, in terms of energy and structure, leads to deep retrofit interventions, whereas functional and architectonic obsolescence asks for a new building organisation and appearance, and in most cases, also a new envelope for the building. These exigencies are often typical of areas in which the social situation is complex, for example, in multi-storey residential buildings of the '50s-'70s that are sometimes characterised by decay or weak neighbourhood areas.

The analysis undertaken classifies some strategies for rehabilitation in the perspective of upgrading the structural, energetic, and functional performances, and overcoming problems that multi-storey residential buildings can carry.

As the "broken window theory" (Wilson & Kelling, 1982) states, social degradation is deeply linked to material decay. This fact brings us to consider the importance of applying a "technological reconnection" (Angelucci, Cellucci, Di Sivo & Ladiana, 2015) in the refurbishment intervention, conceiving an adaptable solution for all aspects, in a holistic way.

The Exoskeleton System could be considered among the various volumetric addition strategies, for its potential to become an "integrated requalification" practice for buildings dating from the period after the second world war. Beyond the energy and structural necessities, which it is able to satisfy, the Exoskeleton System focuses on functional performances through the analysis of the space inclusiveness quality, in order to achieve an architectural upgrade of buildings and solve consequent circulation issues.

In the case of the structural seismic refurbishment in particular, it allows us to bear and to discharge horizontal seismic thrusts to the vertical structures, implementing the resilience of the building through dumper systems. On the other hand, for energetic purposes, it is an adaptive double envelope, able to regulate energy flows from internal environmental conditions to external ones and vice versa. The possibility of expanding volumes leads to its consideration as an *architectural functional prosthesis*, in which new structures afford the empowerment of quality in use: lifts, additional rooms, new flexible private or collective spaces fulfil the requirements of the contemporary way of "living".

Besides those potentialities, however, there are some relevant limits for its application. They can be summarised as *urban-planning constraints*, due to the need for external free space, which defines the building expansion, and *dimensional and spatial constraints,* which ask for an appropriate design in order to respect distances and maximum heights in the urban context.

Alongside those limits, others are *economic and administrative*: sometimes mixed ownership buildings, in which private and public dwellings coexist, are more difficult to renew due to the financial effort of this kind of structure. In this case, a refurbishment intervention purely to the façade is more simple to apply, even if it doesn't bring any functional or social improvement.

The analysed interventions show the high potentiality of volumetric additional methods. In such operations, the technological issues are related to some social benefits, which have to be considered as equally important in the new scenarios of adaptive retrofit. This quality, in fact, is necessarily declined throughout the social impact that buildings have in their life-cycle assessment, for the urban fabric but also for the communities - the social organisations - they contain.

If we read the community of inhabitants as a pre-existing closed organisation, with its own processes, social and relational structures, people and programmes, it is clear that every spatial and technical modification of this *habitat* needs to be the most flexible possible and custom-designed for the specific context.

Read as a socio-technical device, the Exoskeleton is a technological strategy identifiable as an adaptable method for future uses, from the perspective of resilience and adaptability of the already built context.

At an urban scale, it is possible to introduce the Exoskeleton as a strategic issue for the regeneration of communities: new community services, spaces for aggregation and public or collective activities. In addition, the density increase can be seen as an opportunity to develop mixed use zones.

These results, if combined with the European demographic future projection of ageing and the need for flexibility, can determine more sustainable living conditions for communities. Moreover, at the scale of the building, the architectural appearance and performance can be completely modified through the re-design of an adaptive envelope. A new skin for the building, which is able to manage and regulate the energetic flows, creates new spaces for different and sustainable uses such as winter gardens, greenhouses, and new mixed-use rooms and spaces.

The Exoskeleton System can thus be seen as a part of strategic intervention for neighbourhood regeneration: the future perspective of rapid demographic, social, and energetic modifications requires self-adapting, flexible, and resilient buildings.

References

AA.VV. (2010). *Build on top, Duurzame revitalisering Westerpark*. [Build on top, Westerpark sustainable revitalisation] Luxembourg: IEEA European Commission.

Angelucci, F., Cellucci, C., Di Sivo, M. & Ladiana, D. (2015). The measurable and the real quality of life in the city. Urban regeneration as a technological correlation of resources, spaces and inhabitants. *TECHNE - Journal of Technology for Architecture and Environment*, 10, 67-76. DOI: http://dx.doi.org/10.13128/Techne-17502

Angi, B. (Ed.). (2016). *Eutopia urbana / Eutopia Urbanscape, La riqualificazione integrata dell'edilizia sociale, The combined redevelopment of social housing*. Siracusa: LetteraVentidue.

Antonini, E., Gaspari, J. & Olivieri, G. (2012). Densifying to upgrading: strategies to improve the social housing built stock in Italy. *TECHNE - Journal of Technology for Architecture and Environment*, 4, 306- 314. DOI: http://dx.doi.org/10.13128/Techne-11531

Arenghi, A. & Pane, A. (2016). L'aggiunta nel progetto di restauro per l'accessibilità del patrimonio culturale. [The addition in conservation project for the accessibility to cultural heritage] *TECHNE – Journal of Technology for Architecture and Environment*, 12, 57-64. DOI: http://dx.doi.org/10.13128/Techne-19335

BPIE. (2011). *Europe's buildings under the microscope. A country-by-country review of the Energy performance of buildings*. Study prepared by the Building Performance Institute, Brussels.

Carli, P. (2012). The case of Via Barzoni 11. 'Tailored' participatory planning of social housing. *TECHNE – Journal of Technology for Architecture and Environment,* 4, 198-206. DOI: http://dx.doi.org/10.13128/Techne-11520

Castro, R. & Denissof, S. (2005). *Remodeler, Métamorphoser*. [Remodel, Metamorphose]Paris: Le Moniteur.

Cellucci, C. & Di Sivo, M. (2016). *Habitat contemporaneo. Flessibilità tecnologica e spaziale*. [Contemporary Habitat. Technological and spatial flexibility] Milano: FrancoAngeli.

De Vita, R. (1965). Esame e classificazione dei sistemi di prefabbricazione. [Examination and classification of prefabrication systems] In: AA.VV. *Industrializzazione Edilizia*. Bari: Dedalo Libri Ed., 271-313.

Decker, E. H., Elliott, S., Smith F.A., Blake, D.R. & Sherwood Rowland, F. (2000). Energy and material flow through the urban ecosystem. *Annual Review of Energy and the Environment,* 25, 685-740.

Delera, A. (2009). *Ri-pensare l'abitare. Politiche, progetti e tecnologie verso l'housing sociale*. [Re-thinking living. Policies, projects and technologies towards social housing] Bari: Hoepli Editore.

Druot, F., Lacaton, A. & Vassal, J. P. (2007). *Plus + La vivienda collectiva. Territorio de excepción*. [PLUS - Large Housing Projects - Exceptional Territories] Barcelona: Gustavo Gili Ed.

Ipostudio Architetti Associati. (2006). *Sure-Fit: Sustainable Roof Extension Retrofit for High-Rise Social Housing in Europe*. Intelligent Energy – Europe (IEE) Research Project.

Feroldi, F., Marini, A., Belleri, A., Passoni, C., Riva, P., Preti, M., Giuriani, E. & Plizzari G. (2014). Miglioramento e adeguamento sismico di edifici contemporanei mediante approccio integrato energetico, architettonico e strutturale con soluzioni a doppio involucro a minimo impatto ambientale. [Seismic improvement and of contemporary buildings through integrated energy, architectural and structural approach through double-envelope solutions with minimal environmental impact] *Progettazione sismica*, 5(2), 31-47.

Guidolin, F. (2016*)*. The Exoskeleton System as a socio-technical device. Coupling technical devices and social involvement in the rehabilitation process. In: *41st IAHS World Congress on Sustainability and Innovation for the Future, 13-16th September 2016, Albufeira, Algarve, Portugal*.

Guidolin, F. (2017). *Esoscheletri. Strategie additive per la riqualificazione integrata del costruito*. [Exoskeletons. Additional strategies for the integrated refurbishment] (Thesis). Venezia: Università Iuav di Venezia.

Jencks, C. (1977). *The language of Postmodern architecture*. London: Academy ed.

Malighetti, L. (2004). *Recupero edilizio e sostenibilità*. [Building renovation and sustainability] Milano: il Sole 24 Ore.

Marini, S. (2008). *Architettura parassita, strategie di riciclaggio per la città*. [Parasitic architecture, recycling strategies for the city] Macerata: Quodlibet.

Montuori, M. (2014). Eutopia urbana. Buone pratiche per la rigenerazione integrata degli edifici [Urban Utopia. Good Practices for Integrated Building Regeneration]. In: Cappochin G., Botti M., Furlan G. & Lironi S. (a cura di). *Ecoquartieri: EcoDistricts, strategie e tecniche di rigenerazione urbana in Europa - Strategies and Techniques for Urban Regeneration in Europe*. Venice: Marsilio Ed.

OECD/IEA. (2013). Transition to sustainable buildings, strategies and opportunities to 2050. Paris Cedex: IEA publications.

PIAIA E., (2009). EPIQR: sistema di valutazione della qualità negli interventi di recupero edilizio. [EPIQR: Quality assessment system in building refurbishment interventions.] In AA.VV, Low cost, low energy, quality architecture. Una nuova stagione per l'housing., Milano: Be-Ma, pp.90-90.

Piano, R. (2014). *Periferie, diario del rammendo delle nostre città*. [Suburbs, mending diary of our cities]. Report 2013-2014 of the G124. Milano: Il Sole24 Ore.

PUCA. (2012). *REHA: Requalification à haute performance énérgetique de l'habitat*. [Requalification with high energy performance of the habitat] Report. Paris: Le Moniteur.

Reich, Y. (1992). Participation and design: an extended view. In: *Proceedings of the Participatory Design Conference PDC '92, Boston, MA*.

Scuderi, G. (2015). Adaptive building exoskeletons: A biomimetic model for the rehabilitation of social housing. *Archnet-IJAR: International Journal of Architectural Research*, 9(1), 134-143.

Trabucco, D. & Fava, P. (2013). Confronting the question of demolition or renovation. *CTBUH Journal*, IV, 38-43.

Trist, E. & Labour, O. M. O. (1981). *The evolution of socio-technical systems: A conceptual framework and an action research program*. Ontario Ministry of Labour, Ontario Quality of Working Life Centre.

Vermaas, P., Kroes, P., Van de Poel, I., Franssen, M. & Houkes, W. (2013). *A philosophy of technology: from technical artefacts to sociotechnical systems*. San Rafael, CA: Morgan & Claypool Publishers.

WBCSD – World Business Council for Sustainable Development. (2005). *Guidelines for the selection and use of fuels and raw materials in the cement manufacturing process*. Conches-Geneva: WBCSD.

Wigley, M. (1991). Prosthetic theory. The disciplining of architecture. *Assemblage*, 15, 6-29.

Wilson, J. Q. & Kelling, G.L. (1982). Broken window theory. *Atlantic Monthly*, 249(3), 29-38.

Wong, L. (2016). *Adaptive reuse, Extending the lives of buildings*. Basel: Birkhauser.

Wultz, F. (1986). The concept of participation. *Design Studies*, 7(3), 153-162.

Zaffagnini, M. (ed.). (1982). *Progettare nel processo edilizio*. [Designing in the building process]. Bologna: Edizioni Luigi Parma.

Zambelli, E. (2004). *Ristrutturazione e trasformazione del costruito, tecnologie per la rifunzionalizzazione e la riorganizzazione architettonica degli spazi*. [Renovation and transformation of buildings, technologies for the refunctionalisation and the architectural reorganisation of spaces]. Milano: Il Sole 24 Ore.

Zappa, A. (2011). È tempo di re-cladding. [It's time for re-cladding] *Costruire,* 339, 82-86.

Biological Entities and Regeneration by Design

Marija Stamenković[1], Carmelo Zappulla[2] and Saja Kosanović[3*]

* Corresponding Author
1 Faculty of Technical Sciences – Architecture Department, University of Priština in Kosovska Mitrovica, e-mail: marija.stamenkovic@pr.ac.rs
2 Institute for Advanced Architecture of Catalonia (IAAC), Barcelona, e-mail: carmelo.zappulla@iaac.net , carmelo@externalreference.com
3 Faculty of Technical Sciences – Architecture Department, University of Priština in Kosovska Mitrovica, e-mail: saja.kosanovic@pr.ac.rs

ABSTRACT **Regenerative design aims to reverse environmental degradation and generate net positive impact by developing systems that are mutually beneficial and co-evolving for natural and social components of the living environment. As a regenerative approach is not only related to design but also to humans and their activities, this chapter reveals the necessity to establish a new interconnectedness between design principles of environmental regeneration and a tendency to intensify positive environmental effects on humans. This paper identifies biological entities as significant agents in bringing the human perspective closer to the regenerative approach and accordingly explores their application in design by analysing characteristics and benefits of utilisation, and by providing different experimental examples developed by scientists, designers, and the members of academic community. In particular, this work studies design solutions based on the biological principles of growth and finally focuses on how building-integrated plant systems contribute to regeneration.**

KEYWORDS biological entities, greening systems, integration, project, regenerative design

1 Introduction

The performance of provisioning, regulating, supporting, and cultural and amenity ecosystem services (Gómez-Baggethun & Barton, 2013; Millennium Ecosystem Assessment, 2005) in the living environment is, to a large extent, influenced by interrelations established between environmental components. The balance between life processes and functions in the closed cycle of an urban ecosystem is a prerequisite of its sustainability and a challenging goal, especially in densely built areas.

In an urbanising world, the complex network of naturally unique places adapted to local conditions is replaced for a system that is relatively simple, uniform, and generic (Lyle, 1994). The needs of new urban citizens, changes in morphology patterns, and contemporary lifestyle demands all jeopardise the functioning of urban ecosystems, due to pollution increment, microclimate changes, intensification of urban heat island phenomenon, fresh water scarcity, biodiversity loss, etc.

Regenerative design can be understood as an examination, introduction, or mimicking of nature, its models, systems, and processes, with the aim to solve urban problems (Redi, Redi, Daničić, & Russo, 2011). This work investigates regenerative design by focusing on the specific context of biological entities that are believed to play a significant role in bringing the human perspective closer to environmental goals.

1.1 Regeneration by Design

Like in natural processes, regenerative design aims to create resilient systems that try to self-optimise, and not to maximise (Akturk, 2016). Thus, regenerative design is defined as the return to nature and its cyclical flows at sources, consumption centres and sinks, replacing present linear systems and throughput flows (Akihan, 2013).

Regeneration aims to reverse environmental degradation and negative impact by (re)developing interconnectedness between humans and nature. Therefore, a regenerative approach is not only related to design, but also to the activities of humans who, according to the biophilia theory, have an instinctive and innate need to connect with nature (Sayuti, Montana-Hoyos, & Bonollo, 2015). In the regenerative design process, all aspects of systems thinking are included, from resources to biological entities, to social systems (Nugent, Packard, Brabon & Vierra, 2016).

Although there are a number of definitions of regenerative design and regenerative development, the key points, according to Mang and Reed (2012b), include net positive goals for the built environment and the integration of human with natural living systems. Regenerative design is a system of technologies and strategies based on the understanding of the inner workings of ecosystems. It produces solutions to regenerate rather than to deplete underlying life support systems and resources within the socio-ecological wholes. In continuation, regenerative development generates the patterned whole-system understanding of a place, develops strategic systematic thinking capacities, and promotes stakeholders' engagement to ensure regenerative design processes and to achieve maximum systemic leverage and support, which is self-organising and self-evolving (Mang & Reed, 2012b). Regenerative design and development therefore represent two distinct yet synergistic processes, both of which play an essential role in ensuring a greater scope, and neither of which is sufficient without the other (Mang & Reed, 2012b).

Pedersen Zari and Jenkin (2010) defined regenerative design as a means of achieving desired outcomes of regenerative development and explained how it attempts to create or restore the capacity of ecosystems and bio-geological cycles to function without human management. According to Cole (2012a, p. 1), "regenerative design relates to approaches that support the co-evolution of human and natural systems in a partnered relationship. It is not the building that is 'regenerated' in the same sense as the self-healing and self-organizing attributes of a living system, but by the ways that the act of building can be a catalyst for positive change within the unique 'place'".

Du Plessis (2012) framed regenerative design and development into a broader context of 'regenerative sustainability'. Indeed, different authors attempt to establish and define the relationship between sustainable and regenerative design. According to Akturk (2016), regenerative design could be considered as an added value, an extended significance of sustainable design. Although the application of sustainable design principles brings many improvements to conventional design in terms of conserving resources and reducing damage to the environment and humans, it only slows down the degradation of natural systems. Within the causal framework in which regenerative design emerged from the understanding of ecology and living systems principles (Akturk, 2016; Mang & Reed, 2012a), sustainable design can be described as a neutral basis permitting regenerative capabilities to evolve (Cole, 2012b; Mang & Reed, 2012b; McDonough & Braungart 2002; Pedersen Zari & Jenkin, 2008). From the perspective of regenerative design, sustainability should extend beyond net-zero impact to achieve net-positive benefits (Mang & Reed, 2012b; Pedersen Zari & Jenkin, 2009).

Design that follows the proportions, geometry, structure, processes, or functions of the systems found in nature, all at a microscopic scale, is materialised in various forms. In biomimicry, a product (object, element, or system) reacts to the environment by following the solutions typical of systems and organisms found in nature (Benyus, 1997), but the performance, according to the classical theory of life, does not encompass living (Gruber, 2008). On the other hand, regeneration refers to revival, renewal, restoration, healing, or improvement. If design products are not alive, and if regeneration represents basic characteristics of living systems and their cycles, then regenerative design should find the way to biological life. For that reason, the regenerative approach should consider the application of biological and bio-technical measures.

2 Biological Entities and Their Characteristics Applied in Design

Biological entities display numerous properties that justify their actual introduction into design products. Individual characteristics of biological entities with potential application in design are the following: replication, movement, sensitivity, energy and water harvesting, maintenance of stable humidity and temperature and other thermal-related behaviour, bonding, self-healing, self-repairing, self-operation, self-stabilisation, self-organisation, optimisation, genetic programming, adaptation and resilience, and self-cleaning, among others.

On the other hand, growth represents a general common characteristic of living organisms. It includes different sub-features, which underpin the growing process. For instance, to grow, i.e. to develop from seed to full maturity, a plant may feature sensing, thermal-related behaviour, resource harvesting, self-healing, and adaptation. As a major principle, growth is translated into various contemporary design examples, although it was also known in earlier traditions of building with nature, e.g. in suspension bridges made from the aerial roots of living banyan fig trees, described by Myers (2012) as the 'Root bridges of Meghalaya'.

Sayuti et al. (2015) defined four groups of reasons from which designers embed living organisms in furniture: function & practicality, experimentation, aesthetic & semantics, and experience. The group function & practicality, which is the most closely related to the concept of ecological regeneration, encompasses reasons such as to learn, for farming or food, to purify air or water, to generate energy, etc. On the other hand, potential worldwide users of furniture with incorporated living organisms, as revealed in the study, believe that the greatest positive effects of indoor living organisms are to heal, calm, or lower stress. These contrasting results show that human relations towards other living organisms is rather emotional and personal, and point at the need to re-establish the boundaries of regenerative design.

Living organisms are introduced in various design disciplines, from industrial and furniture design, development of building materials and products, to whole building design or urban design. The major part of such achievements, regardless of the scale, belong to experimental design. As these bespoke solutions for the 'integration of life into design' (Myers, 2012) are difficult to typify, they rather invite an individual approach to every single project. For purpose of reviewing, classification may be made according to the introduced species or according to their characteristics. This work combines both typologies to present some recent experimental projects developed by scientists, designers, and academia.

TOC

2.1 Bioreceptivity: Microorganisms

The term 'bioreceptivity', coined by Guillitte (1995), refers to the ability of a given material to be colonised by living organisms. Guillitte proposes an ecological relationship between living organism and material system, thus suggesting a fruitful dialogue between fauna, flora, and its substratum. Cruz (n.d.) customised the general idea and tried to overcome the *Innovation Inspired by Nature* (Benyus, 1997) with the concept of nature-integrated design. In doing so, he defined *Bioreceptive Design,* which "explores the emergence of a new bio-digital, material phenomenon that is changing the environmental performativity of architecture" (Cruz, n.d.). Bioreceptive design intends to generate a new interface between architecture and nature that is the result of integration between external environment, materiality, and the tectonic dimension.

'Bioreceptive concrete facade panels', developed by R. Beckett and M. Cruz in 2015, are aimed towards the facilitation of the colonisation of microorganisms on surfaces, and to overcome expensive maintenance and complex irrigation of green walls. For this to happen, a biologically receptive concrete material has been developed. To promote micro-organism proliferation, concrete has been manipulated by modifying pH value, porosity, and water retention features.

By embedding calcite-precipitating bacteria that is resistant to harsh environments into a concrete mixture, the researchers from Delft University of Technology have developed 'Bio-concrete', a type of self-healing concrete usable in the reparation of existing structures and the construction of new structures with enhanced durability (TU Delft, 2015). In another large-scale project 'Dune', the same ability of bacteria to produce calcite via microbial-induced calcite precipitation was envisaged to quickly transform sand into sandstone in order to control the spread of the deserts (Myers, 2012).

In parallel, scientists are exploring the ways to adapt certain types of bacteria as bioindicators of indoor pollution. For example, the bacterium *Brevundimonas* "could be genetically modified to change colour in the presence of a heavy metals. Other types of bacteria might be grown decoratively on walls or roofs to signal levels of harmful pollutants in cities." (Armstrong & Spiller, 2010, p. 916) This symbiotic behaviour is particularly interesting when it entails the introduction of microbes into architectural materiality.

2.2 Meteorite: Cyanobacteria and Microalgae

Scientists around the world have set the year 2030 as a deadline for sending humans to Mars, and oxygen production represents one of the most problematic issues in achieving this ambitious goal. Since 2015, the National Aeronautics and Space Administration (NASA) and its partner company Techshot are using cyanobacteria and microalgae to develop an oxygen production facility for a Martian colony (Puiu, 2015).

This extraordinary mission triggers new scenarios of possible futures that dissolve the boundaries between artificial and natural, life and death. On the one hand, there is an urge to survive, and on the other hand the fascinating and visionary conquest of new territories. This context has inspired architect Carmelo Zappulla to design a life-giving artificial *Meteorite* machine capable of producing oxygen and food through photosynthesis, i.e. a photo-bioreactor synthesising natural, technological, social, and aesthetic dimensions (Fig. 2.1).

FIG. 2.1 The Meteorite prototype
(Copyright Carmelo Zappulla, 2017)

Algae represent a great resource on Earth, as together with cyanobacteria they generate between 70-80% of oxygen. For that reason, their conscious planetary application could ensure the absorption of carbon dioxide and increase the presence of oxygen in the air. Although current oxygen levels are dropping at a rate that is too slow to affect the climate in the modern world (Poulsen, in: Zielinski, 2015), microalgae could still be used for increasing oxygen levels, reducing global warming and preventing consequences of climate change in future (Greene, in: Borkhataria, 2017). Besides the fact that algae produce more oxygen than other plants, they can also be used for production of biofuels and protein-rich foods.

In the context of this scenario, the Meteorite becomes a provocation, aiming to draw attention to environmental imbalance on the planet. The Meteorite is a liquid techno-garden that informs in real time about the present amounts of oxygen and biomass (proteins and pigments).

At the urban scale, the Meteorite can contribute to the construction of a collaborative public space capable of raising awareness about environmental problems, while cultivating oxygen and food.

Meteorite capsules contain billions of microscopic organisms, comprising *Chlorella Vulgaris* and *Synechocystis 6803*, determined in collaboration with Dr Paolo Bombelli from the Department of Biochemistry at the University of Cambridge. Chlorella is a spherical one-cell alga with a diameter of about $1/20^{th}$ of hair's breadth. It is marketed as a food supplement and labelled as 'super food' for its high protein content (40-50%) and vitamins. Synechocystis is a spherical cyanobacteria with a diameter of about $1/50^{th}$ of a hair's breadth, capable of producing a precious blue pigment called Phycocyanin. This water-soluble pigment belongs to the Phycobilin protein family and is essentially used as a natural dye in many food products. Both Chlorella and Synechocystis can generate oxygen and remove carbon dioxide from the atmosphere. By absorbing light, these organisms break molecules of water into electrons, protons, and oxygen through a process called *water photolysis*. The Meteorite uses light and these photosynthetic organisms to generate about 10 litres of oxygen per day. Considering the occupied area, the amount of oxygen produced by the Meteorite is 8-10 times greater when compared with the amount produced by a coniferous forest.

Like the Pallasites, the Meteorite is comprised of glazing components encapsulated in metallic matrix. The vitreous part consists of glass incubators in which microalgae are grown. Growth is stimulated by pumped air and integrated lighting systems, and monitored with sensor equipment. Sensors measure the amount of produced oxygen (or carbon dioxide) in real time, and the results are shown on a display. Cyclical weekly harvests of algae allow the estimation of the production rate of protein and the precious blue pigment.

The Meteorite was developed through a parametric design process, which synthesised computer numerical control (CNC) steel manufacturing of the external structure, made by F.lli Perin, and Murano blown internal capsules made by Berengo. Altogether, the Meteorite is the product of creative dialogue between contemporary digital manufacturing and millenary craftsmanship.

2.3 Bio-Machines at the IAAC

Is there any sharply defined boundary separating the natural from the artificial? Is it inevitable to treat the products of human activity as artificial and, thus, as irremediably detached from nature?

The design studio G2 at the Institute for Advanced Architecture of Catalonia (IAAC), directed by Claudia Pasquero and Carmelo Zappulla, investigates the urban environment from an essentially non-anthropocentric point of view, on the basis of the belief that it is impossible to draw neat boundaries between nature and artifice, landscape and city, and ultimately between biosphere and urbansphere. The studio is an inclusive design research environment, where learning represents progressive experience aimed towards individual and collective development, and research combines both experimentation and simulation. The experiments are designed to build understanding of various phenomena by identifying cause-effect links. They focus on observation and exemplify different configurations of a research problem. Therefore, the experiments implement analogue research techniques that help to determine the design of an apparatus - a device that integrates all features and parameters of a specific phenomenon. Experiments also resort to the aid of digital fabrication, glass craft, biotechnologies, digital video, and photography. On the other hand, simulations (by using computational models, simulation software, modelling techniques and digital video) represent and describe phenomena through virtuality. Both analogue and digital processes constitute research framework. Data integration between experiment and simulation processes provides a fruitful overview of the components and their relationships.

The studio is mainly focused on four research lines:

- **'Animal Behaviour'** (Von Frisch, 1974) which examines the behaviour of arthropods, their social organisation and three-dimensional construction abilities;
- **'Bio Regeneration'** concentrated on the active remediation of the environment by removing contaminants or by consolidating the environment with the use of biological systems;
- **'Bioluminescent Tectonics'**, which integrates living organisms able to produce light (e.g., fungi, bacteria, insects, Dinoflagellate, or jellyfish) with a designed material system; and
- **'Biophotovoltaics'** (University of Cambridge, Department of Biochemis -try, n.d.) – living solar panels that transform solar energy captured by plants into electrical power through electrochemical reactions.

Animal Behaviour

If human beings are part of nature, then the objects that humans make should also be a part of nature. Human architecture should not be viewed as something different from the architecture of other species, such as wasps, ants, or bees. By studying animal architecture, it is possible to explore how digital and animal inspired fabrication techniques can be combined to produce architectural material systems. To that end, the project *Bee++* examines the honeybees as insects that possess collective intelligence and inhabit a colony. To deepen and describe different aspects of colony behaviour, two different algorithms were used. Simulations were carried out on both macro and micro levels, by recreating the comportment of honeybees in landscape, i.e. by mimicking the way in which they deposit the wax. Research combines simulation with experimentation: while simulation represents specific environmental conditions, experiments reproduce them. But how can the behaviour of honeybees be reproduced?

TOC

Bee ++ speculates on behaviour patterns used to shape a new material system. An XY wax extruder has been built and programmed to pour natural wax onto jute fibres that follow the patterns used by honeybees. The result is a new natural composite whose texture and pattern are generated by same algorithm used to describe the paths that bees trace while fabricating the hive (Fig 2.2).

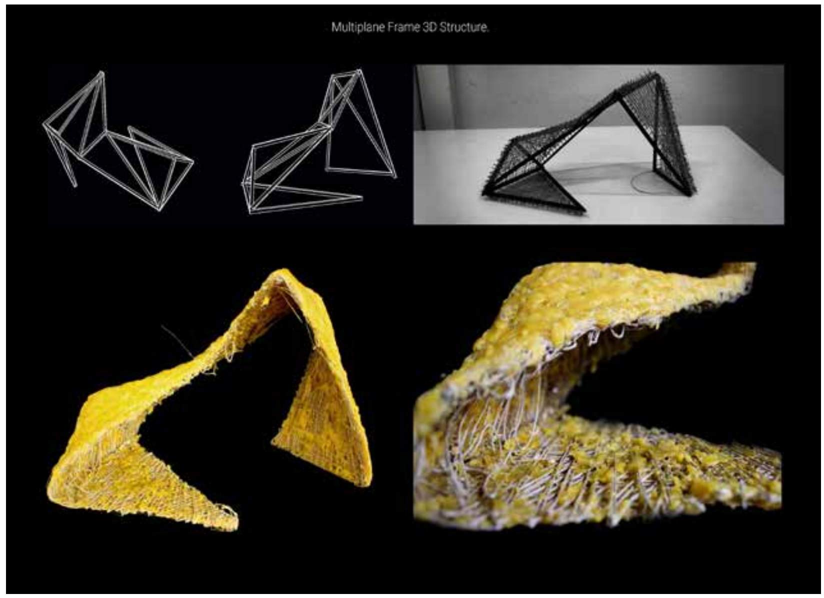


FIG. 2.2 Multiplane Frame 3D structure of the Bee++ *(Image courtesy of Institute for Advanced Architecture of Catalonia)*

Bio Regeneration

Mankind interacts with the environment insofar as both are constitutive parts of one single system. In spite of this, human societies exploit the environment with the sole aim of producing wealth. Consequently, the natural environment is at the same time human habitat and a source of profit, and this leads to the paradox that is the root of the unbalanced use of energy and matter within the biosphere, thus causing the rupture of the relationship between artefacts and the environment. To re-engage humans successfully in the balanced functioning of cities, the importance of 'analogue' experiences, as a means to tangible and material experiences of the world, must be re-discovered.

Algaetecture eco-machine (Fig 2.3) is a wastewater treatment device with *Chlorella Vulgaris,* a system capable of purifying greywater, producing oxygen, absorbing carbon dioxide and generating biomass. Thorough laboratory research and an extensive testing process have been carried out on this microalga to examine its growth mechanism and metabolism of waste materials. To determine the best conditions for wastewater processing, a matrix device that controls various parameters of algae growth (such as the type of lighting, light intensity, temperature, nutrients, type of water contamination) has been developed.

FIG. 2.3 'Algaetecture' eco-machine
(Image courtesy of Institute for Advanced Architecture of Catalonia)

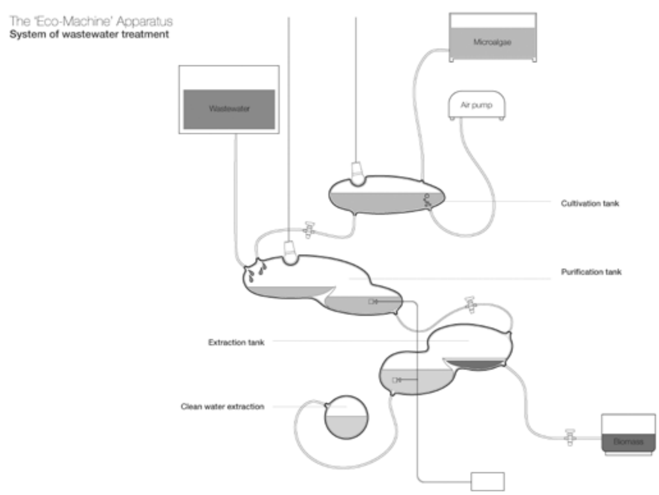


FIG. 2.4 Eco-machine apparatus
(Image courtesy of Institute for Advanced Architecture of Catalonia)

Based on experiments and data collection, water purification phases are developed in a three-step loop, as 'cultivation tank', 'purification tank', and 'extraction tank' (Fig 2.4). The inputs to the eco-machine are wastewater, light, and air, while the outputs are clean water and biomass. This device, depending on the requirements for quality and quantity of wastewater to be treated, can vary in dimension and number of components, and therefore it allows for the adjustment of the scale and the repetition of purification process until desired output quality has been obtained. Eco-machine can be multiplied into a network of components and adapted to different environments and different scales.

Strip MYCO_Puncture is an attempt to solve the problem of coastline erosion of Barcelona's urban beach, which is subjected to continuous loss of sand and replacement with new material from abroad. The proposed solution applies *Mycelium,* a mass of branching hyphae, the vegetative part of a fungus colony. Firstly, the growing behaviour of this living material in a sandy substrate was studied, and numerous experiments preceded by sand cohesions tests were carried out. The results demonstrated Mycelium's ability to grow in the sand and seawater solution. Subsequently, a matrix device was designed and built to inoculate Mycelium at different depths and at precise points, following geometric 3-dimensional reticular patterns. Later, the growth of underground material and its ability to propagate and bond within the sand were analysed. Successive activities were focused on the design of the 'Mycelium Spore Inoculator', which aimed to populate Barcelona's beach at strategic points. It is foreseen that the inoculated Mycelium could grow into dynamic and living structures that would strengthen over time and digest organic debris from the city (Fig 2.5). Thus, the project Strip MYCO_Puncture would not only transform geomorphologies of the coastline dynamics, but also create a synergy between material system and detritus of the urban fabric.

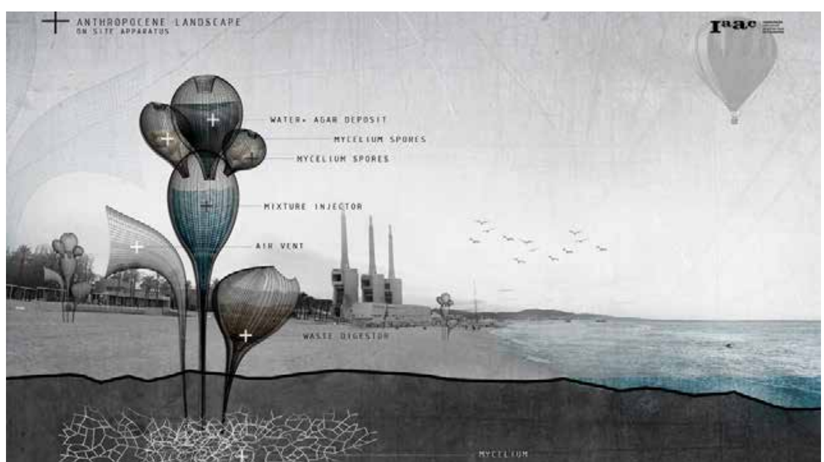
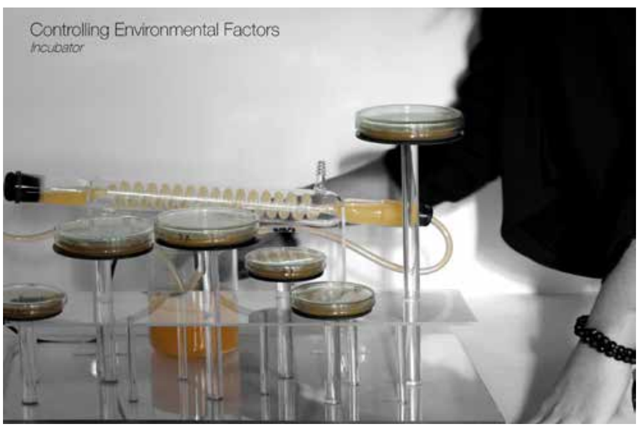


FIG. 2.5 On site 'Mycelium inoculation apparatus' *(Image courtesy of Institute for Advanced Architecture of Catalonia)*

Bioluminescent Tectonics
Bioluminescence is a spectacular phenomenon occurring in marine and land organisms. Moreover, it can also represent a way to reduce overall energy dependence. To that end, the scholars from the Syracuse University (2012) believed that they could create a bioluminescent, 20-30 times more efficient than any previously made. Lighting that does

not require any energy can be created by using nanotechnologies to harness the bioluminescence of fireflies.

In a different way, the project *Living Light* focused on symbiotic behaviour of the bioluminescent bacteria, *Vibrio Fischeri.* The interest in developing the project was focused on the way that bacteria communicates in order to produce light. When cell density of bacteria is low, they do not produce any light, but by means of communication known as quorum sensing, they are able to signal a single cell to sense the number of surrounding bacteria and make a coordinated response to glow. All bacteria have a chemical correspondence between each other. A species-specific language indicates the presence in the colony. Therefore, the first important step was to design an incubator that controls environmental parameters of *Vibrio fischeri* and monitors its growth (Fig. 2.6 and Fig. 2.7).



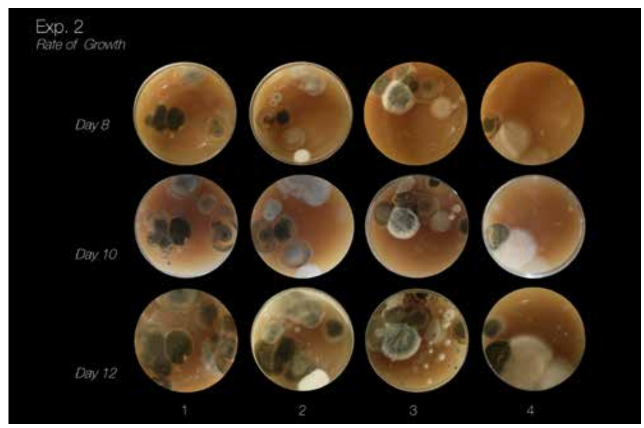


FIG. 2.6 Vibrio fischeri incubator *(Image courtesy of Institute for Advanced Architecture of Catalonia)*

FIG. 2.7 Rate of growth of Vibrio fischeri *(Image courtesy of Institute for Advanced Architecture of Catalonia)*

Once the knowledge about bacteria behaviour was deepened, the potential colonisation of human bodies was speculated upon, and the bioluminescence wearable device was designed. Designed and craft-built blowing glass capsules that house bacteria represented the core of the device. The light is activated by movement, thereby allowing a symbiotic relationship to develop between the human body and the fabricated piece.

Biophotovoltaics as Productive Landscapes

To harvest electrical power from plants, biological photovoltaic devices belonging to the electrochemical system, sometimes called 'living solar cells' (Rosenbaum, Schröder, & Scholz, 2005), can be used. The *Electromoss* project has been developed by using this knowledge.

In general, moss and plants use photosynthesis to convert carbon dioxide into organic substances. On the other hand, the bacteria present in soil decompose these organic compounds by liberating electrons. Thus, if bacteria are added to moss cultivation, electrons can be collected and electrical power produced (Bombelli, 2012). The main elements of such bio-electrical systems are anodic material (moss), the anode (water and carbon fibres), and the cathode (Fig 2.8).

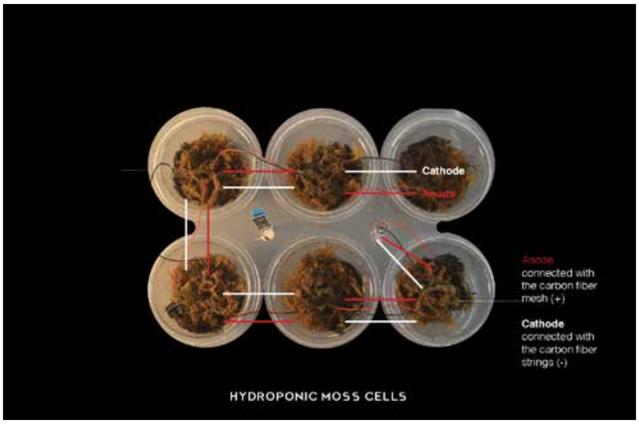


FIG. 2.8 Bio-electrical system used in 'Electromoss' project *(Image courtesy of Institute for Advanced Architecture of Catalonia)*

FIG. 2.9 'Electromoss' prototype *(Image courtesy of Institute for Advanced Architecture of Catalonia)*

The first part of the project focused on the cultivation of hydroponic moss *Sphagnum flexosum* on a bio-gel medium. An apparatus was set to control humidity, nutrients and light, and to monitor the amount of energy produced. According to the results of the experiments, an area of 314cm^2 of moss could produce an average voltage of 2.1V per week. Furthermore, a glazing prototype at 1:1 scale was produced (Fig 2.9), and the concept of an energy garden that can multiply its dimension according to the energy necessities was envisioned.

At the large scale, Electromoss looked for the mechanisms of local production of energy, food and bio-materials in the urban environment, focusing on how these bottom-up processes could contribute to urban morphogenesis of contemporary cities.

How can a landscape be transformed into a productive one? How do water, solar energy, wind or biological processes affect sustainable design cycles for structures and landscape? In 2014, IAAC students had a possibility to explore the transformation of a real site into self-sufficient land in the Torre Baró neighbourhood in Barcelona. Within the experimental spatial context intended for the *Torre Baró Productive Landscape*, the students applied biophotovoltaic (BPV) cells to the landscape. After extensive experimentation to determine the optimal plant species and the ways of increasing bacterial concentration in soil, a sophisticated landscaping strategy was developed. The solution for the techno green island integrated vegetation, electrical circuits, rain water recollection, and a leisure program. BPV cells, as envisioned by the project, adapt their morphology to existing topography and generate a network of nodes connected by paths (Fig 2.10).

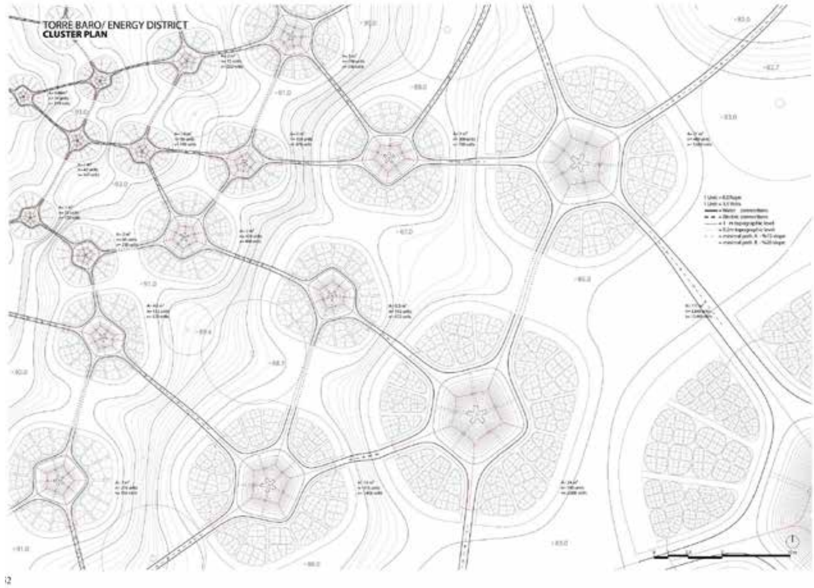


FIG. 2.10 Torre Baró Productive Landscape *(Image courtesy of Institute for Advanced Architecture of Catalonia)*

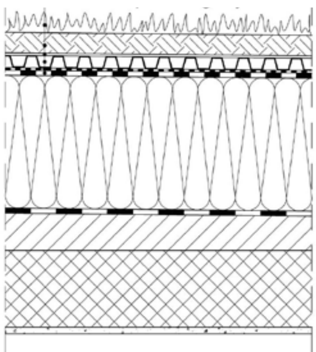
3 Contribution of Biological Entities to Regeneration: Integrated Greening Systems Case Study

The application of the principle of growth on green roofs and vertical greening systems integrated with the building envelope accounts for a measure with high regeneration potential, aesthetic pleasure, and economic support (Juric, 2016).

In general, the structure of a green roof consists of vegetation, substrate, filter, drainage, and a root barrier placed over a waterproofing layer (Vijayaraghavan, 2016) (Fig. 3.1).

The main types of green roofs, according to their characteristics, structural complexity, and function are intensive and extensive (Table 3.1), while semi-intensive green roofs are defined as a variant between the two (Berardi, Ghaffarian Hoseini, & Ghaffarian Hoseini, 2014; IGRA, n.d.). The prevalent use of extensive green roofs is explained by the potential for application on existing buildings. In comparison with intensive type, extensive roofs are characterised by a lighter structure, lower capital costs, easier installation, and a lower level of maintenance (Wilkinson, Lamond, Proverbs, Sharman, Heller, & Manion, 2015). Because of their shallow substrate layer, extensive roofs support vegetation species such as grasses and short-sedum. Extensive green roofs can be designed as accessible and inaccessible, flat or sloped vegetated surfaces with an optimal inclination of up to 45° (Optigreen, n.d.).

While extensively vegetated covers can be added later, intensive green roofs should be well detailed in early design stages because of their heavy weight and structural support requirement. The thick substrate layer in an intensive roof structure allows for the planting of shrubs and trees. Considering the structure and applied vegetation, intensive roofs are mainly flat and accessible, which, besides ecological gains, adds social benefits through its utilisation. Economic benefits of intensive vegetated roofs are achieved despite high initial investment.



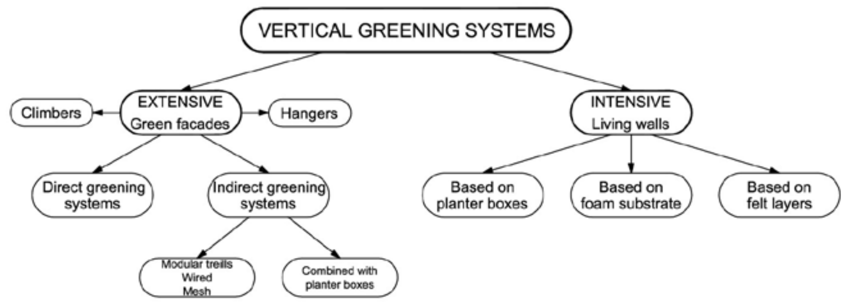


FIG. 3.1 Typical green roof structure. Layers from top: vegetation; substrate; filter layer; drainage layer; root barrier; waterproofing layer.

FIG. 3.2 Vertical greening systems classification *(According to Perez et al., 2011; Perini et al., 2011; Virtudes & Manso, 2016)*

Vertical greening systems are characterised by the distribution of plants on vertical surfaces. Through their application, a number of environmental, social and economic benefits are achieved (Sadeghian, 2016). Depending on the growing method, vertical greening systems can be classified as green façades (extensive systems) and living walls (intensive systems) (Perez, Rincon, Vila, Gonzalez, & Cabeza, 2011; Perini & Rosasco, 2013) (Fig. 3.2). For both types, the main part of vertical structure consists of vegetation and substrate layers.

BASIC CHARACTERISTICS	EXTENSIVE GREEN ROOF SYSTEMS	INTENSIVE GREEN ROOF SYSTEMS
Diversity of plants	Moss, herb and grass	Lawn, perennials, shrubs and trees
Substrate thickness [mm]	Shallow substrate layer (≤ 150)	Deeper substrate layer (≥ 150)
System build-up height [mm]	60 – 200	150 – 1000
Weight [kg/ m²]	60 – 150	≥ 180
Implications for existing buildings	Usually without additional support	Mostly require additional support
Construction	Moderately easy	Technically complex
Accessibility	Both accessible and inaccessible	Accessible
Roof coverage	Cover large expanses of rooftop	Cover less expanses of rooftop
Roof slope [°]	≤ 45 (Optimal)	≤ 5 (Flat roof)
Investment costs	Low	High
Maintenance	Low	High
Irrigation	Often not necessary	Necessity of irrigation systems
Benefits	Ecological and economic	Ecological, economic and social

TABLE 3.1 Basic characteristics of extensive and intensive green roof types *(according to Berardi et al., 2014; IGRA, n.d.; Wilkinson et al., 2015; Wilkinson & Reed, 2009)*

In comparison with green roofs, vertical greening systems have greater potential for achieving environmental benefits as the surface of façade(s) is in most cases larger than the roof surface. However, vertical greening systems are used to a much lesser extent due to complexity of measures needed to secure successful integration with the building structure and the adequate performance (Riley, 2017).

TOC

Green façades refer to scattered vertical distribution of climbers or hanging plant species (Virtudes & Manso, 2016). The plants attach to the surface directly or indirectly, and are supported by cables or a trellis. Indirect greening systems can be combined with planter boxes at different heights along a façade (Perini, Ottelé, Haas, & Raiteri, 2011). In comparison to living walls, green façades are characterised by lower capital cost, easier installation, and a lower level of maintenance. The application of these systems provides similar benefits to living walls, albeit to a lesser extent.

Living walls (also known as vertical gardens) comprise modular panels, where every panel contains its own substrate layer. Considering the principles of growth and conception, living walls are based on: a) planter boxes filled with potting soil, b) foam substrate with supporting steel baskets, and c) felt layers working as substrate and waterproofing, and supported by plastic sheets (Perini et al., 2011). In contrast to their high potential for achieving primarily environmental benefits, the disadvantages of living wall applications include high capital cost, rather complex installation (especially within the existing buildings), and a higher level of maintenance in comparison to green façades.

Although building integrated greening systems could be applied worldwide, the distinctiveness of their design should reflect specific climate characteristics. For securing efficiency in greening systems performance, it is necessary to consider location properties and local plant species (Getter, Rowe & Cregg, 2009; Riley, 2017; Speak, 2013). Custom design adjusted to the specificities and uniqueness of a certain place is in accordance with the principles of regenerative design. Future development of greening systems should be researched through hybrid solutions, including vegetation and photovoltaic elements. Hybrid systems have a great potential for widespread utilisation, considering that photovoltaic systems are already a mature and widely used technology, and that greening systems can act as an accessory in providing regenerative development (Stamenković, Antolović, Kostić & Mitković, 2017; Vijayaraghavan, 2016).

3.1 Provision of Ecosystem Services

Integrated greening systems have a significant potential for urban heat island mitigation, runoff water control, air and noise pollution reduction, and the increment of biodiversity.

Temperature increase in urban areas, known as the urban heat island (UHI) phenomenon, negatively affects the quality of air and water, creates pressure on urban ecosystems and contributes to climate change. UHI occurs as a result of human activities, excessive materialisation of the built environment and excessive utilisation of surface materials with low albedo. On typical roof surfaces, albedo values range from 0.1-0.2 for bitumen, tar, and gravel, to 0.7-0.85 for greenery (Berardi et al., 2014). Even in urban areas that are not affected by the UHI, greenery plays a significant role in temperature regulation on a micro scale, as demonstrated by the examples of neighbourhoods with similar morphological characteristics and differences in terms of existing greening systems (Fikfak, Kosanović, Konjar, Grom, & Zbašnik-Senegačnik, 2017). Greening systems regulate ambient temperature by evapotranspiration and by creating shadows. A wider application of envelope-integrated greening systems would contribute to temperature regulation on an urban level.

Regarding water management, greening systems affect both quality and quantity of runoff water. By covering impermeable building surfaces with greening entities, storm water is retained and its distribution to the sewerage systems in delayed, and by so doing reduces the load on infrastructure and the risk of flooding. In controlling runoff, green roofs are more efficient than vertical systems. Because of the storage capacity of the substrate layer, intensively vegetated horizontal surfaces could reduce up to 100% of runoff (Rowe, 2011). Generally, greening systems improve the quality of runoff water through absorption of pollutants, but the exact performance will depend on substrate layer composition. When the ion concentration in runoff water is high, greening system components act as a sink, thereby lowering the presence of ions. On the other hand, if the concentration of ions in runoff water is substantially lower than in a substrate medium, then some ions will be leached from substrate. As a result, the outgoing runoff water will have a higher concentration of ions than the incoming water (Vijayaraghavan, 2016).

Greening systems are considered to be a clean and practical technology for air purification. Plants have the ability to reduce air pollution directly and indirectly. They absorb gasses through stomata, retain particulate matter on leaves, decompose certain organic compounds, and regulate microclimate (Rowe, 2011; Yang, Yu, & Gong, 2008). Surface temperature decrease by transpiration cooling and shading in turn decreases photochemical reactions that participate in forming the air pollutants. Reduction of the need for air conditioning and lower energy demand will result in lower emissions from power plants (Rowe, 2011). To that end, vegetation is not only important for oxygen generation but also for carbon dioxide reduction.

Greening entities have a great potential to reduce sound pressure in the built environment, having regarded increased envelope insulation and the absorption of sound waves diffracting over roofs and in front of façades. As the vegetation layer displays better sound insulation properties at high frequencies, this imperfection can be improved by multi-layering and by applying denser coverage (Sekulić, 2013). The role of substrate in noise reduction is, however, the most significant, and is most efficient at low frequencies (Connelly & Hodgson, 2008).

The loss of biodiversity in densely built areas causes damage to basic ecosystems processes and cyclic closed loops. Therefore, habitat creation and protection aim to mitigate the adverse effects of urban settings (Bianchini & Hewage, 2012b). Although greening systems as artificially created natural environments play an important role in the growth of urban biodiversity, they cannot replace nature as functional habitat (Speak, 2013). The increase of biodiversity within urban ecosystems improves ecological quality and health, and additionally provides emotional, intellectual, social, and physical benefits to humans (Sadeghian, 2016).

3.2 Provision of Health, Well-Being and Other Social Benefits

Human health and well-being directly depend on provided ecosystem services. By applying greening systems in urban areas, positive impact on the ecological state of the environment and on human health is achieved. Since accessible greening systems encourage social interaction and physical activity, they also affect the well-being of users. Conducted studies indicate a favourable effect on preventing the spread of diseases and potentially on life expectancy (Zhou & Parves Rana, 2012). Green areas within a hospital environment accelerate patients' recovery, especially when visual contact with the outdoor environment is established (Nurmi, Votsis, Perrels, & Lehvävirta, 2013; Wang, Bakker, De Groot, & Wörtche, 2014). Knowing that human health is a "state of complete physical, mental and social well-being and not merely the absence of disease or infirmity", urban greenery also provides a number of psychological benefits (Zhou & Parves Rana, 2012). Greening systems have the greatest visual impact of all sustainability measures introduced to the buildings (Jungels, Rakow, Allred, & Skelly, 2013). The presence of vegetation provides distinct senses of colours, shapes, textures, and sounds (Zhou & Parves Rana, 2012). Greenery systems in densely built areas contribute to stress relief, mental fatigue relief, increase in attention and productivity, achievement of satisfaction, improvement of educational processes, etc. (Al Horr et al., 2016; Wang et al., 2014; Zhou & Parves Rana, 2012).

The integration of greening systems into built structures enhances visual experience. Intensified implementation would contribute to the establishment of visual identity of larger urban areas. The aesthetics of greenery systems are often excluded from common benefit analyses due to the lack of adequate quantitative indicators for evaluation (Bianchini & Hewage, 2012b; Nurmi et al., 2013), but it certainly forms part of regenerative design framework with immeasurable values included.

According to the properties, intensive accessible roofs are similar to parks. Therefore, they provide an optimal spatial setting for the enhancement of physical activity, recreation, and social interaction. The necessity for usable green areas is justified by the fact that about 60% of the population is physically inactive, which represents the main risk to the health (Goode, 2006). Where outdoor space is more frequently used and a similarity with the natural environment is achieved, social interactions are more intensive and a sense of community is more likely to be developed. This indicates the significance of green roofs from the social aspect of research.

3.3 Provision of Economic Benefits

Economic benefits of greening systems refer to the evaluation of financial gains at both urban and building levels. The initial benefit should relate to the advantages of greening systems relative to other measures that aim to reduce the costs of water and air purification, redesign of the sewerage system, sound protection, etc. The main constraint is that the initial economic benefit is not currently taken into consideration in practice, although the concepts of regenerative design and development highlight the need for assessment. Other important benefits of greening systems at building level are energy savings, extended lifespan of the envelope, and increased property value (Berardi et al., 2014; Bianchini & Hewage, 2012b; Perini & Rosasco, 2013; Perini & Rosasco, 2016; Riley, 2017).

In greening systems framework, the improvement of building thermal performance results from optimisation of the balance between shading, insulation, and thermal mass. The extent to which energy demand for space heating and cooling could be reduced depends on climatic conditions, building characteristics, and the type of greening system applied. Although energy savings can be achieved in all climates, the best thermal performance is registered in hot and humid climates, as greening systems provide an efficient cooling effect. The results of conducted studies indicate the reduction of energy demand for air conditioning of about 50% in the Mediterranean climate (Berardi et al., 2014; Perini & Rosasco, 2013).

Since greening systems represent an additional top layer of building envelope, they reduce possibilities for damage from ultraviolet radiation, acid rains, ice, air pollution and daily temperature fluctuations (Perini & Rosasco, 2016; Rowe, 2011), and therefore decrease maintenance costs and increase, or even double, envelope lifespan (Berardi et al., 2014; Bianchini & Hewage, 2012b; Perini & Rosasco, 2016; Rowe, 2011).

Different studies confirm that the value of buildings with integrated greening systems is increased because of introduced 'nature' and its positive effects on air quality improvement, noise protection, visual experience, etc. (Bianchini & Hewage, 2012b; Conway, Li, Wolch, Kahle & Jerrett, 2010). The average value increase for a building with integrated greening system(s), according to the published results, amounts to 10.5% (Bianchini & Hewage, 2012b; Perini & Rosasco, 2013). Although greening systems have higher capital costs compared to other types of roofs and façades, it is justifiable to invest in their construction; after the period of investments return, building integrated greening systems continue to provide economic gains on the basis of quantitative evaluation of ecological and social benefits. This fact confirms the achievement of net-positive goals, which is a fundamental postulate of regenerative design.

4 Discussion and Conclusions

Reed (2007) developed the trajectory of environmentally friendly design and differentiated the transitions from green (characterised by relative improvement), to sustainable (neutral), restorative (assisting the evolution of sub-systems), reconciliatory (where humans are integral part of nature) and ultimately to regenerative design (where the co-evolution of the whole system exists). Green design aims to reduce the degenerative consequences of human activities on ecological systems and to improve the health and comfort of residents (Cole, 2012b; McDonough & Braungart 2002; Reed, 2007). The difference between green, sustainable, and regenerative design approaches is described as doing less harm, doing no harm, and doing some good, respectively (Cole, 2012b). While sustainability is an overarching, globally scaled approach, 'green' and 'regenerative' are complementary approaches to design in the specific context that supports sustainability (Cole, 2012b).

Regenerative design has been identified as a way of maintaining balance and sustainability in urban ecosystems, i.e. a complex approach dealing with the intricate relations within different segments of the environment. Biological entities and their multi-layered purpose provide a comprehensive response to the intricacy of regenerative design.

Vegetation is an important criterion in the ecological evaluation of urban areas (Kosanović & Fikfak, 2016). In densely built urban areas, the role of greening systems is central to the regenerative design framework, as they do not only prevent the degradation but also contribute to the improvement of the overall existing ecological conditions (Kosanović, 2007). Although the research on greening systems has increased in terms of knowledge and technology in recent years, these issues at the same time continue to interfere with personal perceptions and perspectives. This indicates the necessity of providing whole system thinking, and further leads to the more general question about how the regeneration concept is perceived by humans as participants.

The active role of humans in the regenerative framework is purposefully defined. Regeneration, therefore, ultimately intends to bring the needs of citizens into a long-lasting synergy with the requirements for natural integrity. Therefore, humans, at the current point of development, need to recognise (again) their positioning within the living systems and to understand the complex patterns of dynamics (Roetzel, Fuller & Rajagopalan, 2017) in which they are embedded. Bringing humans back to their biological nature ultimately opens a new debate on the relationship to contemporary technologies. In addition, between design that regenerates the environment by involving humans and their activities, and the perspective that looks for ways to intensify positive effects of nature on humans, a new integral framework needs to be defined. The introduction of biological entities into design is believed to represent a significant agent in the integration process.

Acknowledgements

Author Carmelo Zappulla acknowledges the following projects from the programme Master in Advanced Architecture at the Institute for Advanced Architecture of Catalonia (IAAC):

Algaetecture (2015/2016). Students: Andre Resende, Mohamad Atab, Hsin Li, Stefan Fotev, Sureshkumar Kumaravel and Yasamin Khalilbeigi. Staff: Claudia Pasquero (tutor), Carmelo Zappulla (tutor) and Maria Kupstova (assistant);

Bee++ (2015/2016). Students: Burak Paksoy, Michel Alazzi, Nikolaos Argyros, Firas Safieddine and Sameera Chukkapalli. Staff: Claudia Pasquero (tutor), Carmelo Zappulla (tutor) and Maria Kupstova (assistant);

Electromoss (2015/2016). Students: Carlos Daniel Gómez, Anastasia Marcella, Fabio Menezes, Monika Koeva, Sahana Sridhar and Fernando Baptista. Staff: Claudia Pasquero (tutor), Carmelo Zappulla (tutor) and Maria Kupstova (assistant);

Living Light (2015/2016). Students: Thora H. Arnardottir, Karthik Dhanabalan, Jessica Dias, Noor El-Gewely, Maryann Ewais and Ingried Ramirez. Staff: Claudia Pasquero (tutor), Carmelo Zappulla (tutor) and Maria Kupstova (assistant);

Strip MYCO-Puncture (2016/2017). Students: Sebastian Amorelli, Montakan Manosang, Ricardo Mayor Luque, Samarth Agrawal and Pranav Kashyap. Staff: Claudia Pasquero (tutor), Carmelo Zappulla (tutor) and Maria Kupstova (assistant); and

Torre Baró Productive Landscape (2014). Students: Josep Alcover Llubia, Joy Alexandre Harb, Shruti Ramachandran, Yanna Haddad, Zoi Dalfni Arnellou. Tutors: Claudia Pasquero and Carmelo Zappulla.

References

Akihan. (2013). Regenerative Architecture, Beyond Sustainability – Design to Actively Heal the Environment. Retrieved from: https://hubpages.com/education/Regenerative-Architecture

Akturk, A. (2016). *Regenerative Design and Development for a Sustainable Future: Definitions and Tool Evaluation* (Thesis). Minneapolis, MN: University of Minnesota.

Al Horr, Y., Arif, M., Kaushik, A., Mazroei, A., Katafygiotou, M., & Elsarrag, E. (2016). Occupant productivity and office indoor environment quality: A review of the literature. *Building and Environment*, *105*, 369-389. https://doi.org/10.1016/j.buildenv.2016.06.001

Armstrong, R. & Spiller, N. (2010). Synthetic Biology: Living Quarters. *Nature* 467, 916-918. DOI:10.1038/467916a

Benyus, J. (1997) *Biomimcry - Innovation inspired by nature*. New York: Harper Collins Publishers.

Berardi, U., Ghaffarian Hoseini, A.H. & Ghaffarian Hoseini, A. (2014). State-of-the-art analysis of the environmental benefits of green roofs. *Applied Energy*, *115*, 411-428. https://doi.org/10.1016/j.apenergy.2013.10.047

Bianchini, F. & Hewage, K. (2012a). How "green" are the green roofs? Lifecycle analysis of green roof materials. *Building and Environment*, *48*, 57-65. https://doi.org/10.1016/j.buildenv.2011.08.019

Bianchini, F. & Hewage, K. (2012b). Probabilistic social cost-benefit analysis for green roofs: a lifecycle approach. *Building and Environment*, *58*, 152-162. https://doi.org/10.1016/j.buildenv.2012.07.005

Bombelli, P. (2012). Biophotovoltaics. Retrieved from https://biophotovoltaics.wordpress.com/

Borkhataria, C. (2017). Is ALGAE the answer to climate change? Scientists say it could help reduce global temperatures. Mail Online 29.03.2017. Retrieved from http://www.dailymail.co.uk/sciencetech/article-4361188/Is-ALGAE-answer-climate-change.html

Cole, R. J. (2012a). Regenerative design and development: current theory and practice. (Editorial). *Building Research & Information*, *40*(1), 1–6. http://dx.doi.org/10.1080/09613218.2012.617516

Cole, R. J. (2012b). Transitioning from green to regenerative design. *Building Research & Information*, *40*(1), 39-53. http://dx.doi.org/10.1080/09613218.2011.610608

Connelly, M. & Hodgson, M. (2008). Sound transmission loss of extensive green roofs-Field test results. *Canadian Acoustics*, *36*(3), 74-75. Retrieved from: https://jcaa.caa-aca.ca/index.php/jcaa/article/view/2044/1791

Conway, D., Li, C. Q., Wolch, J., Kahle, C. & Jerrett, M. (2010). A spatial autocorrelation approach for examining the effects of urban greenspace on residential property values. *The Journal of Real Estate Finance and Economics*, *41*(2), 150-169. https://doi.org/10.1007/s11146-008-9159-6

Cruz, M. (n.d.) Research interests. Neoarch – Neoplasmatic architecture, the blog of Marcos Cruz. Retrieved from http://marcoscruzarchitect.blogspot.rs/2009/11/research-interests-my-research-is.html

Doppelt, B. (2008). *The power of sustainable thinking:" how to create a positive future for the climate, the planet, your organization and your life"*. London: Earthscan Publishing.

Du Plessis, C. (2012). Towards a regenerative paradigm for the built environment. *Building Research & Information*, *40*(1), 7-22. http://dx.doi.org/10.1080/09613218.2012.628548

Fikfak, A., Kosanović, S., Konjar, M., Grom, J. P., & Zbašnik-Senegačnik, M. (2017). The impact of morphological features on summer temperature variations on the example of two residential neighborhoods in Ljubljana, Slovenia. *Sustainability*, *9*(1), 122. DOI: 10.3390/su9010122

Getter, K. L., Rowe, D. B. & Cregg, B. M. (2009). Solar radiation intensity influences extensive green roof plant communities. *Urban Forestry & Urban Greening*, *8*(4), 269-281. https://doi.org/10.1016/j.ufug.2009.06.005

Gómez-Baggethun, E., & Barton, D. N. (2013). Classifying and valuing ecosystem services for urban planning. *Ecological Economics*, *86*, 235-245.

Goode, D. (2006). *Green infrastructure report to the Royal Commission on Environmental Pollution.* London: Royal Commission on Environmental Pollution. https://doi.org/10.1016/j.ecolecon.2012.08.019

Gruber, P. (2008). The signs of life in architecture. *Bioinspiration & Biomimetrics* 3 (2), 023001, 9 p. Retrieved from http://iopscience.iop.org/article/10.1088/1748-3182/3/2/023001/meta;jsessionid=948DB818FE2F8C4DA341B868B8B3E565.ip-10-40-1-105

Guillitte, O. (1995). Bioreceptivity: a new concept for building ecology studies. *The Science of the Total Environment, 167*, 215-220. DOI: 10.1016/0048-9697(95)04582-L

IGRA – International Green Roof Association (n.d.). *Green roof types*. Retrieved from: http://www.igra-world.com/types_of_green_roofs/index.php

Jungels, J., Rakow, D. A., Allred, S. B. & Skelly, S. M. (2013). Attitudes and aesthetic reactions toward green roofs in the Northeastern United States. *Landscape and Urban Planning*, *117*, 13-21. https://doi.org/10.1016/j.landurbplan.2013.04.013

Juric, M. (2016). *The perception of advantages and disadvantages of green roof design in Riverside County, California* (Master thesis). Pomona, CA: California State Polytechnic University.

Kosanović, S. (2007). *Istraživanje mogućnosti za promenu ekoloških uticaja zgrada na okruženje* [A study of the possibilities for change of environmental impact of buildings](Magistarski rad). Beograd: Arhitektonski fakultet.

Kosanović, S., & Fikfak, A. (2016). Development of criteria for ecological evaluation of private residential lots in urban areas. *Energy and Buildings*, *115*, 69-77. https://doi.org/10.1016/j.enbuild.2015.02.037

Lyle, J.T. (1994). *Regenerative Design for Sustainable Development*. New York: John Wiley and Sons.

McDonough, W. & Braungart, M. (2002). *Remaking the way we make things: Cradle to cradle*. New York: North Point Press.

Mang, P., & Reed, B. (2012a). Designing from place: a regenerative framework and methodology. *Building Research & Information*, *40*(1), 23-38. http://dx.doi.org/10.1080/09613218.2012.621341

Mang, P. & Reed, B. (2012b). Regenerative Development and Design. *Encyclopedia of Sustainability Science & Technology*, 2112, Chapter 303, Springer.

Millennium Ecosystem Assessment (2005). *Ecosystems and Human Well-Being: Biodiversity Synthesis*. Washington, DC: World Resources Institute.

Myers, W. (2012). *Bio design: nature - science - creativity*. New York: The Museum of Modern Art.

Nugent, S., Packard, A., Brabon, E. & Vierra, S. (2016). Living, regenerative and adaptable buildings. Whole Building Design Guide - A program of the National Institute of Building Science. Retrieved from https://www.wbdg.org/resources/living-regenerative-and-adaptive-buildings

Nurmi, V., Votsis, A., Perrels, A., & Lehvävirta, S. (2013). *Cost-benefit analysis of green roofs in urban areas: case study in Helsinki*. Helsinki: Finnish Meteorological Institute.

Optigreen (n.d.). Green roof system solutions. Retrieved from: http://www.optigreen.co.uk/system-solutions/

Pedersen Zari, M. & Jenkin, S. (2008). Value case for a sustainable built environment–towards regenerative development. Research Document. Wellington, New Zaeland: Ministry for the Environment.

Pedersen Zari, M. & Jenkin, S. (2009). Rethinking our built environments: Towards a sustainable future. Research document. Wellington, New Zaeland: Ministry for the Environment.

Pedersen Zari, M. and Jenkin, S. (2010). Re-defining cutting edge sustainable design: from eco-efficiency to regenerative development. *Sustainable Building Conference (SB10), New Zealand*. Retrieved from: https://www.researchgate.net/profile/Maibritt_Pedersen_Zari/publication/261367575_Re-defining_cutting_edge_sustainable_design_from_eco-efficiency_to_regenerative_development/links/542881210cf2e4ce940c4e5e.pdf

Perez, G., Rincon, L., Vila, A., Gonzalez, J. M. & Cabeza, L. F. (2011). Green vertical systems for buildings as passive systems for energy savings. *Applied energy*, *88*(12), 4854-4859. https://doi.org/10.1016/j.apenergy.2011.06.032

Perini, K., Ottelé, M., Haas, E. M. & Raiteri, R. (2011). Greening the building envelope, façade greening and living wall systems. *Open Journal of Ecology*, *1*(1), 1-8. http://dx.doi.org/10.4236/oje.2011.11001

Perini, K. & Rosasco, P. (2013). Cost–benefit analysis for green façades and living wall systems. *Building and Environment*, *70*, 110-121. https://doi.org/10.1016/j.buildenv.2013.08.012

Perini, K. & Rosasco, P. (2016). Is greening the building envelope economically sustainable? An analysis to evaluate the advantages of economy of scope of vertical greening systems and green roofs. *Urban Forestry & Urban Greening*, *20*, 328-337. https://doi.org/10.1016/j.ufug.2016.08.002

Puiu, T. (2015). Algae and bacteria will provide oxygen for astronauts living on Mars. Retrieved from http://www.zmescience.com/space/algae-bacteria-oxygen-on-mars-05534/

Reed, B. (2007). Shifting from 'sustainability'to regeneration. *Building Research & Information*, *35*(6), 674-680. http://dx.doi.org/10.1080/09613210701475753

Redi, I., Redi, A., Daničić, D., & Russo, M. (2011). Urbani eko-sistemi: Holistički pristup prema regenerativnoj arhitekturi [Urban eco-systems: A holistic approach to regenerative architecture]. In Spasić, S. (Ed.), *Održiva gradnja i urbane oaze* [Sustainable building and urban oases] (pp. 27-34). Beograd, RS: Organizacija civilnog društva „Ekoist".

Riley, B. (2017). The state of the art of living walls: Lessons learned. *Building and Environment*, *114*, 219-232. https://doi.org/10.1016/j.buildenv.2016.12.016

Roetzel, A., Fuller, R. & Rajagopalan, P. (2017). Integral sustainable design - Reflections on the theory and practice from a case study. *Sustainable Cities and Society,* 28, 225-232. https://doi.org/10.1016/j.scs.2016.09.002

Rosenbaum, M., Schröder, U. & Scholz, F. (2005). Utilizing the green alga *Chlamydomonas reinhardtii* for microbial electricity generation: a living solar cell. *Applied Microbiology and Biotechnology,* 68 (6), 753–756. https://doi.org/10.1007/s00253-005-1915-4

Rowe, D. B. (2011). Green roofs as a means of pollution abatement. *Environmental Pollution*, *159*(8), 2100-2110. DOI: 10.1016/j.envpol.2010.10.029

Sadeghian, M. M. (2016). A Review on Green Wall, Classification and Function. Retrieved from: http://ijsrst.com/paper/256.pdf

Sayuti, N., Montana-Hoyos, C. & Bonollo, E. (2015). A study of furniture design incorporating living organisms with particular reference to biophilic and emotional design criteria. *Academic Journal of Science* 4 (1), 75-106. Retrieved from http://www.universitypublications.net/ajs/0401/html/DE4C321.xml

Sekulić, M. (2013). *Razvoj i transformacije krovnog vrta od nastanka do savremenih tendencija* [Development and transformations of the roof garden from emergence to contemporary tendencies] (Doktorska disertacija). Novi Sad: Univerzitet u Novom Sadu, Fakultet tehničkih nauka.

Speak, A. F. (2013). *Quantification of the environmental impacts of urban green roofs* (Doctoral dissertation). Manchester: University of Manchester, Faculty of Humanities.

Stamenković, M., Antolović, S., Kostić, D. & Mitković, M. (2017). Analysis of the requirements for installing photovoltaic systems in order to achieve improved performances: Case study of the City of Niš. *Facta Universitatis: Series Architecture and Civil Engineering*, *15*(2), 145-152. DOI: 10.2298/FUACE160328010S

Syracuse University. (2012). SU researchers use nanotechnology to harness power of fireflies. Retrieved from: https://news.syr.edu/2012/06/bioluminescence-resonance-energy-transfer/

TU Delft. (2015). TU Delft self-healing bio-concrete nominated for European Inventor Award. Retrieved from: https://www.tudelft.nl/en/2015/tu-delft/tu-delft-self-healing-bio-concrete-nominated-for-european-inventor-award/

University of Cambridge, Department of Biochemistry. (n.d.). Biological photovoltaics (BPV). Retrieved from: http://www.bioc.cam.ac.uk/howe/about-the-lab/biological-photovoltaics-bpv

Vijayaraghavan, K. (2016). Green roofs: A critical review on the role of components, benefits, limitations and trends. *Renewable and Sustainable Energy Reviews*, *57*, 740-752. https://doi.org/10.1016/j.rser.2015.12.119

Virtudes, A. & Manso, M. (2016). Applications of green walls in urban design. In: *IOP Conference Series: Earth and Environmental Science*, *44*(3), 1-6. IOP Publishing. DOI:10.1088/1755-1315/44/3/032016

Von Frisch, K. (1974). *Animal architecture*. Harcourt.

Wang, Y., Bakker, F., De Groot, R. & Wörtche, H. (2014). Effect of ecosystem services provided by urban green infrastructure on indoor environment: A literature review. *Building and Environment*, *77*, 88-100.

Wilkinson, S., Lamond, J., Proverbs, D. G., Sharman, L., Heller, A., & Manion, J. (2015). Technical considerations in green roof retrofit for stormwater attenuation in the central business district. *Structural Survey*, *33*(1), 36-51. https://doi.org/10.1108/SS-07-2014-0031

Wilkinson, S. J. & Reed, R. (2009). Green roof retrofit potential in the central business district. *Property Management*, *27*(5), 284-301. https://doi.org/10.1108/02637470910998456

Yang, J., Yu, Q. & Gong, P. (2008). Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment*, *42*(31), 7266-7273. https://doi.org/10.1016/j.atmosenv.2008.07.003

Zhou, X. & Parves Rana, M. (2012). Social benefits of urban green space: A conceptual framework of valuation and accessibility measurements. *Management of Environmental Quality: An International Journal*, *23*(2), 173-189. https://doi.org/10.1108/14777831211204921

Zielinski, S. (2015). Earth's oxygen levels can affect its climate. Retrieved from: http://www.smithsonianmag.com/science-nature/earths-oxygen-levels-can-affect-its-climate-180955572/

Index