PROPOSED RESEARCH AGENDA FOR ACHIEVING INDOOR AIR QUALITY SUPPORTING HEALTH AND COMFORT IN HIGHLY ENERGY EFFICIENT BUILDINGS

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ABSTRACT

Research topics that need to be addressed so that the future highly energy efficient buildings do not compromise health and comfort of the building occupants were identified. They can be used to form the short-term and long–term research agenda. Research priorities were identified during two workshops. During first workshop, the stakeholders involved in the building design, construction and operation, and invited experts from different disciplines formed the first list of the priorities. The list was subjected to public review and supplemented in the subsequent workshop held during large international congress. The impact of user behavior with respect to control of the indoor environmental quality was the topic that received distinctively higher priority than the other topics. It was also highly advised to benchmark differences in health risks, exposures and sources of these exposures in the traditional buildings, energy retrofitted buildings and new highly energy-efficient buildings. Many other research topics identified received quite similar priority; the effort needed to accomplish the research work was estimated. Developing data bases with benchmarking results and information on past and current projects was seen as an important task for the future. The research agenda includes also developing policies and training courses, which have been considered as an important step to promote highly efficient energy buildings with high indoor environmental quality. Crosscutting and harmonization of different policies needs to be promoted in that process.

KEY WORDS

Energy efficient buildings; Research priorities; Effort; Indoor air quality; Ventilation

1 INTRODUCTION

Buildings create shelter and conditions for working, learning, leisure and comfortable living. A built environment should be safe with no health hazards for its users either due to poor design and construction, or due to poor operation, maintenance and performance. Negligence and/or compromise of any of the actions required to achieve high criteria set for the conditions indoors can bring about serious problems resulting in the substantial costs and numerous undesirable consequences (Wargocki, 2011). The holistic approach for creating

indoor environmental quality in buildings is hence required involving different disciplines and harmonization with policies and regulations. Numerous determinants of healthy, productive and comfortable indoor environments must be considered comprising among others outdoor air pollution and climate, as well as the expectations and behavior of buildings' users to name just few (Oliveira Fernandes et al., 2009). The approach should also take into account the potential limitations defined, e.g. by the access to the necessary technologies and energy resources.

A considerable amount of energy is used in buildings to support the processes, which ensure that the indoor environment is of a high quality promoting healthy living. This situation is changing at present as a response to the stringent requirements and limitations for energy use in buildings. These requirements are imposed by the policies and regulations having aim to reduce the carbon footprint and slow down the process of climate change. An example of such policy includes the Energy Performance of Building Directive released by European Commission in 2002 with a recast in 2010 (EPBD, 2002; 2010). Voluntary building certification schemes contribute to this change, as well. They are considered signatures of modernism, prestige and excellence. The building stock portfolio is changing, too. The number of highly energy efficient buildings (termed also nearly zero energy buildings) is increasing at a high rate. Many existing buildings also fall into this category after undergoing the renovation and retrofit processes in order to reduce substantially the energy use.

This fairly radical and rapid change is not adequately supported by the scientific evidence on the effects (both benign, positive and negative) on health and comfort of users of highly energy efficient buildings. Among others, it is important to understand what the common perception is of highly energy efficient buildings, what the health implications are including occupant behavior and the parameters of indoor air quality as well as what the trade-offs are between different factors including energy and indoor environmental quality.

The urgency for developing research agenda addressing these issues thus exists. The agenda should identify the most critical aspects of highly energy efficient buildings that need to be examined, as well as the proper steps that need to be taken to avoid the potential negative consequences of the ubiquitous strive for meeting the rigorous targets for maximum energy use in buildings.

The present paper describes an attempt to develop such an agenda. It is achieved by defining research topics that need to be addressed so that the future energy efficient buildings do not compromise health and comfort of the building occupants. Indoor air quality in highly energy efficient buildings is the main focus of the agenda but it is recognized that thermal, acoustical and visual environment are also components of the indoor environmental quality (Frontczak et al., 2012); they are not directly addressed here.

2 METHODS

Two workshops were held to create the research agenda.

During the first workshop, experts from the following disciplines were invited: ventilation, medicine, epidemiology, building systems and building policies. The legislators and stakeholders involved in the building design, construction and operation were invited too. During two-day interactions and discussions, they identified research issues that need to be addressed to ensure that a built environment in highly energy efficient buildings, both new ones and those that have undergone the energy retrofit, is safe and comfortable for its users. The issues addressed broad areas related to basic human requirements, technical solutions,

policies and training programs supporting implementation. The results of the workshop were used to draft the first version of the research agenda, which was then reviewed and agreed upon by the participants of the workshop.

In the next step, the agenda was subjected to external review during the workshop held at the major international conference; its content was presented and discussed with the workshop participants. One aim of this additional workshop was to supplement the agenda with the new topics potentially overlooked during the first workshop. Another aim was to prioritize the identified topics and estimate how much effort is expected for their accomplishment.

The agenda was developed following the conceptual framework presented in Figure 1. This framework defines the steps, which are needed to achieve healthy comfortable and productive indoor environments in the highly energy efficient buildings. The steps are as follows:

- Step 1. Definition of performance parameters needed for achieving high indoor air quality. These parameters should consider among others expectation and needs of the users, as well as the known evidence on the conditions having potentially harmful effects, and those promoting well-being.
- Step 2. Definition of processes for controlling the release and distribution of contaminants having harmful effects on humans, as well as the precursors for such contaminants. These processes should include among others careful selection of building materials, furnishing and consumer products, and the use of technologies for dilution, removal, filtration and air cleaning, as well as defining the proper use and maintenance routines.
- Step 3. Implementation of the design methods supporting the creation of high indoor air quality in the built environment. This pertains predominantly to ventilation systems.
- Step 4. Proper implementation and execution of the systems ensuring that air quality levels are high. This again mainly pertains to ventilation systems.
- Step 5. Diligent, practical and judicious operation and maintenance of buildings and all systems installed in buildings.

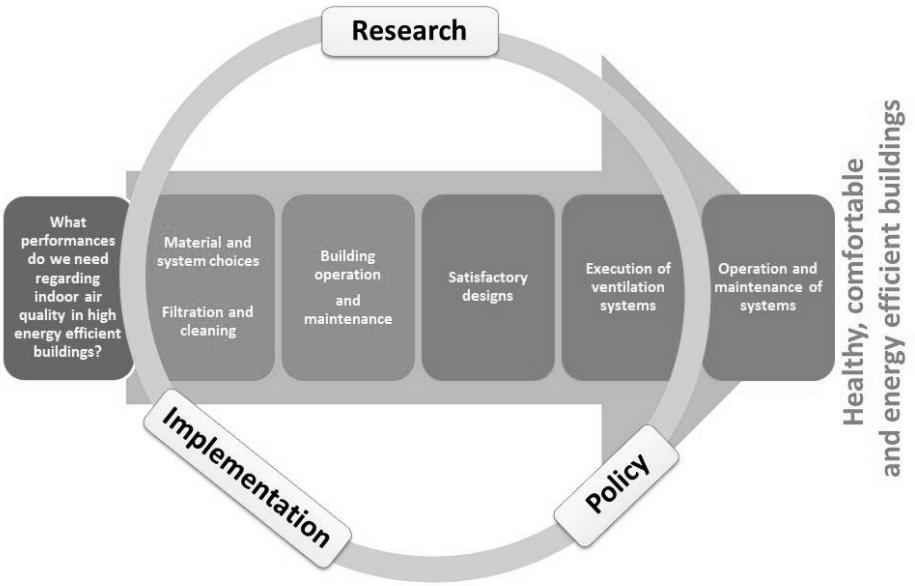

Figure 1: Framework for achieving indoor air quality supporting healthy, comfortable and productive highly energy efficient buildings

3 RESULTS

Research priorities identified by the participants of the two workshops are presented in Tables 1 to 3. They list the topics that need an action in highly energy efficient buildings. The topics are grouped to address basic research requirements, the issues related to the solutions for achieving healthy and comfortable highly energy efficient buildings, as well as the policies and training programs needed to support the implementation of solutions.

Basic research requirements include issues such as identification of health and comfort problems experienced by the users of highly energy efficient buildings, definition of the needs and expectation of users of highly energy efficient buildings as regards indoor air quality, prioritization of health and comfort endpoints, and identification of hazardous sources and pollutants.

The topics related to solutions include both the existing solutions that are effective and efficient for mitigating and preventing potential problems, as well as identification of the missing solutions.

The topics related to the implementation of solutions try to determine, whether there are any barriers experienced during design, construction, operation and maintenance of highly energy efficient buildings that can compromise indoor environmental quality, in particular air quality, whether they are perceived similarly by different stakeholders and how they should be mitigated and prevented.

Tables 1-3 indicate also, how the topics were prioritized by 30 participants of the second workshop on the scale from 5= high priority to 1=low priority, and whether they were considered to require 5=large or 1=small effort in order to be accomplished. The topics having high priority can be considered as topics, which require immediate action and attention (short-term priority topics). Those with the lower priority should not be considered as irrelevant. They still need to be resolved to ensure that health and comfort requirements are met in highly energy efficient buildings but their implementation and execution can be delayed (long-term priority topics).

Table 1: The proposed research agenda for achieving indoor air quality supporting healthy, comfortable and energy efficient energy buildings – Basic research needs

Topic/issue	**Priority***	**Effort****
1-1 Impact of user behavior with respect to control of the indoor environmental quality	4.2	3.7
1-2 Development and implementation of new advanced methods for monitoring indoor air quality, and monitoring of health and comfort in relation to indoor air quality	3.8	3.1
1-3 Definition of ventilation requirements and the parameters defining these requirements	3.5	2.9
1-4 Definition of the pollutants of concern in highly energy efficient buildings	3.5	3.1
1-5 Definition of expectations of users of highly energy efficient buildings in relation to indoor air quality, and their change compared with the expectations in traditional and retrofitted buildings	3.1	3.0
1-6 Exploration of differences in health risks in traditional buildings, energy retrofitted buildings and new highly energy efficient buildings	3.1	4.0
1-7 Examination of the impact of non-building related variables (gender, age, social and work status) on the requirements related to health and comfort	2.9	3.1
1-8 Development of improved and simplified toxicological characterization of pollutants	2.4	3.5

*Indicated on an interval scale from High=5 to Low=1 with step of 1; ** Effort to accomplish the task indicated on an interval scale from Large=5 to Small=1 with step of 1

Table 2: The proposed research agenda for achieving indoor air quality supporting healthy, comfortable and energy efficient energy buildings – Solutions

Topic/issue	**Priority***	**Effort****
2-1 Evaluation of new advanced ventilation strategies on health and comfort	3.6	3.3
2-2 Identification of the barriers that block innovation in building process relative to the indoor environment	3.3	2.9
2-3 Development of means for active involvement of building users in creation of healthy and comfortable indoor air quality (intervening on people's habits)	3.3	3.5
2-4 Flexibility of design to account for variations	3.2	3.1
2-5 Comparison of natural ventilation, mechanical ventilation, ventilation on demand or other ventilation solutions in the context of highly energy efficient buildings taking into account the purpose and circumstances of their use	3.0	3.2
2-6 Development of harmonized methodology for measurements of emissions from building materials and consumer products, and simple, i.e. comprehendible emission classes	2.8	2.6
2-7 Impact of labeling of building materials and consumer products on health and comfort	N/A	N/A

*Indicated on an interval scale from High=5 to Low=1 with step of 1; ** Effort to accomplish the task indicated on an interval scale from Large=5 to Small=1 with step of 1

Table 3: The proposed research agenda for achieving indoor air quality supporting healthy, comfortable and energy efficient energy buildings – Policy needs, methods of harmonization between policies, proper execution, better management and implementation

Topic/issue	Priority*	Effort**
3-1 Development of methods assuring more responsibility of contractors, designers and installers	3.7	3.3
3-2 Tools and methods for ensuring performance-based design operation and maintenance of building systems securing indoor air quality	3.7	3.5
3-3 Examination of the importance of health and comfort outcomes in terms of public health, economy and costs	3.7	3.8
3-4 Methods securing robust design assuring high indoor air quality	3.6	3.3
3-5 Guidelines for operating buildings in multi-objective environment as well as simple manuals and user-interfaces for building users	3.5	2.9
3-6 Development of educational and training programs for different stakeholders involved in building processes including the provision of certification for different stakeholders from architects, designers and engineers to installers and facility managers	3.3	2.9
3-7 Development of long-term economic incentives for creation of healthy and comfortable indoor environments in form of add-on-values rather than penalties	3.1	3.4
3-8 Development of methods assuring more responsibility of contractors, designers and installers	N/A	N/A
3-9 Development of training programs including provision of certification for different stakeholders	N/A	N/A

*Indicated on an interval scale from High=5 to Low=1 with step of 1; ** Effort to accomplish the task indicated on an interval scale from Large=5 to Small=1 with step of 1

4 DISCUSSION

Present agenda, though not reviewed and discussed publicly by wide groups of scientists and stakeholders involved in the building process, can still be considered to provide a reasonable and useful appraisal of what is needed as regards the research, the implementation of solutions and policies in highly energy efficient buildings. It is interesting to see that many of the research topics have been indicated to have generally similar priority. This may suggest that the agenda has a very wide scope, and that many stakeholders and disciplines involved in the building process and creation of indoor environmental quality were represented when the agenda was created.

The impact of user behavior with respect to control of the indoor environmental quality was the only topic to receive distinctively higher priority than the other topics. This reflects well the current intensive discussions on the importance of human behavior among the stakeholders and scientists involved in the research, construction, design and operation of the buildings. New research data indicate that humans, their actions, attitudes and behaviors are an important and in some cases even a dominant element in the entire approach for creation of healthy and comfortable built environment. The data imply that even best policies, technology and regulation are not going to be effective unless behavioral aspects are taken into account. Still the panels providing the input to the present agenda consider that information on this issue is insufficient and it should have high priority in research. In particular, the reasons should be investigated behind certain actions taken by the users of the buildings. In addition, their motivation to perform these actions needs to be examined. In addition, future research should investigate the extent to which the control should be delegated to humans as well as which aspects of control of indoor environmental quality should be delegated to humans. The studies need to determine the balance between the fully automated building and a building with as few controls as possible. Another important topic is to study how to engage and motivate the occupants to be more responsible for the environments, in which they live.

Benchmarking differences in health risks in the traditional buildings, energy retrofitted buildings and new highly energy-efficient buildings were considered to take the largest effort to complete. It was strongly voiced that these studies should be accompanied by examining the exposures and the sources, which are responsible for the effects observed. Although quite elaborate and intensive, it was felt that these measurements can create a true reference point (benchmark) for the future developments of built environment. In particular, such reference is needed to assess the performance, effectiveness and success of the mitigation practices, as well as the performance of future technologies. There is an apparent lack of such reference and benchmark at present. The benchmarking should not only include buildings with problems but also buildings in which there are no problems (the successful projects) to cover the whole representative range of the buildings. This will also facilitate understanding of the differences between well-performing buildings and the buildings where the problems are observed. Benchmarking allows collection of the comparable data across different countries and characterization of exposures using similar methods and approaches, which is yet additional value. However, it also needs standardized measuring protocols to achieve this goal; their development can be considered as an additional deliverable of developing and using the benchmarking protocols. The multi-disciplinary approach is needed in this endeavor. It should integrate not only the “traditional” disciplines involved in the indoor air research, but also social sciences and anthropological approaches. Health impact assessment and risk monitoring should receive similar importance as the traditional methods for examining the effects of indoor environmental quality on health and comfort.

Methodological aspects of the experimental studies are of paramount importance for collection of decent scientific evidence. Traditionally funding is however not given for the research on the methodological aspects of experiments. This is one of the reasons, why topics related to the experimental design are not listed in Tables 1 to 3. The proper characterization of research methods would require an elaborate and comprehensive multidisciplinary approach beginning with the decent review of the literature and the assessment of the data presented therein. Examples of such effort include reviews by Nordworks and Euroworks (Sundell et al., 1999). The methodological aspects worth investigating are among others proper control of confounding and bias through selection of reference and control groups. They also include the sufficient and representative size of the studied building populations and human cohorts. Long-term data are also of the importance considering that so far research has been using monitoring of the data for short periods usually being non-representative fractions of actual indoor exposures. Examining advantages and disadvantages of using different experimental designs in the context of indoor air research has been encouraged. These designs include large cross-sectional studies taking a snap-shot of the conditions in the buildings through longitudinal prospective cohort studies monitoring the same population for the extended period of time, to intervention studies which again should use different length of examination periods. The advantages of chamber and field studies need to be considered as well. Toxicological methods should further be developed including both methods involving humans and animals. Especially the latter is the largest source of error and uncertainties, and therefore the improved toxicological information on this aspect is necessitated. The new advanced objective methods for measuring the effects on health comfort and mental performance should learn largely from the past evidence. The methods that have been shown to be ineffective should be rejected.

No specific pollutants have been specified that should be especially examined as regards their impact on health and comfort in highly energy efficient buildings. As a minimum approach, the compliance with WHO Air Quality Guidelines (WHO, 2006; 2010) and the recommendations of INDEX project (Kotzias et al., 2005) has been recommended; the data in these documents are based on the available scientific evidence that has been scrutinized carefully and thoroughly. At the same time it must be acknowledged that neither WHO Guidelines nor INDEX project have specified all pollutants of concern. Therefore, in the proposed studies characterizing exposures in highly energy efficient buildings strong effort should be placed on exploring which pollutants should be specifically addressed in the future highly energy efficient building. Among the pollutants that potentially need a special focus are ambient and indoor generated particles (both submicron, nano- and ultrafine particles as well as traditionally recognized PM2.5 and PM10) and the composition of pollutants adsorbed on their surfaces, dust depots and reactive indoor air chemistry pollutants, gaseous pollutants with a special emphasis on formaldehyde and acrolein and other pollutants which in risk modeling are shown to be mainly responsible for reduced healthy life years expressed as DALYs (Oliveira Fernandes et al., 2009; Jantunen et al., 2011; Logue et al., 2012), new emerging pollutants such as SVOCs, PCBs, phthalates, flame retardants, persistent occurring pollutants and endocrine disrupting pollutants, moisture and biological pollutants, as well as contagions and viruses responsible for communicable infectious diseases so far studied to a lesser extent in connection with the impact of indoor air quality on their transmission in the built environment (except hospitals and medical care buildings). Definition of pollutants of concern should also take into account the effects of mixtures, even when individual components are clearly below their low effect level, as well as the potential additive, adjuvant and synergistic effects, which have so far been studied to much lesser extent than the effects

of individual pollutants, except for the studies with ozone and its capacity to modify the exposures through reactive products (Weschler, 2011). The limitations for advanced characterization of exposures have been one reason while so called “cocktail effects” of many contaminants present have been studied to a lesser extent. These methods have advanced in the recent years, and it is expected that they will advance even more. It is likely that there could be pollutants of concern that are yet not identified but may have significant health effects considering the constant change in chemical composition of indoor air. Thus, only systematic monitoring through proper experimental approach with representative groups and control for confounding would be able to assess their importance. Relationships between indoor conditions and wellbeing of occupants are complex because many pollutants contribute to annoyance, irritation and perception. This is also because different parameters (e.g., age, gender, and health status) and conditions not related to indoor environment (e.g., psychosocial stressors, type of work, social status) have been hypothesized to make individuals more susceptible to environmental exposures. Their role and subsequent confounding of the experimental data collected especially in field measurements is not fully understood and requires further elucidation.

Definition of pollutants of concern should also be accompanied by examination of methods for effective control of exposure to these pollutants. They can at best include source and emission control, but may also need to include local exhausts, dilution and removal through ventilation, passive and active air cleaning using the specialized equipment, and perhaps materials having properties to seal emission of pollutants or clean the air from unwanted pollution already released into the air (Darling et al., 2012). In any case, the impact on health and comfort should always be examined after the different exposure and emission control methods have been applied in existing buildings; this applies particularly to air cleaning which often is tested under experimental conditions in the laboratory for specific contamination and no tests are performed under real conditions and for mixtures of pollutants (Zhang et al., 2011).

Traditionally acute effects on humans are monitored and there is quite limited research data on the chronic comfort and health effects in the built environment including serious chronic effects such as cancer. Without finding the reasons on why these data re missing, it should be underlined that the future research needs to document the relationship between the chronic and acute effects, and whether the decision criteria for setting the requirements regarding indoor air quality in buildings should be based on the chronic or on acute effects, or both. In addition, it should be decided whether the requirements should be based on health or comfort end-points, or both, most of the current ventilation standards are using comfort as decision criteria. The expectations of the users of highly energy efficient buildings regarding their performance should not be neglected. They should include opinions of all different stakeholders involved in the building process and not only users of the buildings.

It is clear from Figure 1 that achieving healthy and comfortable highly energy efficient buildings require not only sufficient scientific evidence but also proper solutions, implementation and support in form of the regulations and policies. Although not traditionally included in the research agenda the topics dealing with the implementation and policies have been considered in the present work. It was felt that they were as important as purely scientific topics. The listed policies should appeal to the authorities for taking responsible role for creating conditions in built environment supporting healthy and comfortable living.

The present research agenda only indirectly discusses the potential impact of climate change on the built environment and the indoor environmental quality. This issue has been considered to have high priority especially in relation to the effects of overheating (often reported in modern energy efficient buildings), on morbidity, as well as on the aspects of aging population (longer at work, long exposure times indoors, etc.). The definition of climate severity index was proposed during workshops as a tool for design of the built environment to address somehow this issue. Since the climate change and the related research agenda has been covered previously (IOM, 2011), it was therefore decided to exclude it from the present work.

There is no doubt that implementation of the actions illustrated in Tables 1-3 need a substantial funding. The listed topics can be used when the funding programs, research directions and priorities are formed by different public, private, national and international agencies supporting research.

The research agenda and their outcomes need to be properly communicated not only in the form of the scientific discourse, but also in form that can be easily comprehended by the average citizen. She/he should understand the implications of certain actions and behaviors and the needs for application of specific solutions and undertakings, which at first may be even considered as costly and unjustified. Proper PR is an important key especially when it is intended to increase the delegation of responsibility to building users that are important link in the successful operation of building systems, as indicated above. Consequently, it is very important that the users of highly energy efficient buildings are properly informed and instructed among others on how to use the building and the different technologies so that their health and comfort are not compromised.

5 CONCLUSIONS AND OUTLOOK INTO THE FUTURE

The future work should take into consideration the past and current research programs, partially to learn what issues have not been addressed already that are on the list of research priorities identified in the present paper, which issues need further elucidation, and also in order not to repeat the work that has already been completed. The open-source Internet-based database assembling the information, or search engine finding information on research studies investigating the impact of indoor environmental quality on health and comfort in modern and traditional buildings would be a useful tool for advancing the sciences in this context. The information on the running and completed projects is already available on web sites of different funding agencies, but it is difficult to access and is not available in the standardized format. Developing databases with benchmark measurements would be useful as well.

Future policies should build upon the existing ones and the particular focus should be directed towards achieving crosscutting, integration, harmonization and compliance between different policies.

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