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Assessment of Sustainability Aspects of Daylighting in Buildings

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Abstract

The term sustainable development means the development where all four aspects are equally balanced: health, environmental, social and economic. Despite the fact that the term has been in existence for almost three decades (WCED, 1987), wrong definitions are still in use, where only one aspect of development is well considered, while others are ignored. Additionally, methods for the evaluation of sustainability aspects of buildings are for the moment scarce. The purpose of this study is to upgrade the developed methodology (Dovjak and Krainer, 2013) to evaluate sustainability aspects of daylighting in buildings with the main emphasis on health. The method was upgraded according to the specifics of real treated cases. Based on the evaluation, the problems are identified and recommendations are designed. The main problems relate to legislation, especially on the level of criteria for non-visual effects on well-being. Recommendations include step-by-step activities important for building renovations: legislation, concepts of bioclimatic design-building/systems, active spaces, occupant awareness.

Key-words: assessment, daylighting, sustainability, recommendations

1. Introduction

The term sustainable development was defined by Brundtland Report in 1987 and by the UN Conference on Environment and Development in Rio de Janeiro in 1992 (WCED, 1987). It means the development where all four aspects are equally balanced: health, environmental, social and economic. Despite the fact that the term has been in existence for almost three decades, generally only one-sided energy/economy aspects are well considered while others are intentionally or unintentionally ignored. There are currently no standardized processes, which would enable the development of sustainable building concepts. Additionally, methods for the design and evaluation of sustainability aspects are for the moment scarce. However, Dovjak and Krainer (2013) developed a methodology for the design of sustainable building concepts, where all four aspects of sustainable development are equally balanced. It was developed on the basis of engineering principles by Morris Asimow (Asimow, 1962). The purpose of this study is to show the application of the developed methodology (Dovjak and Krainer, 2013) to evaluate sustainability aspects of daylighting in buildings. Based on the evaluation, the problems are identified, and recommendations for future improvements are defined. Assessment of sustainability aspects of daylighting in buildings presents an important step towards building renovations, required by EU Directives (Directive 2012/27/EU).

2. Method

Regarding the purpose of our study, the methodology for the design of sustainable building concepts was used (Dovjak and Krainer, 2013). The methodology enables the design of products (i.e. buildings, constructional products) on the basis of defined step-by-step activities (Fig.1). It starts with basic need identification, and continues with feasibility study, concepts of basic design, detailed design, planning for production, consumption and ends with waste management. Upgrading is focused on four steps: Step 1 - Analysis of real-state conditions, Step 2 - Definition of sustainable indicators, Step 3 - Definition of goals

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and targets, and Step 4 - Final Assessment. The steps cover the whole life cycle of the building. The method was upgraded according to the specifics of real treated cases. The main emphasis is on four steps of the upgraded methodology (Fig. 1).

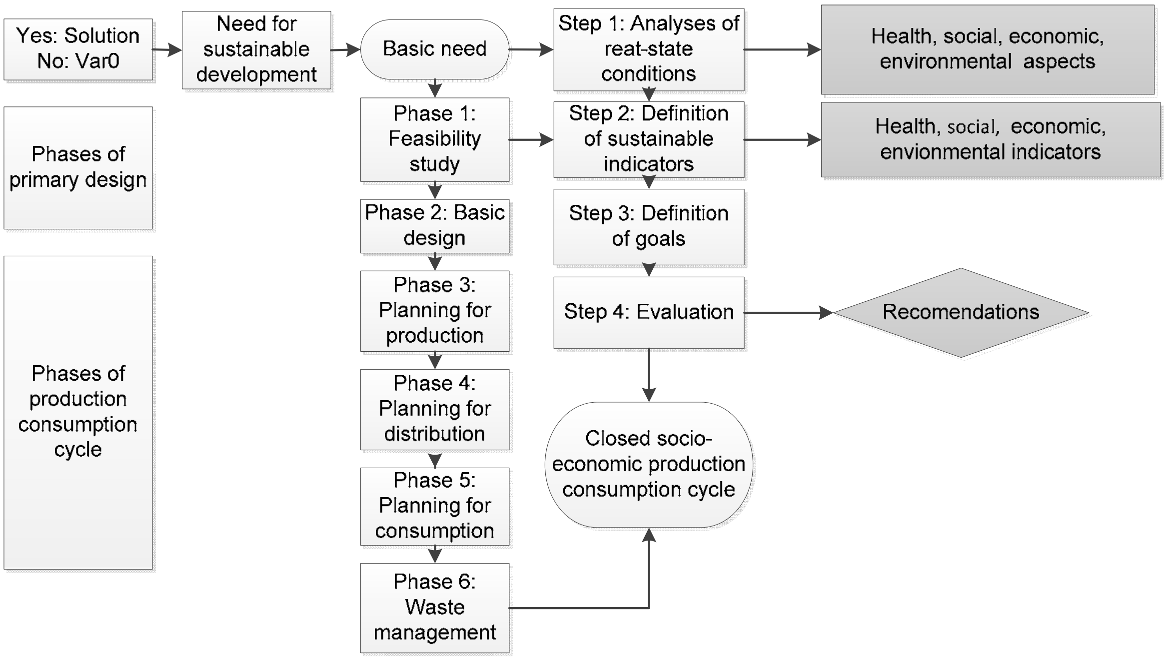

Fig. 1: Basic framework of the upgraded methodology (white–original phases, grey–further upgrading)

3. Results

3.1. Results on comprehensive literature review (Step 1)

Step 1 presents the analysis of real-state conditions, where statistical data, case studies, real-time measurements and simulations are reviewed. In the framework of Step 1, a comprehensive literature review was carried out studying social, environmental, health and economic aspects of various buildings (i.e. office, educational, health care facilities, industrial, retail, others). We searched two bibliographic databases (Science Direct and Pub Med) for peer-reviewed publications from 1928 to 2014. The key-words were written in English. Titles, abstracts or both, of all articles, were reviewed to assess their relevance. We also reviewed reports, guidelines, legislation, ISO standards, manuals, handbooks and other relevant documents. Data of the analysis of real-state conditions were organized into databank (Fig. 2).

Environment, population / aspects	**Health aspect**	**Social aspect**	**Economical aspect**	**Environmental aspect**
General environment: general population	**Visual:** Daylighting has been associated with reduced eyestrain (Robbins, 1986). **Emotional:** Daylighting has been associated with improved mood,	**Decrease in productivity, absenteeism** (Markussen and Roed, 2014; Begemann et al., 1997).	**Energy efficient** integration of daylight and artificial light in buildings potential for energy savings on lighting in Leeds ranged from **10.8% to 44.0%** over all room sizes and room ratios for an external	Less energy use, consumption of fossil fuels, RES Less negative effects on ecosystems, flora, fauna
Office environment: office workers	Window views in offices in Netherlands are beneficial to building occupants by **reducing discomfort** (Aries et al., 2010). **Stress reduction** and **attentional focus** can	**Improvements in in morale** among night shift workers have also been attributed to better lighting (Luo, 1998).	Benefits in daylit and full-spectrum office environments include **financial savings** due to better health, **reduced absenteeism, increased productivity**, and preference of workers (Franta and Anstead	For a typical 6-storey office building, annual energy savings for lighting of 56–62% and a **reduction in CO2 emissions of nearly 3 tonnes** are
Educational environment: children, students	Physiological benefits due to daylight on school children are **less dental decay**, improved eyesight, **increased growth**, and **improved immune system** (Bailey, 1998). Poor spectral light can create **strain** on students' eyes, leading to a **decrease in information processing** and **learning ability**, causing **higher stress levels** (Liberman, 1991). Students in the Canadian full-spectrum fluorescent schools **grew 2.1 cm more** in two years compared to students who attended traditional fluorescent-lit schools. The increased activity of hormones	A study of the fullspectrum fluorescent Canadian schools reported that students had an **attendance increase of 3.2 to 3.8 more days per year** than the students in traditional fluorescent lighting schools (Hathaway, et al. 1992). The Johnston County school study compared the scores of students from newly constructed daylit schools to schools that were artificially lit. Students in the daylit schools had **higher reading and math achievement scores** (Nicklas and Bailey 1997).	Hathaway et al. (1992) concluded that there could be significant benefits for education in several areas. On the basis of the daily per pupil **educational expenditure** in 1984-85 ($21.42 per pupil space per day) and with a **difference of 9.49 days of absence per year** for students under different lighting systems, the cost of having these spaces vacant because of these **absences amounts to $203.28 per pupil per year** (i.e., an average expenditure of $203.28 is made to provide a pupil space which is not used). On the basis of reduced **dental cavities, a further saving was calculated at $115.75 per pupil per year. These benefits total $320.03 per pupil per year.**	

Fig. 2: Example of state-of-the-art analyses of sustainable aspects of daylighting in buildings: cutting for the databank

Health aspects: Positive influences of daylighting (DL) on well-being have been researched since 1950s. DL has two important effects on the human body: visual and non-visual. Fist studies were concerned with visual effects (i.e. reduced eyestrain, Robbins, 1986) and psychological benefits of DL (i.e. improved mood, Heerwagen, 1986). The physiological mechanisms of non-visual effects were fully explained with the discovery of the third photoreceptor cells by David Berson (Berson et al., 2002). Since 2002, studies have been focused mainly on non-visual effects of DL. Non-visual effects include direct or non-circadian effects, indirect or circadian effects, effects on skin (vitamin D synthesis, skin tanning, dissociation of bilirubin) and other unexplored effects. Non-visual effects depend on intensity, spectral distribution and time exposure (van Bommel, 2006). Vice versa, the visual effect depends on intensity, contrast, colour, spectral distribution, surface and time distribution. Visual and non-visual effects are in constant interaction (Goodman et al., 2006). Non-visual or circadian effects are related with the functioning of more than 100 body functions that have circadian rhythms, i.e. regulation of body core temperature, heart frequency and arterial pressure (alertness, sleep), hormone secretion (levels of melatonin), urine production, cortex activity, hunger, locomotor activity, etc.. Direct or non-circadian effects are stimulative effects that result in direct activation of the human body, increase of productivity, work motivation, decrease of workplace accidents (Hadlow et al., 2014; Modesti et al., 2013).

Current studies demonstrate positive impact of DL in office environment, educational institutions, retail environment, health care facilities and also in prisons. Nicklas and Bailey (1997) performed an analysis of the performance of students in daylighted schools. They compared two groups of students from elementary schools in Alberta, Canada: the 1st group attending a school with full-spectrum light, the 2nd group attending a similar school with normal lighting conditions. The results showed that the 1st group of students were healthier and attended school 3.2 to 3.8 days more per year; full-spectrum light induced more positive moods in students. Because of the additional vitamin D received by the students in the 1st group, they had 9 times less dental decay and growth in height 2.1 cm more than students in the 2nd group.

Health benefits of DL have also been demonstrated in healthcare facilities. Benedetti et al. (2001) investigated the effect of direct sunlight in the morning on the length of hospitalization of bipolar depressed patients. The length of hospitalization was recorded for a sample of 415 unipolar and 187 bipolar depressed patients, assigned to rooms with eastern or western windows. Bipolar patients exposed to direct sunlight in the morning had a mean 3.67-day shorter hospital stay than patients in western rooms. No effect was found in unipolar patients. Similar study was performed by Beauchemin and Hays (1996). Patients in sunny rooms had an average stay of 16.9 days compared to 19.5 days for those in dull rooms, i.e. a difference of 2.6 days (15%). Heerwagen (1986) found out that patients with a tree view had a better post-surgical recovery, while patients in the same hospital with a view of a brick wall stayed longer, took more narcotic analgesics, and had more post-surgical complications. Choi et al. (2012) studied the effect of DL on patients' average length of stay, they compared different orientations of patient rooms in each ward of the general hospital in Incheon, Korea. The results showed shorter hospital stay by 16 to 41% in certain wards with optimal daylight conditions (Choi et al., 2012).

DL has an important role also in curative and preventive medicine. Terman et al. (1986) claimed that improved interior lighting could alleviate the common subclinical problems in the population at large such as oversleeping, overeating, energy loss, and work disturbance. Light can help cure rickets, osteomalacia and Seasonal Affective Disorder (SAD). Lack of DL in built environment has adverse health effects on human health and their determinants.

Social aspects: DL has been associated with improved mood and enhanced morale (Robbins, 1986). Clark and Watson (1988) found out that negative moods are associated with discomfort and distraction, whereas positive moods are associated with the physical setting at work and daily activities such as social interactions among employees, which often results in higher absenteeism rate. Markussen and Røed (2014) examined the impact of hours of daylight on sick-leave absences among workers in Norway. They found out that each additional hour of daylight increases the daily entry rate to absenteeism by 0.5 % and the corresponding recovery rate by 0.8 %, ceteris paribus. The overall relationship between absenteeism and daylight hours was negative. Nicklas and Bailey (1997) investigated the relationships between elementary and middle school student performance in North Carolina and natural daylighting. The results showed that the students who attended daylighted schools outperformed those who were attending non-daylighted schools by 5 to 14 %. Moreover, children under electric lights all day show decreased mental capabilities, agitated physical behaviour, and fatigue (Hathaway et al., 1992).

Economic aspects: Economic benefits of DL were analysed especially in office environment, resulted from the increased productivity. Romm and Browning (1994) illustrated the relationship between cost per employee and average cost per square foot by estimating the savings for any commercial building lighting retrofit. An approximately 1% gain in productivity is equivalent to the entire annual energy cost. Every 1% gain in productivity is worth $500 per employee ($50,000 salary times 1%), or $1.5 million ($500 times 3,000 employees) per year (Thayer , 1995).

Similar conclusions can also be made for educational environment, due to health benefits with decreased number of absence days. Hathaway et al. (1992) revealed that on the basis of the daily educational expenditure per pupil in 1984-85 ($21.42 per pupil space per day) and with a difference of 9.49 days of absence per year for students under different lighting systems, the cost of having these spaces vacant because of these absences amounts to $203.28 per pupil per year (i.e., an average expenditure of $203.28 was made to provide a pupil space which was not used). On the basis of reduced dental cavities, a further saving was calculated at $115.75 per pupil per year. These benefits total $320.03 per pupil per year.

Environmental aspects: Studies on environmental benefits of DL are scarce. Jenkins and Newborough (2007) calculated annual energy savings for lighting and CO_2 emissions by changing the lighting for a typical 6-storey office building. Jenkins and Newborough (2007) showed that annual energy savings for lighting of 56–62% and a reduction in CO_2 emissions of nearly 3 tonnes are predicted by changing the lighting and daylighting specifications for a defined "2005" scenario to those of a low-carbon "2030" scenario. The associated reduction in peak lighting-load, and hence heat gain due to lighting, is 3 W/m^2.

3.2. Definition of sustainable indicators (Step 2)

Health indicators	
General environments	**Industrial environments**
• concentration of hormones, body core temperature, blood pressure, • parameters measured with daysimeter, • symptoms of sick building syndrome, SBS), • qualitative and quantitative characteristics of daylight for visual and non-visual effects (illuminance, wavelength, time availability, spatial distribution, etc.), • interactive influences between daylight and indoor air quality, thermal comfort.	safety issues, work accidents, errors. **Educational environments** dental decay, body growth. **Health care environments** hospital stay, recovery time, health complications. **Other environments** stress-related sick calls.

Fig. 3: Selected health indicators

Economic indicators	
Working environment	**Educational environment**
• financial savings (health costs, energy), • employee turnover, • staff vacancy rate.	• cost of absence/student/day breakdown, • test achievement scores, • financial savings related to improved health.
Health care facilities	**Educational environment**
• length and costs of hospital stay.	• number of sold products, • sensory issues of products, • productivity.

Social indicators	
Working environment	**Educational environment**
• productivity, • absenteeism, • job satisfaction.	• students, attendance, days of absence per year, • test achievement scores, • learning rate.

Environmental indicators
• reduction of CO2 emissions, • energy savings, consumption of fossil fuels, RES, • soil, water, air pollution, • effects on ecosystems, flora, fauna.

Fig. 4: Selected economic, social and environmental indicators

In Step 2, sustainable indicators are defined for all aspects of sustainable development. The results of Step 2 present the basis for further definition of goals and final assessment. They are used to guide our decisions and actions at all hierarchical levels. The selected indicators are presented in Figures 3 and 4.

3.3. Definition of goals (Step 3)

Goals and targets that are measurable and identifiable are defined on the basis of real-state conditions, national and international legislation (Step 3). Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC states that the construction works as a whole and in their separate parts must be fit for their intended use, taking into account in particular the health and safety of persons involved throughout the life cycle of the works. One of the main issues of the Regulation are health and sustainability that are explicitly defined in basic requirements No.3, Hygiene, health and the environment and No.7, Sustainable use of natural resources. The Regulation shall be binding in its entirety and directly applicable in all Member States, and harmonized with their horizontal and vertical legal framework.

Regulations, standards, guidelines and recommendations in the field of natural daylight in living environment define only the criteria for the execution of visual tasks on the level of working height. As a stimulus of positive non-visual biological effects of natural daylight on building occupants, i.e. human beings, different intensity and spectral composition of natural daylight is required. And moreover, it includes the component on the level of human eye. Demands for sufficient qualitative visual perception differ from the demands for performing of visual tasks.

3.4. Evaluation (Step 4)

Step 4 presents the final assessment of daylight in buildings, where all sustainability aspects are evaluated. Based on the evaluation, the problems are identified, and recommendations for future improvements are defined. Problems were identified especially on the level of legislation, where the criteria for non-visual effects on well-being are not defined. Recommendations include step-by-step activities important for building renovations: legislation, concepts of bioclimatic design-building/systems, active spaces, occupant awareness.

- **Legislation:** Implementation of Regulation EU 305/2011 and its basic requirements No.3 (Hygiene, health and the environment), No.6 (Energy economy and heat retention) and No.7 (Sustainable use of natural resources) into national legislation. Requirement with defined qualitative and quantitative parameters for non-visual effect of DL should be defined. Implementation of national requirements in the field of building and systems; definition of specific requirements according to building types and individual users.
- **Building design:** based on the concept of bioclimatic design, starting on the specific location; optimal orientation, arrangement of active spaces, according to the purpose, health and energetic issues. Building envelope: thermally well insulated, optimal position and surface area of transparent/non-transparent parts; effective prevention against overcooling, overheating problems.
- **Constructional complexes:** Optimal thermal conductivity, minimized impact of thermal bridges, active regulation of surface temperatures, protection against mould growth, control of building air tightness. Transparent parts of building envelope: optimization between thermal conductivity and visible transmittance. Optimal orientation of building according to the purpose of active spaces, attaining overall comfort, health and energetic issues.
- **Integral approach for DL design:** starting with the analysis of building location, building envelope insolation, openings, organisation of active spaces (hierarchy, ergonomic issues), DL control, efficiency analyses, final selection of materials. Introduction of ergonomic principles into living and working environment, quality and quantity aspects of DL for visual an non-visual effects on well-being.
- **Overall efficiency of HVAC systems** that supports health and thermal comfort of individual users, application of low-temperature H, high-temperature C systems, regulation of microclimate parameters for individual user. Energy efficiency of all systems. Easily accessible, periodical maintenance, inspection

and replacement of old systems. More functional decentralised control systems with individualisation of active spaces: monitoring, reporting errors, and optimizing performance.

- **Education and training of all employees.**

4. Conclusions

Identification of health, social, economic and environmental benefits of DL in buildings is of key importance for the design of sustainable buildings. The goal in the strategy of building design is the attainment of health and comfort conditions and to meet Maslow` needs (Maslow, 1943). On the path towards "healthy" building renovations, holistic strategy should be well implemented. It includes step-by-step activities on the level of legislation, concepts of bioclimatic design-building/systems, active spaces, occupant awareness. Legislation should include all criteria for non-visual effects on well-being. DL should present the main guide on all stages of building design. Moreover, more educational activities should be performed, focused on physiological and psychological benefits of DL.

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