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OPPORTUNITIES OF BUILDING TALL AND GREEN – AN OVERVIEW FROM A EUROPEAN PERSPECTIVE

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ABSTRACT

The purpose of the article is to answer the question of whether a tall building, throughout its entire life cycle, can be sustainable. A literature review and online searches were conducted in order to gather data on the impact of environmental trends on chosen aspects of tall European building design. The conducted analyses confirm the hypothesis that the European approach considers sustainable aspects and can be the basis for general guidelines for the construction of green tall buildings, ensuring that the tall building's location, floor areas and heights are functionally justified. Despite the demanding climate conditions, high-rise buildings are designed using bioclimatic solutions and take the use of passive phenomena and a reduction in the operating time of mechanical systems into account. The necessary technical infrastructure uses highly efficient, energy-saving equipment and solutions. Obtaining energy from renewable sources is present in architectural solutions but not very popular – these technologies are still growing and gaining importance.

Keywords: high-rise building, skyscraper, green city, ecology, sustainability

INTRODUCTION

The growing awareness of the impact of human activities on the environment and – conversely – the effects natural factors have on humans result in changes in the philosophy of design. Activities defined as green, environmentally conscious, sustainable, eco-tech, etc., are aimed at limiting the pressure exerted on the natural environment and providing people with friendly living conditions. This issue is described in more detail in Pietrzak (2013a) and Pietrzak (2013b). Therefore, urban development should focus primarily on sustainable development and respect for the natural environment with humans a part of it (Jaworska-Michałowska, 2010), as well as developing systems functioning similarly to the ecosystem.

Yeang (2008) writes that tall buildings are the most non-ecological type of structures and one can only strive to minimise their negative impact on the environment. However, doubts about the appropriateness of high-rise developments will not result in the sudden abandonment of this type of building. Further skyscrapers will be built to meet the needs of urban development and the ambitions of developers. The need for skyscraper design cannot be denied, and instead, designers have to mitigate their negative environmental impacts (Yeang & Powell, 2007).

Because of the scale of the buildings and the design approach, including interdisciplinary collaboration and awareness of the ecological problems (Rees et al., 2013), the search for the guidelines for the sustainable

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design of future tall buildings has been limited to an analysis of European trends, as well as buildings and projects emerging in Europe.

The hypothesis is that the European approach can be the basis for general guidelines for the construction of green tall buildings. The purpose of the analyses discussed in this paper was also to answer the question of whether a tall building, throughout its entire life cycle, can be seen as sustainable. A literature review and online searches were conducted in order to gather data on currently constructed and planned tall buildings. The collected data was then consolidated and analysed in order to determine the impact of environmental trends on the design, construction, and functioning of buildings. The following aspects were analysed: the evolution in the design of tall buildings, the problem of urban sprawl, aspects of determining the form of tall buildings and possibilities of energy consumption reduction. The article presents selected, particularly pertinent aspects of the researched issues.

THE EVOLUTION IN THE DESIGN OF EUROPEAN TALL BUILDINGS

In the first period of intensive development of European high-rise buildings between 1960–1975, modernist skyscrapers with glazed, often dark façades (Fig. 1a) were being constructed. The buildings were characterised by large heat losses, overheating and lack of natural light, and were only able to function with the use of air conditioning and artificial lighting. As a result of the energy crises occurring in the 1970s, designers' attentions turned to energy-efficient design: limiting heat losses and gains, lighting the interiors with natural light, implementing the latest technological solutions, and introducing IT systems for building management (Scicolone, 2012). Compact tall buildings with translucent façades were being designed (Fig. 1b), and as a result of the introduction of double-glazing, they had better insulation (Oldfield, Tarbucco & Wood, 2008). However, the usability of buildings still depended on the efficiency of mechanical systems, of which the most important became ventilation and cooling (Pawłowski & Cała, 2013). Karfik wrote: "A modern office building should be equipped with an excellent year-round air-conditioning system, completely automated and remotely controlled from a central control point" (Karfik, 1976, p. 82). The author also recommended the use of non-opening windows and the possibility of ignoring the orientation towards the surroundings (Karfik, 1976).

In the 1980s (Fig. 1c, 1d), a new type of building was introduced, the so-called intelligent building that combined the requirements of ensuring the comfort and safety of users with the maximum reduction in the cost of obtaining it (Niezabitowska, 2005). Buildings traditional in form, but equipped with extensive, advanced technical infrastructure were being designed. For example, there was automatic regulation of interior microclimate parameters. The elements of the spatial layout conditioned by the technical solutions adopted were few, such as the height of the storeys, and the size and distribution of toilets, technical rooms and storage rooms (Pietrzak, 2013a).

Towards the end of the 1990s, even more attention was being paid to environmental efforts, particularly to energy-saving measures. In addition to new developments, the redevelopment of existing buildings that were decades old was increasingly being designed, adapting them to contemporary aesthetic and functional requirements. Since the construction of the new Commerzbank Tower in Frankfurt am Main (Fig. 2), the implementation of environmental considerations has contributed to redefining the image of the high-rise building. The implementation of pro-environmental norms has contributed to the redefinition of the image of a tall building (Hart, 2011). Economical energy management, minimisation of environmental pollution during the construction and use of the building, as well as the use of natural resources, were postulated (Pawłowski & Cała, 2013). The year-round use of an air-conditioning system was considered to be environmentally unfriendly. The need to provide adequate insulation of the enclosure, natural light to the interiors, protection from overheating, and natural ventilation was pointed out (Wells, 2005).

Fig. 1. Tall buildings erected in the 1960s, 1970s and 1980s: a – Commercial Union (now Aviva Tower), London, 1969; b – Tour Gan, Courbevoie, 1974; c – Deutsche Bank Towers, Frankfurt am Main, 1984; d – Messetorhaus, Frankfurt am Main, 1985

Source: [a]Skyscrapercity.com [n.d.]; [b]Olivier Passalacqua 2006; [c]Thomas Wolf 2013; [d]Sebastian Kasten 2005.

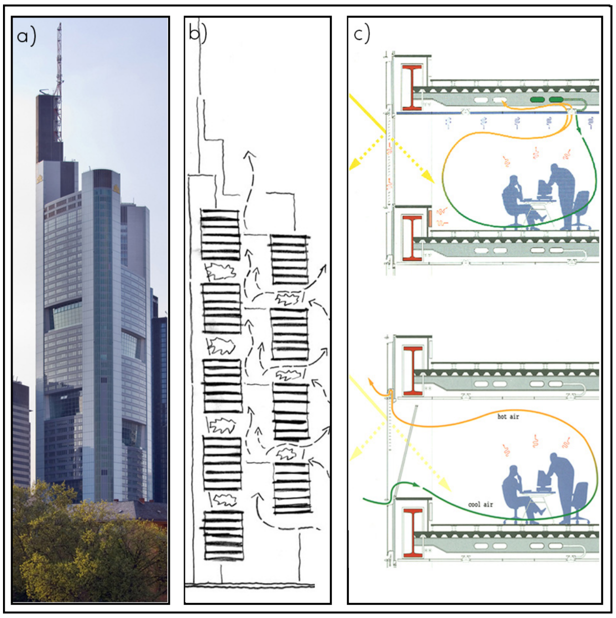

Fig. 2. Commerzbank Tower, Frankfurt am Main, 1997: a – view; b – diagram of the natural ventilation in the atria; c – diagram of the HVAC system and natural ventilation

Source: [a]Mylius 2009; [b]© Foster + Partners 2024; [c]Davis (1997, pp. 200–201).

The unique character of European tall buildings was emphasised, the specificity of which was not due to participation in the global height race, but to the integration of the tall building with the historic fabric and environmentally friendly standards. The model building was characterised by shallow tracts, or additions to deeper ones with atria, and large glazed areas, providing access to natural light and fresh air, providing all rooms with access to light and air. Due to the need to adapt the building to the local microclimate, external shaft locations began to be considered (Trabucco, 2010).

Responding to local conditions, the building form was intended as a tool to control the interior microclimate. Rather than relying solely on mechanical systems, natural or mixed ventilation was introduced. A significant change was the use of a double façade, which acts as a thermal and acoustic buffer, and allows for natural ventilation and the opening of windows. Other solutions and technologies being introduced to save energy are heat recovery systems, provision of night cooling, low-energy ventilation and water systems, advanced zoned air-conditioning and intelligent building management systems (Zukovsky & Thorne, 2000). More frequent attention was given to the sources of energy used in the building, as well as the need to introduce vegetation in the interiors of high-rise buildings.

The benefits associated with environmental activities have become increasingly quantifiable for developers ever since the spread of certification systems for green buildings (Heller, 2014; Sharma & Nair, 2021), such as: LEED, BREEAM, DGBN, SPeAR, E/STEP, and HQE as indicators of the prestige of a given development. Certification requirements, however, can become the basis for a kind of standardisation, and designers should primarily consider adapting the tall building to the microclimate, rather than stop at introducing high-performance systems (Goodwin, 2015).

TALL BUILDINGS VERSUS URBAN SPRAWL

Progressing urbanisation is the result of the search for a new way of life in cities to which more and more inhabitants are arriving (Dupre, 2008). Also, the social expectations in Europe are changing – people want to live and work in city centres. In many cities, such migrations are associated with, among others, the uncontrolled sprawl of the urban fabric. There are only two scenarios in the planning of expanding cities – the amount of urbanised terrain will increase, or the height of the urban fabric will increase. Meanwhile, one of the key building planning criteria is the reduction of carbon footprint (Dalton & John, 2008). In order to meet these criteria, it is necessary to limit individual journeys and organise effective urban transport systems, which is possible thanks to high urban fabric intensification.

Striving for sustainable development, reducing urban sprawl and saving energy used to transport people and goods is leading to the planning of cities with higher building intensities (Partridge, 2015), achieved, among other things, by concentrating tall buildings. The introduction of high urban fabric intensification in relatively small areas, as well as combining various building functions (office, residential, hotel, service, or cultural functions) allows, among others, for the preservation green areas, more efficient use of land (Wood, Henry & Safarik, 2014), limiting the transport of people and goods (Partridge, 2015), as well as providing people with the opportunity to live, work, use services, and rest in the same area. There is already a type of vertical neighbourhood (Johnson, 2014), which is formed by a single multifunctional building or a group of buildings with different functions connected by footbridges.

However, in European cities today, high-rise buildings are generally not a type of urban fabric (Asendorf & Kaltenbrunner, 2005), and this type of building is needed only in metropolises with several million inhabitants. Tall residential buildings are a solution to problems such as a growing population and the urban sprawl of cities that lack land for new property development. Cities such as the greenbelt-limited London cannot ‘sprawl’, so the height of buildings, especially residential buildings, must increase (Murray, 2013). Within Moscow’s administrative boundaries, there was a lot of vacant land suitable for development, but very high housing needs also necessitated the introduction of tall buildings (Shuvalova, 2015).

DETERMINING THE FORM OF TALL BUILDINGS

Nowadays, not only is the originality of a skyscraper sought, but also its logical explanation. The different types of high-rise development in different cities is due to, among other things, the physical and environmental context (Wood, 2013). Most architects agree that an analysis of local conditions should be the basis for design development (Jaworska-Michałowska, 2010). Increasingly, references to the material and environmental context, including the landscape, weather, the topography of the terrain, and the geological conditions of the plot, are considered to be key elements of the design process (Dupre, 2008). Environmental conditions, due to their endemicity, objectivity and relative immutability, are logical determinants of the direction of the design process (Ryńska, 2001).

Bioclimatic design

Daniels (1998) distinguished three design strategies depending on the technical level at which energy savings are achieved. The low-tech approach is to save energy passively by designing simple buildings made from natural resources and based on naturally occurring processes. The light-tech approach means an efficient use of natural resources, relying primarily on recycling. The high-tech design method implies the use of technologically advanced solutions and equipment to create an optimum indoor microclimate. The aforementioned strategies are further supplemented by Yeang (2008) with a mixed mode (a combination of low-tech and high-tech elements on a permanent or periodic basis, e.g. depending on the season) and a production mode, with which energy is generated in the building (however, this requires the introduction of further advanced high-tech elements and distances the building from nature).

Yeang emphasises that it is a misunderstanding to stop at the introduction of eco-gadgets and technical elements that complement the building, which is an approach that has become very common in the design of high-rise buildings. One should always aim for at least a mixed mode, using passive solutions in all possible aspects of the project. In general, a tall building is designed using the most advanced (high-tech) materials, technologies and technical solutions, but these should only be in addition to the logically designed spatial form of the building – the low-tech approach can be applied to this aspect of the design. This is not to use the simplest level of technology for high-rise buildings, but to take advantage of the characteristics of the location and naturally occurring processes. Yeang described this approach to design in the 1990s. He wrote in his book: “Bioclimatic design is a passive, low-energy design approach that uses energy from the surrounding microclimate to create a comfortable environment for building occupants” (Yeang, 1999, p. 11). The approach described aims to reduce non-renewable energy consumption and restrict the use of mechanical systems.

In cities, the most strongly influencing element of the built environment is microclimate – climatic factors considered at the scale of a building’s neighbourhood of approximately 1,000 m. In particular, solar radiation, temperature, air circulation and water balance are taken into account (Zielonko-Jung, 2013). It should be emphasised that in the European climate, it is virtually impossible to operate a tall building based solely on interactions with the local microclimate. Designing for a temperate European climate requires consideration of a large spectrum of changes in atmospheric conditions. In winter, it is desirable to provide high thermal insulation of the building envelope and passive heating of the interior, and in summer, intensive ventilation of the rooms and protection against overheating. In addition, shading elements should protect against solar radiation in summer and allow it to enter the building in winter (Wood & Salib, 2013). In a European bioclimatic building, a high-performance standard is determined by a harmonious cooperation between the use of local climatic phenomena and mechanical systems (Ryńska, 2001).

Shaping of the spatial form

One of the fundamental issues in the design of bioclimatic buildings is to strive for compact forms (Fig. 3) and achieve the highest possible ratio of the projected area to the length of its perimeter, thus minimising the façade area as well as heat loss and gain.

Important factors taken into account in the design of a bioclimatic high-rise building are its orientation with respect to compass points (Rokicki & Pietrzak, 2013), the exposition-dependent shape of the building and the location of different functions within the tall building. Such an approach, associated, for example, with the placement of all technical rooms, toilets, etc., on the north side, allows for maximum daylight in the interiors (Fig. 4). The buildings are designed to maximise the use of natural daylight (shallow tracts, orientation of the façade in relation to compass points) – see Figure 5b. On the other hand, locating the core on the south side may be related to its use as a shield against overheating and glare from sunlight for workers (Trabucco, 2008; Fig. 6). The design of the building should also take into account changes in the components of the microclimate (e.g. wind, temperature) at the height of the building and should not consist of a series of repetitive floors (Wood, 2015).

In the 21st century, technological evolution has also extended to the design of tall buildings. The introduction of CAD model building software, parametric design, computers with ever-increasing computational capabilities, and the use of optimisation algorithms allow the design of increasingly complex forms which are increasingly responsive to external factors and internal conditions, and buildings that fit more and more precisely into their surroundings. CAD model building software has enabled greater design freedom for architects and engineers alike, resulting in forms previously unheard of – fluidly changing or twisting (Vollers, 2009).

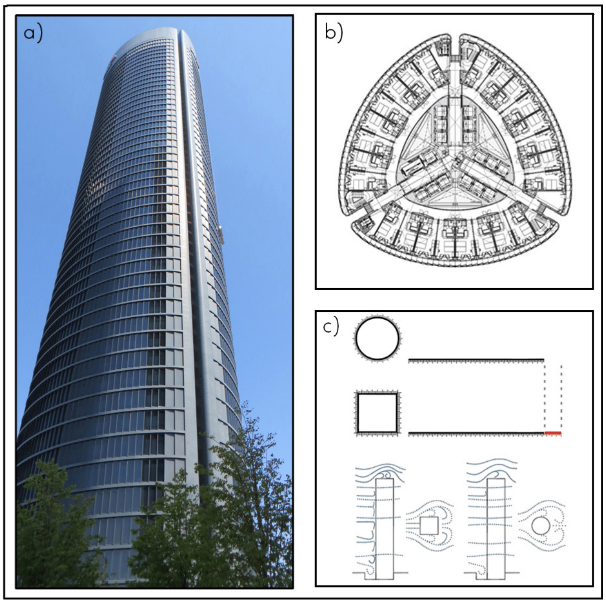

Fig. 3. Torre PwC, Madrid, 2008: a – view; b – floor plan; c – benefits of the circular form

Source: [a]Joanna Pietrzak 2011; [b]© Rubio & Álvarez-Sala, [c]Workdifferent.wordpress.com 2010.

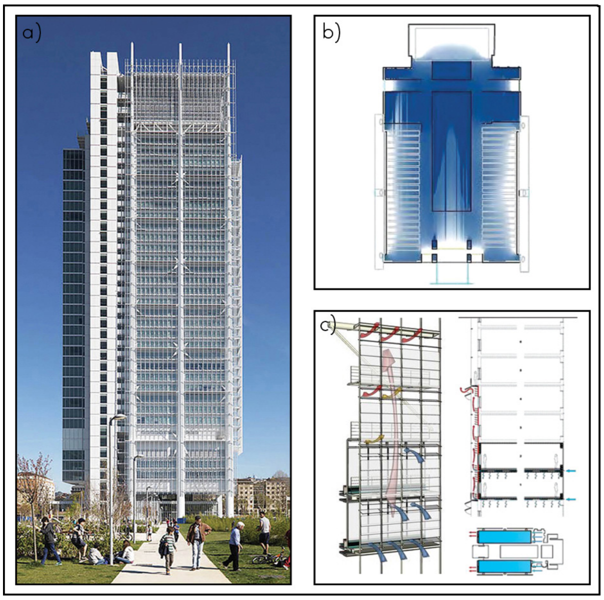

Fig. 4. Grattacielo Intesa Sanpaolo, Turin, 2015: a – view; b – floor plan and analysis of the natural lighting; c – diagram of the functioning of the gravity ventilation in the double façade

Source: [a]© Enrico Cano; [b,c]© Renzo Piano Building Workshop.

Aerodynamic form

It is a common procedure to determine the characteristics of wind phenomena occurring around a high-rise building through wind tunnel testing (Johnson, 2014). In particular, the proximity of a dense and complex urban fabric necessitates reasonably precise analyses to determine the impact of the surroundings on a new building. These studies have resulted in the increasing emergence of high-rise buildings with streamlined, bionic shapes, which are characterised by less resistance to wind and a corresponding reduction in the loads acting on the building and its enclosure. The most common type of aerodynamic skyscraper is a building with a cylindrical, egg or cucumber (Figs 3, 6, 7) form (Binder, 2006).

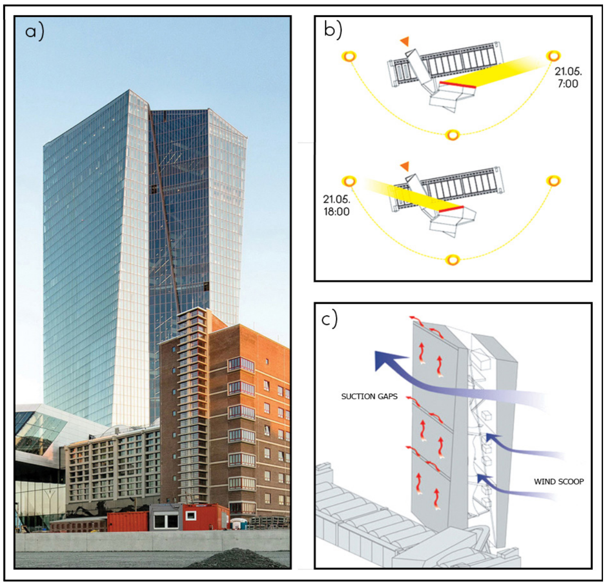

Fig. 5. ECB Tower, Frankfurt am Main 2014: a – view; b – the building plan dependent on solar exposure; c – diagram of cross and gravity ventilation

Source: [a]© European Central Bank/Robert Metsch; [b,c]© Coop Himmelb(l)au.

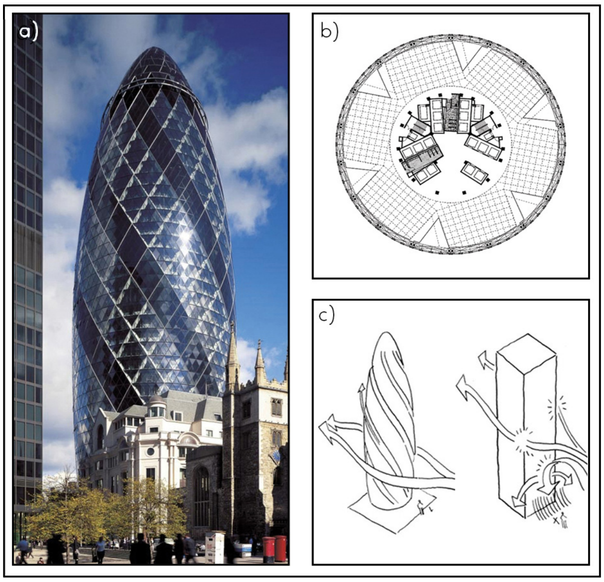

Fig. 6. Building at 30 St Mary Axe, London, 2004: a – view; b – floor plan; c – diagram of the airflow around the building

Source: [a]Wikiarquitectura, 2017; [b,c]© Foster + Partner.

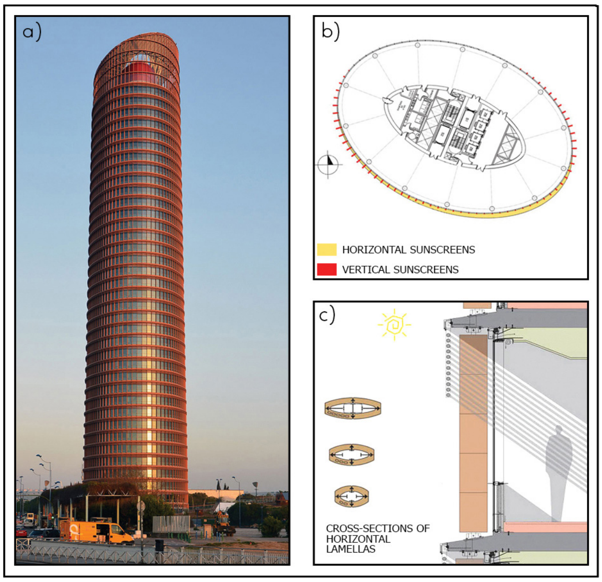

Fig. 7. Torre Sevilla, Sevilla, 2016: a – view; b – façade design scheme dependent on the orientation; c – detail of the façade solution

Source: [a]Gzzz (2015); [b,c]© Pelli Clarke Pelli Architects.

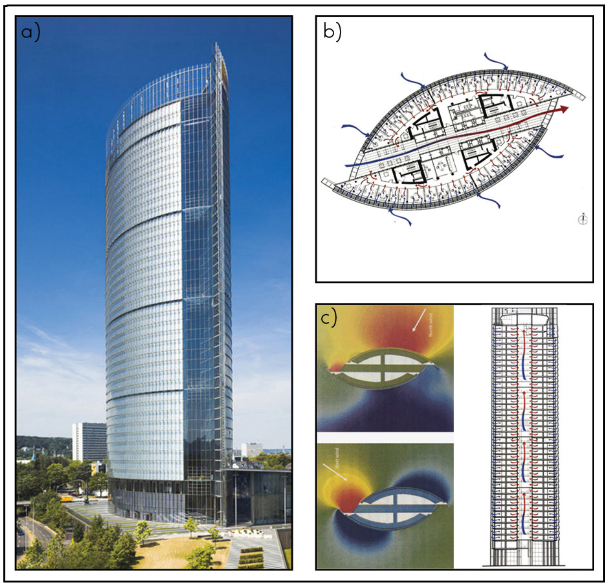

Fig. 8. Post Turm, Bonn, 2002: a – view; b – floor plan and cross ventilation diagram; c – pressure distribution around the building and gravity ventilation diagram

Source: [a]© Murphy/Jahn; [b,c]Wood and Salib (2013).

Natural ventilation

Aerodynamic studies and analyses allow the use of wind phenomena to generate a pressure differential that is used to initiate the process of natural cross ventilation (Etheridge & Ford, 2008). At the windward end of the enclosure, air is drawn into the building and at the leeward end, air is drawn out. Appropriately shaped forms of bioclimatic buildings allow the desired pressure distribution around the skyscraper to be generated, taking into account different wind directions (Figs 5, 8). The process of natural ventilation can also occur due to buoyancy forces caused by differences in air density at different temperatures (Wood & Salib, 2013). This phenomenon is also known as the chimney effect and is mainly dependent on height. In order to introduce this type of natural ventilation, an internal atrium, chimney or other vertical shaft should be provided (Figs 2, 4, 5, 8).

Interior divisions

Interior divisions are also important. In hotels and residential towers, a large number of small rooms are required. In order to provide natural daylight, rooms should be located along the façade to provide natural light and ventilation. For this reason, elongated floor plans (e.g. rectangular) with a higher perimeter-to-area ratio are advantageous for multifunctional high-rise buildings. In office buildings, open spaces should be located at the perimeter of the building, and closed rooms should be in the centre.

The limited depth of the tracts and the correspondingly high height of the rooms allow for efficient use of daylight and natural ventilation. A large group of high-rise buildings are characterised by a net storey height of 2.7–2.8 m, and this value generally does not exceed 3.0 m. Flats and hotels (Fig. 9b) can only be effectively designed on shallower tracts, with tracts typically no smaller than 7.0–9.0 m for functionality. Such dimensions allow practically the entire usable area to be lit by natural light. The design of buildings with an office function (Fig. 9a) is more varied. Minimum tracts in such high-rise buildings are about 7.0 m deep, typically around 12.0–13.0 m. Only with double-sided daylighting do the tracts reach depths of up to 40 m, and the record building width of the Salesforce Tower (50.0 m) is the result of the introduction of an atrium (Fig. 10).

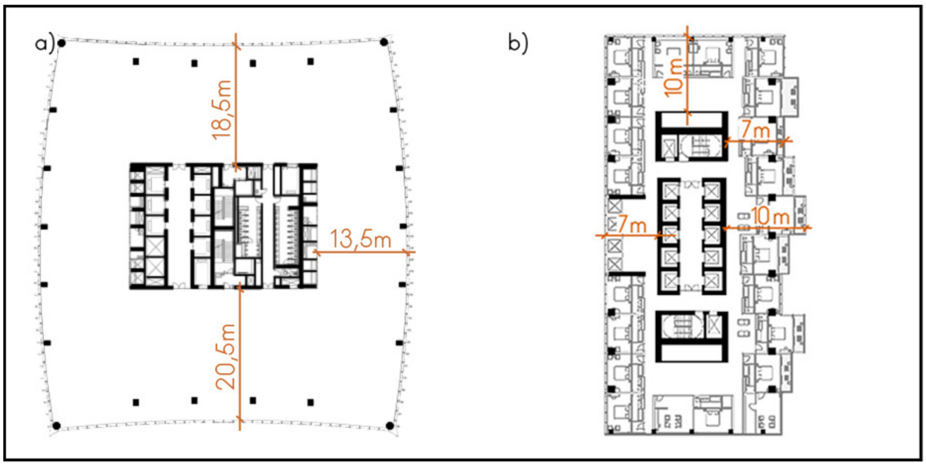

Fig. 9. Tract depths in a building: a – with an office function: 20 Fenchurch Street building, London, 2014; b – multifunctional: DC Tower, Vienna, 2013

Source: own elaboration based on: [a]twentyfen.co.uk (2022); [b]© DEKA Immobilien.

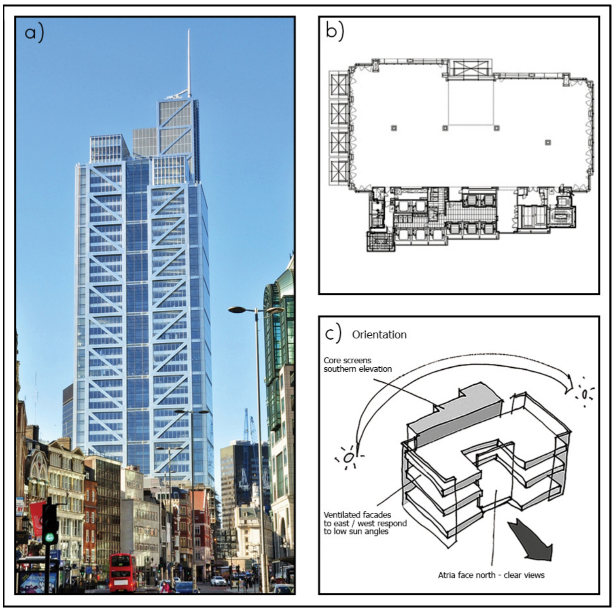

Fig. 10. Salesforce Tower, London 2011: a – view of the north elevation; b – floor plan; c – scheme of the orientation of the building

Source: [a]Eluveitie (2012); [b]Cbre.co.uk [n.d.]; [c]© KPF.

Solutions such as atria (Fig. 11a) or winter gardens (Fig. 11b) are highly beneficial: they provide natural ventilation chimneys, improve access to natural light, act as solar collectors and thermal buffers, and are spaces where greenery can be introduced (Wood & Salib, 2013). Despite their many benefits, atria are generally not introduced in contemporary European high-rise buildings because the loss of floor space is too great.

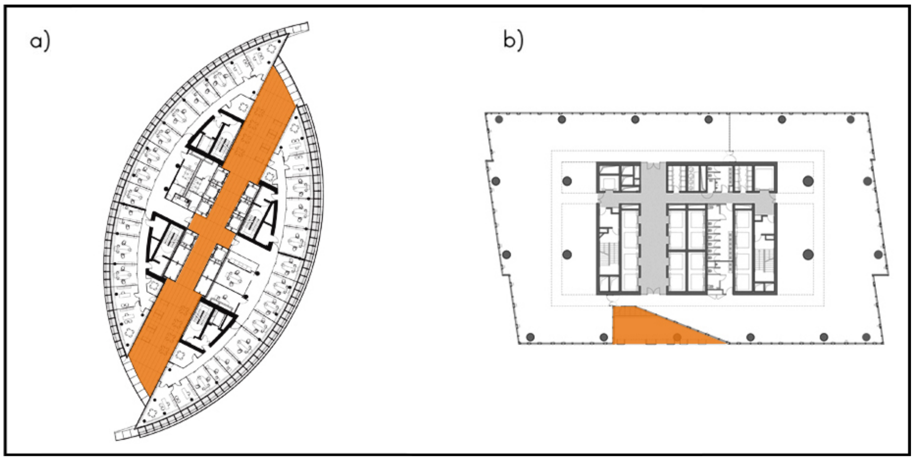

Fig. 11. A tall building with: a – atrium – Post Turm, Bonn, 2002; b – winter garden – Tour Majunga, Puteaux, 2014

Source: own elaboration based on: [a]Wood and Salib (2013); [b]© Jean Paul Viguier et Associes.

Façades

Instead of atria, double façades (Figs 2, 4, 5, 8) are very often introduced in the design of European high--rise buildings, which perform similar functions and take up significantly less space. With such a solution, consisting of two glass shells separated by a void, it is also possible to open windows shielded from the effects of undesirable atmospheric agents and, above all, strong winds (Etheridge & Ford, 2008). Double-glazed façades provide space for air circulation. In winter, they can be used as a thermal buffer and a passive heat collector. In addition, they are usually equipped with mobile elements, allowing them to be opened and provide intensive ventilation and cooling in summer. Often, the façades are equipped with additional shelves, louvres, etc., which protect against solar radiation in summer and allow the sun's rays into the building in winter (Lotfabadi, 2015).

Also, other types of façades are increasingly often appearing as an integral complement to the building's form, and their shaping is associated with the design of both the interior and exterior of the building. A properly designed enclosure has to be adjusted to the climatic zone, site characteristics, orientation of the building form and the window-to-wall ratio (Oh, 2020).

A varied façade adapts the building to exposure from all sides (Fig. 7), through elements that prevent dazzling sunlight, limit or maximise solar gains, constitute a visual barrier, or control gusts of wind and allow for the windows to be opened (Johnson, 2014). Some studies even indicate that the thermal transmittance and insulating properties of the enclosure should change with increasing height, as the amount of heat gains and losses changes (Saroglou, Meir, Theodosiou & Givoni, 2017).

The use of the increasing computational capabilities of computers, design processes and optimisation algorithms has allowed buildings enclosures to more precisely fit into their surroundings. The microclimate parameters changing at the height and perimeter of a skyscraper (Gui et al., 2021; Saroglou, Meir & Theodosiou, 2022) are more accurately analysed, and their spatial forms can be designed as increasingly complex and better adapted to local conditions. The individual façade elements can be adapted to the place of installation.

It is now common to see a trend towards fully glazed façades. However, this is not a favourable solution in terms of energy savings (glass is not the most efficient insulating material) and also in terms of the bioclimatic design of the façade, which requires, for example, the addition of elements to protect against excess solar radiation (Aminmansour, 2019). In a building designed with respect for energy consumption, glazing should constitute no more than 50% of the façade area (Al-Kodmany, 2022).

There is also a visible trend for transforming the façades, especially of residential buildings, into vertical gardens or even urban forests. Green walls, as well as plantings of shrubs and trees on balconies and terraces, are being introduced (Al-Kodmany, 2023a; Basso, Bisiani, Martorana & Venudo, 2023). Vegetation acts as a wind buffer. In summer, vertical landscape elements give shade, as well as absorb and reflect a high percentage of the sun's radiation, thus lowering the ambient temperature. In winter, they let solar radiation through. The soil layers contribute to further cooling of the air around the building, in addition to increasing retention. However, "vertical planting is far more expensive than horizontal planting" (Al-Kodmany, 2023a, p. 48). The integration of greenery into a tall building requires a sophisticated technical design of the skyscraper structure (additional loads) and the technical infrastructure (watering, drainage of excess water). Specialised, continuous maintenance is also required for plants that do not grow in their natural habitat. Water consumption and the cost of supplying water can be significant. Ultimately, maintaining plants can be expensive both financially and environmentally, even though plants absorb carbon dioxide, filter air pollutants, reduce temperatures and increase humidity. In addition, outdoor greenery cannot be planted at considerable heights either, because of, for example, the damaging effect of strong winds. Therefore, at considerable heights, greenery is rather introduced in atria or sky gardens closed in a huge greenhouse.

REDUCTION OF ENERGY CONSUMPTION

Yeang states that the design of the built environment should be directed towards ecomimicry, i.e. mimicking the interrelationships occurring in the ecosystem (Yeang & Powell, 2007). The most important features to be considered should be: no waste (everything is recyclable), combining inorganic and organic elements (i.e. introducing biomass), and using only solar energy (i.e. renewable sources). Minimising the negative impact of a tall building on the environment is an increasingly important issue, especially the reduction of pollutant emissions and waste production, as well as the reduction of energy consumption throughout the life cycle of the building (Trabucco & Belmonte, 2021). The need to reduce the carbon footprint is now particularly emphasised (Amiri & Sakeena, 2021; Miranda & Safarik, 2021).

Efficiency of adopted solutions

For developers, the cost-effectiveness and efficiency of solutions adopted in the project are often more important than their environmental friendliness. Meanwhile, rational design can combine these three aspects. The energy consumption needed for the production of materials, construction, provision of use, and finally, demolition of a skyscraper is immense. Therefore, when designing a tall building, one should seek rational and economical solutions that will increase the efficiency of this process and diminish its negative effects on the environment.

As energy consumption further increases with the height of the building, the tallest buildings in the world often contradict the promotion of an economical approach in the design of skyscrapers and, therefore, are certainly a contradiction of the idea of environmentally friendly design. The scale of European projects, which are generally not taller than 200 m, and often do not exceed 100 m in height, is more acceptable. In an interview, William Mitchell (Niederhoffer & Kenner, 2011) noted that the higher the building, the more floor space on subsequent floors must be allocated to construction and technical infrastructure. One always reaches a height at which adding the next floor ceases to have any justification except for ambition. In most European high-rise buildings, subsequent floors are justified in sufficiently large usable areas, which means that the associated energy consumption is also more justified.

The projects recommend the use of local and recycled materials (Finnigan, Gerardy, Popa, & Trabucco, 2019). Structural plans should be selected to ensure the effective use of materials and to reduce their use (Ali & Armstrong, 2010). Design effectiveness depends on, among others, the optimal dimensioning of elements that limit the bulk of the building, the use of prefabricated elements, and the variability of the load--bearing structure strength as a function of height. From a global perspective, energy consumption and the carbon footprint associated with the production of the materials used to build a high-rise building are also important. Therefore, research is being conducted into the more environmentally friendly production of traditionally used construction materials, concrete and steel (Finnigan, Gerardy, Popa & Trabucco, 2019; Law, 2021), as well as into the use of timber for the erection of high-rise buildings (Applegath, Veres, & Wu, 2021; Bahrami & Rashid, 2024).

In the design of tall buildings, it is also important to design durable, and at the same time multifunctional and flexible structures, that can easily be adapted or restructured to suit other functions in the future (Kashkooli, 2010; Gupta, 2012).

Ensuring the proper functioning of the building

Innovative technological solutions allow architects to plan how the buildings will function at the design stage. Accurate digital modelling permits us to simulate and programme the processes that will take place within the building (Robinson, 2007), test all available solutions, make informed decisions about the final shape of the building, and equip it with the necessary mechanical systems. It is possible to carry out, among others, simulations of wind loads and natural ventilation, natural light and indoor shade, and thermal characteristics. It is also possible to carry out a comprehensive energy use simulation for the entire building, allowing the assessment of the building's performance and the comparison of costs of different energy--saving and carbon footprint strategies (Simmonds, 2005).

Today, the systems that consume the most energy over a building's life cycle are those systems that keep a building functioning: primarily ventilation, cooling and heating, but also artificial lighting, vertical transport, plumbing, computers and other equipment used by users. Although improvements in the efficiency of equipment and systems make the energy used to produce the embedded materials and erect the building increasingly important, its value is still secondary (Ali & Armstrong, 2010). While appropriate technical infrastructure is necessary, the goal is to reduce the amount of time when it is being used to a minimum.

Crucial are solutions introduced to ensure energy savings (Fig. 12) – reduction in energy losses and consumption – first of all: natural ventilation, passive and mixed cooling and heating systems, provision of night cooling, heat storage elements, heat recovery systems, increased insulation of the building envelope, protection against overheating of interiors, illumination with natural light, low-energy water systems, advanced zoned air-conditioning systems, and more efficient vertical transportation systems. It should be noted that elevators account for 2–10% of a building's energy consumption and during peak hours even for 40%. This is why the development of vertical transport technology is so important for the energy balance of a high-rise building. Recent advances in elevator technology help to implement many energy-saving solutions, even energy-generating elevators (Al-Kodmany, 2023b; Ali, Al-Kodmany & Armstrong, 2023).

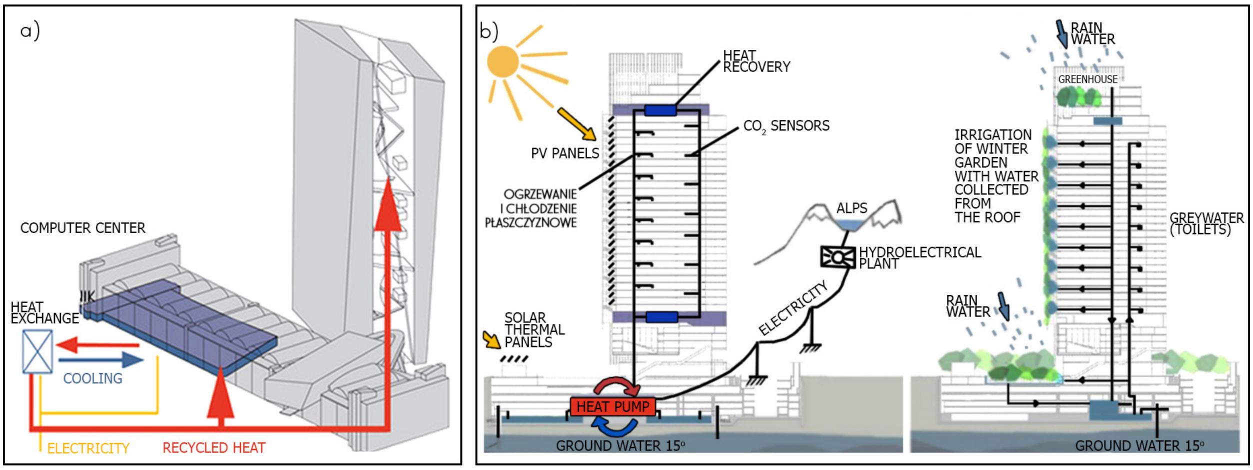

Fig. 12. High-tech solutions in high-rise buildings: a – ECB Tower, Frankfurt am Main, 2014: extracting heat from the computer centre; b – Grattacielo Intesa San Paolo, Turin, 2015: electricity from natural sources, HVAC system and installations – grey water and rainwater

Source: [a]© Coop Himmelb(l)au; [b]own elaboration based on: skyscrapercity.com [n.d.].

Tall buildings are also equipped with integrated building management systems (e.g. BMS), which control the other systems and elements of the building. Intelligent building management aims to reduce energy consumption (Kamal & Ahmed, 2023) by assessing the functioning of the entire structure, conducting diagnostics, and efficient detection of failures and breakdowns.

Energy from renewable sources

In architectural design, and nowadays also in the design of tall buildings, efforts are made to obtain energy from renewable sources (Imam & Kolarevic, 2018). However, the idea of a zero-energy tall building postulated in many projects (Ali & Al-Kodmany, 2012; Gupta, 2012) remains debatable (Pawłowski & Cała, 2013). Because of the large sizes and relatively small building areas, obtaining energy from renewable sources is a big challenge (Dalton & John, 2008), but ongoing research may indicate that there is great potential for solar and wind power (Land, 2008; Vita, Šarkić-Glumac, Hemida, Salvadori & Baniotopoulos, 2020; Kim & Im, 2021).

The provision of biomass makes the operation of the building dependent on a complex supply chain. Heat pumps, on the one hand, can only be implemented in a building located on large plots of land, but on the other hand, can be installed in the ground surrounding the underground parts of a high-rise building. Interesting solutions are also emerging, based for example on heat recovery from large server rooms or data centres (Fig. 12a).

Solar energy can be used passively or actively. Direct solar gain – the heating of spaces adjacent to the façade and the use of thermal storage mass from the building's elements are usually undesirable due to the priority of preventing overheating and even the need for cooling. In addition, the weight of materials that accumulate thermal energy well is a significant factor in structure design (Lotfabadi, 2015). However, thermal energy storage can be taken into account if the building structure is designed with reinforced concrete. Passive systems are usually based on indirect gains – through the design of large-scale greenhouse structures (atria, winter gardens) or double glass façades, and heat is extracted and used to support heating systems and stimulate air circulation.

Active solar design is associated with the use of collectors or photovoltaic panels. The location of solar thermal collectors is generally limited to roof planes so that the transmission path of the medium to the lower floors is greatly extended, reducing the efficiency of the system (Marchwiński & Ruchała, 2015). In addition, there is a much greater need for cooling than for hot water in a high-rise building. The use of photovoltaic systems has much greater potential. A building can be equipped with photovoltaic roof panels, as well as a system of façade cladding or shading panels with PV cells and even photovoltaic glass. However, the roof area of a tall building is relatively small and is often used for representative rather than technical functions. The shape of the plot determines how much of the façade area is insolated, and the surrounding buildings can shade a significant part of the building. The integration of façade elements with PV cells results in interior shading, which can be disadvantageous or have positive effects, but only in summer, which is why such solutions are usually only used in windowless zones or for technical rooms (Marchwiński & Ruchała, 2015). Furthermore, photovoltaic panels in Europe should be sloped rather than fixed on flat walls or roofs, so few buildings have planes that allow their effective use (Fig. 13a). However, the use of shading shelves with PV modules on the upper floors significantly reduces the wind loads. Furthermore, panel production requires a huge amount of energy, and there is still no way to recycle them effectively.

Descriptions of using wind turbines with horizontal axes of rotation in tall buildings regularly appear in the literature (Johnson, 2014), but they only appear in experimental designs (Fig. 13b). Large wind turbines with horizontal axes of rotation require a certain wind speed blowing from a certain direction. However, in a dense and, moreover, time-varying urban environment, it is impossible to unambiguously define wind directions (Zielonko-Jung, 2013). The shape of the plot of land may also influence the form of the building and the possibility of locating a building-integrated turbine directed towards the prevailing wind direction. In addition, large turbines generate dynamic loads (which are particularly dangerous in the case of several turbines whose operation is synchronised), the impact of which has to be estimated and neutralised.

Fig. 13. Obtaining energy from natural resources: a – Tribunal de Paris, Paris, 2017 – inclined panels with PV cells; b – Strata building, London, 2010 – integrated wind turbines

Source: [a]Sergio Grazia 2017; [b]Colin 2014.

Fig. 14. Buildings which underwent façade replacement or reconstruction in the 1990s: a – Intraco I, Warsaw – façade replacement in 1998; b – CityPoint, London – alteration, 2000

Source: [a]Astrorek [n.d.]; [b]StoneColdCrazy 2007.

This can be a very difficult, time- and cost-consuming task due to the difficult-to-define range of wind impacts. In addition, the movement of the large turbines and the vibration of their structural components and the building generates noise that negatively affects users (Al-Kodmany, Ali & Armstrong, 2023). However, the use of turbines with a vertical axis of rotation is becoming increasingly popular. They are smaller and less efficient but can be located on the roof of an elevated building as one of the additional elements of its technical equipment, thus not being a limitation in the shape of the building (Marchwiński & Ruchała, 2015). The use of such a solution significantly reduces vibration and noise, and the turbines can be operated in winds blowing from different directions.

Redevelop, do not demolish

In cities where tall buildings have been built since the 1960s, as early as the 1990s, it proved necessary to adapt them to new utilitarian and aesthetic requirements (Fig. 14), as well as the requisite levels of energy saving (Ysebrant & Zielonka, 2008). The problem of adapting buildings to the changing standards has intensified in the 21st century and will be an increasingly common phenomenon. A design approach in line with sustainable development guidelines requires the renovation of an existing building, and the preservation of as many elements of the existing building as possible: the entire structure, the core, the foundations or at least, for example, gypsum boards from the old building (CTBUH Staff, 2021). Demolition leads to large time and money expenses, as well as huge energy consumption and the creation of waste (Scheublin, 2008). Therefore, the redevelopment of an existing building, combined with an upgrade of its standard, changing the façade, form or even height, is preferred (Rees et al., 2013).

In densely built-up cities, tall building construction is often preceded by the demolition of an existing but significantly lower building. Such decisions have necessitated the realisation of almost all newly constructed high-rise buildings in Frankfurt and central London. The authorities in the latter city have a policy of encouraging the erection of skyscrapers in designated locations and the demolition of 1960s buildings of unsatisfactory quality (Binder, 2006). A skyscraper, The Shard, has even been built on the site of a 100-metre building. Demolitions are also taking place in Warsaw. However, a sustainable design approach rather requires the renovation of an old building (Rees et al., 2013). Therefore, new developments in cities such as Paris, Frankfurt, Moscow, Brussels, Warsaw, Belgrade, and London do not always involve an expansion of tall buildings but only a change in their standard, appearance and even height.

Therefore, when it comes to newly designed buildings, the need to take into account possible future transformations and changes to their functions, as well as the question of demolition and subsequent recycling of embedded materials (Gupta, 2012), are strongly emphasised. Tall buildings are more and more often designed as multifunctional and flexible so that they can be adapted to the changing requirements of the market and users without the need for refurbishment (Kashkooli, 2010). The renovations carried out usually involve the replacement of all elements of a high-rise building except the core structure. Its adaptability to new conditions becomes crucial to the perception of the building as environmentally friendly (Rees, 2008). Most importantly, maximum flexibility of space limited by structural elements should be ensured, enabling the building to be adapted to new standards and functions by simply replacing the installation and finish (Rees et al., 2013).

SUMMARY

High-rise buildings are justified in the largest cities, where their introduction will prevent urban sprawl. In Europe, only a few cities have reached the size of a metropolis, but it is in these areas that high-rise buildings are being built. The pursuit of reducing urban sprawl and preserving energy used for transporting people and goods leads to planning cities with a higher building intensity. This can be achieved, among others, through the concentration of tall buildings. The erection of tall buildings is also justified in cities lacking land for new property development.

The height of European tall buildings is limited, with almost no buildings higher than 300 m and most of the continent's outstanding developments not exceeding 200 m. The height limitation is a great advantage, as the buildings realised are not just a display of ambition and unjustified excessive material and energy expenditure. The heights and usable floor areas of buildings are justified by functional needs.

Since the 1990s, European tall building designers have been increasingly focused on operating in line with natural conditions and respect for ecological values. Further development of these trends can be anticipated. Contemporary projects demonstrate a new approach to tall buildings: as consumers of natural resources, they are transformed into structures that are intended to function in accordance with the laws of nature and the norms of sustainable development.

As the greatest energy consumption is related to the functioning of installations ensuring the correct parameters of the interior microclimate, the basic action becomes limiting their use through the design of the building and the use of natural processes. Compared with some other climatic zones, European high-rise buildings may require higher energy expenditure for the mechanical systems, ensuring the comfort of users. However, climate constraints are objective factors, and the rational approach to designing European high-rise buildings is to maximise the use of passive solutions and reduce the operating time of mechanical systems. In order to do so, the latest technologies are used to create an efficient design for both the building form and modern high-efficiency installation solutions.

There is a trend towards the use of advanced computer technology at all stages of the design process to analyse local conditions, for generative design and the modelling of more complex geometric structures, as well as to analyse the subsequent functioning of the building (particularly in terms of energy efficiency and creating high user comfort). Thanks to innovative technologies related to the design process, the form and façades of tall buildings are shaped in accordance with the local microclimate. As a result of correctly shaping the form and façade of the building, as well as taking advantage of naturally occurring processes, it is possible to limit the use of devices and systems that ensure the suitable microclimate of the interior.

Currently, all skyscrapers being built in Europe are equipped with a number of installations from a group of advanced technologies – these increasingly efficient systems consume less energy, as well as allow for energy to be recovered. Integrated building management systems control the mode and time of operation of other systems, limiting the energy consumption needed for their operation. In subsequent projects, effective methods of obtaining energy from renewable sources are sought. None of the sources of renewable energy are yet being used effectively in high-rise buildings, but ongoing research may indicate that there is great potential for solar (especially indirect passive gains and PV panels) and wind power (rather small turbines with a vertical axis of rotation).

As high-rise buildings have been constructed in Europe for more than 70 years, the continent's approach to ageing high-rise buildings can serve as a guideline for designers in other parts of the world. Design issues are now being considered in relation to the entire life cycle of the building.

CONCLUSIONS

The outcomes of the literature review described in this paper allow the conclusion that tall buildings in Europe are becoming more and more sustainable, and the idea of sustainable development is applied to the entire life cycle of a skyscraper. The conducted analyses confirm the hypothesis that the European approach can be the basis for general guidelines for the construction of green tall buildings. They all need to go through a holistic design process aimed at not just achieving certification but also planning the whole building's life cycle.

Skyscrapers should only be built in large cities, where there is a need for a large amount of new floor space and it is not possible to enlarge these cities or increase their area, which could lead to the urban sprawl phenomenon.

The global race to the skies should be limited so that the gains from floor space in high-rise buildings compensate for the consumption of the energy and the materials used in their construction and later building operation.

In some climates, buildings cannot operate primarily on the basis of appropriate form, façade design and passive phenomena. However, irrespective of the climate, the aim should be to reduce the operating time of mechanical systems as much as possible, using a bioclimatic design approach.

The installation solutions designed for tall buildings should be based on the latest technological developments – e.g. advanced, energy-saving technological solutions, highly efficient equipment, and energy recovery systems.

The use of available local and recycled materials and renewable energy sources should also be considered. In tall buildings, photovoltaic panels and wind turbines can be of particular importance, and their use should be further researched and developed.

The tall buildings have to be designed including future changes in function, technical infrastructure, façade and even the addition of further floors. It must not be assumed that the building will be demolished if any change is necessary.

Thanks to computer simulations and analyses, the building's future performance should be checked during the design stage, and what spatial form shaping and choice of infrastructure is optimal in terms of reducing energy consumption and carbon footprint.

It is impossible to say whether high-rise buildings will ever reach the level of zero-energy buildings, but by analysing the European approach to their design, it is possible to formulate guidelines that will help to construct buildings that result in significantly lower energy consumption.

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MOŻLIWOŚCI WZNOSZENIA BUDYNKÓW WYSOKICH I PROEKOLOGICZNYCH – OCENA Z PERSPEKTYWY EUROPEJSKIEJ

STRESZCZENIE

Celem artykułu jest odpowiedź na pytanie, czy budynek wysoki w całym swoim cyklu życia może być ekologiczny. Zaprezentowano syntetyczne wyniki przeglądu literatury oraz stron internetowych dotyczących aspektów proekologicznych w projektowaniu wieżowców. Potwierdzona została hipoteza, że europejskie podejście do projektowania wieżowców uwzględnia aspekty rozwoju zrównoważonego i może być podstawą ogólnych wytycznych do projektowania „zielonych" budynków wysokich. Przede wszystkim w przypadku europejskich realizacji lokalizacje, powierzchnie i wysokości są uzasadnione funkcjonalnie. Ponadto, pomimo wymagającego klimatu, wieżowce projektowane są z wykorzystaniem rozwiązań bioklimatycznych oraz z uwzględnieniem wykorzystania zjawisk pasywnych i skrócenia czasu pracy systemów mechanicznej wentylacji i ogrzewania. Niezbędna infrastruktura techniczna wykorzystuje wysokosprawne, energooszczędne urządzenia i rozwiązania. Pozyskiwanie energii ze źródeł odnawialnych jest obecne, choć mało popularne – technologie te wciąż się rozwijają i zyskują na znaczeniu.

Słowa kluczowe: budynki wysokie, wieżowce, zielone miasto, ekologia, rozwój zrównoważony