RESIDENTIAL ARCHITECTURE IN TERMS OF THE INDOOR ENVIRONMENT

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ABSTRACT: Nowadays, when the population of the developed world spends more than 90% of their time indoors, the quality of the environment in the interior of buildings is gaining in importance, especially in the case of residential development. How does the architectural concept of residential buildings affect the parameters of the resulting indoor environment? In the article, case studies of three residential buildings in Prague are presented: a tenement house from the late 19th century in a block development in Prague Vinohrady, a precast panel house in a neighbourhood from the late 20th century and a residential complex from the twenty-first century. The light, acoustic and thermal microclimate in the apartments is assessed in the context of current requirements, taking into account the requirements at the time of construction. In the nineteenth century, the requirements for the quality of the indoor environment were not explicitly set, with a few exceptions, but the parameters of the apartments in tenement houses often hold up in the current context. In the second half of the twentieth century, specific criteria for the indoor environment were already laid down in legislation, with demands for daylight and sunlight playing a disproportionate role in the architecture of buildings and the urban design of residential neighbourhoods. At present, the requirements for residential buildings are very complex, not only in terms of the quality of the indoor environment, and are usually met to the minimum necessary extent, with the economic aspect playing a key role. The architect plays the role of coordinator; whose task is to achieve a balance between a number of often conflicting requirements.

KEYWORDS: indoor environment, residential buildings, daylight, acoustics, thermal technology

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INTRODUCTION

The inhabitants of developed countries spend more than 90% of their time inside buildings. The quality of indoor environment, namely in the residential buildings, is one of the key factors affecting the population's health. The indoor environmental quality is still considered to be less important compared to the environmental performance by the professionals [1]. Most of the energy consumed during the buildings' life cycle is however related to regulating and maintaining the indoor environment, mainly temperature, indoor air quality and lighting. Requirements for the quality of the indoor environment are therefore an essential starting point for determining the energy performance of a building. In the recent years, the indoor environment is starting to gain importance in the professional discourse and its assessment is becoming a part of evaluation tools for the building sustainability. There is a shift from separate components towards a holistic approach that, besides the quantifiable parameters, also takes into account the "soft" parameters, mostly linked to the psychology of users and their behaviour [2]. However, the issue is still viewed as aspects of the indoor environment rather than in terms the architectural design and its process, although the architect is the one who determines the final quality of the building's indoor environment, as is based primarily on the architectural design of the building as such, especially on the mass, layout and material solution.
The knowledge gap this research is trying to bride is the linking of the building physics aspects of the indoor environment with the architectural design process. This article is a part of a larger research project which aims to demonstrate, for both architectural students and practicing architects, the principles of building physics that can be implemented in the conceptual design phase and may lead to creating a quality indoor environment in the designed building.

METHODS

To illustrate the connection between the quality of the indoor environment and the architectural concept of the house, the method of case studies of existing buildings was chosen. In this article, the representatives of three typologies of residential development in Prague are presented. First is a tenement house from the 1890s in a block development in Prague Vinohrady, build using traditional technologies, with solid brick walls and partitions and double casement windows with wooden frames and single glazing. Next, a precast panel house in the neighbourhood Velká Ohrada, built in 1988-1993, using the VVU ETA construction system of sandwich panels made of concrete and expanded polystyrene, with doubled wooden frame windows. The contemporary development is represented by the residential complex 4Block by Chmelař architects, built in 2015. 4Block has monolithic reinforced concrete load bearing walls insulated by ETICS system of mineral wool and double glazed thermal insulation windows.

Fig. 1.: Tenement houses in Machova street, Vinohrady (Source: Wikipedia Commons)

Fig. 2.: Drone photo of Velká Ohrada precast panel neighborhood (Source: Wikipedia Commons)

Fig. 3.: Housing complex 4Blok (Source: Archiweb)

These buildings are analysed in terms of three areas of indoor environment quality, which fall within the competence of building physics: lighting technology, thermal technology and acoustics. In each of the addressed areas, aspects of the quality of the indoor environment were selected, which are already determined by the architectural design (not by technologies), are commonly used to evaluate the quality of the indoor environment and their use is established in legislation. These aspects are evaluated in accordance with the requirements of currently valid legislation, taking into account the requirements at the time of the construction of the house. The assessment is focused on a typical apartment, for some aspects, broader contexts in the scale of the whole house or residential unit are also taken into account.

DAYLIGHT

Daylight requirements at the time of construction and now

The daylight requirements have not changed much over the course of history; the requirement of the currently valid legislation in the Czech Republic roughly corresponds to the idea formulated by Vitruvius in the first century BC [3]. At the time of construction of the tenement house (1890s), the daylight requirements were not explicitly defined. Legislative requirements for the amount of daylight in buildings and for the duration of sun exposure were set after the Second World War and, in addition to expert data, they were also based on the principles of the Athens Charter. The first standard concerning daylighting in the Czech Republic was created in 1949 [4], and the requirements for the sun exposure of residential rooms were set in 1955 [5]. At the time of the construction of the Velká Ohrada neighbourhood (1988-1993), the requirements for the amount of daylight were based on ČSN 36 0035 Daylighting of buildings from 1968 [6], depending on the class of visual activity. For living rooms, a value of D = 0.5% (minimum value in the darkest place) was required. The requirements for sun exposure have been established in the standard ČSN 73 4301 Residential buildings [7] since 1960 - 90 minutes on March 1.

The ČSN 73 0580 – 2 Daylighting in buildings [8], valid also during the construction of the residential complex 4Blok (2015), determines two calculation points on the working plane at a height of 0.85 m in the middle of the room depth at a distance of 1 m from the side walls for the calculation of daylight in side-lit residential buildings. The minimum value of the daylight factor at these two points must be 0,7%, the minimum average value from these two points must be 0,9%. At the time of construction, the requirements for a sun exposure period of 90 minutes were valid in Prague, assessed in accordance with ČSN 73 4301 Residential buildings, but in 2018 they were repealed in the Prague Building Regulations [9].

In 2019, a new European standard EN 17037 Daylighting of Buildings [10], came into force, which assesses the daylighting factor on a grid of points located on the reference plane. A target illuminance of at least 300 lux must be achieved in the middle of the reference plane and a minimum target illumination of 100 lux must be achieved in 95% of the reference plane, in half of daylight hours. The standard enables a simplified calculation using the daylight factor, where for Prague the minimum target illumination of 100 lux corresponds to D = 0.7% and the target illumination of 300 lux corresponds to D = 2.0%. However, Czech legislation maintains the validity of two-point evaluation according to ČSN 73 0580 for the evaluation of residential buildings. As in the current Czech standard, the criterion for assessing sun exposure is the sun exposure time (minimum 90 minutes on a selected day between 1st February and 21st March), but the location of the reference point and the limiting angles of incidence of the sun's rays differ, which may cause differences in the resulting sunlight duration.

Daylight assessment in the case studies

Daylight and sun exposure in residential rooms are assessed. Daylight is evaluated using the total daylight factor, which is the ratio between the illuminance of the (working) plane by direct and reflected sky light at a given time and the simultaneous illuminance of the outdoor unshaded horizontal plane. In addition to the real conditions in the given urban situation of flats on the 1st floor, the daylight factor of selected flats is also evaluated in ideal conditions without external shading, in order to better illustrate the connection between the architectural design of the building and lighting conditions. The daylight calculations were performed in the software Building Design by Astra Software, using the computing module Wdls 5.0 – Daylight calculation and ČSN EN 17037 – Daylight of Buildings [11]. Note: some of the daylight calculation have already been presented at the EnviBUILD 2019 conference.

Without external shading, all evaluated apartments meet the applicable legislative requirements for daylighting. However, in some rooms, even in this ideal situation, the values of the daylight factor are at a minimum. With the exception of one of the bedrooms of the panel house, none of the evaluated rooms meets the minimum requirements of the new European standard ČSN EN 17037.

Due to the cramped urban situation, the rooms in the tenement house do not meet the current requirements for daylighting. In the precast panel house, the lighting conditions remain essentially unchanged compared to the ideal (unshaded) situation, given that the housing estate was designed with emphasis on hygienic conditions in the apartments.

The apartment in the contemporary housing complex does not meet the requirements for daylight, which is caused mainly by shading the balconies of apartments on higher floors. In the table above, the entire area of the rooms (including the kitchen unit and built-in cabinets) was included in this assessment. However, even after reducing the room by this area, the bedroom does not meet the requirements.

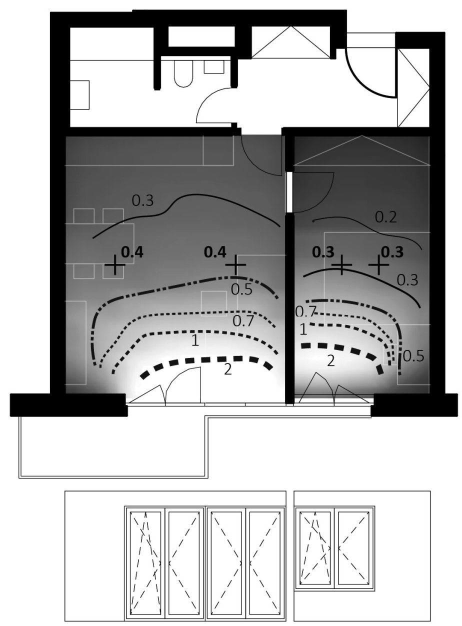


Fig. 4.: Daylight factor[%] on the ground floor of the contemporary housing complex (Source: author)

Sunlight duration

The period of sun exposure in the living rooms of flats on the 1st floor is set for March 1, but for comparison it is evaluated by the original ČSN 73 4301 methodology (valid at the time of construction of the panel house and 4Blok) and the methodology according to the new European standard EN 17037, using minimum sun height of 13° and 5°above the horizon, as this is not currently specified in the valid Czech legislation. The sunlight duration was calculated using the Světlo+ software by JpSoft [12].

	ČSN 73 0580 – 2 DF values [%]					EN 17037 % of work plane area				uniformity of daylight
	point1	point2	>0.7	mean	>0.9	DF>2.0%	>50%	DF>0.7%	>95%	
19th century tenement house										
kitchen	0.9	0.9	yes	0.9	yes	16%	no	73%	no	0.200
room	1.2	1.4	yes	1.3	yes	33%	no	94%	no	0.075
Precast panel building										
bedroom1	1.2	1.2	yes	1.2	yes	33%	no	67%	no	0.054
bedroom2	2.6	2.6	yes	2.6	yes	60%	yes	100%	yes	0.110
living	0.8	0.9	yes	0.9	yes	19%	no	63%	no	0.092
Contemporary housing complex (4Blok)										
bedroom	0.8	0.9	yes	0.9	yes	17%	no	56%	no	0.050
living	1.6	1.2	yes	1.4	yes	27%	no	95%	yes	0.073

Tab. 1. Daylight assessment with no external shading

	ČSN 73 0580 – 2 DF values [%]					EN 17037 % of work plane area				uniformity of daylight
	point1	point2	>0.7	mean	>0.9	DF>2.0%	>50%	DF>0.7%	>95%	
19th century tenement house										
kitchen	0.3	0.2	no	0.3	no	10%	no	28%	no	0.030
room	0.4	0.4	no	0.4	no	13%	no	32%	no	0.052
Precast panel house										
bedroom1	1.2	1.2	yes	1.2	yes	33%	no	67%	no	0.054
bedroom2	2.6	2.6	yes	2.6	yes	60%	yes	100%	yes	0.110
living	0.8	0.9	yes	0.9	yes	19%	no	63%	no	0.092
Contemporary housing complex										
bedroom	0.3	0.3	no	0.3	no	8%	no	22%	no	0.034
living	0.4	0.4	no	0.4	no	6%	no	27%	no	0.100

Tab. 2. Daylight assessment on ground floor

19th century tenement house	precast panel house	contemporary housing complex
ČSN 7304301		
115	230	136
EN 17037 (minimum sun height 13°)		
111	224	92
EN 17037 (minimum sun height 5°)		
111	274	176

Tab. 3. Sunlight duration [minutes] on 1. 3. in the best sunlit room on 1st floor

In all the evaluated apartments on the first floor, there is at least one room which meets the minimum sunlight duration. However, there is a large difference between the sunlight duration assessment methods and the precise methodology (especially the minimum sun height above the horizon) is not yet specified in the valid Czech legislative.

THERMAL TECHNOLOGY

Thermal requirements at the time of construction and now

At the time of the construction of the tenement house, the requirements for the thermal technical properties of the building structures were not set. However, regulations for air exchange and ventilation already existed, although they were not required by the Austrian Hungarian building code. The requirements of thermal technology in our territory were set after the Second World War by the set ČSN 73 0540 Thermal protection of buildings [13] (designation still used nowadays), of which the first standard was developed in 1954. The criteria for the thermal technical properties of building structures were based on the properties of masonry made of solid bricks with a thickness of 450 mm. At the end of the 1970s, in connection with the climate crisis, a thermal engineering revision was carried out and a new standard was issued, which set stricter requirements for the properties of building structures and also introduced new requirements for windows. The revised compositions of the structural elements of the VVÚ ETA panel system used for the construction of the Velká Ohrada housing estate are also based on this standard. The initial parameter for the creation of this standard was thermal comfort during the year and the evaluation already included thermal stability in winter and summer.

Today's standard requirements correspond to European legislation. In addition to the requirements for the properties of building structures, great attention is paid to the evaluation of energy performance of the building. Since the construction of the 4Blok complex in 2015, the changes in requirements mainly concern the assessment of the energy performance of the building. A revision of Decree 78/2013 Sb. Energy performance of buildings [14] is currently being prepared., which will tighten the requirements for the energy performance of new buildings and alterations to completed buildings

Thermal assessment of case studies

In terms of energy performance of the building, the average heat transfer coefficient Uem of the building envelope and the heat transfer coefficients of individual envelope structures (or structures at the system boundary of the residential zone of the building) are compared for the analysed apartment buildings. These values are directly influenced architectural design, especially the spatial and material solutions and articulation of the facade. Although the detailed compositions of structures are often not the subject of an architectural study, their dimensioning and the load-bearing system of the house are usually determined at this stage. For this assessment, the software ENERGIE 2019 by Svoboda software [15] was used.

Furthermore, a critical room is selected for the solved houses, for which the thermal stability in the summer is evaluated, using the software SIMULACE 2018 by Svoboda software [16]. The last parameter of thermal technology is the possibility of cross-ventilation of apartments, studied within the floor plan of a typical floor.

Thermal assessment - results

	Maximum indoor air temperature 21. 8. [°C]			
	19th century tenement house	precast panel house	contemporary housing complex	required $\theta_{ai,max}$
$\theta_{ai,max}$	29.95	39.82	29.13	27.00

Tab. 5. Maximum indoor air temperature in critical room

	Heat transfer coefficient [W/(m^2.K)]				
	19th century tenement house	precast panel house	requirement at time of construction	contemporary housing compex	contemporary requirement $U_{N,rc,j}$
average heat transfer coefficient U_{em}	0,83	0,55	-	0,45	-
Outer wall	0,94-1,25	0,54	0,89	0,25	0,3
Roof	1,014	0,418	0,51	0,16	0,24
Floor on ground	2,15	2,18	-	0,75	0,85
Windows	2,7	2,4	3,7	1,04	1,5
Floor above basement	0,849	0,937	-	0,369	0,6

Tab. 4. Heat transfer coefficient of the building envelope structures

	Heat transfer coefficient [W/(m^2.K)]				
	19th century tenement house	precast panel house	requirement at time of construction	contemporary housing compex	contemporary requirement $U_{N,rc,j}$
average heat transfer coefficient U_{em}	0,83	0,55	-	0,45	-
Outer wall	0,94-1,25	0,54	0,89	0,25	0,3
Roof	1,014	0,418	0,51	0,16	0,24
Floor on ground	2,15	2,18	-	0,75	0,85
Windows	2,7	2,4	3,7	1,04	1,5
Floor above basement	0,849	0,937	-	0,369	0,6

Tab. 6. Acoustic properties of building structures

Besides the material composition of the structures, the main difference between the architectural features that influence the summer thermal stability is in the window treatment. The double casement windows of the tenement house did not originally have any treatment against overheating. The precast panel house windows have horizontal blinds on the inside. In the contemporary housing complex, external aluminium horizontal blinds are installed. However, even with this treatment, the critical room does not meet the requirements for maximum indoor temperature and air conditioning is used to maintain the desirable indoor environment. This is caused mainly by the large window area (see Fig. 4).

Cross ventilation

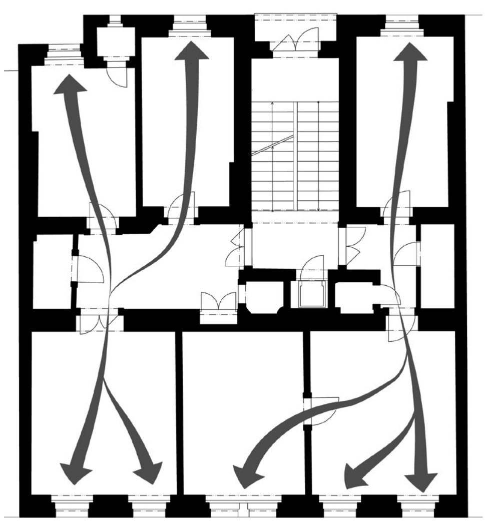


Fig. 5.: Cross ventilation in the 19th century tenement house (Source: autor)

On a typical floor of the 19th century tenement house, both (two-bedroom) apartments allow for cross ventilation, facing opposite facades. In the precast panel house, there are 24 apartments on the typical floor and all the two bedroom apartments allow for cross ventilation. In this particular building, there are 20 two bedroom apartments facing opposite facades, one two-bedroom apartment in the corner section facing perpendicular facades and only three one-bedroom apartments which face only one façade and are not possible to cross ventilate.

In the contemporary housing block, the ratio is much different. Out of the 35 apartments on a typical floor, only 5 have windows facing the opposite facades and 6 more face perpendicular facades. The rest of the apartments face only one façade, not allowing for cross ventilation.

ACOUSTICS

Acoustic requirements at the time of construction and now

In the nineteenth century, there were also no requirements for acoustics in buildings. It was not until the beginning of the 20th century, when the basic physical law of building acoustics was formulated - the Mass law which describes the transmission of airborne sound across a solid wall or a single skin partition - that the Austro-Hungarian building code required 25 cm thick [17]. The first normative regulation that mentioned the requirements for permissible noise values was the Czechoslovak state standard from 1953 [18]. This regulation already addressed, among other things, the principles of layout of residential buildings from an acoustic point of view.

At the time of the construction of the Velká Ohrada neighbourhood, the requirements for acoustics were set out in ČSN 73 0531 Protection against noise in buildings [19]. This standard introduced single number values for soundproofing indexes of building structures. Already with the previous standard from 1961, requirements for soundproofing of technological equipment were set.

At present (and also during the construction of 4Block) the main legislative regulation of building acoustics is Government Regulation No. 272/2011 Sb. [20], which sets hygienic limits for noise and vibration and a set of standards ČSN EN 12354 Building acoustics and ČSN 73 0532 - Acoustics - Protection against noise in buildings and related acoustic properties of building products - Requirements [21] regulating the required acoustic properties of building structures. For old, especially panel construction, the possibility of the original requirements is left, if the construction system does not allow additional sound insulation measures.

Acoustic assessment of case studies

The airborne soundproofing of building envelope structures, including window fillings, is determined for all buildings. Furthermore, the airborne soundproofing of dividing structures between flats and partitions separating living rooms and the airborne and impact soundproofing of ceilings between residential floors are determined. For this, the software Neprůzvučnost 2010 by Svoboda software [22] was used.

In a typical floor, the location of noise sources within apartments (especially sanitary installations) and within the whole house (elevators) in relation to protected rooms is investigated.

(Acoustic properties of building structures in Tab. 6.)

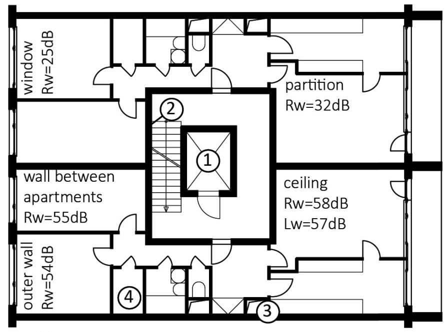
The protection against airborne noise in the 19th century house is on par with the current standards, as it is mostly dependent on the basis weight of the construction. The largest weakness of the 19th century structures lies in the protection against impact sound of the traditional wooden beamed ceiling. Reconstructions of these apartments therefore usually include modifying the composition of the ceiling and adding a floating floor (which the high ceilings allow for). In the precast panel house, additional floor layers are usually not possible, as the ceiling height (2.55 m) is already below the current standard minimum. Therefore, the legislative limits are adjusted for this type of dwelling.

Noise sources within the layout

Inside the apartments, the most significant noise source are the sanitary installations and kitchen extractor hoods. In the 19th century tenement house, the bathrooms are usually oriented towards light shafts, either at the gable wall or in the middle of the layout adjacent to the corridor, where there are the vertical installations, which keeps the separate from the protected rooms. The horizontal pipes can sometimes however be put in the bedroom walls. In the precast panel houses, the vertical installations are concentrated in shafts that are separated in the layout from bedrooms (see Fig. 6).

There is little need for horizontal pipes, as the bathroom fixtures are clustered around the installation shaft. The formica walls sometimes used for the bathroom core however provide very low airborne noise protection. Also in the contemporary apartment complex, the vertical pipes are placed in installation shafts. The horizontal pipes are placed in installation prewall of plasterboard and in the layout, they are kept from the walls adjacent to noise protected rooms, especially bedrooms.

The most prominent noise source from inside the house are the vertical communications – staircases and elevators. In the tenement houses, the stairs are usually granite, embedded in the load bearing brick walls which are adjacent to rooms and can be a source of impact noise. Additionally installed elevators are placed either in the light shafts (where there is often little to no space for dilatation and the noise may transfer into the apartments) or in the stairwell between the flights of stairs (which keeps the elevator separate from the apartments). Alternatively, the elevator is placed on the court façade of the house (accessible from the landing), which may be a noise source for the rooms whose windows open onto the courtyard not just in the building itself, but for the neighbours as well. In the layout of the construction system VVU ETA that the precast panel house is built of, the elevator shaft is separated from the apartments (Fig. 6). However, if the elevator is directly fixed to the shaft walls, it can become a source of impact noise. In the contemporary apartment house, the elevator shafts have double walls, with a self-bearing inner shaft and flexible installation of the elevator motor. The stairs in both the precast panel and the contemporary house are made of concrete prefabricated and the critical aspect of protection against impact noise is their flexible attachment to the load bearing structure.



1 elevator separated from apartments
2 staircase next to a bedroom (potential noise source)
3 extractor hood away from bedrooms
4 closet separates sanitary installations from bedrooms

Fig. 6. Noise sources in a section of the precast panel house (source: author)

CONCLUSION

The aim of this article was to find the connection between the architectural features of residential buildings and the indoor environment in the apartments and to pinpoint how the development of the indoor environmental quality requirements influenced the architectural design.
In the 19th century, there were almost no explicitly stated demands on the indoor environment. One of the main limiting factors for the street profiles and the building structures were fire safety restrictions.
Due to large construction height of the floor, the windows in the tenement houses have very high window lintels, which leads to quite satisfactory lighting conditions in the apartments by themselves. The provision of daylight and direct sunlight is however significantly limited by the cramped urban situation. Due to the large basis weight of traditional building structures (brick walls and wooden beam ceilings), the protection against airborne noise in the tenement houses is on par with the current demands. However, the traditional structures cannot keep up with the requirements on impact noise protection and thermal demands.
In the second half of the twentieth century, the residential development already had to consider the indoor environment requirements, as they were set in legislation. Disproportionate emphasis was placed on sufficient daylight and direct sunlight provision inside the apartments, whose demands, in addition to the actual layout of the apartments, also affected the urban layout of residential neighbourhoods, especially street profiles. The demand on building structures in term of thermal and acoustic properties have undergone a steep development and brought a fundamental change in the way of building.
Nowadays, there is a plethora of requirements placed on the residential development. Besides the building physics and technological demands, there is an increasing economic pressure on the composition of apartment layouts. While until the end of 20th century, the majority of apartments had two or more bedrooms (intended for families with children), currently the prevailing layout is a one-bedroom apartment. This has a great influence on some properties of the indoor environment. Due to the fact that these smaller flats usually have windows oriented towards only one facade, it is, for example, much more difficult to meet the requirements of sun exposure (to ensure that at least one of the rooms gets enough direct sunlight) or to achieve cross-ventilation of the apartments.
In particular, new houses meet the requirements for building structures, which can be explicitly determined by numerical values and therefore it is easy to check whether the structures meet them. It is no longer possible for the architect to assess all those requirements and therefore a number of specialized professionals come into play. The architect is in the role of coordinator, who must find a balance between often conflicting requirements.

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