Czech Technical university in Prague

Faculty of Architecture

Department of Building Construction II

ARCHITECTURAL DESIGN PROCESS IN TERMS OF THE INDOOR ENVIRONMENTAL QUALITY

Teze k disertační práci
Theses of dissertation

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Doctoral study programme: Architecture and Urbanism

Prague, 2022

Disertační práce byla vypracována v kombinované formě doktorského studia na Ústavu stavitelství II Fakulty architektury ČVUT v Praze.

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Abstract

The indoor environmental quality (IEQ), consisting of light, thermal comfort, indoor air quality and acoustics, is the building performance area with the most impact on occupants' health and well-being. Since the physical properties of the indoor environment are largely determined by the architectural design features of the building, the architects' decisions made early in the design process have a key role in creating healthy and comfortable buildings.

The aim of this thesis is to closely link indoor environmental quality and building physics to the architectural design process by regarding the topic from the architectural point of view. An original framework matrix linking the individual IEQ areas to the iterative loops of architectural design process was used to find the connections and compromise solutions in architectural design that directly affect the indoor environmental quality of the designed spaces. Beside literature and an analysis of IEQ metrics, the main source of information were case studies of 15 buildings realized in the Czech Republic in the years 2010 – 2020. The architects of these buildings were interviewed and the IEQ metrics calculated and analyzed.

The research tried to determine what form should design decision support take to facilitate the architects design decisions concerning the indoor environmental quality. The findings indicate that architects do consider indoor environmental quality from the start of the design process, when they need to make imprecise decisions with incomplete information. The design decision support tools should therefore be oriented to pointing the architect in the right direction, rather than providing a precise numerical assessment.

Keywords: Indoor environmental quality; IEQ; architectural design process; building performance; design decision support

Abstrakt

Kvalita vnitřního prostředí (IEQ), která se skládá z osvětlení, tepelné pohody, kvality vnitřního vzduchu a akustiky, je oblastí vlastností budov s největším vlivem na zdraví a pohodu obyvatel. Vzhledem k tomu, že fyzikální vlastnosti vnitřního prostředí jsou do značné míry určeny parametry architektonického návrhu budovy, hrají rozhodnutí architektů učiněná na počátku procesu navrhování klíčovou roli při vytváření zdravých a pohodlných budov.

Cílem této práce je úzce propojit kvalitu vnitřního prostředí a stavební fyziku s procesem architektonického navrhování, a to prostřednictvím pohledu na toto téma z architektonického hlediska. K nalezení souvislostí a kompromisních řešení v architektonickém návrhu, které přímo ovlivňují kvalitu vnitřního prostředí navrhovaných prostor, byla použita originální rámcová matice propojující jednotlivé oblasti kvality vnitřního prostředí s iterativními smyčkami procesu architektonického návrhu. Vedle literatury a analýzy veličin popisujících kvalitu vnitřního prostředí byly hlavním zdrojem informací případové studie 15 budov realizovaných v České republice v letech 2010-2020. S architekty těchto budov byly provedeny rozhovory a byly vypočteny a analyzovány veličiny kvality vnitřního prostředí v budovách.

Výzkum se snažil zjistit, jakou podobu by měla mít podpora rozhodování při navrhování, která by architektům usnadnila rozhodování při návrhu týkající se kvality vnitřního prostředí. Ze zjištění vyplývá, že architekti berou v úvahu kvalitu vnitřního prostředí již na začátku procesu navrhování, kdy musí činit nepřesná rozhodnutí s neúplnými informacemi. Nástroje pro podporu rozhodování při navrhování by se proto měly orientovat spíše na to, aby architekta nasměrovaly správným směrem, než aby poskytovaly přesné číselné hodnocení.

Klíčová slova: kvalita vnitřního prostředí; IEQ; proces architektonického navrhování; výkonnost budovy; podpora rozhodování

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Glossary of terms and abbreviations

IEQ	**indoor environmental quality** the set of physical conditions inside buildings that surround the occupant and affect their senses the commonly defined areas of IEQ are: light, thermal comfort, indoor air quality and acoustics
IAQ	**indoor air quality**
BP	**building performance** a measure of how well the building fulfills its intended function the most commonly mentioned building performance aspects are the occupant comfort and health, including the indoor environmental quality and energy efficiency and sustainability
BPS	**building performance simulation**
DDS	**design decision support**

Introduction

The indoor environmental quality in buildings is a complex multidisciplinary topic that significantly impacts the health and well-being of the occupants. The physical properties of the indoor environment are determined by the architectural elements of the building, from the site and surroundings, through the massing and layout, the façade articulation and materiality to the interior design and materials. These aspects are primarily in the scope of the architectural design in the early stages of the project. Although it is to some extent possible and necessary to enhance the indoor environmental quality in the later design stages (primarily by but not limited to building systems and technologies), any changes to the design are difficult and costly, both in terms of money and energy efficiency. Therefore, the architects and their ability to foresee the impact of their early stage design decisions on the indoor environmental quality of the final building play a key role in creating healthy and comfortable buildings.

This research aims to facilitate architectural design decision making by closely linking indoor environmental quality concerns to the architectural design process, in other words to switch the perspective from the building physics of the individual IEQ areas to the architectural design elements.

Current state of the art

In today's developed world, people spend more than 90% of their time inside buildings (KLEPEIS et al., 2001). The impact of indoor environmental quality on occupants' health and well-being has been well established (Mujan et al., 2019; Ortiz et al., 2017). There is a growing body of research on managing and achieving healthy indoor environment.

In all the areas of indoor environmental research and theory, two schools of thought can be observed: the first promotes highly controlled, uniform indoor environment, with neutrality as the ultimate goal. Simply put, the best stimuli would be no stimuli, with the occupant not being distracted by the environmental conditions. The second school prefers more nuanced, diverse environment, providing the occupant with adaptive opportunity; people prefer an environment they can interact with to one they can ignore.

The uniform comfort model is appealing to building physicist and lawmakers, since it can be quantified and measured. The metrics and values based on this model form the base of most of the indoor environmental legislation, standards and green building certification schemes.

The diverse, adaptive comfort model may be more appealing to architects, who are likely to think about the build environment more holistically and are vary of reducing the reality to quantifiable metrics.

In the most current research, a combination of these approaches is applied, with a rise of various human centric IEQ metrics, that may be more effective in predicting the occupants' satisfaction with the built environment.

The indoor environmental quality is the key aspect of building performance, along with energy efficiency. The priorities and emphasis on these areas are continuously evolving in the scientific and professional discourse. During and after the Covid19 pandemic, the focus has shifted towards public health, but the energy crisis of 2022 seems to indicate the scales tipping to the energy efficiency side again.

The indoor environmental quality and energy efficiency are of course hardly opposing sides, but rather communicating vessels, since achieving and maintaining the desired indoor environment quality is one of the main drivers of energy consumption in buildings. In 2020, building construction and operation accounted for 36% of global energy consumption, 85% of which was consumed by building operation. Almost half of that was used for achieving and maintaining the desirable indoor environmental quality (space heating, cooling and lighting) (United Nations Environment Programme, 2021).

Decisions made in the early design stages have the most profound impact on the final building performance (MacLeamy, 2004). In the traditional design process, the schematic design (architectural study) is often carried out by the architects, with minimal input from building performance specialists, who are only involved in the later design stages, such as the technical specification and building permit documentation. Although this is changing nowadays with the growing trend of the integrated design process, which involves all the stakeholders from the early design stages, some initial design decisions are still solely or mainly in the architects' competence. Even when the collaboration with specialist is moved earlier into the design process, it is still up to the architect to recognize the point in the design process when the specialist need to be consulted and also which building performance aspects need to be considered and when.

Experienced architects have learned to address the indoor environmental quality concerns and building performance in general though practice. However, for architecture students and beginning architects, it can be very difficult to:

- orient themselves in the plethora of often contradictory requirements they need to consider.
- predict the impact of their early stage design decisions on the indoor environmental quality and overall performance of the finished building.
- recognize when to consult specialists or verify some building performance aspects.
- project their technical knowledge and the specialist's feedback into the design.

This may lead to undesirable and costly compromises in later design stages, as well as frustration on the side of the architects, who may feel their design intent has been ruined by the necessity to accommodate the legislative and technical requirements on building performance.

In the traditional architectural engineering education model (also practiced at the Czech Technical University in Prague), the technical subjects are taught by specialists independently of the design studio courses. The knowledge in the technical classes is typically illustrated on model examples, either of already designed buildings or simplified assignments without a direct link to the architectural concept design. The integration of technical knowledge into a project of the students' own design is a part of the bachelors' thesis, but even then, it is preceded by an architectural study, designed in the previous semester. The integration of technical subjects into studio teaching can be addressed by the Project Based Learning (PBL) teaching model, practiced for example at the Aalborg University (Knudstrup, 2004).

Considering the building performance requirements in the early design stages can also be facilitated by various methods of design decision support (DDS). Beside the traditional design decision support methods, such as handbooks, rules of thumb and specialist consultations, there is a growing body of research and industry development on building performance simulation (BPS) via software tools. However, literature suggests that architects are still reluctant to integrate the BPS software into their practice for various reasons (Kanters et al., 2014; Attia et al., 2012; Purup & Petersen, 2020).

The discrepancy between the existence of available design decision support tools and the architect's reluctance to use them indicates a need for a deeper understanding of the connection between building performance concerns and the architectural design process, both to help the architects better incorporate those concerns and to help the design decision support tools creators make those tools more accessible and usable to the architects.

Research aim, objectives and questions

The aim of this thesis is to *closely link indoor environmental quality and building physics to the architectural design process*. This means regarding the building performance concerns through the lens of an architect, changing the perspective from the separate areas of different specializations to the architectural features.

To achieve this aim, the following objectives are defined:

Find the connections and compromise solutions (or trade-offs) in architectural design decisions that directly affect the lighting, thermal, aerial and acoustic qualities of the designed spaces.

To create a supplementary learning material for architectural students and practicing architects which will facilitate the consideration of the indoor environmental concerns in the architectural design process.

This establishes the following research questions:

Q1: *Which architectural features determine the indoor environmental quality and which indoor environmental concerns act as form givers in the architectural design?*

Q2: *Which architects' decisions form the indoor environment and when are those decisions likely to be made in the architectural design process?*

Q3: *What should the design decision support for the conceptual stage of the architectural design process look like to facilitate the achievement of good indoor environmental quality?*

Expected contributions of this research

To provide a deeper understanding of the connection between building performance (mainly indoor environmental quality) concerns and the architectural design process.

To improve the teaching of building physics subjects for architects at the Czech Technical University in Prague, and ultimately at other architectural study programmes.

To provide the architectural students and practicing architects with a guide to understanding what indoor environmental quality concerns are best addressed when in the architectural design process (since the architectural design process is non-linear and iterative, the “when” is often understood in a cause-effect kind of way, rather than chronologically).

To facilitate the creation of design decision support tools (both software and handbook) that are accessible and useful for architects.

To improve the collaboration between architects and building performance specialists by helping them find a common language and manage expectations.

Research strategy and methods

Since the aim of the thesis it to approach the indoor environmental quality from the architectural perspective, the strategy is based on the nature of the architectural design and the way it differs from other professions involved in the building design process.

The most salient characteristics of architectural research are:

- Holistic – even when focusing on a single aspect of the design, the architect always keeps the big picture in mind and considers the relative importance of requirements in the context of the entire design
- Iterative – all aspects of the design go through multiple iterations. The iterative loops are not linked consecutively (Figure 1a) but rather are interconnected (Figure 1b) - each design decision influences other aspects, so the architect needs to look outside the “loop” he is currently in.

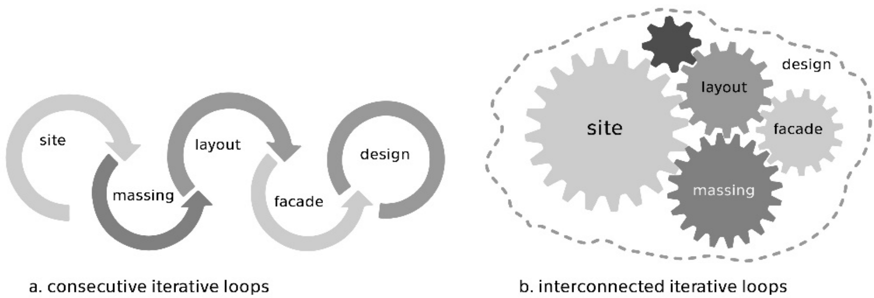


Figure 1 The holistic, iterative nature od architectural design process (source: author)

Due to the nature of the architectural design, it is not possible to identify a universal design process model. Attempts at prescribing a certain workflow are viewed negatively by architects, rendering the design decision support useless. This has been proven by (Purup & Petersen, 2020) via a survey of Danish architects.

It is more effective to approach the architectural design process as a series of design task, the order of which differs on a case-by-case basis. For the purpose of this research, the design tasks have been grouped into seven groups, also referred to in this text as “iterative loops”. They are arranged in the approximate order of level of detail, from site and context up to interior design and materials. This is also the most common chronological order in which these tasks appear, but the precise workflow is always case specific and in some extreme cases (such as prefabricated housing), the order may be significantly rearranged.

There is also significant overlap between these groups. For example, windows (which are arguably the building element most influencing the IEQ) are designed in almost all of them.

The connections between architectural elements and indoor environmental quality have been organized in a framework matrix formed by the seven iterative loops and the four main areas of indoor environmental quality (Table 1).

Table 1 Framework matrix

	Light	**Thermal**	**IAQ**	**Acoustics**
interior design				
building systems				
structural construction				
façade envelope				
spatial layout				
massing volume				
site context				

As with other building performance areas, the “translation” between the architectural features and the indoor environmental quality (simply put, between what the building looks like and what in can do) in not obvious (Bluyssen, 2009, p. 181). Therefore, quantitative metrics are used as “converters”, enabling the prediction of final indoor environmental quality based on the building elements. The connections between the architectural design and IEQ have been identified using several resources, ranging from general (literature) to individual (case studies of existing buildings) and approaching the question from both directions: architectural elements determining the IEQ and IEQ concerns as form

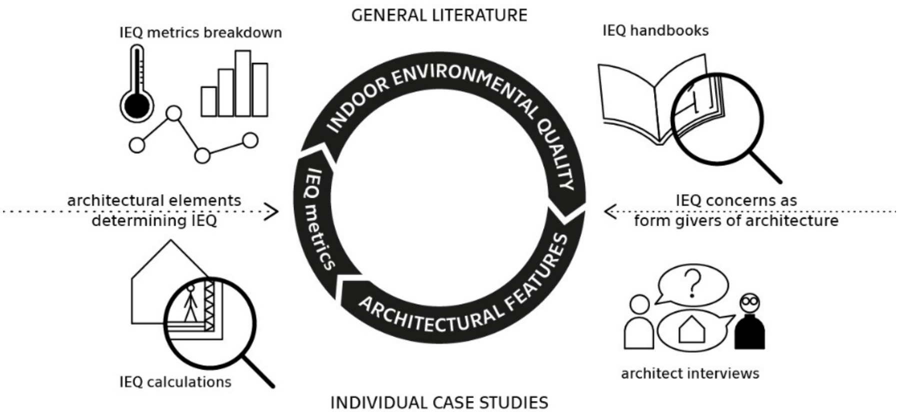


Figure 2 The resource for identifying connections between IEQ and architectural design (source: author)

givers for architectural design (see Figure 2).

IEQ metrics breakdown

To identify how the architectural elements determine the indoor environmental quality in general, a breakdown of the metrics most commonly used to predict IEQ have been performed. For each metric, it was identified which architectural elements are used for their calculation.

Handbooks of IEQ design

To identify which IEQ concerns generally act as form givers in the architectural design, several handbooks (written by respectable authorities on the field of indoor environment in buildings) have been studied. The information drawn from these have not been analyzed statistically, the number of resources has been optimized to reach information saturation.

The information extracted from general resources serve as a basis for the individual case studies described below.

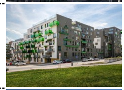
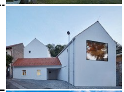
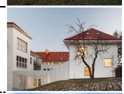
Case studies

The case studies methodology is chosen because architects (and especially architecture students) have a hard time grasping building performance concepts outside the context of a building design scenario (Folan, 2011). Presenting the indoor environmental quality issues using real buildings and including the opinions and concerns of their architects makes them both easier to understand and more trustworthy.

To find the connections between architectural design and IEQ on an individual building level, 15 case studies of buildings realized in the Czech Republic in years 2010 - 2020 have been have been conducted. To identify the IEQ concerns that are considered by the architects when designing the building, the architects (and in one case, also the chief project engineer) of those projects have been interviewed. To illustrate and sometimes supplement the information provided by the architects, some indoor environmental metrics have been calculated, analyzed or acquired directly from the project documentation provided by the architects.

The examples have been chosen from the following typologies (3 each): residential (both multi-family and single-family), schools (kindergarten and elementary) and office buildings. These are the types of buildings people spend most of their time in and also in those typologies, all the indoor environmental quality areas apply quite proportionately (meaning there is not an emphasis on one of them). The list of case studies can be found on the following page.

The information from the case study interviews was used both to find a connection between the architectural design decisions and IEQ quality and to determine when in the design process have the decisions been made.

		Building	design year build year	Authors (interviewed in **bold**)	
residential	multi-family	Apartment House Ostravská Brána	2006 - 2007 2008 - 2010	Kuba, Pilař | **Tomáš Pilař**, Ladislav Kuba	
		Residential Block 4BLOK	2011 - 2016 2015-2017	Chmelař architekti | **David Chmelař**, Vojtěch Nedorost	
		Villa Houses Krásnopolská	2015-2016 2017-2018	Atelier 38 s.r.o. | **Tomáš Bindr**, Petr Doležal	
	single-family	Terraced Houses Zruč	2012 2014-2015	PRO STORY **Jiří Zábran**, Tereza Nová	
		Family House Prokop	2016-2017 2017-2018	ASGK Design, s.r.o. | Gabriela Kaprálová, **Karolína Jiroušková**, Monika Tomšová	
		Family House in Jinonice	2016 2018-2019	ATELIER 111 architekti s.r.o. | **Jiří Weinzettl**, Barbora Weinzettlová, Veronika Indrová	
schools	kindergartens	Kindergarten Sedlejov	2016 2018	ARCHOO s.r.o. | **Jiří Ondráček**, Jaroslav Svoboda	
		Kindergarten Přístavní	2016 2018	XTOPIX | **Barbora Buryšková,** Pavel Buryška	
		Kindergarten Nová Ruda Vratislavice	2015-2018 2017-2018	Petr Stolín, **Alena Mičeková**	
	elementary schools	Jára Cimrman Elementary School Lysolaje	2015 2017-2018	Progres atelier | Vojtěch Kaas, **Jan Kalivoda**	
		Elementary School Líbeznice	2014 2015	Projektil architekti | **Adam Halíř**, Ondřej Hofmeister, Marek Sankot, Bohdana Linhartová, Adam Hašpica	
		Elementary School Amos Psáry	2014-2017 2019	SOA architekti, s.r.o. | **Ondřej Píhrt**, Štefan Šulek, Ondřej Laciga	
office buildings		Office Building THE BLOX	2008-2013 2013-2015	DAM architekti s.r.o. | **Jan Holna**, Petr Šedivý	
		Office Building Konplan	2016 2019	PRO-STORY s.r.o. | **Jiří Zábran**, Tereza Nová chief project engineer: **Jiří Kott**	
		Prague 7 Townhall	2016-2017 2017-2020	Atelier bod architekti | **Vojtěch Sosna,** Jakub Straka, Jáchym Svoboda	

The interviews were performed in Czech using the following guide:

Interview guide (translated into English):

Introductory question:

- What does the indoor environment mean to you? What do you imagine by this term?

Project-specific questions:

- Were there any specific requirements for the quality of the indoor environment in the project brief? What requirements were the project based on? (only mandatory legislation or other?)
- At what stage of the design process did you start thinking about indoor environmental quality?
- Did you work with any specialists/professionals in the concept phase (architectural study)? Alternatively, did you use any tools to verify the properties of the indoor environment/building physics before consulting with specialists? (e.g. software, diagrams, orientation rules...)
- What compromises (architectural, conceptual) have you had to make to meet the requirements of the indoor environment?
- Did you have to make any architectural changes to meet the requirements for the indoor environment and satisfy the authorities? (at later stages of the project)
- Were you surprised by anything about the finished building in terms of the quality of the indoor environment? Did anything turn out differently than you had imagined/expected/designed?

General questions (on their architectural practice):

- What do you need to know as an architect to design a building with a good indoor environment?
- What would make it easier for you to design a good indoor environment for buildings?
- (legislation, environment, software and tools...)
- What do you consider essential in terms of collaboration between architects and specialists/professionals?

Results

One example of a case study is included in this summary. All the case studies are included in the full dissertation.

Apartment house Ostravská Brána

Design year: 2006 - 2007
Build year: 2008 - 2010
Place: Kostelní náměstí, Moravská Ostrava, Ostrava
Author: Kuba & Pilař architekti | **Tomáš Pilař** (interviewed), Ladislav Kuba

Figure 3 Apartment House Ostravská Brána (source: archiweb.cz)

Figure 4 Apartment House Ostravská Brána interior (source: ekonom.cz/c1-53744210-stavby-ktere-letos-bodovaly-u-odborniku)

Interview excerpts:

The basic footprint was determined by a zoning decision that another investor had had there for some time (…) so we had to fit into that footprint and just in some nuances where we rounded that corner and did that console there, so we had to work with it that way. In the end it turned out that the planning permission wasn't quite able to meet the requirements of the developer in terms of floor area and number of apartments, so the building was modified anyway and then the planning permit and the building permit were done together.
Some of the apartments, if they were one-sidedly oriented either to the street or to the square, just didn't meet the required values of the sunlight and daylighting, so the apartment mix was dealt with for a long time. We

had to stretch the apartments across the layout, so the apartments got bigger. The layouts are quite deep in some cases, since we had to get the sunlight into the apartments somehow, because the investor didn't want to have any kind of non-apartments, so called ateliers. The investor's originally planned for more smaller apartments on the lower floors. In the end, it turned out that even the second floor towards the street would be non-residential space, commercial units. Then, facing the street, there are duplexes, precisely because it was not possible to make those apartments in the 2nd floor (upper 1st floor/mezzanine).
The only building in close proximity is the Bishop's building. The daylight and sunlight levels there, when the diagrams were done, came out fine and then on the opposite side, there was nothing standing there at the time, so we didn't have to deal with that.
(...) it was expected that the street 28. října would be busier in the future, so a noise study was done and then the values on the facade and in the interior were calculated on the basis of that.
Of course, there was also a noise study of the stationary sources both from the surrounding area and then from ours, and then there was also a noise study of the indoor environment in terms of the noise of the parking lot impacting the 1st and 2nd floor, the soundproofness of the structures.
We then did a study for the city on the material and general conceptual solution of the public space of the whole square. Unfortunately, the reconstruction ended up being a big compromise. There was supposed to be some artwork in that space, but that just didn't happen. And it became more of a traffic solution than a quality public space."

IEQ aspects most considered by the architects:

sunlight and daylight provision for apartments – investor didn't want so called "ateliers"

district heating, asecondary heat exchange stations in apartments

natural ventilation in apartments, mechanical ventilation only in commercial spaces

noise from surroundings, noise from parking inside house → soundproofing of structures

Table 2 Apartment House Ostravská Brána - framework analysis (interview)

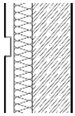
	Light	Thermal	Indoor air quality	Acoustics	Other aspects
interior design					
building systems		*heat recuperation only in commercial spaces, not apartments asecondary heat stations in each apartment"*	*mechanical ventilation - only in commercial spaces, natural for apartments*	*noise from mechanical equipment – impact on surroundings calculated*	
structural construction				*noise from indoor parking →soundproofing of structures*	
facade envelope				*noise study from surroundings – façade soundproofing*	
spatial layout	*apartment mix and building program determined by sunlight requirements*			*parking in souterrain - noise source for 1st and 2nd floor*	
massing volume					*basic footprint determined by previous planning permit*
site context	*craped urban situation →difficult to achieve sunlight and daylight only the Bishop's building in close proximity (daylight not worsened there)*				*also designed the public space – nor realized to their satisfaction*

Table 3 Apartment house Ostravská Brána - design process (interview)

	site analysis + pre-requisites	architectural study	building permit documentation	after building
interior design				
building systems			*mechanical ventilation with heat recuperation only in commercial spaces, not apartments* *district heating + asecondary heat exchange stations in apartments* →	*partial heating autonomy advantageous in uncertain energy situation*
structural construction		*noise from indoor parking →soundproofing of structures*		
façade envelope		*noise study from surroundings – façade soundproofing*		
spatial layout	*investor didn't want any non-apartments ("ateliers")* →	*apartment mix and building program determined by sunlight requirements*		
massing volume	*basic footprint determined by previous planning permit*			
site context	*street expected to become noisier* *only the Bishop's building in close proximity* →	*daylight and sunlight values on the neighboring façade sufficient*	*noise from mechanical equipment – impact on surroundings calculated*	*designed the public space – compromise, more traffic solution than public space the public spaces and ground floor not used as expected – the locality not central enough in urban context*

structures composition and properties (1:50)

exterior wall



-interior plaster 10mm
-reinforced concrete 250mm
-mineral wool 120mm
-air gap 50mm
-glass-cement panel 10mm

U = 0.35 W/m²K (<0.38/0.30)

R'w = 63 dB (>43 all envelope)

wall between apartments

-interior plaster 10mm
-Porotherm (bricks) OR reinforced concrete 240 mm
-interior plaster 10mm

R'w (Porotherm) = 53dB (>53/53)

R'w (concrete) = 55 dB (>53/53)

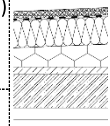
partition inside apartment

-interior plaster 10mm
-Porotherm (bricks) 115 mm
-interior plaster 10mm

R'w = 42 dB (>42/40)

roof

- river rock aggregate
- waterproofing sheets 5 mm
- thermal insulation 180mm
- sloping thermal ins. 50-220 mm
- concrete screed 50 mm
- reinforced concrete slab 220 mm

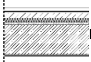


- air gap - grid
- plasterboard ceiling

U = 0.16 W/m²K (<0.24)

ceiling between apartments

- 3-layer glued flooring 10 mm

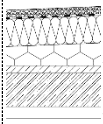


- concrete screed 50 mm
- step insulation 30 mm
- levelling layer 20 mm
- reinforced concrete slab 220 mm
- interior plaster 10 mm

R'w= 65 dB (>52/54)

L'n,w = 32 dB (<58/53)

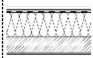
ceiling above loggia



- 3-layer glued flooring 10 mm
- concrete screed 50 mm
- step insulation 30 mm
- levelling layer 20 mm
- reinforced concrete slab 220 mm
- mineral wool 180 mm
- ventilated air gap 270 mm
- ceiling panel glass cement 10 mm

U =0,18 W/m²K (>0.24)

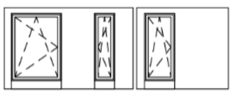
loggia floor (= terrace roof)



- ceramic tiles 10 mm
- mortar targets 5 mm
- waterproofing sheets 5mm
- 180 mm foam glass panels
- reinforced concrete slab 120 mm
- interior plaster 10 mm

U = 0.23 W/m²K (>0.24)

windows schema (1:200)



clear height = 2.66 m
window height = 2.2 m
window sill = 0.26m
window lintel = 2.5m
window frame 30-40%

τ_k = 0.6-0.7 (triple glazing)

$\tau_{s,nor}$ = 0.779

U = 1.04 W/m².K (>1.70/1.50)

R'w = 36 dB (>43 all envelope)

Daylight and sunlight

The sunlight requirements determined the apartment mix. It was not possible to place smaller one-bedroom apartments on the upper 1st floor (mezzanine) as the investor originally planned and in the upper floors, the apartments had to be stretched through the layout to achieve the required sunlight duration in at least one room (Figure 5).

Due to the cramped urban situation, the daylight levels on the façade directly adjacent to the neighboring Bishops' building on south are already low, which is exacerbated inside the apartments by the narrow windows with deep window linings (which would need to be even deeper if the exterior wall was to meet the current U value requirements) (Figure 6).

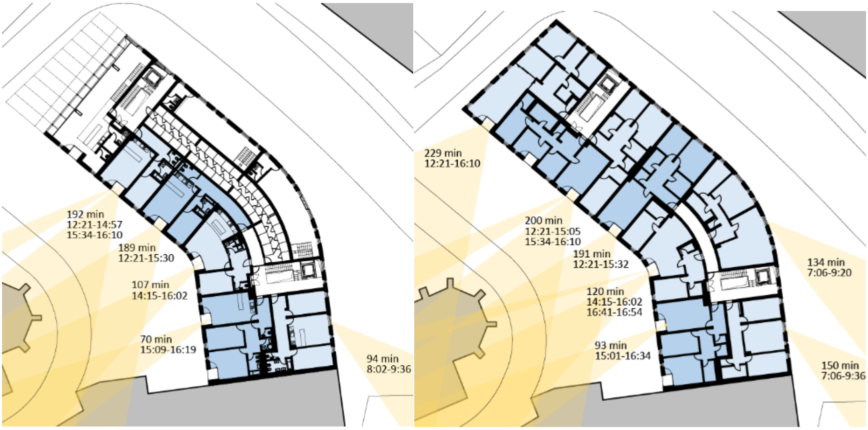


Figure 5 Apartment House Ostravská Brána sunlight in apartments on upper 1st floor (left) and 3rd floor (right) in urban context (1:1000) (source: author)

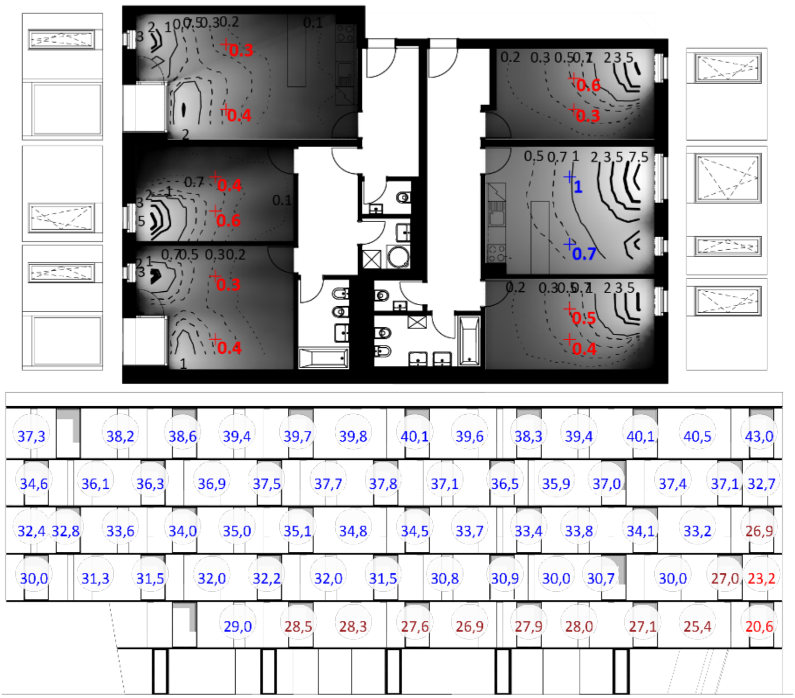


Figure 6 Apartment House Ostravská Brána daylight factor [%] in upper 1st floor (mezzanine) apartment (1:250) and on southwest facade (1:500) (source: author)

Thermal and indoor air quality

Only 3 of 8 apartments on typical floor can be cross-ventilated (oriented on opposite facades).
The exterior wall doesn't comply with the current U value requirements, which became stricter since the time of construction.

Figure 7 Apartment House Ostravská Brána natural ventilation schema on typical floor (1:1000) (source: author)

Acoustics

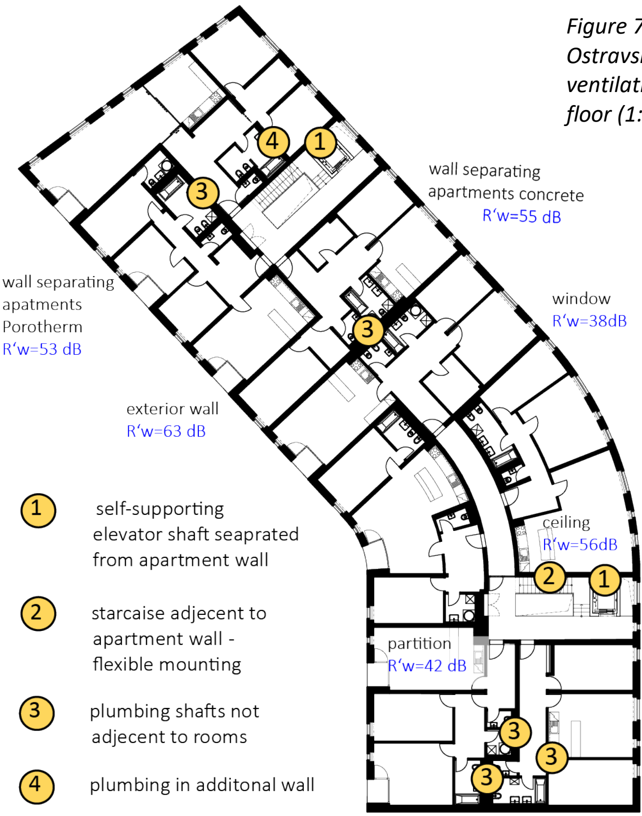


Figure 8 Apartment House Ostravská Brána acoustics (1:500) (source: author)

Table 4 Apartment House Ostravská Brána - framework analysis (interview + IEQ metrics)

	Light	Thermal	Indoor air quality	Acoustics	Other aspects
interior design					
building systems		*heat recuperation only in commercial spaces, not apartments asecondary heat stations in each apartment"*	*mechanical ventilation - only in commercial spaces, natural for apartments*	*noise from mechanical equipment – impact on surroundings calculated*	
structural construction				*noise from indoor parking →soundproofing of structures*	
facade envelope	**narrow windows and deep linings → low daylight levels inside**	**façade does not meet U requirements now (did at time of construction)**		*noise study from surroundings – façade soundproofing*	
spatial layout	apartment mix and building program determined by sunlight requirements		**only the largest apartments can be cross-ventilated**	*parking in souterrain - noise source for 1st and 2nd floor*	
massing volume					*basic footprint determined by previous planning permit*
site context	craped urban situation →difficult to achieve sunlight and daylight only the Bishop's building in close proximity (daylight not worsened there)				*also designed the public space – nor realized to their satisfaction*

Summary and discussion

The connections between architectural design decisions and IEQ

The research questions related to the first objective, to find the connections and compromise solutions (or trade-offs) in the architectural design decisions that directly affect the lighting, thermal, aerial and acoustic qualities of the designed spaces, were answered by analyzing several resources using the framework described in Research strategy and methods.

The answers to the first research question (*Q1*: *Which architectural features determine the indoor environmental quality and which indoor environmental concerns act as form givers in the architectural design?*) derived from the general resources (IEQ metrics analysis and handbooks for architects) are compared to the answers from the architect interviews performed in the case studies.

The framework of connections derived from general literary resources (Table 5) and from the individual case studies, primarily the architect interviews (Table 6) are shown on the following pages. In most areas, there was significant overlap. However, there are some notable differences.

The biggest difference between the architects answers and the general advice concerned standards and legislation, or rather that some of the issues don't need to be addressed in depth in the architectural design, because they are standardized – building materials and their safety from harmful substances; thermal resistance of envelope structures – those are default values that don't really differ on a case by case basis.

The investor's relationship to the building and willingness to pay for measures to improve the IEQ played the major role in the resulting solution. This was most prominent in the acoustic measures, where more expensive materials were often crossed out of the project, and in building systems, where “green” energy sources were sometimes vetoed by the client.

Note: the current energy efficiency requirements often rely on green technology solutions and make the achievement of desirable indoor environmental quality solely via natural means less and less possible, so a lot of the presented solutions would no longer be allowed by the current legislation.

Table 5 Combined framework from the general resources (IEQ metrics analysis and IEQ handbooks)

	Light	Thermal	IAQ	Acoustics
interior design	interior surfaces - color, reflectance furniture layout (usable area)	wall surfaces (thermal conductivity)	building materials and finishes: insulation, plywood, paint, furniture (particle board), floor/wall covering material – pollutant sources adsorption/desorption capability → mold growth interior plants	surface materials (noise attenuation) – possibility of multiple reflections resilient floor finishing layer (carpet or rubber), noise absorbent surface materials glazed walls – sound reflective
building systems	shading devices - movable blinds (user scenarios) self-controlled solar screens (glare prevention)	heating and cooling systems designed according to comfort requirements easy heat recovery from mechanical ventilation internal heat sources local thermostatic controls fast response heating - lower base temperature	ventilation - mechanical, heat and moisture recuperation ventilation system components (filters, ducts, humidifiers) as pollutant sources moisture (washing machines…)	noise sources mechanical ventilation can be noisy, especially at low frequencies active noise control (powered system)
structural construction	floor height room sizes - height, ceiling span	construction system (load bearing structures) thermal mass → reduce temperature swings	floor height → room volumes	load bearing structure → impact noise conduction floor and walls composition → noise dampening (impact and airborne) floating floor or vibration dampeners to prevent construction vibrations
facade envelope	windows - size (height/width), placement on room wall, glazing, frame shading - balconies, overhang, fixed blinds wall thickness, color size and distribution of apertures solar-reflecting glazing reflectance of exterior finishes	structure composition (materials, thickness) glazing/wall ratio; wall + roof colors shading - balconies, overhang, fixed blinds windows - glazing, frame; air tightness	natural ventilation moisture and condensation - permeable structures air leakage – not a good way to ensure natural ventilation (uncontrollable)	structure composition (thickness, mass) window placement, properties, openability provide openable windows even towards noisy street
spatial layout	room geometry (depth, width, ceiling depth) orientation towards views circadian rhythms - shallow plan rooms	natural ventilation - cross ventilation, chimney effect user scenarios - number of occupants orientation of spaces for solar heat gains	occupants - number, group clean air supplied to the right places location of pollutant sources: smoking areas, laser printers, fireplaces (CO, PMs) washing machines, bathrooms (moisture)	noise sources within layout room geometry (height, width)
massing volume	shading obstacles (height, distance) to itself and surroundings facade orientation	shape façade/volume ratio façade orientation room angle and orientation		
site context	terrain shape, landscape, greenery surrounding buildings - height, distance, color (reflectivity) access to views	orientation to cardinal directions surroundings - shading, wind protection climate - sun, wind, heating/cooling hours	air quality (pollution, traffic) presence of radon in soil ventilation - consider wind direction, air quality outside	local sound pressure levels: noise sources - traffic, industry (existing and future) background noise levels vibrations

Table 6 Combined framework from all the architect interviews

	Light	Thermal	IAQ	Acoustics	Other aspects
interior design	visual purity	ceiling cooling/heating systems require suspended ceilings	mechanical ventilation pipes and exhausts → strong visual element suspended ceilings	spatial acoustics and indoor materials: glazing, concrete, acoustic cladding	
building systems	(automatic) shading elements (exterior roller blinds) combined lighting in offices	heat recuperation automatically included in mechanical ventilation impact of heat and cold sources placements on occupants (ceiling vs. floor heating/cooling) acquisition cost often ruled out "green" building systems (automatic) roller blinds to prevent overheating	mechanical ventilation usually only when necessary	building system units on roofs → noise source for building itself and surroundings	aim for low operational cost sophisticated building systems require qualified maintenance
structural construction		thermal mass		noise carries through construction, especially in situ concrete	supervision during construction important to fulfill architectural intent
facade envelope	window sizes to allow daylight and views (contact with exterior) orienting windows to achieve insolation or, conversely, to avoid overheating	structures designed to meet standard requirements (often for passive buildings) glazed surfaces shaded to prevent overheating	openable windows also in mechanically ventilated spaces	when windows meet thermal requirements, noise reduction usually sufficient large glazed areas negatively impact spatial acoustics	fire safety affects possible window sizes and placements
spatial layout	cardinal orientation considered when possible sunlight requirements form residential layouts (or bypassed by "ateliers")	orientation to prevent overheating when possible cooling via natural ventilation	natural ventilation – openable windows, chimney effect	movable partitions → noise carries between rooms (airborne and impact though floating floors concrete layer) room height and shape → spatial acoustics distancing from exterior noise sources when possible	fire safety (fire escape routes, length of corridors)
massing volume	orienting facades toward daylight and sunlight (or away from the sun)	shading by overhangs and balconies to prevent overheating cardinal orientation to prevent overheating		building system units on roofs require acoustic barriers	
site context	availability of sunlight and daylight shading towards surroundings typically addressed on city planning level	district heating availability on site	poor exterior air quality may necessitate mechanical ventilation	building systems on roofs → noise source for surroundings noise levels outside may necessitate mechanical ventilation	investor participation important important to pre-consult with authorities (especially hygiene department)

Summary of the design process analyses

Several project stages were recognized:

- site analysis, pre-requisites
- competition proposal
- architectural study
- building permit
- construction documentation
- during building
- in-use feedback

Not all of them appear in every project, sometimes they are merged (for example, the site prerequisites were part of the architectural study design, the architectural study and competition proposal were merged, or in one case, architectural study and building permit were basically merged). But in the combined table, all those are mentioned.

The design process is very case-specific, but some frequently occurring themes are listed in Table 7.

Table 7 Design process summary from case studies

	site analysis, pre-requisites	competition proposal	architectural study	building permit	construction documentation	during building	in-use feedback
interior design			acoustically reflective/absorbent materials considered		spatial acoustics calculated and refined		
building systems	need mechanical ventilation?	building systems to be refined later		building systems refined building systems on roof → noise study			sophisticated building systems require qualified maintenance
structural construction					specification and construction supervision critical for good result		noise carries through structures
façade envelope		window sizes to allow daylight and views natural ventilation (chimney effect if possible)		daylight study sometimes requested by authorities			shading sometimes added on clients' request
spatial layout	possibility of sunlight and daylight	cardinal orientation if possible natural ventilation (chimney effect if possible)	apartment mix	apartments not fulfilling requirement's → "ateliers"			
massing volume	basic footprint and height limited by city planning			building systems on roof require acoustic barriers			
site context	site morphology and orientation city-planning requirements: distancing, function outside noise air quality client requirements			building systems may be a noise source for surroundings important to pre-consult authorities (especially hygiene department)			

Summary of non project-specific parts of the architect interviews

How do the architects define indoor environmental quality?

The primary definition given by the architect was in most cases occupant related. The architects spoke about people and making the indoor environment comfortable and pleasant for them, in the sensory perception kind of way. Most architects also mentioned that the indoor environment must be in harmony with the overall building concept, with the operational, spatial and aesthetic aspects.

The “building physics” definition of indoor environment, in terms of the four most commonly accepted components (light, thermal comfort, indoor air quality and acoustics) were only mentioned by seven of the architects. Three of the architects even implied that the indoor environmental quality (and building physics) concerns are mainly in the competence of the specialists and civil engineers, not architects (although their later answers revealed they actually do address the indoor environment in the conceptual design, which indicates it is more a matter of terminology then lack of consideration).

Most of the architects also include the energy efficiency and environmental concerns (in the sustainability sense) seamlessly when thinking about the indoor environment, as well as the legislative and standardization requirements.

Compromise in architectural design

When asked about the compromises they needed to make in the design, there were basically two answers, equally frequent. One indicated that the word “compromise” has strong negative connotations and the architects claimed they did not need to make any compromise. They further explained that when making some necessary trade-offs between requirements, they don’t consider it a compromise if they manage to resolve them successfully. The other group said than any building is a set of compromises and the architect’s job is to find the best possible solution.

These answers don’t seem to be in opposition and indicate more a semantics issue, but it is worth noting the necessity of being careful when using the word compromise, as to some, it may mean a solution no-one is satisfied with.

What do the architects think they need to know from building physics and IEQ?

All the architects agreed that some knowledge of building physics is important for an architect. However, they differed quite greatly in the scope of knowledge they consider necessary. Most commonly, they agreed that they need to be able to comprehend the calculations and assessments performed by specialists and understand whether they make sense. Several architects were wary of too deep knowledge of building physics, saying it may limit their creative freedom and distract them from focusing on other aspects of the architectural design, especially the operational, spatial and aesthetic ones. It was mentioned that blind following of standardized requirements may prevent the design of best possible spaces for the given purpose.

What role does education play in the necessary IEQ knowledge?

All the architects said they learned a lot more about the indoor environment in practice than at school. As the main shortfall of architectural education in the indoor environmental and building physics subjects, they mentioned the detachment from reality. While they learned how to perform building physics calculations, they were not taught to relate them to the specific building they were designing. Although the courses (not just on building performance, but also for example structural engineering) went quite in depth in the technological expertise, the architects felt they didn’t provide them with basic principles and rules of thumb needed to approximately estimate the architectural means necessary to achieve the desired outcome. It was also mentioned that the technical drawings were sometimes merely an item on a checklist. This was also confirmed by the architects that have experience with teaching design studios at architecture schools, saying that their students are not capable of applying the theoretical knowledge to the design.

What design decision support do the architects use?

The decision support tools the interviewed architects use to inform their design decisions in regard of the indoor environmental quality could be summed up into four groups: standards and guidelines, examples of good practice, consulting specialists and software tools, including building performance simulation. Bellow, the interviewed architects’ relationship to each of these decision supports options is discussed.

The role of legislation, standardization and authorities in architectural design Standards and guidelines

Almost all the architects expressed frustration with the current state of legislation and standards. Although the architects acknowledged the need to consider and comply with the standardized legislative requirements, they don’t consider the standards to be helpful as guidance, but rather an obstacle course of nonsensical demands they have to pass through in order to get the project built. Some even stated that the blind following of standardized requirements may lead to a worse design in terms of spatial and aesthetic qualities. They especially abhor the sunlight duration requirements compulsory for residential buildings in the Czech Republic, claiming they make it impossible to build housing in the traditional urban structure.

The design decision support tools should serve as a guideline that facilitates decision making, that makes the translation between the desired indoor environmental quality) and the architectural means necessary to achieve it by setting metrics and benchmarks. In some areas, the interviewed architects confirmed the standards are useful for their practice, for example for selecting structural compositions and windows in compliance with the standardizes heat transfers coefficient and sound reduction index values.

However, there is often a confusion between the end (a healthy and comfortable indoor environment) and means (standardized values of related IEQ metrics).

The most glaring example of this discrepancy is the architects' approach to daylight and sunlight requirements. The often don't view the set benchmarks for sunlight and daylight provision as a guide to create a well-lit indoor space, but rather a formal requirement they need to comply with to get the project approved by the authorities. The required sunlight duration in apartments is indeed seen as a pesky obstacle to designing the layouts they consider best for the occupants, the site and the investor's intent. The interviewed architects often seemed to have no qualms about bypassing the legislation, by passing the non-compliant apartments as "ateliers" and the non-compliant rooms as "home offices" or "gyms". While the author doesn't wish to advocate for such practices, their common occurrence indicates the need to reframe those requirements as a guidance rather than a one size fits all requirement.

Despite the interviewed architects pointing out the unnecessary strictness of Czech building regulations (as Jan Holna put it: "*This is a common practice of the Czech architect, where there are a number of things that we architects have to grapple with, and compromise I would say is our standard battlefield. It's also evident that when some architects from abroad come here, big names, they usually break their teeth because they are not able to work in those compromises.*"), the architects' skepticism towards building regulation is not a Czech specific issue.

A survey of British architects on the role of building regulations in their practice (Imrie, 2007) points to similar issues: the architects sometimes view the building regulation as too restrictive and detrimental to their creative freedom.

The architects do acknowledge the usefulness of standards as a counterweight of the cost-oriented limitations imposed by the investor, where legislative requirements may serve as an incentive for the investors to pay for more expensive measures to achieve healthy indoor environment. The architect also pointed out that complying with legislative requirements protects the designer and the developer from later occupants' complaints which may result in litigation and demanding discounts from the developer (this is again confirmed by (Imrie, 2007).

The architects are also quite distrustful of quantifiable indoor environmental metrics, which to them don't really describe the qualities of the space. Labelling and classifying buildings according to certification schemes may seem arbitrary and unrealistic to the interviewed architects.

Several architects mentioned the necessity of pre-consulting the design with the authorities (in the case of indoor environmental quality, mainly the hygienic station).

Examples of good practice

The interviewed architects mentioned using examples of (mostly foreign) realized buildings as inspiration, especially in the early stages of the design process. They looked up how a certain indoor environmental issue was dealt with (for example ventilation of classrooms in the Elementary School Amos Psáry). A critical examination and interpretation of the realized buildings is necessary to extract the information relevant to the task at hand (as Alena Mičeková put it: "*…the experience that you have to constantly not only design, but at the same time examine other people's realizations and discover maybe some mistakes or things"*).

Some of the architects expressed certain frustration over the impossibility to implement the principles from abroad into the Czech context, due to legislative restrictions. Jiří Zábran remarked *"When I see a nice thing abroad, I think, wow, but it has to work here too. It snows there* *too, there are people like us there too, and if it works there, why can't we build it here?"*

The use of examples of realized buildings as an inspiration source is common in the architectural practice (Petersen & Purup, 2019). A study on postgraduate architectural student's information seeking behavior (Makri & Warwick, 2010) highlights the importance of visualizing, appropriating and interpreting the inspiration sources.

Since the relation between indoor environmental quality and architectural features is not immediately obvious from architectural drawings and photographs, the analytical framework and graphical interpretation of IEQ metrics presented in this thesis may serve as a useful tool to comprehensibly present refences to architectural students and architects.

Consulting specialists

Almost all the architects declared mutual respect as the most important thing for successful collaboration. Five of them even mentioned their specialists by name. Several expressed frustrations with specialists who regard architects as too impractical and concerned with aesthetics ("the architect is being difficult").

The second most important quality the architects appreciated in specialists was the ability to see the big picture in the project beyond their specialization (Tomáš Pilař formulated it as "stepping out of the shadow of their Excel spreadsheets"). The architects wish for the specialists to help them find alternative solution, rather than simply saying "that's not possible".

The interviewed architects said they usually consult at least some building performance specialists early in the design process. This applied mostly to daylight and sunlight experts, where the requirements were form-giving even for the massing. Other specialists were often introduced to the project in the later design stages, such as the building permit documentation.

The architects wished for the specialists to be able to see the big picture of the project and think creatively, instead of just focusing on their area of expertise. They claimed that early in the design project, they know most of the architectural features and need to be refined later, but they need to know they are going in the right direction.

The collaboration between architects and building performance specialists is a current topic often discussed in literature, especially in connection with the integrated design process (for example (Engebø et al., 2020; Leoto & Lizarralde, 2019; Alsaadani & Bleil De Souza, 2016).

Beside the technical issues, addressed by BIM technologies, it also necessary to focus on the human side of architect- specialist collaboration (Alsaadani & Bleil De Souza, 2016). The collaborative process participants' attitude should be already addressed on the educational level.

The civil engineering students are accustomed to having a clearly defined assignment, focusing on one problem at a time. In contrasts, architectural design is open-ended, without a single right answer (Olsen & Mac Namara, 2014, p. 182; 184). When confronted with the iterative nature of architectural design, engineering students tend to become frustrated with the design changes and prefer to perform their analyses only after the design is well formed, which defeats the purpose of early collaboration (Simonen, 2014).

Software tools and building performance simulation

Most of the interviewed architects do not use any building performance simulation software in the conceptual design stage. The most cited reason for not incorporating software tools to verify indoor environmental quality aspects was lack of time, both to learn the tools and to incorporate them in the architectural study.

This is in line with literature, which lists that architects view the BPS tools as too complex, too expensive, their use is too time consuming and not integrated in the architects' workflow (possibly also due to the tools not being integrated in CAAD software used by the architects) (Kanters et al., 2014) and that the difference in geometry representation and design language used by architects and the building physics language of the BPS tools (Attia et al., 2012) may also act as obstacle to integrating BPS in the architectural design process.

The interviewed articles said that if they were to use a software tool for indoor environmental quality, it would above all need to be integrated in the CAD software they use and give them fast response (Jan Kalivoda:*“…if maybe some program that we're modeling the building in could already give you an outline of how it's going to work. In terms of lighting, acoustics, depending on the materials chosen.”*)

A survey of Danish architects (Purup & Petersen, 2020) on how can BPS simulation tools be conformed to fit the architectural practice confirms the above-mentioned findings, while adding that the tools should not prescribe a specific workflow, but rather be usable for various design activities. The framework of iterative loops described in this thesis may serve as a useful basis for deigning such a software tool.

Conclusion

The fulfillment of aim and objectives

The aim of this thesis was to closely link indoor environmental quality and building physics to the architectural design process. This meant regarding the building performance concerns through the lens of an architect, to "flip the script" from the separate areas of different specializations to the architectural elements.

This was done rather successfully by incorporating an original framework (developed by the author of this thesis) of "iterative loops", into which the architectural elements usually designed together are grouped. This framework worked well for addressing the objectives of the thesis.

The first objective, to find the connections and compromise solutions (or trade-offs) in architectural design decisions that directly affect the lighting, thermal, aerial and acoustic qualities of the designed spaces, formed two closely linked research questions:

Q1: Which architectural features determine the indoor environmental quality and which indoor environmental concerns act as form givers in the architectural design?

Q2: Which architects' decisions form the indoor environment and when are those decisions likely to be made in architectural design process?

These were answered via several resources, both general and case study related. The general framework combined from all the resources can be found in Chapter 5.1.

However, the generalization may not be ideal to present to the architects, since it strips the individual case from the analysis. Both the literature review and the case studies (especially the architect interviews) indicated that the indoor environmental issues are better graspable by the architects (and especially architectural students) in the context of a specific project, where they are illustrated by the real-life design scenario. Abstracting them from the particular building may lead to confusion and distrust from the architects.

Another objective of this research was to create a supplementary learning material for architectural students and practicing architects which will facilitate the consideration of the indoor environmental concerns in the architectural design process. The research question associated to this objective was *Q3: What should the design decision support for the conceptual stage of architectural design process look like to facilitate the achievement of good indoor environmental quality?*

The architect interviews confirmed the premise (derived from literature review) that demonstrating the indoor environmental principles on examples of real buildings is one of the best ways of explanation. Since such a publication is not currently available, at least in the central European environment, the results of this research are hopefully going to be quite useful as a teaching tool.

The framework developed by the author of this thesis flips the perspective from specialist, single discipline oriented to architectural, building elements-oriented and the case studies it has been applied to (and indeed, the framework itself) may serve as a very useful tool for guiding students through the process. Although some of the conclusions may (and actually should) appear banal to seasoned architects, who have learned to view the indoor environmental and other building performance concerns through similar lens, it can help the students situate themselves is the complicated plethora of requirements. It can help the students see which concerns raised, for example, in the site analysis stage may become form givers in later design stages.

Limitations and future work

The cases studies including architect interviews were all of buildings that are already built and in use for some time (having been completed in the decade between 2010 and 2020). This was decided so that the user feedback (as reported by architects) and the reception by public could be included in the assessment. However, since the design process, from first assignment through all the design stages and obtaining the necessary permits to the construction and implementation, takes several years, the design process was viewed by the architects in retrospective. While this may have served as a filter for the design concerns that were still fresh in the architects' minds, it is also likely some of the design decisions and iterations may have fallen through the cracks, so to speak.

This could probably be prevented by following a building project all the way through in real time, from first brief to several years after it had been in use. This project would however not be in scope for a doctoral research, especially if multiple cases were to be included, and it is questionable whether the information value would have been worth the effort.

The presented case studies and architect interviews are very specific in their national setting. The building process in the Czech Republic infamously has one of the longest durations, partially due to an involvement of a large number of authorities and legislation.

Another possible limitation may have been the fact the most of the case study interviews only included the architects' point of view (with the exception of the Office Building Konplan, for which both the architect and the main project engineer were interviewed upon the architect's suggestion). The other stakeholders' opinions (especially the investors'' requirements and the occupants' feedback) were therefore only mediated via the architects, whose view may be biased. Since the interviews ended up discussing the collaboration between architects and specialist quite heavily, it may be interesting in future research to engage the entire design team, including the building physics specialists and also other stakeholders, most importantly to interview the investors and the occupants. An analysis of a time-lapse following a project after its completion would undoubtedly provide further understanding into the indoor environmental considerations and architectural decisions that form the real indoor environmental quality in a building and therefore the health and wellbeing of the occupants. This, again, would have been difficult to carry out in the scope of case studies that have been included in this research, but is strongly recommended for future work.

In future work, the author suggests to develop design decision support tools that use the findings of this thesis, especially the architects' need for imprecise but early available information that points them to the right direction early in the design process. The analytic framework developed and used in this thesis could be a starting point for software tools, as well as teaching.

Recommendations emerging from this research

Recommendations for teaching

The building physics education in architectural schools is certainly not lacking in technical expertise. However, some modifications might be suitable to make the indoor environmental principles more comprehensible for students. One of them is relating the information to real life examples as much as possible (the author is not saying this is not done already, especially in lectures, merely wishes to emphasize the importance). The case studies compiled in this thesis will hopefully be useful for that.

Another crucial modification is closer integration of technical subjects with design studio teaching. This goes hand in hand with the contemporary trend of integrated design. The most promising method the author is aware of is the Project Based Learning (PBL). By allowing the students to discover in their own design studio project which indoor environmental aspects need to be addressed in which stage of the design process, this method puts the technical knowledge into perspective and also helps teach the students how to communicate with specialists in the context of architectural design scenario.

Recommendations for design decision support

The preferred method of design decision support are consultations with specialists. The traditional method of consulting specialist only after the building form has already been decided upon is no longer viable in the increasingly complex word of building design. The architects need to consult the specialists already in the conceptual stages of the project.

This may require a different approach to architect-specialist cooperation than both sides are accustomed to, since in those stages, the design is often not yet developed enough to allow for precise assessment and calculation in the indoor environmental quality metrics. Rather than providing the architects with numerical values (which the interviews indicate that they are quite distrustful of anyway), the specialist need have a wider overview of the project to be able to point the architect in the right direction or to recognize whether the conceptual approach selected by the architect is viable or not. Again, real-life examples of good practice, either from the specialist’s own experience or from case studies and literature may serve as explanation tool.

Some modification may be necessary also in the education of building science specialists, who are perhaps more accustomed to clearly defined assignments where all the information necessary for calculation are already available (as is customary in the traditional route of assessing finalized building design projects).

Recommendations for software tools

For a software tool to be usable by architect, it needs to be integrated in the CAD software they already use. Otherwise, the hassle of importing or even remodeling the 3D model is too discouraging for architects. The software tool also needs to be capable of providing “imprecise results with incomplete information”, meaning that the architect does not need to wait until all of the building elements have been designed – this would beat the purpose of using the tool for supporting design decisions, rather than merely verifying their correctness when it may already be too late to make any relevant change to the design.

The main contributions of this research

This research brought deeper understanding of the architects' approach to indoor environment and building performance in general and their attitude towards design decision support. It confirmed that architects are reluctant to accept the indoor environmental requirements that they see as disconnected from the entire architectural design and solidified the importance of presenting the technical requirements within the real-life context of an architectural design project.

The framework developed and tested by the author of this thesis clearly and concisely demonstrates where the requirements of each indoor environmental area fits within the context of the architectural design process. In the case studies, the framework highlights the connections between indoor environmental quality and the architectural design decisions. It provides a comprehensive overview of causal relations between the indoor environmental concerns and other elements of the architectural design, as well as between the individual areas of the indoor environment.

The complex indoor environmental and building physics issues are presented in an easily understandable visual form, with a focus on the simplified principles instead of precise numerical values. This way, the specialized problematic can be introduced and explained to architectural students and practicing architects in a way that informs their design decisions without limiting their creative freedom.

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List of candidate's publications

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Awarded speaker at the SGEM 2019 conference