Elisabeth SIBILLE

OPTIMIZED INTEGRATION OF VENTILATION WITH HEAT RECOVERY IN RESIDENTIAL BUILDINGS THROUGH THE IMPLEMENTATION OF INNOVATIVE AIR DISTRIBUTION STRATEGIES AND PRE-FABRICATED COMPONENTS

DISSERTATION

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Kurzfassung

Lüftung mit Wärmerückgewinnung ermöglicht erhebliche Energieeinsparungen und gleichzeitig die Erreichung von modernen Komfortanforderungen in Wohngebäuden. Die Integration ist in der Regel jedoch immer noch mit hohen Kosten verbunden, welche meistens für einen Investor abschreckend wirken. Einfache Installationen, Vorfertigung und zuverlässige Planungshilfen sind daher notwendig. Vor diesem Hintergrund sind in dieser Arbeit vereinfachte Luftverteilungskonzepte für den Wohnbau untersucht und weiterentwickelt.

Insbesondere ist das Konzept der erweiterten Kaskadenlüftung im ersten Teil dieser Arbeit analysiert, bei dem auf das Zuluftventil im Wohnraum verzichtet wird. Durch die damit verbundene Reduktion des Gesamtvolumenstroms führt dieses Konzept zu einer deutlichen Verringerung der Betriebskosten (ca. 25 %) und zu einem besseren Raumklima im Winter. Eine systematische, simulationsbasierende Analyse dieses Konzepts für verschiedene Arten von Grundriss-Konfigurationen zeigt, dass die meisten der üblichen Konfigurationen für erweiterte Kaskadenlüftung geeignet sind. Aus den Ergebnissen entstand ein freizugängliches interaktives Online-Tool, um Lüftungsplanern die Verwendung dieses Konzeptes zu erleichtern.

Der zweite Teil dieser Arbeit untersucht ein „kanalfreies“ Zuluftnetz mit aktiven Überströmern. Diese Strategie ist bei Sanierungen besonders attraktiv, wobei bisher klare Dimensionierungsregeln für eine korrekte Planung noch gefehlt haben. Daher sind mit Hilfe von Simulationen die Luftvolumenströme definiert, die zur Erreichung eines optimalen Raumklimas zu planen sind. Die Simulationsmodelle sind anschließend mit Messdaten validiert. Die Ergebnisse zeigen, dass mit den derzeit erhältlichen Produkten (aktive Überströmer bei 70 m³/h) ein Gesamtvolumenstrom von 80 m³/h für eine Drei-Zimmer Wohnung empfohlen ist. Das Konzept mit aktivem Überströmer stellt sich als vertretbare Alternative zur Kaskadenlüftung dar, obwohl es mehr elektrische Energie benötigt (bis zu 30 % mehr Verbrauch). Dennoch ist diese Strategie äußerst vielversprechend für eine luftbasierte Verteilung von Heiz- und Kühllasten in der Wohnung. Die Produktentwicklung sollte sich daher auf die Erhöhung des Volumenstroms (Zielwert 150 m³/h) bei gleichzeitiger Reduzierung der Schallemissionen und der Erleichterung der Integration in bestehende Konstruktionen fokussieren.

Neben der Luftverteilung ist die Integration des Lüftungsgeräts auch ein entscheidender Faktor zur Senkung der Kosten. Diese Arbeit untersucht daher im dritten Teil auch die Machbarkeit der Integration der Außen- und Fortluftleitungen mit Frostschutzeinrichtung in einem vorgefertigten koaxialen Rohr für Wohnungs-Zentralgeräte. Die Ergebnisse von Messungen an Prototypen und Simulationen bestätigen die Praktikabilität dieses Konzepts. Die Durchführbarkeit der Verwendung von Heat-Pipes als Alternative zum klassischen Vorheizen mit Strom wird ebenfalls bestätigt.

Die Ergebnisse dieser Arbeit sowie die beobachtete Kostenentwicklung von Wohnraumlüftung in den letzten Jahren zeigen, dass die Zukunft der Lüftung im Wohnbau in der Entwicklung weiterer vereinfachter Lösungen sowie Planungsleitfäden hierfür liegt. Wenn die Tendenz weitergeht, können Investitionskosten von 2.000 € pro Wohnung bis zum Jahr 2020 erwartet werden.

Abstract

Ventilation with heat recovery allows the achievement of significant energy savings, while meeting modern comfort requirements in residential buildings. However its integration is still generally associated with high costs, which are often dissuasive for an investor. Simple installations, pre-fabrication and reliable planning tools are therefore needed. In this context, this work surveys and develops simplified air distribution concepts for residential application.

Particularly, the analysis of the concept of extended cascade ventilation, in which the supply air valve in the living room is suppressed, attests a significant reduction in operating costs (approx. 25 %) and an improvement in indoor climate in winter, related the reduction of the total airflow rate. A systematic, simulation-based analysis of this concept for different types of floor plan configurations shows that extended cascade ventilation is appropriated for most of the common apartment configurations. Subsequently, an open-source and interactive online tool intended for ventilation designers has been developed in order to facilitate the planning of this solution.

The second part of this work surveys a “duct-free” air supply distribution concept using active transfers. This strategy is particularly attractive for refurbishment, however clear design rules were still missing for correct planning. This work thus defines the optimal global airflow rates in the apartment, depending on the performances of the active transfers and on floor plan configuration. The simulation model is subsequently validated with measurement data. Basically, with the currently available products (active transfers operating at 70 m³/h) a global airflow of 80 m³/h is recommended. The concept with active transfers appears to be a fungible alternative to cascade ventilation but still consumes more electrical energy (up to 30 % more consumption). Nevertheless this strategy appears extremely promising for an air-based distribution of heating and cooling loads in the apartment. Product development must thus focus on increasing the airflow performances (target value 150 m³/h), while reducing sound emissions and facilitating the integration into existing constructions.

Besides air distribution, the integration of the ventilation unit is also a central perspective of the cost reduction strategy. Particularly, this work surveys the feasibility of integrating both inlet and exhausted air into a pre-fabricated coaxial duct, including air defrosting for an apartment-central unit. Measurements from prototypes and simulations results confirm the practicability of this concept. The feasibility of using heat-pipes as an alternative to classical pre-heating with electricity is also confirmed.

Eventually, the results of this work and the observation of the evolution of investment costs in the past years show that the future of ventilation in residential buildings relies on the development of further simplified solutions and on corresponding design guidelines. If the trend goes on, investment costs by 2.000 € per apartment are expected by 2020.

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General introduction

The building sector currently represents almost 40 % of total energy consumption in Europe (EU, 2010). Taking advantage of the saving potential of this area is thus an essential path to significantly reduce greenhouse gas emissions. In fact, the European Directive for Energy Performance of Buildings requires a reduction by at least 20% of total greenhouse gas emissions in the building sector by 2020. This objective is all the more ambitious as people spend on average up to 90 % of their time in indoor environments (U.S. Environmental Protection Agency., 1989) and tend to demand increasing comfort standards. The current challenge for the construction sector and particularly in residential buildings, which represent 75% of the built area in Europe (Atanasiu et al., 2011), hence consists in facing the issue of energy saving, while meeting these requirements.

In this context, building ventilation plays a crucial role. Since an airtight and well-insulated envelope reduces drastically the heat losses of a building, ventilation becomes compulsory to prevent the accumulation of humidity and contaminants in the building. Numerous studies have shown that, when complying with current energy standards, window opening twice a day for half an hour is not sufficient to prevent damage due to humidity in an apartment (Feist, 2004). This result underlines the necessity of a mechanical system to ensure ventilation, regardless of user behaviour. Today, extract air systems are widespread in dwellings. Although they enable air exchange in an apartment, the energy losses due to the extraction of warm air however nullify the efforts made to improve the building envelope insulation.

Considering, for example, the refurbishment process of a typical apartment building with five floors and a total of 25 apartments that has an original heating demand of 100 kWh/(m^2.a). The renovation of the envelope with high-efficiency components (for example, improved air tightness, 200 mm high-efficiency insulation and triple glazed windows) leads to a reduction of almost 80 % of the heating demand. However with the addition of a ventilation system without heat recovery (pure extract air system), these savings drop to only 50 %. Such an operation is not profitable to an investor.

On the contrary, ventilation with heat recovery makes it possible to effectively extract moisture and contaminants from the building, while minimizing heat losses. In fact, the outside air is pre-heated by the energy from the extract air in a central heat exchanger before being distributed to the rooms (Figure 1).

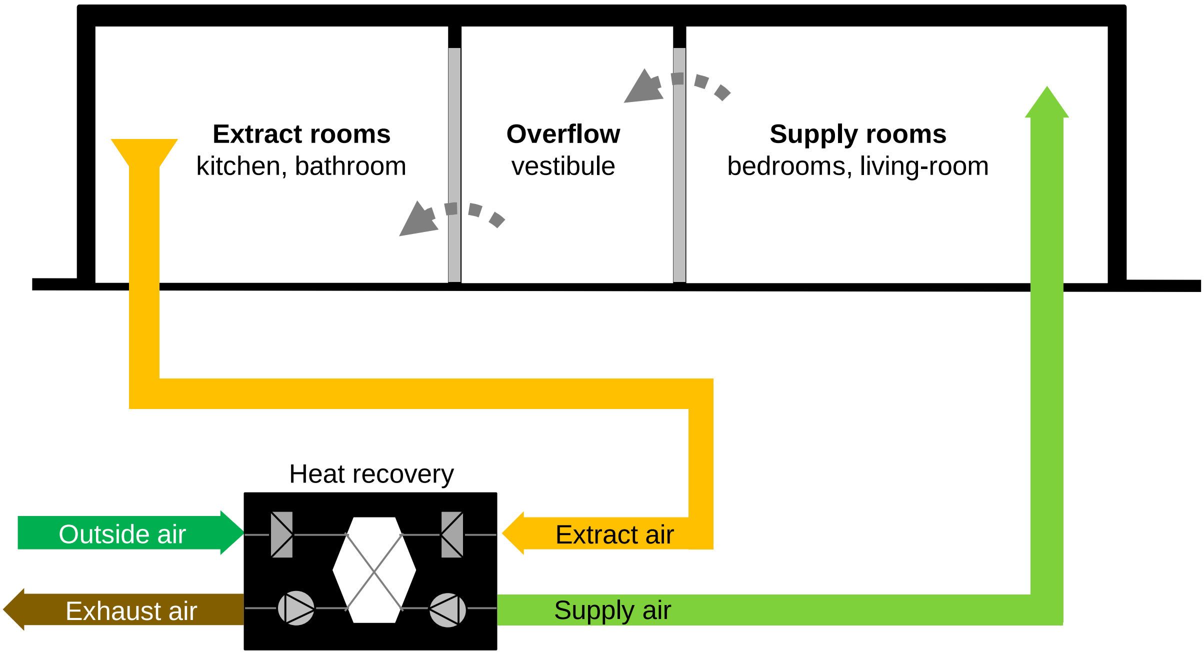


Figure 1: Typical air distribution in “cascade” for ventilation with heat recovery in an apartment

For the previous example, the whole refurbishment including ventilation with heat recovery brings the heating demand down to 25 kWh/m².a (Passive House standard for refurbished buildings), and makes the operation economically profitable.

The advantages of ventilation with heat recovery in residential buildings have been proven through numerous surveys and field measurements in the past decades. As a result, a wide range of related products are also now available on the market. The costs incurred by the installation of ventilation with heat recovery in residential buildings are still very high however, and are also disproportional to the directly corresponding energy savings. This discourages many investors and owners who ultimately opt for cheaper and less efficient solutions. As a result, a lot of buildings retain a significant, unexploited level of energy saving potential, and also fail in meeting modern comfort requirements.

Two reasons for these high costs can be identified. One is a lack of simple solutions, especially those designed for the ventilation of dwellings. Most solutions derive from the ventilation of industrial buildings, which have been scaled down to meet residential needs. Most of the time, the installation, air distribution and adjustment of the ventilation concept thus generally becomes a tedious and expensive process. On the other hand, a lack of integrated design processes including ventilation strategy also often lead to complex and expensive implementation. This issue is particularly prominent in refurbishment cases, where no provision was made for ventilation in the original construction.

Significant savings in the installation and operating costs of ventilation can therefore be made by developing and optimizing the planning process of simple and pre-fabricated solutions.

This research work aims at exploring concepts and device designs that simplify the installation of ventilation systems with heat recovery in residential buildings, and that optimize their operation. Particularly the air distribution system, which is responsible for half the investment costs (Pfluger, 2004), is at stake. The feasibility and saving potential of different innovative air distribution strategies that minimize ductwork are therefore explored and investigated in the two first parts of this work. The concept of extended cascade ventilation, surveyed in the first part, discusses the necessity of an additional air supply in the living room, depending on the floor plan configuration. Indeed, if previous studies showed the feasibility of this concept for a reference floor plan, it still needs to be investigated for other typical configurations in order to be implemented on a large scale. The objective is to establish fungible guidelines that can be directly used by ventilation designers. The second part of this work focuses on the concept of air supply distribution using active transfers. This strategy is particularly attractive in refurbishment cases because it is almost duct free; however clear design rules are still missing for a correct planning of this concept. As above, the objective is therefore to define fungible planning guidelines for designers, and also to influence future product development.

Besides airflow distribution, the installation of the ventilation unit is a crucial issue. Apartment-central ventilation solutions are often preferred because they can be more easily integrated in the design process (particularly with regard to fire protection) and require less space inside the building in the case of refurbishment. Highly prefabricated components with optimized installation are therefore particularly attractive. In this frame, the concept of a coaxial duct combining outside air inlet, exhaust air outlet and pre-heating (frost protection of the heat exchanger) is examined in the third part of this work.

Chapter 1

Implementation of extended cascade ventilation according to floor plan configuration

1. Introduction

Using ventilation with heat-recovery in residential areas, cascade ventilation is a well-spread air guidance scheme. In this concept, the outside air is guided from a central unit to each of the supply air rooms (bedrooms and living room) via an air ductwork. The air flows from there into the hallway and then into the exhaust air spaces (bathrooms, toilet, kitchen, etc.). For a correct operation that minimizes ex- or infiltration, well dimensioned overflow elements must be planed between the rooms.
The concept of cascade ventilation has clear advantages, particularly compared to room-wise ventilation, which requires the installation of one unit per room, and thus more maintenance and space demand. However the installation of cascade ventilation is still related to some issues:

- The installation of the ductwork in the apartment is most of the time related to high costs because of important and tedious manual work on site (installation and covering work)
- The airflow rates must be well designed and correctly adjusted to ensure good indoor climate to the occupants. Particularly, too high airflow rates operated in apartments located in central Europe lead to dramatically low levels of relative humidity. This effect leads to uncomfortable or even unhealthy indoor climate and diminishes the acceptance of ventilation systems in dwelling areas (Waldemar Wagner; Monika Spörk-Dür;Roland Kapferer, Michael Braito, Rainer Pfluger, Fabian Ochs, 2012).

A possible solution to those issues is to suppress the air supply valve in the living room and to keep the bedrooms as only supply air zones. In fact, as the occupants are either in the bedrooms or in the living room, this concept would still always provide them the same amount of fresh-air. This concept is called extended cascade ventilation.

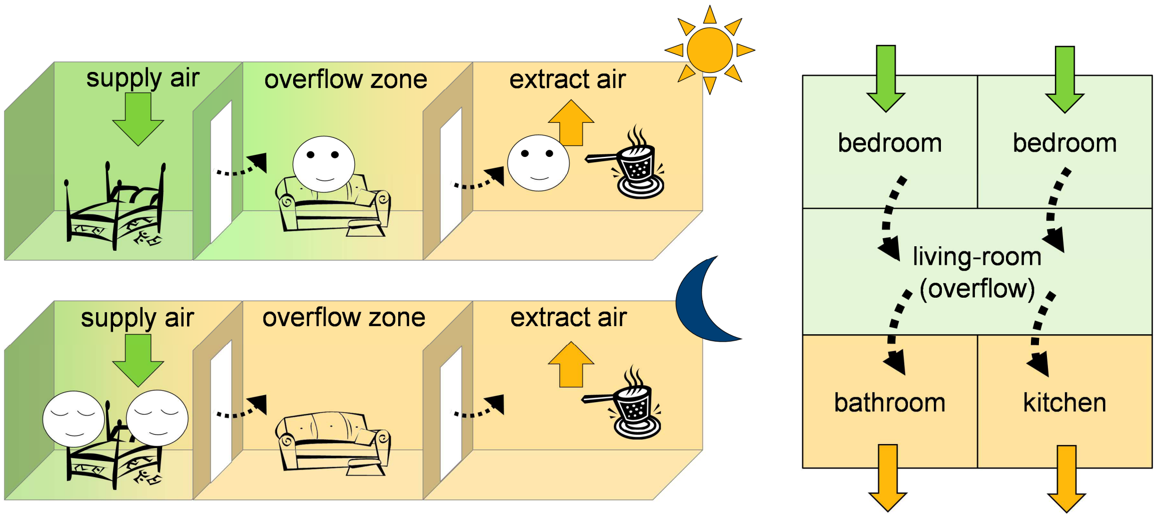


Figure 2: Principle of extended cascade ventilation. No supply air valve is needed in the living room because the occupants are either in the living room or in the bedrooms. The air is thus "double-used".

The installation work is simplified and the reduction of the airflow leads to higher humidity rates

The principle of extended cascade ventilation has been already realized in Switzerland in 2009, in an apartment with two bedrooms and one living room with integrated kitchen. Though the issue of the air quality in the living room without own air supply valve quickly became apparent. A rather complicated geometry of the room seemed indeed not to stimulate natural convection and air mixing. The airflows and contaminants concentrations were therefore investigated with measurements and CFD simulations. The results actually revealed well air mixing in the living room and a permanent satisfying indoor air quality (Barp, Fraefel, Huber, & Bau, 2009).

Those encouraging results led to conduct further investigations on extended cascade ventilation with the goal of its systematic realization. This was the objective of the research project "Doppelnutzen" (Pfluger, Sibille, Rojas-Kopeinig, Rothbacher, & Malzer, 2013), with a focus on the following issues:

(1) What is the saving potential on investment and operating cost of extended cascade ventilation compared to "standard" cascade ventilation (with additional supply valve in the living room)?

(2) Is extended cascade ventilation actually possible for any floor plan configuration? Are there some cases where the air quality in the living room becomes an issue?

(3) What are the optimal airflow rates in the bedrooms by standard and extended cascade ventilation, considering both contaminant removal and healthy humidity rate?

Based on the results of the optimal airflow rates in the different rooms (Rojas, Pfluger, & Feist, 2015), this work first determines the expected costs and energy savings due to extended cascade ventilation. Beside, its implementation for any type of floor plan configuration is also surveyed and leads to the development of a planning tool.

2. Expected savings on investment and operating costs

2.1. Method

Depending on the strategy used for the air distribution, on the floor plan configuration and on the size of the apartment, the investment and operating costs of ventilation can vary significantly. The method used here to estimate the saving potential of extended cascade ventilation compared to standard cascade ventilation is a global cost analysis on a real apartment building project. This example was chosen because it is a typical housing project and because it has three different sizes of floor plans.

The selected building is a housing project in Kramsach, Tyrol ("Aktivklimahaus | Aktiv Klimahaus Wohnanlage Kramsach |," n.d.). The building is composed of nine apartments, each comprising a living room with integrated kitchenette, a variable number of bedrooms (from one to three), a bathroom and an additional toilet. There are three apartments of each type in the building, type A1 with two bedrooms, type A2 with one bedroom and type A3 with three bedrooms. A central ventilation unit with heat recovery is installed in every dwelling.

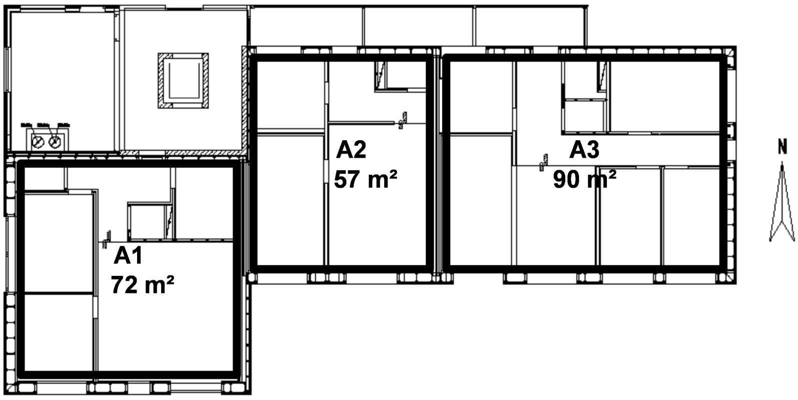


Figure 3: Floor plans of a standard storey of the chosen floor-plan (the building has three storeys)

Four different air distribution concepts have been analysed for each apartment. They differ in material, network type but also in the principle of air guidance ("standard" and "cascade ventilation").

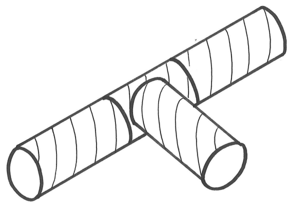
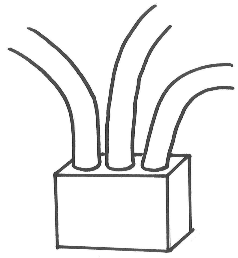
Type	Characteristics of the system	Sketch
T_st	"Traditional" concept. Folded spiral seam pipe. Pipes are mounted and sealed by operator on site in a "Tree" distribution (T-pieces etc.). Standard cascade ventilation	
T_ext	"Traditional" concept. Folded spiral seam pipe. Pipes are mounted and sealed by operator on site in a "Tree" distribution (T-pieces etc.). Extended cascade ventilation	
M_st	Plastic flexible ducts. Distribution with manifold. Throttling at manifold. Standard cascade ventilation	
M_ext	Plastic flexible ducts. Distribution with manifold. Throttling at manifold. Extended cascade ventilation	

Table 1: Summary of the surveyed variants

For each of these four variants, the investment costs and the operation costs have been calculated, and compared to each other.

2.2. Savings on the investment costs

For each of the four variants, the material and installation costs deriving from several offers were analyzed and compared. The table below summarizes the costs of each position for each apartment type and each ventilation concept.

Apartment A1 - 72m²	Metal spiral pipe		Semi-rigid duct	
	standard CV	**extended CV**	**standard CV**	**extended CV**
Manifold (sound insulated)	-	-	450 €	450 €
Duct + fittings + sound attenuators	910 €	811 €	195 €	167 €
Supply valves	147 €	98 €	217 €	145 €
Extract valves	40 €	40 €	241 €	241 €
Masking	1 500 €	1 500 €	-	-
TOTAL only ductwork + masking	**2 597 €**	**2 450 €**	**1 104 €**	**1 003 €**

Apartment A2 - 57 m²	Metal spiral pipe		Semi-rigid duct	
	standard CV	**extended CV**	**standard CV**	**extended CV**
Manifold (sound insulated)	-	-	450 €	450 €
Duct + fittings + sound attenuators	620 €	505 €	163 €	113 €
Supply valves	98 €	49 €	145 €	72 €
Extract valves	30 €	30 €	181 €	181 €
Masking	1 500 €	1 500 €	-	-
TOTAL only ductwork + masking	**2 248 €**	**2 084 €**	**938 €**	**816 €**

Apartment A3 - 90 m²	**Metal spiral pipe**		**Semi-rigid duct**	
	standard CV	**extended CV**	**standard CV**	**extended CV**
Manifold (sound insulated)	-	-	450 €	450 €
Duct + fittings + sound attenuators	1 012 €	914 €	263 €	217 €
Supply valves	196 €	147 €	289 €	217 €
Extract valves	40 €	40 €	241 €	241 €
Masking	1 800 €	1 800 €	-	-
TOTAL only ductwork + masking	**3 049 €**	**2 902 €**	**1244 €**	**1125 €**

Table 2: Description of the investment costs per position for each apartment and each ventilation concept

The followings statements come out of the compilation in *Table **2***:

- The installations with metal ducts are more than twice as expensive as with semi-rigid ducts! This huge cost difference can be explained with the much lower installation and manual work requirement of the concept with semi-rigid duct, which is highly pre-fabricated. In reality, this difference may vary significantly depending on the choice of the installation firm.
- Extended cascade ventilation implies an average reduction of 6 % of the investment costs on spiral metal pipes.
- Extended cascade ventilation implies an average reduction of 11 % of the investment costs on semi-rigid ducts.

As a conclusion, the expected savings in the investment costs by installing extended cascade ventilation are on average relatively low. Savings primarily appear through the choice of highly prefabricated systems.

2.3. Savings on the electricity consumption

In order to estimate the expected savings on electricity demand with extended cascade ventilation, the electric power consumption of the fans for the ventilation units has been calculated for each of the four cases investigated before.

2.3.1. Theoretical background

The electric power of a fan is directly proportional to the total pressure drop and to the airflow rate. Therefore the electricity consumption of the fan can be expressed:

$$P_e = k_{fan} \cdot \Delta p_{total} \cdot \dot{V} \tag{1.1}$$

With:

P_e	electric power of the fan [W]
k_{fan}	efficiency coefficient of the fan. The fan should be chosen in a way that this coefficient is minimal for the scope of flow rate and external pressure drop in which the system is going to be operated.
Δp_{total}	total pressure drop of the circuit.
$\dot{V}$	airflow rate at the fan [m³/h]

The pressure drop of a ductwork corresponds to the fluid resistance through ducts, fittings, terminals, filters etc. Theory and basic equations of system losses into ducts and fittings are described in (ASHRAE - American Society of Heating Refrigerating and Air-Conditioning Engineers INc., 2009), chap 21. These losses can be separated in two types:

- Friction losses along duct length, calculated by Darcy equation.

$$\Delta \boldsymbol{p_f} = \frac{\mathbf{1000} \cdot \boldsymbol{f} \cdot \boldsymbol{L}}{\boldsymbol{D_h}} \cdot \frac{\boldsymbol{\rho} \cdot \boldsymbol{V}^2}{\mathbf{2}} \tag{1.2}$$

With:

Δp_f	Pressure drop through friction losses in [Pa]
f	Friction factor [-]. It depends on several parameters, such as Reynolds number, duct surface roughness and internal protuberance.
L	Length of the duct section [m]
D_h	Hydraulic diameter of the duct [m]
ρ	Density of air [kg/m³]
V	Velocity of air in the section [m/s]

- Dynamic losses due to flow disturbance through the fittings, junctions, terminals and transitions:

$$\Delta p_d = C \cdot p_d \tag{1.3}$$

With:

Δp_d	Pressure drop through dynamic losses [Pa]
C	Dimensionless local loss coefficient, which depends on several parameters of the fitting and the flow. The value of this coefficient can be taken out of tables, curves or equations, like in (ASHRAE - American Society of Heating Refrigerating and Air-Conditioning Engineers INc., 2009) pp. 21.10 to 21.67.
p_d	Velocity pressure [Pa], depending on fluid velocity.

The total pressure drop Δp of a ductwork can be determined combining the friction losses along the total length of the ducts of equation (1.2) with the sum of the dynamic losses that occur through each fitting in equation (1.3). The total pressure drop can thus be expressed:

$$\Delta p_{total} = \Delta p_{f,total\ length} + \sum_{fittings} \Delta p_d \qquad (1.4)$$

Replacing in the velocity pressure in equation (1.3) by its expression with the velocity of air in the section, we obtain the expression of the total pressure drop through a ductwork, known as Dracy-Wiesbach equation:

$$\Delta p = \left[\frac{1000.f.L_{total}}{D_h} + \sum_{fittings} C\right] \cdot \frac{\rho V^2}{2} \qquad (1.5)$$

Thus, it possible to express the electricity consumption of a fan in a circuit (for example the air supply distribution in an apartment) with:

$$L_e = k \cdot V^3 \cdot \Delta t \qquad (1.6)$$

With:

L_e	the electricity consumption of the fan [W.h]
k	coefficient, calculated with the previous equations, that depends on the friction in the duct length, on the fittings types, on the duct diameter and on the air density.
V^3	air velocity at the fan [m/s]
Δt	considered time period [h]

This expression highlights that the electricity consumption of the fan grows with the cube of the air speed. Thus, it is highly recommended to design circuits with low air speed (for example by increasing duct section area), in order to limit electricity consumption. In residential area, air speed below 2 m/s is recommended, which also prevent noise emissions.

In practice, the electric power of a fan is often calculated with the equation:

$$L_e = \dot{V} \cdot \varphi(\Delta p) \qquad (1.7)$$

With:

L_e	the electric power of the fans of the unit [W]
$\dot{V}$	the airflow rate through the fans [m³/h]
$\varphi(\Delta p)$	the input power of the fan in [W per m³/h]

The value of the input power of the fan $\varphi(\Delta p)$ depends on the efficiency of the fan itself, on the external pressure loss in the ductwork and on the airflow rate. Its value is often given by producers through graphs or tables.

In order to estimate the expected savings on electricity costs with extended cascade ventilation, the electric power consumption of the fan of the ventilation units has been calculated for each of the four cases investigated before. For this, the first step was the external pressure drop of each of the four systems in order to find $\varphi(\Delta p)$ for each system.

2.3.2. Metal spiral pipes

AutoCad (Autodesk) ventilation Plugin CADVent (Lindab) allows for modelling pipe ductwork directly in three dimensions and then calculates total pressure loss of the system, given design airflow rate. The configurations with metal spiral pipes for each floor plan with standard and extended cascade ventilation have been thus modelled and calculated.

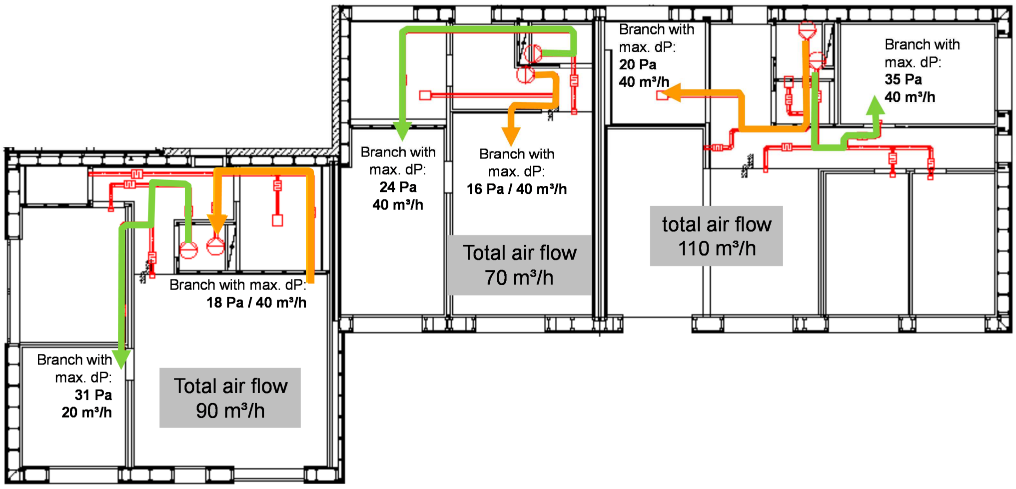


Figure 4: Floor plans of the three apartments A1, A2 and A3 with ductworks designed in CADVent with the concept of standard cascade ventilation. The authoritative branch (with highest pressure loss) is represented in bold.

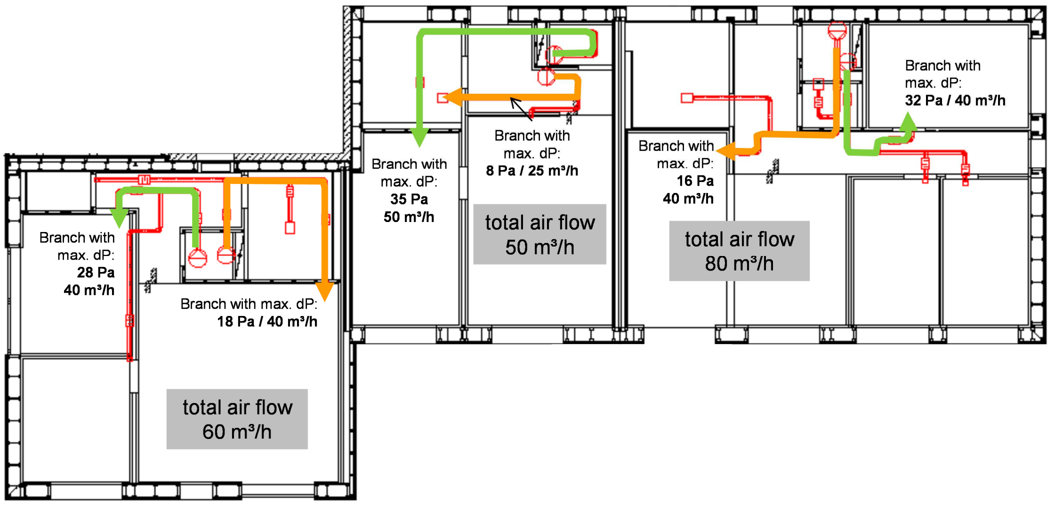


Figure 5: Floor plans of the three apartments A1, A2 and A3 with ductworks designed in CADVent with the concept of extended cascade ventilation. The authoritative branch (with highest pressure loss) is represented in bold.

The calculation of the electricity consumption of the fan considers the highest pressure drop in the circuit.

2.3.3. Semi-rigid ducts

Systems with semi-rigid ducts are mostly installed inside the concrete slab and run directly from the sound insulated manifold to the terminal, with minimal need of fittings or junctions. The producer of the system with semi-rigid ducts has its own design software with calculation of pressure loss.

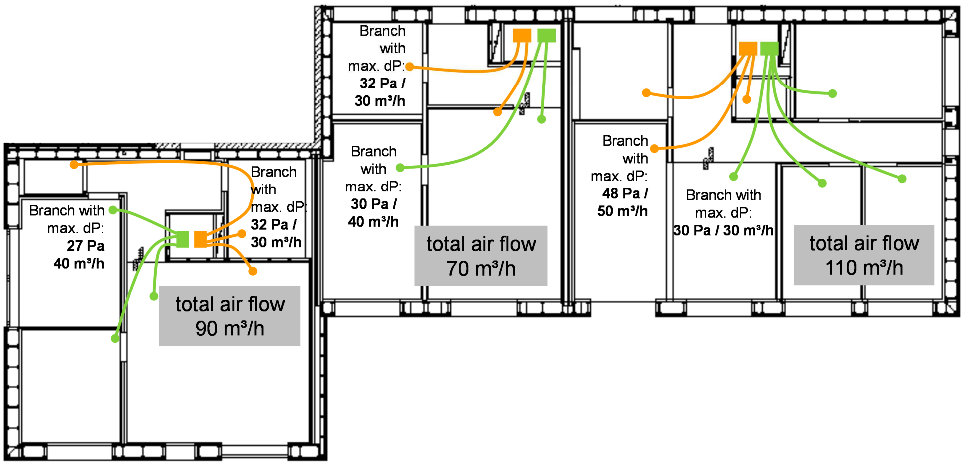


Figure 6: Floor plans of the three apartments A1, A2 and A3 with semi-rigid ducts with the concept of standard cascade ventilation. The authoritative branch (with highest pressure loss) is represented in bold.

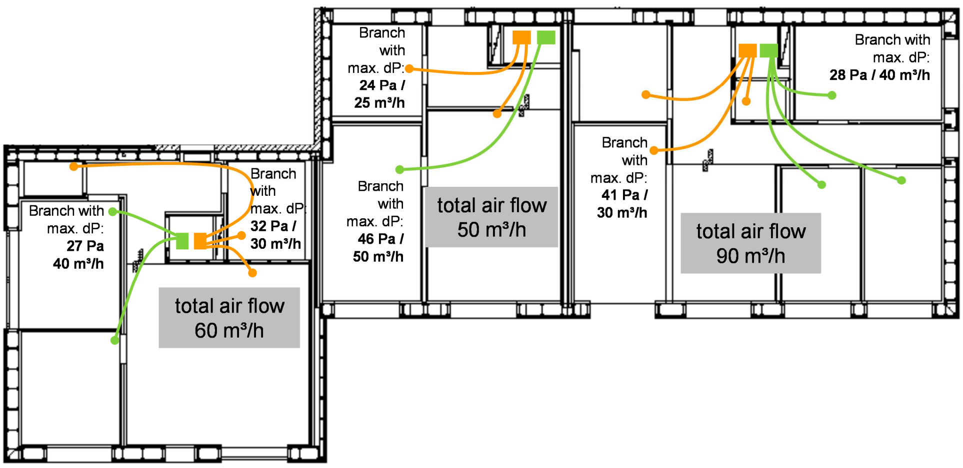


Figure 7: Floor plans of the three apartments A1, A2 and A3 with semi-rigid ducts with the concept of extended cascade ventilation. The authoritative branch (with highest pressure loss) is represented in bold.

For each configuration, an additional internal pressure loss in the ventilation unit was added due to the heat exchanger and the filter (a clean filter was assumed). The values were taken from a similar case where measurements of internal pressure loss by several airflow rate have been driven (Rochard, 1994) (see annex 1).

2.3.4. Results

The energy consumption of the ventilation units can be calculated with the help of the tables and graphs taken from producer brochure of a typical high quality apartment-central unit with heat recovery and passive house certification. The detailed results can be consulted in Annex 2. The total yearly energy consumption of the several variants are summarized in the following table:

	Yearly electricity consumption [kWh/a]			
	Metal spiral pipes		Semi-rigid ducts	
	standard cascade	extended cascade	standard cascade	extended cascade
Apartment A1	197	147	205	158
Apartment A2	166	140	172	149
Apartment A3	260	197	279	213

Table 3: Yearly electricity consumption of the unit for each variant

Following statements come out of these results:

(1) On average over the three apartment types, the yearly electricity consumption of the ventilation unit is about 215 kWh/a with standard cascade ventilation. This represents approximately 43 €/a per apartment (assuming 0,20 €/kWh).

(2) On average, switching to extended cascade ventilation allows for a reduction from 15 % to 25 % of the electricity consumption, depending on the apartment type. This difference is due to the reduction of the airflow rate in the unit and ductwork.

(3) The air distribution type (metal spiral pipe or semi-rigid duct) has only little influence on the energy consumption (approx. 6 % less consumption with metal spiral ducts).

As a conclusion, the principle of extended cascade ventilation allows for a 15-25 % reduction in electricity consumption of the ventilation unit. These savings are due to the reduction of the airflow rate in the apartments.

2.4. Savings on the heating demand

The reduction of the global airflow rate also has consequences on the heating demand of the building and thus on its global energy consumption. The yearly losses through ventilation can be calculated with:

$$L_v = \rho \cdot c_{p.} \cdot \left[\dot{V}_v \cdot (1-\eta) + \dot{V}_i\right] \cdot HGT \qquad (1.8)$$

With:

L_v total yearly energy losses through ventilation (mechanical and infitration) [kWh/a]

ρ density of air [kg/m³]

c_p specific thermal capacity of air [Wh/(kg.K)]

$\dot{V}_v$ total airflow rate of the unit [m³/h]

η real heat loss coefficient [-]

$\dot{V}_i$ average airflow rate through infiltration and exfiltration [m³/h]
HGT heating degree hours per year for the [kKh/a]

The total yearly ventilation losses have been calculated for each apartment for both standard and extended cascade ventilation for the climate of Innsbruck (HGT = 83 kKh/a) for a unit with 85 % heat recovery rate. Infiltration rate was calculated according to a value of η_{50}=0,6 h^{-1} by air tightness test (typical value for passive houses).

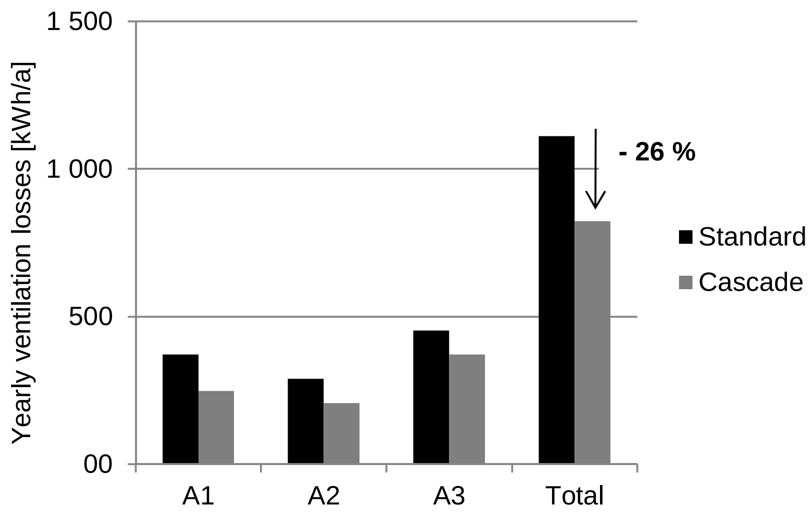


Figure 8: Yearly ventilation losses calculated for the residential area in Kramsach with standard and extended cascade ventilation.

The results show that with extended cascade ventilation, the reduction of the total airflow rate allows for a reduction of the ventilation losses of approximately 26% for the whole building. This means a reduction of the heating demand and thus of the heating costs of the building.

3. Expected air quality according to floor plan configuration

3.1. Introduction

The previous part showed that the concept of extended cascade ventilation in apartment buildings leads to significant savings in the operation expense. However, this concept should not be implemented to the detriment of air quality or comfort, particularly in the living room, where the supply air valve is suppressed.
In (Rojas et al., 2015) the optimal airflow rates in the bedrooms and in the living room for a typical 3-room apartment floor plan are discussed. The results of this survey show that an optimum between CO_2, TVOC concentration and humidity level is reached when a supply airflow rate of 20 m³/h per person is applied in the bedrooms, and no supply air at all in the living room (which corresponds to extended cascade ventilation). Applying higher airflow rates in the rooms would decrease CO_2 and TVOC concentration in the rooms (better air

quality), however, this would also lead to critical values of the relative humidity level in the rooms in winter.
This study was realized for a given floor plan configuration with a central living room to which all the other rooms of the apartment are connected via internal doors. This gives rise to the question of whether every floor plan configuration is suitable for the concept of extended cascade ventilation.

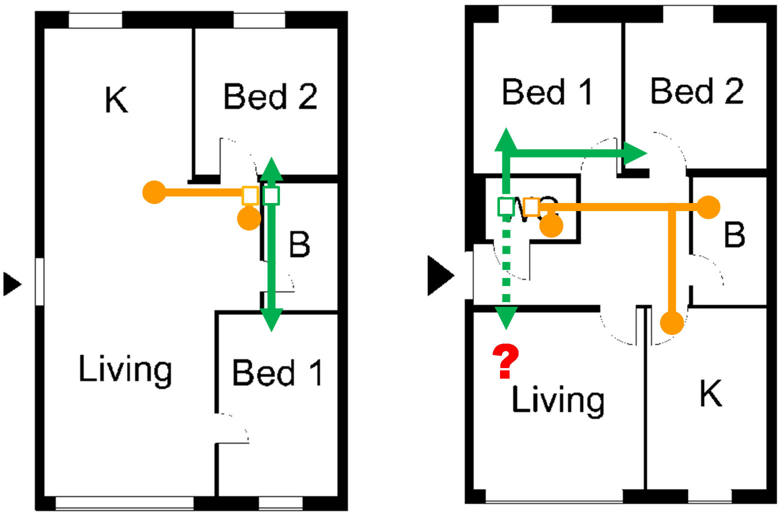


Figure 9: Left: floor plan investigated in (Rojas et al., 2015), for which extended cascade ventilation leads to an optimum between air quality and air humidity. Right: is extended cascade ventilation also possible for this configuration?

The objective of the following chapters is to define the floor plan configurations for which extended cascade ventilation can be applied, without impairing the air quality in the living room. Based on a classification of the usual floor plans, this chapter compares the air quality and humidity for standard and extended cascade ventilation for each possible configuration. Eventually, the results are summarized in an interactive tool addressed to ventilation designers.

3.2. Method of evaluation of air quality and humidity

The method to evaluate the air quality and humidity in the living room is developed in (Rojas-Kopeinig, Sibille, & Pfluger, 2012). This method is based on the evaluation of different criteria, defined through a target and a limit value.
Carbon dioxide (CO_2) concentration was chosen as an indicator for the global air quality inside the rooms. It is not the only contaminant in indoor spaces and also not the most toxic one, however, according to (Tappler, Hutter, Hengsberger, & Ringer, 2014), it can be assumed as a sufficient indicator for the air quality in apartment rooms with mechanical ventilation. The impact of other contaminants in the air (for example TVOC) on the global air quality is therefore neglected in this study.
Relative humidity rate (H_2O) appears in several studies to be one of the most critical acceptance factors of the occupants in the winter time in central Europe (Knotzer et al.,

2015). Therefore it is retained as an indicator of the indoor climate in this study. Other criteria like draft risk or temperature difference were neglected in this study.
The evaluation method compares the concentration of the two surveyed species (CO_2 and water vapor) in the air through given target and limit values. These values are chosen according to several and well-spread literature sources and standards on comfort and health of the occupants.

Evaluation criteria at 22°C	**$CO_{2\ rel}$* ($CO_{2\ abs}$) [ppm]** *** above outside air concentration**	**Humidity rate [%]**
Target value (IDA 2)	< 600 (1050)	> 30 %
Temporary acceptable (IDA 3)	600 to 1000 (1050 to 1450)	20 % to 30 %
Limit value (unacceptable: IDA 4)	> 1000 (1450)	< 20 %

Table 4:Evaluation criteria according to (Rojas-Kopeinig, Sibille, et al., 2012) CO2 values (IDA "InDoor Air quality") and humidity rate values come from (DIN EN 13779:2007-09, 2005).

The evaluation of CO_2 concentration is based on the frequency and the amplitude of overstepping of the target value over the surveyed time period. This value is compared to the maximum possible deviation over this period. The resulting value called "relative overstepping or deviation of the target value" (or: τ_{CO2}), represents a weighted percentage of time in which CO_2 concentration oversteps the target value. This principle is explained on Figure 10.

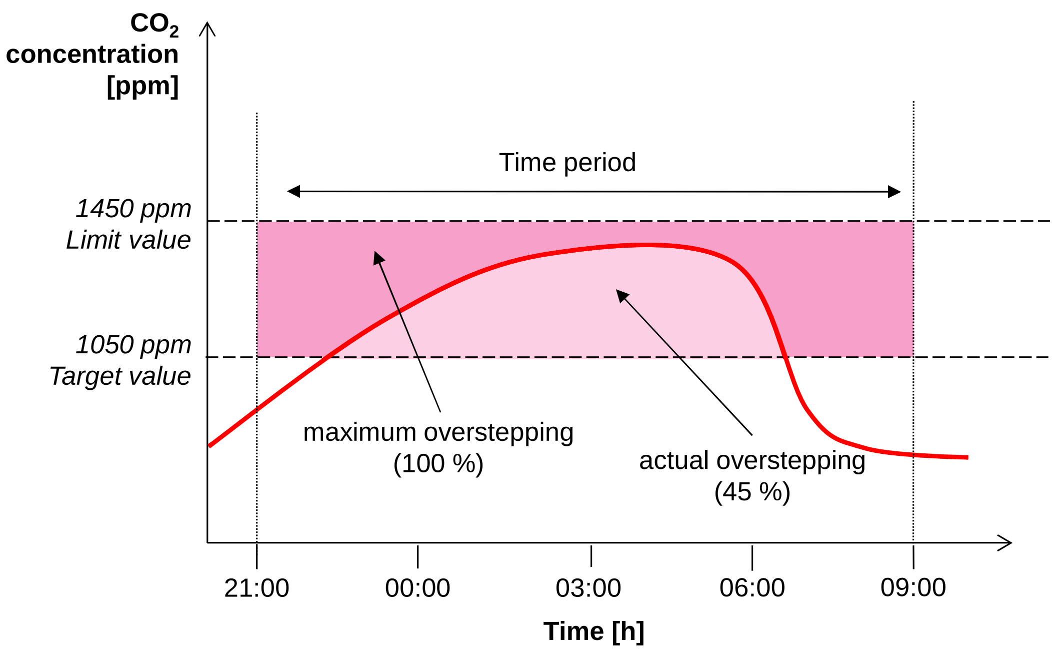


Figure 10: Illustration of the evaluation method for CO_2 concentration. The relative overstepping of the target value is calculated as the ratio between the integral of the overstepping amplitude over the surveyed time period (zone in light red), and the in integral of maximum overstepping amplitude (here the pink rectangle delimited by the target and limit values, and the time period).

The relative overstepping of the target value for CO_2 concentration is calculated with:

$$\tau_{CO2} = \frac{\int_T (\max(C_{Co2>C_{target},t} - C_{target}), 0)dt}{T \cdot (C_{limit} - C_{target})} \cdot 100\ \% \qquad (1.9)$$

With:

τ_{CO2}	the relative overstepping value of the CO_2 concentration target value [%]
T	the surveyed time period (by occupancy) [h]
$C_{Co2>C_{target},t}$	value of the concentration of CO_2 at time t [ppm]
C_{target}	target value of CO_2 concentration, here 1050 ppm. [ppm]
C_{limit}	limit value of CO_2 concentration, here 1450 ppm [ppm]

The lower the relative upper deviation (τ_{CO2}) is, the more effective contaminant removal in the living room, and thus the better the air quality in the room.

For the evaluation of relative humidity, it is the relative under-stepping value of the relative humidity in the room, τ_{H2o} [%]is calculated with a similar method.

$$\tau_{H2O} = \frac{\int_T (\max(C_{target} - C_{H2O<C_{target},t}), 0)dt}{T \cdot (C_{target} - C_{limit})} \cdot 100\ \% \qquad (1.10)$$

With:

τ_{H2O}	the relative under-stepping value of relative humidity target value [%]
T	the surveyed time period (by occupancy) [h]
$C_{H2O>C_{target},t}$	value of the concentration of H_2O at time t [%]
C_{target}	target value of H_2O concentration, here 30 % [%]
C_{limit}	limit value of CO_2 concentration, here 20 % [%]

The lower τ_{H2O} the more is relative humidity kept above the target value of 30 %.

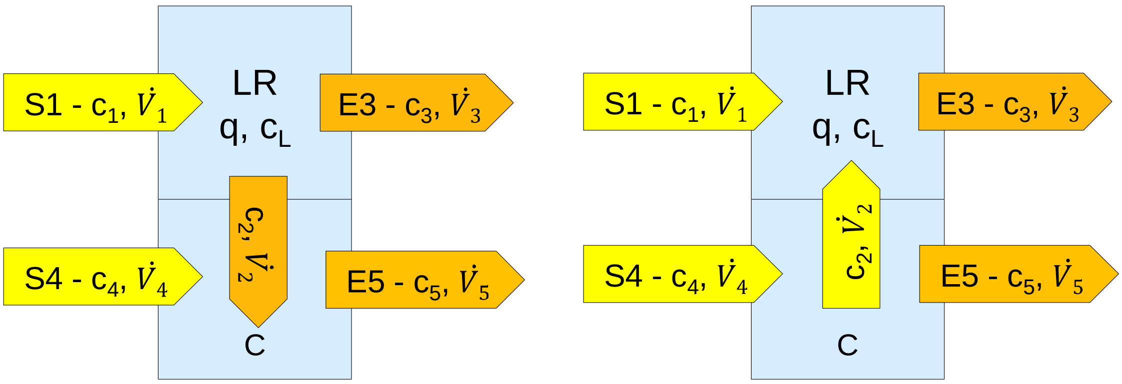
The advantage of this method is that relative deviation of the target values for CO_2 concentration (τ_{CO2}) and humidity rate (τ_{H2O}) are both expressed as percentages, which allows for an evaluation of air quality and air humidity on the same scale.

3.3. Analytical approach

3.3.1. Model with perfect mixed zones

In this first approach, each room of the apartment is considered as one zone, in which the air is assumed as perfectly mixed. This assumption implies that the concentration of the species is uniform through the room at each time and equal to the extract concentration. This assumption is confirmed in (David & Mats, 1996) and (J. Schnieders, 2003) for mechanical ventilated apartment rooms in apartment that have usual dimensions. The limits of this assumption are discussed in the part 4.4 of this chapter.

According to cascade ventilation principle, each room is either a supply zone, an extract zone or an overflow zone, depending on its functionality. Each zone is assumed to be separated from the next one with a door. When the door is closed, the air overflow still takes place in one direction through the door gap (or through another overflow element). In this first approach, the doors are supposed always closed and the envelope is assumed perfectly tight (no infiltration or exfiltration). Considering these assumptions, the overflow pattern through the living room and corridor can be modeled like in Figure 11:



$$\dot{V}_1 = \dot{V}_2 + \dot{V}_3 \qquad \dot{V}_3 = \dot{V}_1 + \dot{V}_2$$
$$\dot{V}_1 > \dot{V}_3 \qquad \dot{V}_1 < \dot{V}_3$$

Figure 11: Model of the flow pattern through the living room and corridor with assumption of perfect mixed zones.

With:

$\dot{V}_1$	airflow rate coming from one or more bedrooms (zone 1) with air supply valves directly connected to the living room to the living room through overflow (door gaps), in [m³/h].
$\dot{V}_2$	airflow rate coming from the corridor (C) to the living room or going from the living room to the corridor, in [m³/h].
$\dot{V}_3$	airflow rate going from the living room to extract air room(s) (zone 3) directly connected to the living room, in [m³/h].
$c_{1\ or\ 4}$	Carbon dioxide concentration in supply zone S1 or S4 in [kg_{CO2}/kg_{air}]
c_2	Carbon dioxide concentration the corridor (C) in [kg_{CO2}/kg_{air}]
$c_{3\ or\ 5}$	Carbon dioxide concentration in extract zone E3 or E5 in [kg_{CO2}/kg_{air}]
c_L	Carbon dioxide concentration in the living room in [kg_{CO2}/kg_{air}]
q	total CO_2 load from the occupant in the living room. Depending on the number of occupant, their age and activity in [kg_{CO2}/h]

The evolution of carbon dioxide concentration was analytically surveyed for a typical occupancy scenario.

3.3.2. Example

As an example, the following scenario is surveyed: the occupants were sleeping the whole night in their respective bedrooms and gather in the morning in the living room for a couple of hours. The loads are transferred from the bedroom to the living room. In addition, the contaminants have already accumulated in the living room during the night because of the overflow from the bedrooms. In order to simplify the problem, it was assumed that CO_2 concentrations in every room have reach steady state at the end of the night, before the occupants move to the living room. We consider here the case when $\dot{V}_1 < \dot{V}_3$, which corresponds for example to a configuration where the parent room and all the extract air rooms are connected to the living rooms. In the morning, before the occupants leave the room, the CO_2 concentration in zone S1 and S4 can be written:

$$c_{1\ or\ 4,initial} = \frac{q_{1\ or\ 4}}{\rho_{air} \cdot \dot{V}_{1\ or\ 4}} \quad (1.11)$$

With:

$c_{1\ or\ 4,initial}$ final value at steady state of CO_2 concentration in zone S1 or S4

$q_{1\ or\ 4}$ sum of the loads in zone S1 or S4 (depends on floor plan configuration and on occupancy pattern)

ρ_{air} density of air at 20°C

$\dot{V}_{1\ or\ 4}$ overflow rate from zone S1 or S4 to living room or corridor [m³/h]

In the corridor, the initial concentration is the same than in supply room S4. :
The concentration in the living room before the occupants arrive (steady state) is:

$$c_{L,initial} = \frac{q_{total}}{\rho_{air} \cdot \dot{V}_3} \quad (1.12)$$

With:

q_{total} sum of the loads in the whole apartment

ρ_{air}: density of air at 20°C

$\dot{V}_3$ total extract airflow rate from living room to zone E3

The application of mass conservation in each zone connected to the living room lead to the following equations that describe the evolution of the CO_2 concentrations in the different zones:

- in zone S1 and S4:

$$\frac{dc_{1\ or\ 4}}{dt} = \frac{\dot{V}_{1\ or\ 4}}{V_{1\ or\ 4}} \cdot (c_0 - c_{1\ or\ 4}) \quad (1.13)$$

- in the corridor:

$$\frac{dc_2}{dt} = \frac{\dot{V}_4}{V_2} \cdot (c_4 - c_2) \quad (1.14)$$

- in the living room:

$$\frac{dc_L}{dt} = c_1 \cdot \frac{\dot{V}_1}{V_L} + c_2 \cdot \frac{\dot{V}_2}{V_L} - c_L \cdot \frac{\dot{V}_3}{V_L} + \frac{q}{\rho_{air} \cdot V_L} \tag{1.15}$$

This system of four equations from first order was solved with the help of Matlab code and the solutions are plotted on Figure 12.

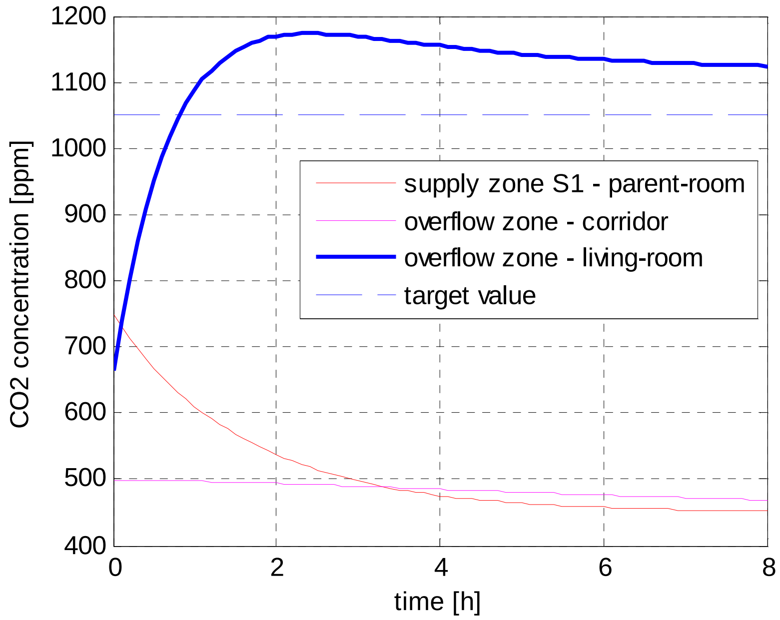


Figure 12: CO2 concentration in the different zones. The occupants all leave the bedrooms and gather in the living room for a couple of hours by extended cascade ventilation. In the configuration presented here, the parent's bedroom and all extract air rooms are connected to the living room, only the child's room is connected to the corridor.

A peak of CO_2 concentration can be observed on Figure 12, approximately at the second hour of occupancy. This is due to the fact that the supply air coming from the bedrooms still has a accumulated contaminants. When the concentration in the bedrooms becomes lower, this critical period is over and the CO_2 concentration in the living room slightly decreases to a steady state (after approx. 5 to 6 hours). In reality, the occupant stays most of the time only for short periods in the living room. Thus realistic scenarios can be hardly investigated with the analytic method.

Since the goal of the study is to investigate the air quality and humidity from a practical and realistic point of view, an alternative method with numerical models was chosen to survey more efficiently these criteria on different floor plan configurations.

3.4. Floor plan typology

The previous paragraph showed how the carbon dioxide concentration and thus the air quality in the living room depends on the supply or extract airflows, and thus on the floor plan configuration.

In order to study the scope of operation of extended cascade ventilation, from a practical point of view, realistic scenarios of occupancy and a survey of different floor plan configurations are necessary. A method based on a floor plan typology was therefore developed.
The study was made for a 3-room apartment with two bedrooms, one living room, one kitchen, one bathroom and one WC. All the rooms have a given area and height that are average taken from the data about residential building in Austria (Statistik Austria, 2004). The characteristics of the rooms are summarized in Table 5 below:

Room or zone	**Area**	**Ventilation (standard / cascade)**
Bedroom 1	13 m²	Supply valve 30 m³/h / 30 m³/h
Bedroom 2	13 m²	Supply valve 30 m³/h / 30 m³/h
Living room (opt. with kitchen and dining)	18 m² to 31 m²	Supply valve 30 m³/h / 0 m³/h
Kitchen (opt. with dining)	4 m² to 13 m²	Extract valve 40 m³/h – 27 m³/h
Bathroom	5 m²	Extract valve 30 m³/h – 20 m³/h
WC or storage room	1,5 m²	Extract valve 20 m³/h – 13 m³/h
Corridor (optional)	10 m²	Overflow zone

Table 5: Area and airflow characteristics of the different rooms

The first step was to identify and classify which are all the theoretically possible arrangements of the rooms in the apartment. A review of residential floor plans in old and new buildings showed that the arrangement and the shapes of the rooms can be extremely different. However, using the assumption of perfect mixed zones, only the connections between the rooms are relevant. It was thus possible to model each floor plan configuration with as simple symbolic system (Figure 13).

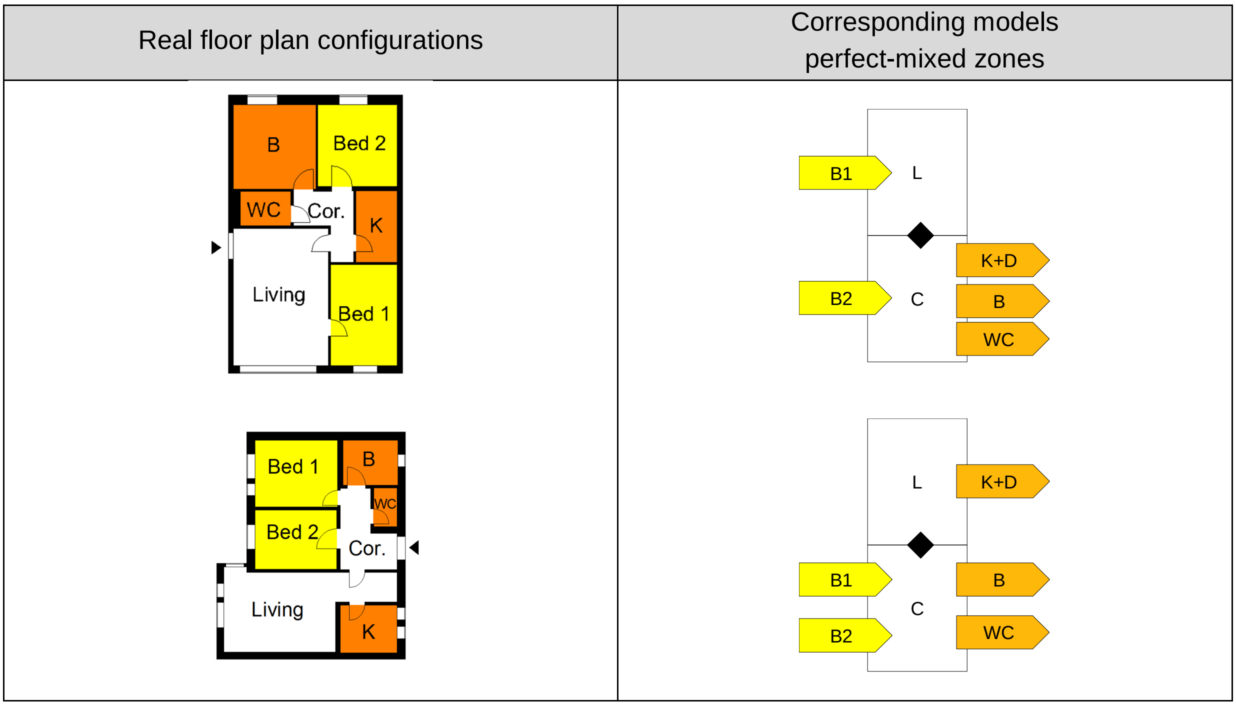


Figure 13: Example of real floor plans and their corresponding models with the assumption of perfect mixed zones

This way, a typology of all possible arrangements of the rooms in the floor plan could be established. A method using a tree structure in 4 steps was used to determine all the possible configurations:

- First step: configuration of the cluster formed by the corridor and the living room. There are two possibilities: either they are separated with a door and compose then two distinct zones in the model, or they are directly connected without any separation. In this case, they form only one zone, in which the air is assumed perfectly mixed. The configurations with door separation are called “C-Type”. The configurations without separation between the living room and the corridor are called “O-Types”.

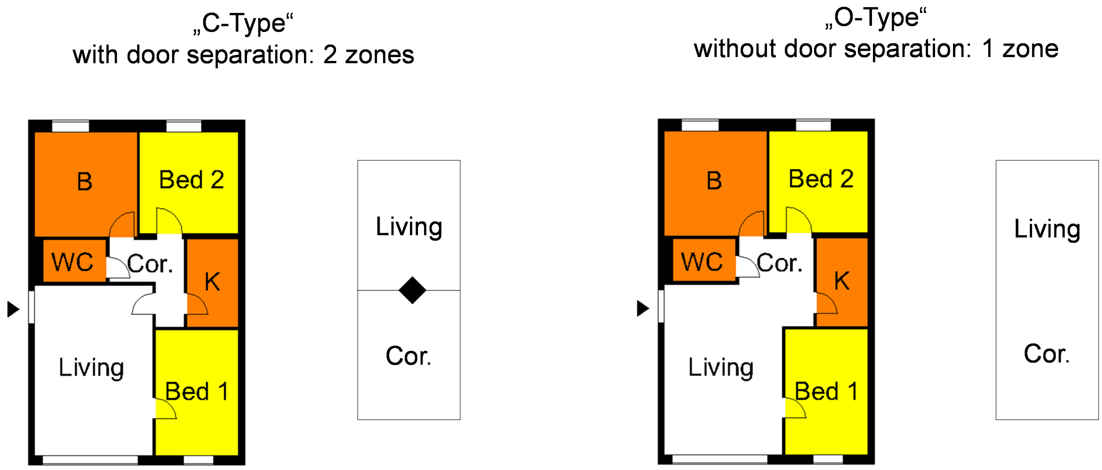


Figure 14: "C-Type" with separated living room and corridor, and “O-Type” where they form only one zone.

- Step 2: configuration of the cluster formed by the kitchen, the dining space and the living room. Three options were retained:
  - o Kitchen and dining space are integrated into the living room. The cluster form only one zone in the model. These configurations are called “L-D-K-Types”
  - o Only the dining space is integrated into the living room, the kitchen is separated. These configurations are named “L-D-Types”.
  - o The dining space is integrated into the kitchen (larger kitchen) and they both form one zone separated from the living room. These configurations are named “L-Types”

- Step 3: connections of the bedrooms with the living room or the corridor. With two bedrooms, this leads to four possibilities (Figure 15).

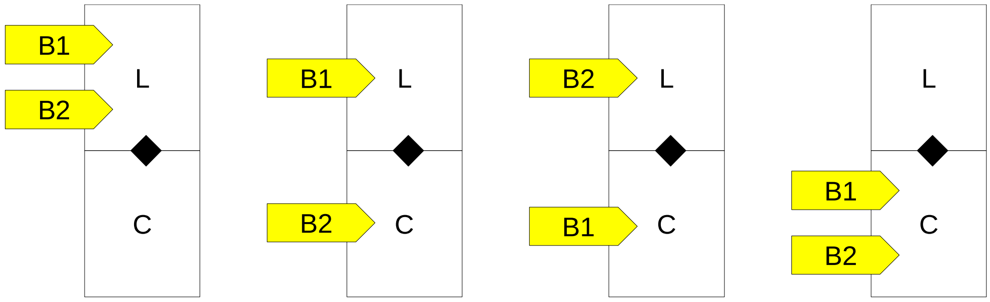


Figure 15: Four possibilities of connections between the bedrooms and the living room

- Step 4: connection of the extract air rooms (kitchen, bathroom and WC) to the living room or corridor.

A total of 75 different configurations of floor plan are theoretically possible. However, some of the configurations were considered very unlikely from an architectural point of view, and would hardly be found in reality. In order to reduce the number of configurations for the calculations, the following configurations have been therefore deleted of the typology:

- All configurations where only the bathroom is connected to the living room (the kitchen is connected to the in the corridor) were deleted.
- All configurations where the WC is connected to the living room, except when all other extract air rooms are also connected to the living room. In this case, the corridor would be only a small entrance (from the point of view of the airflows, it is like the “O-types”.)

All the remaining 47 combinations composing the floor plan configuration typology were classified in a “tree structure” as illustrated in Figure 16.

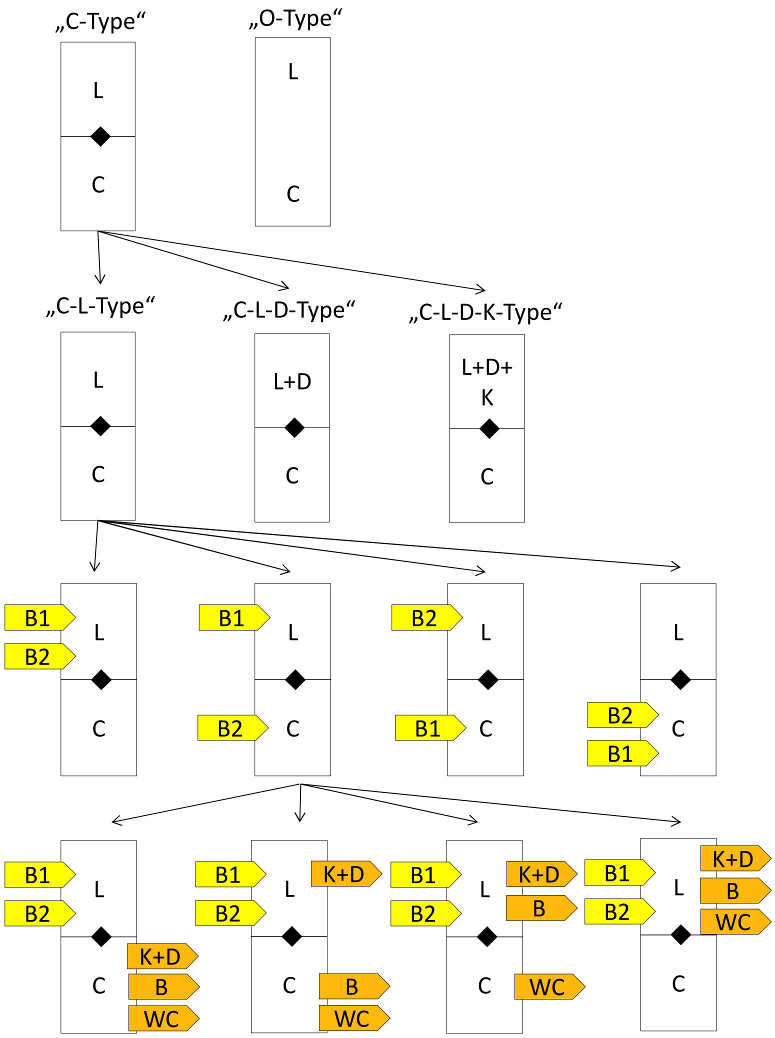


Figure 16: Illustration of the four steps for the classification of the floor plan configurations of a 3-room apartment. Here one branch is represented fully (except the configurations which were considered as architecturally very unlikely).

Based on this classification, each configuration was surveyed in terms of air quality (through carbon dioxide concentration) and relative humidity, with the help of simulations.

3.5. Simulation models

The multi-zone simulation software CONTAM (NIST) was chosen for the simulation. Each room of the apartment is represented as one zone, in which the air is assumed perfectly mixed. This is thus perfectly adapted to the floor plan typology described in the previous part. The program analyses dynamically the flow patterns between each zone and calculates at each time step the concentration of the selected contaminants in each zone. A huge variety of models are available for overflows, for the contaminants sources and sinks, or for occupant schedules etc., which allows the conception of highly realistic models.

3.5.1. Door model and user behaviour

Model of door closed:

For the model closed door, the air is assumed to flow only through the 10 mm door gap left under the door. The previous study on overflow components (Rojas-Kopeinig, Rothbacher, & Pfluger, 2012) validated the model of air overflow through door gap with the equation:

$$\dot{V} = C \cdot (\Delta P)^n \tag{1.16}$$

This model was used for the model in CONTAM. The parameters C and n were taken from the results of the quoted paper.

Model of door open:

The model of the opened door has been selected from (Dols & Walton, 2013) as a two ways flow model with one opening. This model has been especially adapted for airflows through doorways and considers simultaneous flow in two directions through the opening. The calculated flow in each direction depends on the height and the width of the door as well as the temperature difference between the two zones.

User behaviour:

It is hardly possible to determine a standard pattern of internal door opening inside an apartment because every occupant has their own particular habits. However, in the frame of research project low-vent.com (Knotzer et al., 2015), the opening time of the door between corridor and living room have been measured over several weeks for several apartments of a building. Every apartment is equipped with ventilation with heat recovery. The average frequency of opening of the door between living room and corridor is shown in Figure 17.

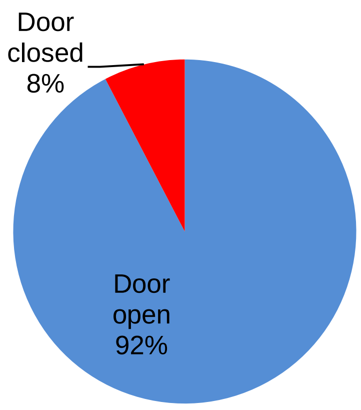


Figure 17: Average frequency of the opening of the door between the living room and the corridor

The measurements showed also that the door between the living room and the corridor is most of the time left open.

According to the model of open door in CONTAM, a slight temperature difference between the two zones induces important air exchanges in the two directions (approx. 250 m³/h in each direction). The air in the living room and corridor can be thus quickly assumed as well-mixed. However, the occupant may prefer to leave the doors inside the apartment closed (acoustic and light separation) and this behaviour should not impair the air quality. Thus, the simulations were performed for the worst case, when the internal doors are almost always closed in order to make statements that are independent of occupant behaviour on door opening.

- Bedrooms doors have been assumed to be almost always closed (door opening 10 minutes in the morning and in the evening)
- Kitchen door is assumed to be almost always closed. It is open only 30 minutes after dinner in the evening.
- Bathroom door is assumed to be almost always closed. Door is left open 30 minutes in the morning and in the evening.
- WC door is assumed to be always closed.
- A realistic, but still “pessimistic” opening pattern for the door between corridor and living room was assumed: The door closed when occupants are in the living room and during night. This means that this door is closed more than 50 % of the time, which is far higher than the observation in Figure 17. The scenarios where this door is always open and always closed were also simulated in order to evaluate the influence of the door opening.

The opening and closing periods of the doors were described in the CONTAM model with a schedule.

3.5.2. Occupancy scenarios

As carbon dioxide and water vapour are both exhaled from occupants in the room, the concentration of these species in the air inside a room is mainly dependant on the number of occupants and on their frequency of occupation. Therefore a preliminary study was conducted to establish realistic and typical occupation patterns in the several rooms.
According to recent statistics, the typical occupation rate of a 3-room apartment in Austria is two adults and one child (Statistik Austria, 2012). A typical schedule for each occupant could be also set from the information gathered in (Statistik Austria, 2009) and (International Energy Agency, 2002), which describe typical activities of children and adults during the week and the weekend. Figure 18 illustrates the resulting weekly schedules of occupancy of the rooms, which were used in the simulations.

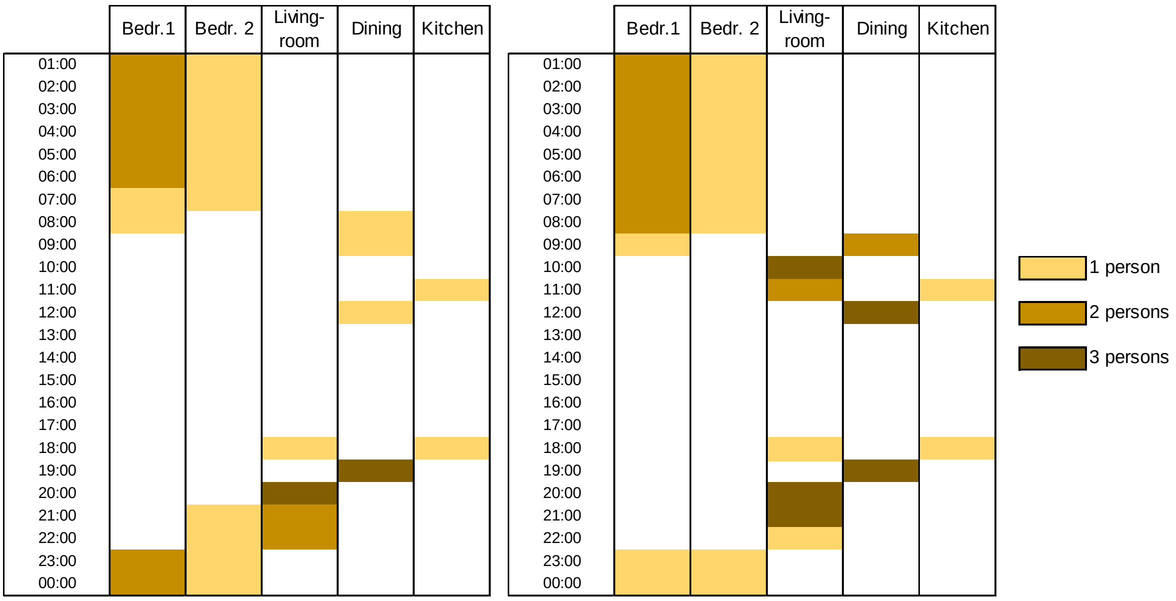


Figure 18: Occupation level of the different rooms of the apartment during the week (left) and the weekend (right)

The typical CO_2 exhalation rate of an adult and a child was set according to(International Energy Agency, 2002):

	Sleeping	Awake
Adult	12 l/h	18 l/h
Child	8 l/h	12 l/h

Table 6: Typical production rates of carbon dioxide by human beings

Carbon dioxide concentration of the outside air was assumed to be constant by 450 ppm for all the simulations.

For the water vapour sources, the standard value of humidity production through human presence and activity have been taken from (International Energy Agency, 2002). The humidity production for a 3-persons household are based on (Hartmann et al., 2001).

	Sleeping	Awake
Adult	0,36 l per hour	0,55 l per hour
Child	0,30 l per hour	0,45 l per hour
Cooking	0,8 l per day, distributed in morning, lunch and dining time	
Bath	0,8 l per day, distributed in the time spend in the bathroom	
Cloths drying	2,3 l per day	
Other sources	0,17 l per day per m² (bedrooms and living room only)	

Table 7: Typical production rates of humidity by human beings and activities

Buffering effects of humidity through the drywalls were also taken into account in the model. The input values have been taken from an existing model that have been already validated in (Pfluger, Sibille, et al., 2013). As humidity rate is likely to be critical in the winter time, the simulation focused on the airflow and contaminant concentrations between Dec. 1st and Feb. 28th and by occupancy in the rooms. The humidity rate of the outside air was taken for the local climate, using data from software Meteonorm 7.0 (METEOTEST) (Jan et al., 2014).

3.5.3. Simulation models

A general model of the surveyed living situation was established in CONTAM. This model is based on the existing model of a three-room reference floor plan, which had been already validated with numerous measurement data (Pfluger, Sibille, et al., 2013). This general model was built in a way that it could represent any floor plan configuration by only changing some parameters or properties.

With the help of a Matlab script, 47 copies of the general model were produced. For each copy, the code opens the project file and changed the values of several properties of the model in order to create one particular configuration, as illustrated on Figure 19. Occupancy schedules were also adapted accordingly.

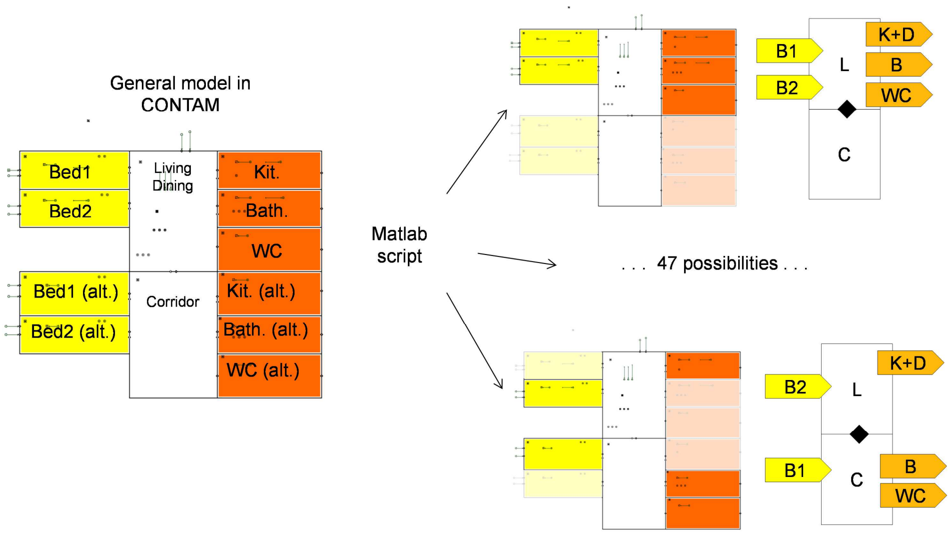


Figure 19: Generation of a model for each configuration (right) deriving from the general model (left) with the help of a Matlab script.

This way, all the CONTAM project files corresponding to the different floor plan configurations were generated automatically

3.6. Simulation results

3.6.1. Results on air quality

<u>"O-Type" configurations</u>

When there is no door between the living room and the corridor, the CO_2 concentration in the living room remains always below the target value for standard cascade ventilation.

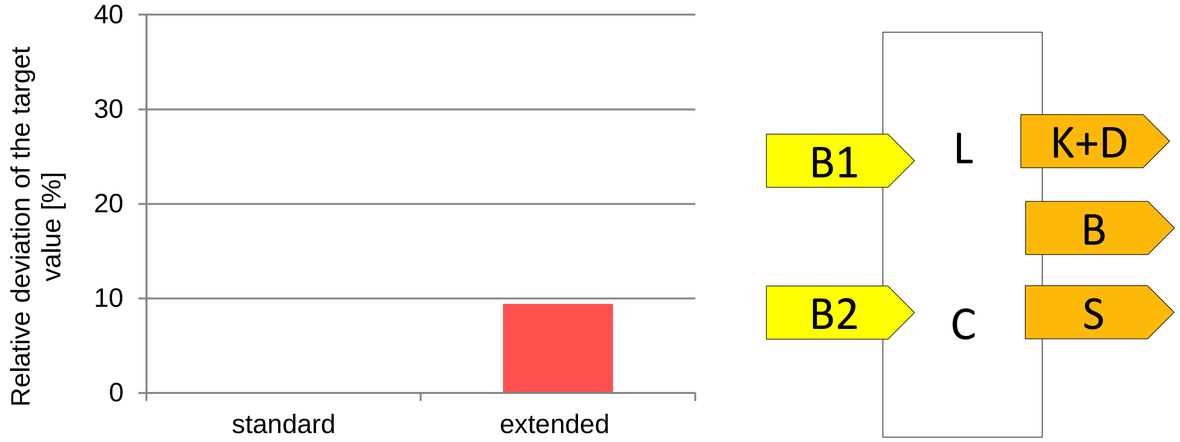


Figure 20: Relative overstepping of the target value for “O-Type” configurations.

For extended cascade ventilation, the relative standard deviation remains below 10 %. This means that for all the floor plan configurations, with no separation between the corridor and the living room, the air quality remains 90 % of the time by occupancy within IDA 2 in the living room.

<u>“C-Type” configurations</u>

The graphs in Figure 21 and Figure 22 show the relative deviation of the target value of carbon dioxide concentration, τ_{Co2} for the configurations with separated living room, corridor and kitchen, for standard and extended cascade ventilation. The results are presented for standard occupancy pattern, when the door between living room and corridor closed by occupancy and at night.

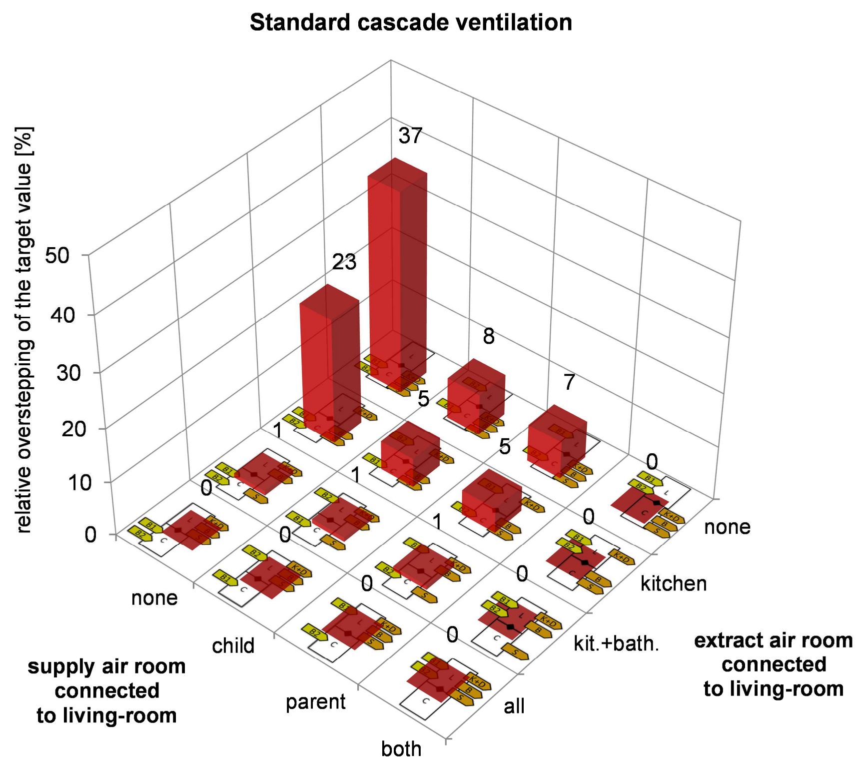


Figure 21: Relative deviation of the target value of CO_2 of the living room by standard cascade ventilation.

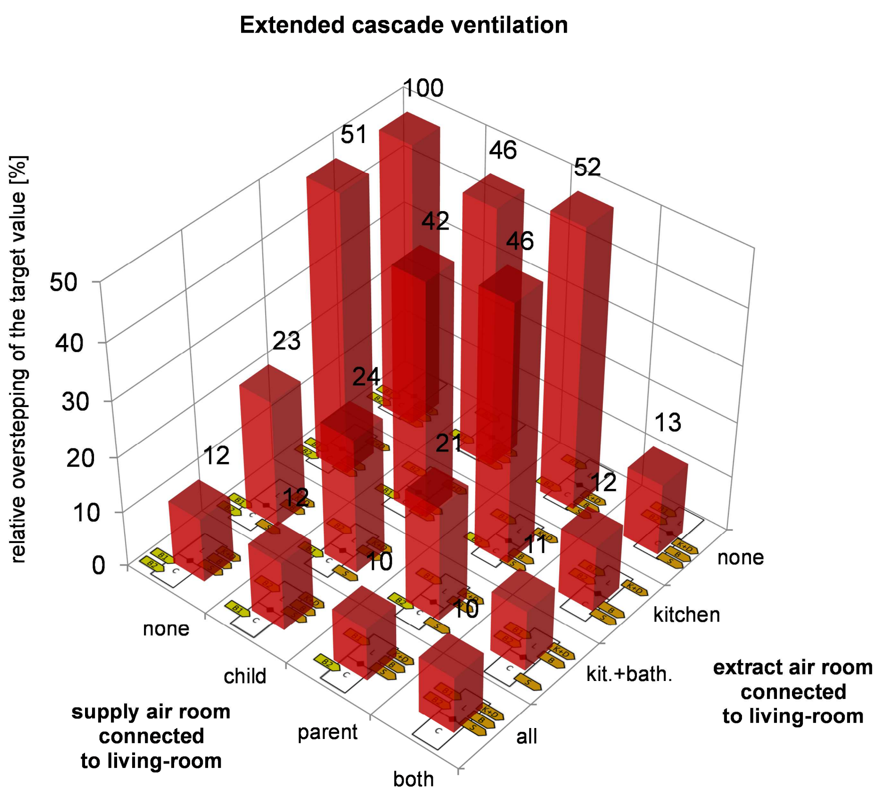


Figure 22: Relative deviation of the target value of CO_2 of the living room by extended cascade ventilation.

The results by standard cascade ventilation show that the relative deviation of the target value remains below 10 % for almost all the floor plan configurations. This means that the CO_2 concentration in the living rooms remains 90 % of the time by occupancy under 1050 ppm (IDA 2).

The results by extended cascade ventilation show that the air quality in the living room is globally poorer. However, for the configurations where either both bedrooms or at least the kitchen and the bathroom are connected to the living room, the relative deviation of the target value remains below 25 %. This means that 75% of the time, the air quality stays within IDA 2. The six other configurations are more critical. Detailed analysis is shown in Figure 23 and Figure 24 for these configurations.

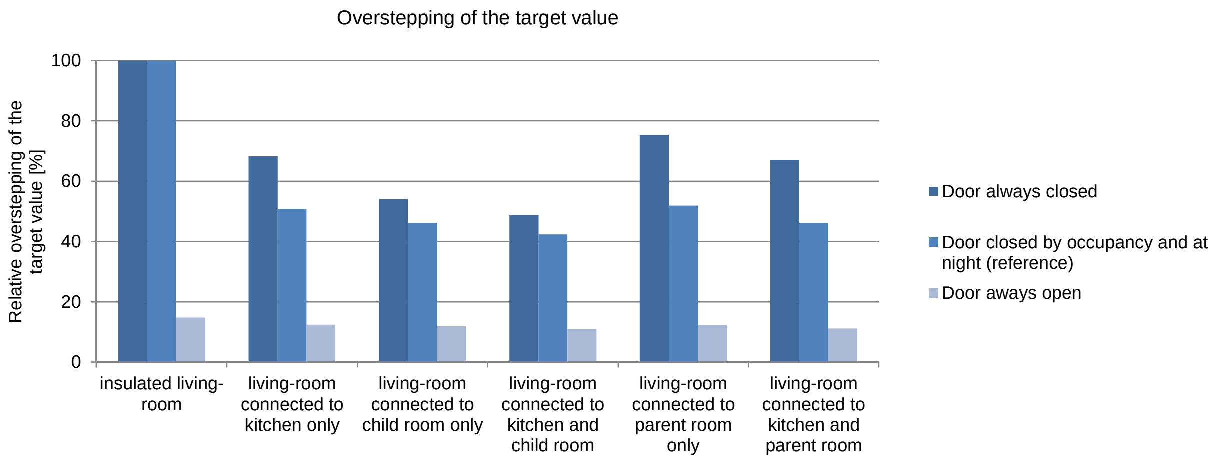


Figure 23: Relative overstepping of the target value (outside concentration + 600 ppm) for the critical floor plan configurations, and for various opening scenarios of the door between the living room and the corridor. The values above 100 % are truncated.

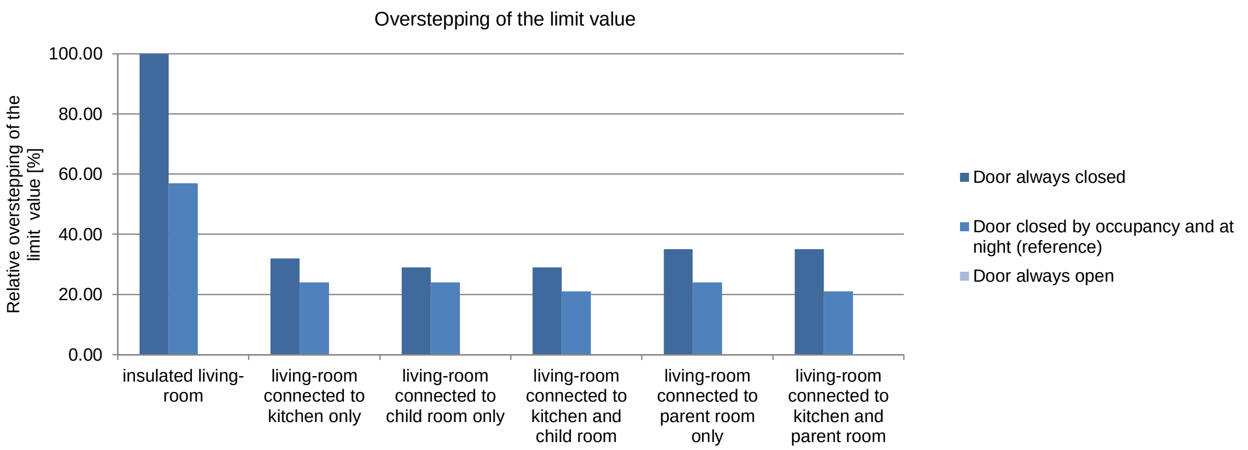


Figure 24: Relative overstepping of the limit value (outside concentration + 1000 ppm) for the critical floor plan configurations, and for various opening scenarios of the door between the living room and the corridor. The values above 100 % are truncated.

The results show that, for the configuration with insulated living room, extended cascade ventilation is not a fungible concept because carbon dioxide (and thus also the other contaminants) are not efficiently removed from the living room.
For the other five configurations, the deviation of the target value varies between 40% and 50% with the reference pattern of the opening of the door. However, the overstepping of the limit value (1450 ppm) never exceeds 25%. This means that 75 % of the time the air quality still remains within IDA 3, which is still tolerable. In addition, when the door between the living room and the corridor is left open, the results show that the relative deviation is reduced to 10 %. As shown in part 3.5.3, this door actually remains often open, which means that the situation for these configurations may be in reality less critical.

The simulations results on the other floor-plan configurations show that:

- The results on air quality are the same for the the C-L types (dining space integrated in the kitchen) and the C-L-D types (dining space integrated in the living room).
- The results on air quality for the C-L-K configuration (dining space and kitchen integrated in the living room) are the same as for the configurations for which the kitchen is directly connected with a door to the living room.

To avoid redundancies, the detailed results for these other configurations are not presented in this part. However, the results are available in the web tool presented in part 4.3 of this chapter.

3.6.2. Results on air humidity

“O-Type” configurations

In case of “O” type floor plans, the results on Figure 25 show that with extended cascade ventilation, the relative deviation of the target value for the humidity rate (30 % relative humidity) is significantly reduced.

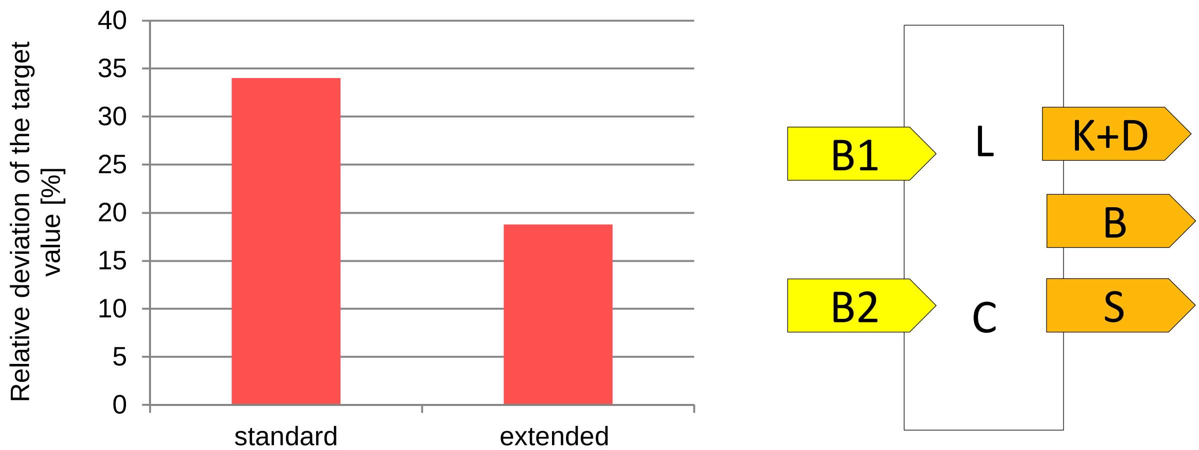


Figure 25: Relative under-stepping of the target value of relative humidity for “O-Type” configurations.

This result confirms the expectation that reducing the global airflow rate improves the humidity rate in the winter period.

<u>"C-Type" configurations</u>

For the configurations, where the living room and the corridor are separated, the results of the simulations show the opposite trend than for the air quality. The more insulated the living room is, the lower the relative deviation of humidity rate.

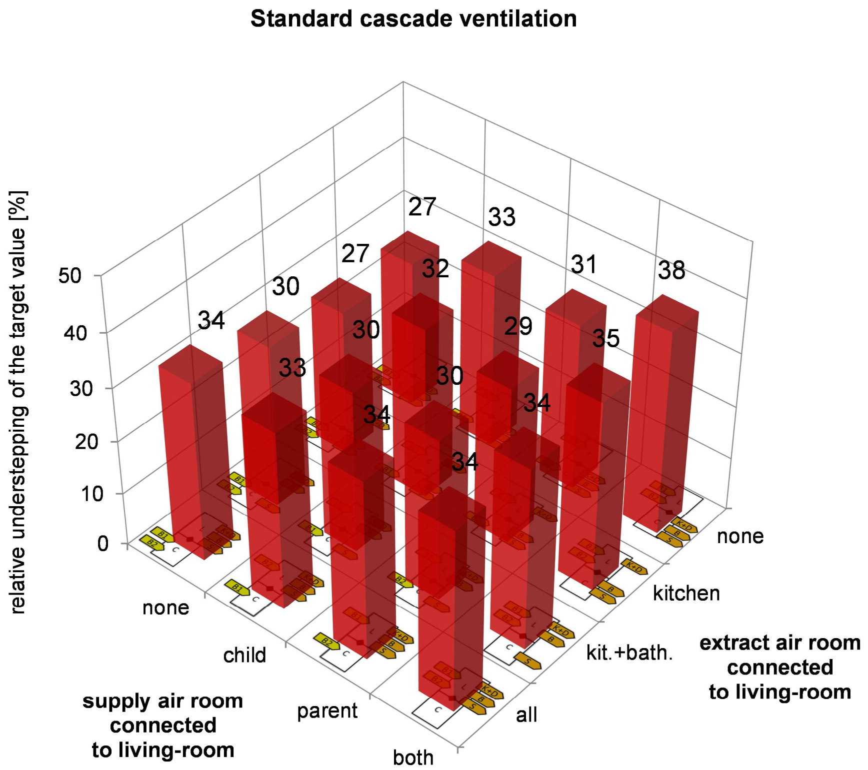


Figure 26: Relative deviation of the target value of relative humidity by standard cascade ventilation.

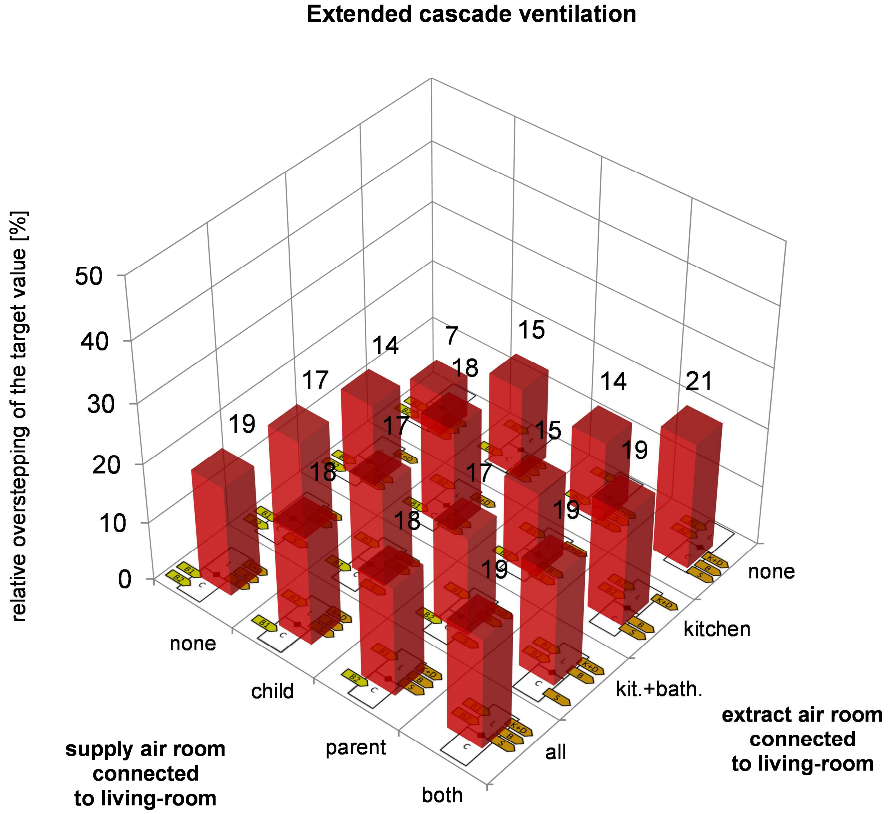


Figure 27: Relative deviation of the target value of relative humidity by extended cascade ventilation.

Figure 27 shows that for <u>standard</u> cascade ventilation, the relative deviation of the target value of the humidity rate inside the living room is approximately the same for every floor plan configuration (on average approx. 30% relative deviation). The results show that switching to extended cascade ventilation allows generally for higher humidity rates in the living room.
These results confirm the expectation that the reduction of the airflow rate in the apartment leads to higher humidity rates. The situation where the living room is completely insulated show the lower relative deviation. This is because the humidity sources, which are actually very important the living room (occupants, clothes drying etc.) are hardly removed in this configuration.

The simulations results on the other floor plan configurations show that:

- The results on air humidity are the same for the for the C-L types (dining space integrated in the kitchen) and the C-L-D types (dining space integrated in the living room).
- The results on air humidity for the C-L-K configuration (dining space and kitchen integrated in the living room) show that the relative deviation of the target value is approx. 30 % lower than in the configuration where the kitchen is separated with a door from the living room. This is because the water vapour from the cooking activities is instantaneously mixed with the air of the living room.

To avoid redundancies, the detailed results for these other configurations are not presented in this part. However, the results are available in the web tool presented in part 4.3 of this chapter.

Those results imply that for most of the usual floor plan configurations, the concept of extended cascade ventilation does not affect significantly the air quality in the living room. The accumulation of contaminants in the living room highly depends on the door opening between the living room and the corridor. In addition, the results confirm that the reduction of the airflow rate associated with the concept extended cascade ventilation improves significantly the relative humidity level in the apartment, for all the configurations.

3.6.3. Global evaluation of the indoor climate

The advantage of the evaluation method using the relative deviation of a target value chosen for two different species is that these criteria can be compared on the same scale.
For the "O-type" configurations (central living room, no corridor), the sum of the relative deviation of the target values for air quality and air humidity in shown on Figure 28, for standard and extended cascade ventilation.

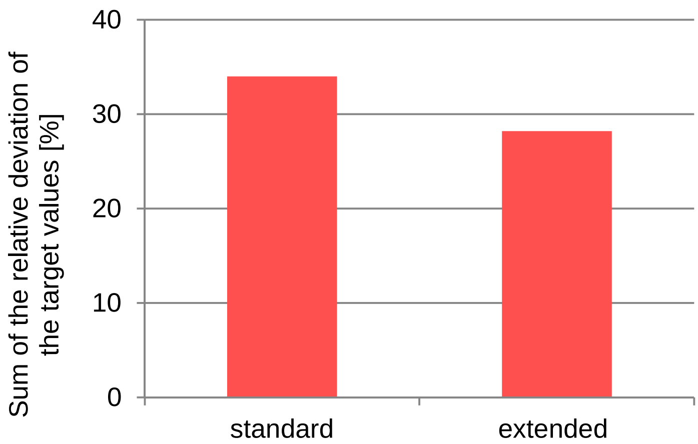


Figure 28: Sum of the relative deviation of the target values (CO2 and humidity) by standard and extended cascade ventilation

For the "C-type" configurations (separated corridor and living room), Figure 29 and Figure 30 show the sum of the relative deviation of the target values for air quality and air humidity, for standard and extended cascade ventilation.

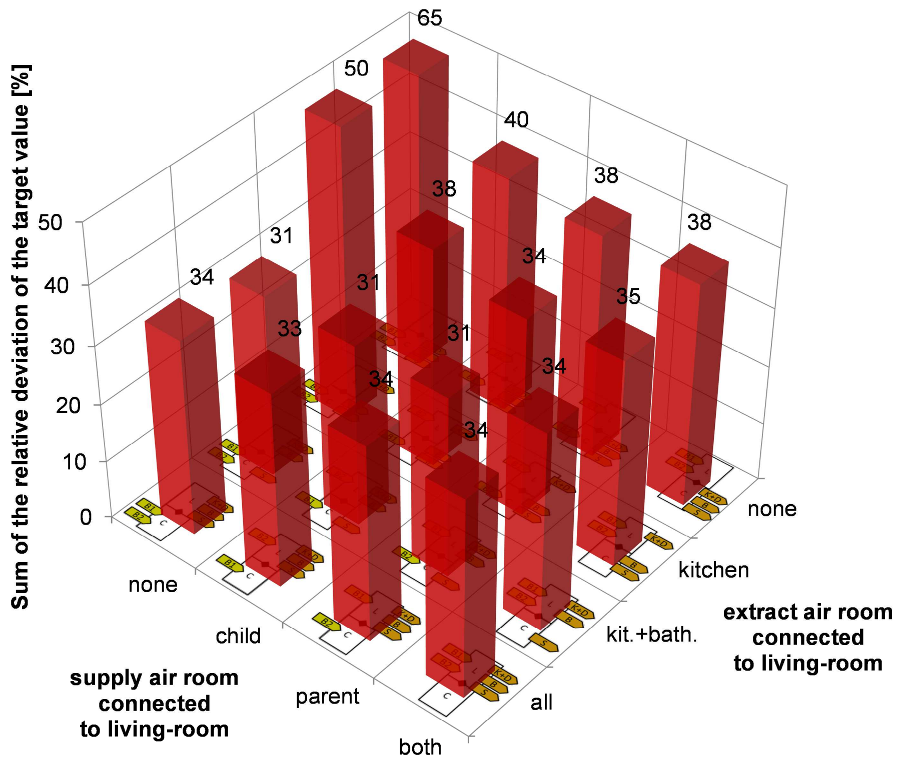


Figure 29: Sum of the relative deviation of the target values (CO2 and humidity) by standard cascade ventilation

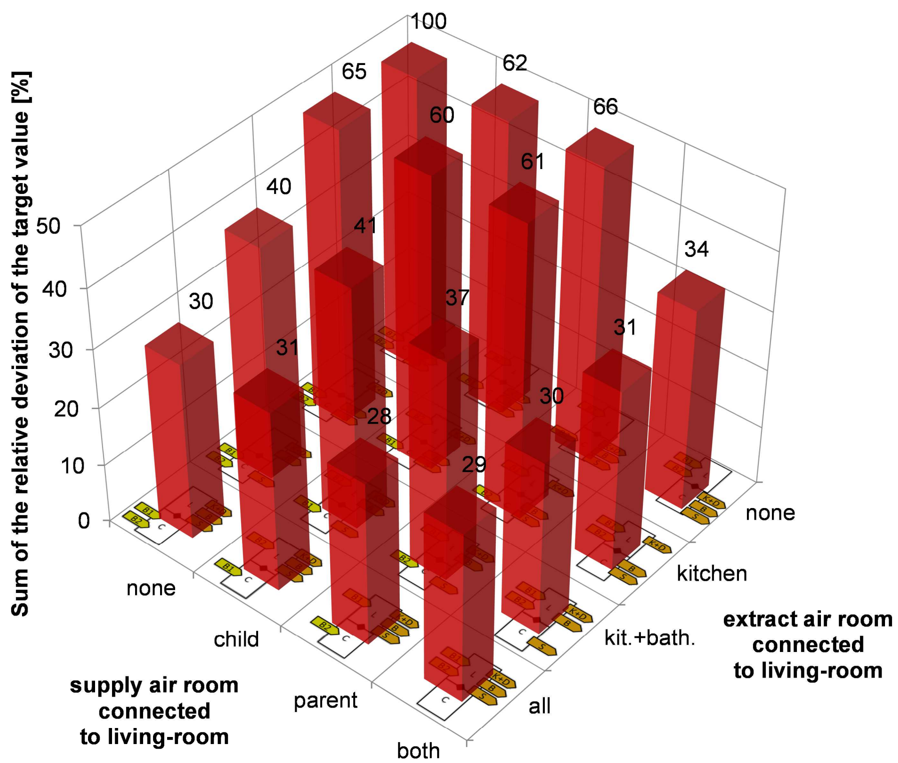


Figure 30: Sum of the relative deviation of the target values (CO2 and humidity) by standard cascade ventilation

The comparison of the results in the diagrams above shows four different cases:

- For some floor plan configurations, the sum of the relative deviation is lower for extended than for standard cascade ventilation. Typically, this happens when the suppression of the supply valve in the living room does not affect significantly the air quality but improves significantly the air humidity rate. This is the case for the O-type floor plan as well as for the C-types with both bedrooms, or with all the extract air room connected to the living room.
- For some configurations, the results are almost similar for standard and extended cascade ventilation. This happens when the deterioration of the air quality in the living room is “balanced” by the improvement of the air humidity in winter.
- For the other configurations, the deterioration of the air quality in the living room is prevailing in comparison to the improvement of the air humidity rate in winter, by extended cascade ventilation. The sum of the relative deviation of the target values is thus significantly higher with this concept.
- Especially for the configuration with insulated living room, extended cascade ventilation lead to dramatically high values of CO_2 concentration in the living room.

These results lead to different recommendations for the planning of extended cascade ventilation, depending on the floor plan configuration.

4. Planning recommendations and web tool

4.1. Planning recommendation according to floor plan configuration

According to the results of the previous part, the surveyed floor plan configurations can be classified into three categories.

4.1.1. Category 1: extended cascade ventilation is recommended

For some of the surveyed floor plan configurations, the results of the simulations showed that the implementation of extended cascade ventilation leads to on average similar of even better indoor climate than standard cascade ventilation. For these configurations, suppressing the supply air valve in the living room does not affect significantly of the air quality in the living room (carbon dioxide concentration remains more than 75% of the time in IDA 2). In addition, the associated reduction of the airflow rate improves significantly the humidity rate in the rooms in winter. In addition, the operation costs are also reduced. Hence, for these configurations, it is recommended to plan extended cascade ventilation rather than standard cascade. These configurations are:

- the “O” type floor plans, where all rooms are connected to a central living room. This kind of configuration is very frequent in contemporary housing projects.

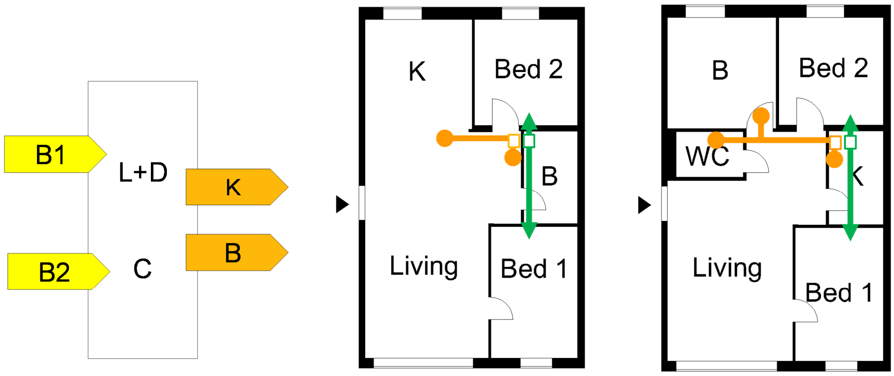


Figure 31: Left: functional diagram of an “O” type. Middle and right: examples of floor plan with “O” type configurations with suggestion for ventilation design in extended cascade (first example is taken from the project “Lodenareal” (“Neue Heimat Tirol - Projekte - Innsbruck, Lodenareal 2. Bauabschnitt,” n.d.)).

- The configurations where the two bedrooms are connected to the living room. These configurations are less usual in contemporary buildings but are frequent in older buildings. This means that when these buildings are renovated, the ventilation would be optimally designed in extended cascade.

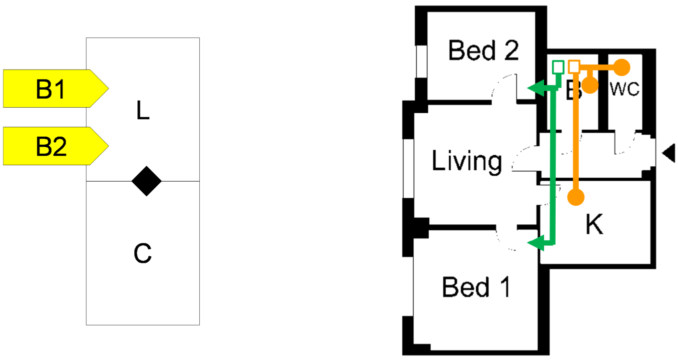


Figure 32: Functional diagram (left) and example (right) of floor plan configurations with the two bedrooms connected to the living room, and with a suggestion of the design of the ventilation in extended cascade.

- The configurations where the kitchen and the bathroom are connected to the living room produce no significant deterioration of the global indoor climate with extended cascade ventilation. This concept is therefore recommended for these configurations, especially for apartments located in cold and dry regions, for which the issue of air humidity in winter is particularly crucial.

4.1.2. Category 2: extended cascade ventilation is borderline

For these floor plan configurations, the planning of extended cascade leads to a significant deterioration of the air quality in the living room, which is prevailing in the global evaluation of the indoor climate. In case of apartments located in cold and dry regions, where the occupants particularly face the issue of too low humidity rate in winter, extended cascade ventilation can still be recommended. However, in this case, the users must be encouraged to let the door between living room and corridor open in order to prevent contaminant accumulation in the living room. For example, these configurations are:

- The configurations for which only the kitchen is connected to the living room (or integrated into the living room).

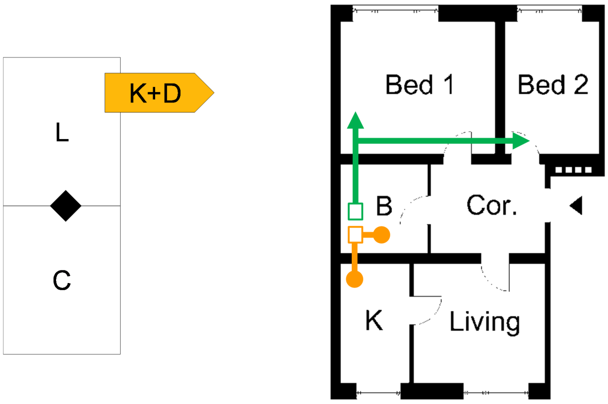


Figure 33: Functional diagram (left) and example (right) of a floor plan configuration with kitchen only connected to the living room, and with a suggestion of the design of the ventilation in extended cascade.

- The configurations for which only one bedroom are connected to the living room.

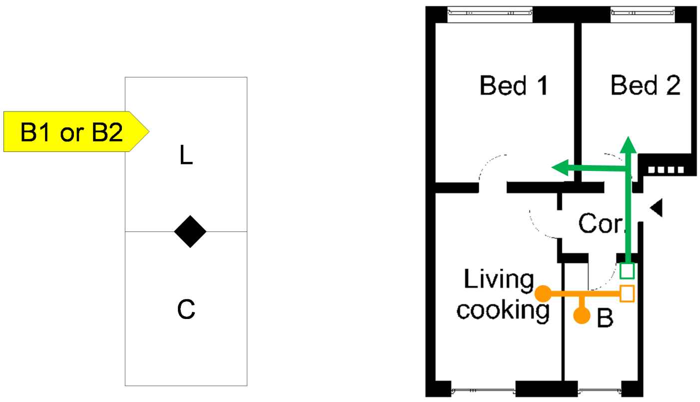


Figure 34: Functional diagram (left) and example (right) of a floor plan configuration with the kitchen and one bedroom connected to the living room, and with a suggestion of the design of the ventilation in extended cascade..

These configurations are quite frequent for flats in buildings erected in the 1960s in Austria. A lot of these buildings are nowadays subject to intensive refurbishment with the integration of ventilation. In this case, it may be appreciated by the occupant to suppress the door between corridor and living room, in order to create an open space and bring more light into the corridor. With this simple change, the floor plan also becomes well-adapted for extended cascade ventilation (Figure 35).

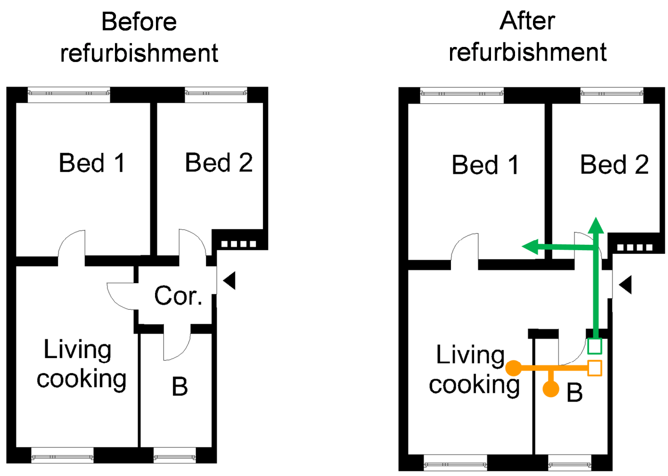


Figure 35: left: configuration before refurbishment, not perfectly adapted to extended cascade ventilation. Right: configuration after refurbishment, the separation between vestibule and living space has been removed and extended cascade ventilation is perfectly adapted. Installation is simpler and cheaper.

4.1.3. Category 3: extended cascade ventilation is not recommended

For this kind of floor plan, extended cascade ventilation is clearly not adapted because the risk of poor air quality in the living room is too important. This is the case when the living room is completely insulated.

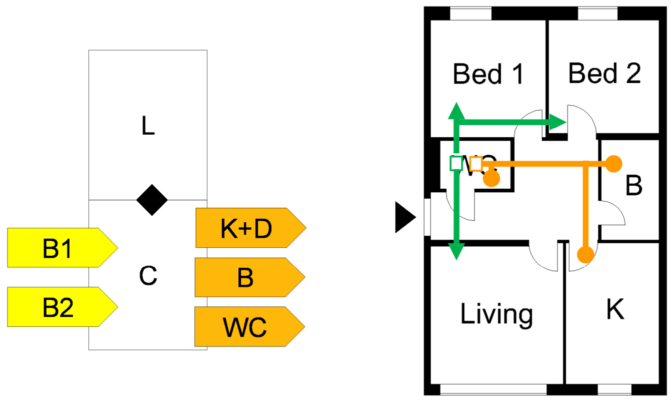


Figure 36: Functional diagram and example of floor plan configuration, which is not appropriated to extended cascade ventilation. For this kind of floor plan, a tolerable air quality in the living room can be achieved only with standard cascade ventilation design as sketched on the floor plan (right).

This kind of floor plan is also quite frequent in the housing buildings of the 1960s in Austria. In this case, either standard cascade ventilation should be installed, or the floor plan configuration should be changed for a suitable one, during refurbishment work, for example. A ventilation concept using active transfers is also possible (see chapter 2, part 5.4).

4.2. Remark on one-bedroom apartments

In (Rojas-Kopeinig, 2013), a minimal extract airflow of 60 m³/h is recommended in order to prevent any damage due to humidity accumulation in the apartment. The extract air is distributed between the kitchen and the bathroom. In the case of one-bedroom apartments, the supply air is distributed between the living room and the bedroom; in case of extended cascade ventilation, only in the bedroom. However, a supply of 60 m³/h in the bedroom may lead to very dry conditions in winter.

Therefore, for one-bedroom apartments, it is recommended to distribute the necessary airflow rate through the bedroom and the living room, by applying standard cascade ventilation. Extended cascade ventilation is not recommended in this case.

4.3. Web tool

The goal of this work is to support the realization of extended cascade ventilation in dwellings. For this, the results should be accessible and disseminated in a practical way. For this purpose, a web site has been created, hosted by the Passive House Institute in Innsbruck: http://www.phi-ibk.at/luftfuehrung/. The objective of this web site is to give an overview on the advantages of extended cascade ventilation and of the possible cost savings, and also to help the designers to recognize if a considered floor plan is adapted to extended cascade ventilation.

The home page delivers some general information about air guidance and cascade ventilation. The results from other research studies related to cascade ventilation are also available on this web site. An interactive web-tool is also available to check if a particular floor plan is adapted to extended cascade ventilation or not.

This tool is structured with four selection steps that refer to the tree structure of the floor plan classification developed in chapter 1, part 3.4. The user selects the configuration corresponding to the surveyed floor plan (connections of the supply air rooms (bedrooms) and of the extract air rooms to the living room), as illustrated in Figure 37.

Figure 37: Screenshot of the overview of the web-tool after selection through the four steps

After the last selection step, a pop-up window automatically opens and shows the results for the selected configuration (Figure 38).

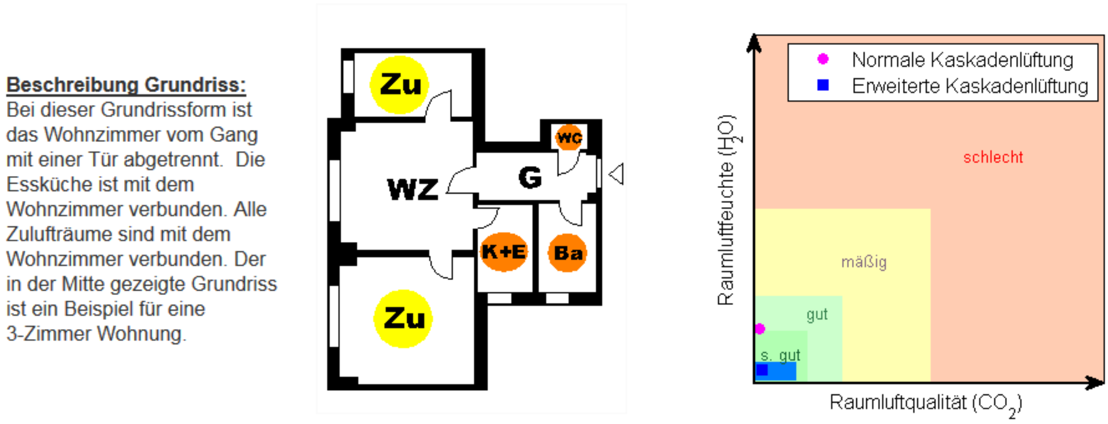


Figure 38: Screenshot from a pop-up window for the floor plan configuration with two bedrooms directly connected to the living room.

In the pop-up window, the selected floor plan configuration is shortly described and an example of floor plan corresponding to this configuration is displayed. A diagram with the results of the simulations for this configuration is shown next to it. The diagram shows in the x-axis the relative overstepping of the target value of CO_2, τ_{CO2} and in the y-axis the relative under-stepping of the target value of H_2O, τ_{H2O}, under the standard conditions. The pink point represents the results with standard cascade ventilation and a blue point for extended cascade. The influence of occupant behavior on door opening is also illustrated for extended cascade with a blue field on the x-axis, showing the range of variation of the overstepping of the target value of CO_2.

The points are located in one of the three colored zones, which correspond to the three categories described in part 4.1:

- Blue point in the green zone: Extended cascade ventilation is recommended
- Blue point in the yellow zone: Extended cascade ventilation is borderline. It leads to better humidity rate in winter and to savings on investment and operation costs. However, the air quality in the living-room is significantly poorer than with standard cascade ventilation. It is therefore recommended only for apartments located cold and dry climate zones. In addition, the user must be encouraged to keep the door between living room and corridor open as much as possible.
- Blue point in the red zone: extended cascade ventilation is not recommended because the risk of intolerable the air quality in the living room is too high.

An explanation text below the diagrams gives some further information about the selected floor plan configuration. If the configuration is not adapted to extended cascade, the text also includes some suggestions to change the floor plan (for example, suppress the separation between the living room and the corridor).

4.4. Limits of the assumption of well-mixed zones

The whole study of floor plan configurations relies on the assumption that the air is well-mixed in each zone, or each room of the floor plan. This assumption has two consequences:

- The air quality is uniform at each point of the zone, all the time, regardless of its size or geometrical configuration.
- There is no air short-cut between supply and extract air inside one zone. The air supply is always perfectly mixed inside the zone before being extracted.

As seen in part 2, the assumption of well-mixed zones has been validated in the frame of several studies for rooms that have standard size and configurations in apartments. Nevertheless, some of the encountered floor plan configurations are worth questioning this assumption and its consequences.
According to previous study, configuration where corridor and living room have no separation is perfectly compatible with extended cascade ventilation. Though, some geometrical shapes of the living room are suspected to be critical because of possible dominating stack effect or air short-cut issue:

- The case where living room and corridor form only one zone but on several floors, particularly if the living room is the only room on the upper floor and all rooms are connected to the lower floors.
- The case where all bedrooms and extract air rooms are connected to the corridor side, in a way that all the doors (thus all the overflow elements) are very close to each other (next to each other or directly in front of each other).

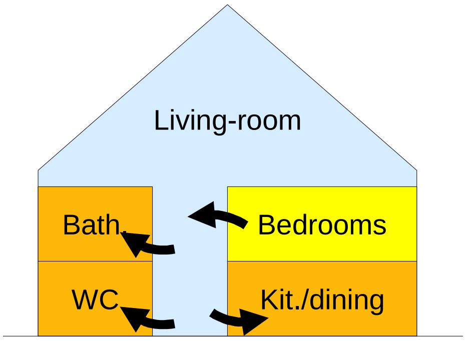


Figure 39: Example of configuration where the ventilation of the living room can be critical because of the dominating stack effect that produces short-cut between supply and extract (left). Example of configuration where the ventilation can be critical due to short-cut effects between the supply and the extract air rooms (right).

These particular configurations have been surveyed in (Rojas & Pfluger, 2014). The results showed that the issue of short-cut between supply and extract air rooms by extended cascade ventilation can be eliminated if the designer pays attention to the positions of the overflow openings.

5. Conclusion

This study allowed for a better understanding of the floor plan related factors that influence air quality and relative humidity in the living room by standard and extended cascade ventilation. It showed that for most of the floor plan configurations, extended cascade ventilation is a fungible air guidance concept that even significantly improves the comfort of the occupant through higher humidity level in winter.
Extended cascade ventilation is thus recommended for the floor plan configurations where either all supply and extract air rooms are directly connected to a central living room or where at least two bedrooms are connected to the living room (and the other to the corridor). Also the floor plans where the kitchen only is connected to the living room (or directly included) can be planned with extended cascade ventilation, but it leads to worse air quality, particularly if the user leaves the connection door to the corridor always closed. The concept of extended cascade ventilation is not recommended for configurations where the living room is completely insulated, because it leads to a high risk of inacceptable air quality in the living room. It is also not recommended for one bedroom apartments because would lead a high risk of too dry air in winter time in the bedroom.
These results have been summarized in an interactive online tool addressed to ventilation designers who find design guidelines adapted to each floor plan configuration.

The study also evaluated the savings in the investment and operation cost savings that are expected when implementing extended cascade ventilation. Suppressing the supply air valve in the living room allows only limited savings in the investment costs. These costs actually rather depend on the chosen type of distribution and on the pre-fabrication level. In this frame, semi-rigid plastic ducts are preferred. However, extended cascade ventilation has a huge influence on the operation costs; through the reduction of the total airflow rate in the apartment, the electrical consumption of the fans decreases significantly. Up to 25 % of the yearly operation costs can be saved with extended cascade ventilation. Besides, reducing the airflow rates also decreases the heating demand of the building.

Chapter 2

Analysis and design of a ventilation concept using active transfers

1. Introduction

In the previous part, we observed that the investment costs are mainly due to the installation and the covering work of the ducts in the apartment. This issue becomes crucial in refurbishment cases because there is no provision for the ventilation ductwork in the original construction. In fact, in Germany and Austria, more than 70 % of the flats are located in buildings or houses erected before 1989 (Statistik Austria, 2013), (Statistische Ämter des Bundes und der Länder, 2011). These buildings now face deep energy renovation work including high performant ventilation in order to achieve the goals of the European directive for 2020 (European Parliament, 2012). In this context, adapted ventilation strategies that combine efficiency and simple installation are required.
In the concept investigated in this part, the whole supply air ductwork is reduced to only one main valve installed in a so-called "mixed air room". The mixed air room can be either the corridor or the living room. The fresh air from the main valve is brought into the bedrooms by mean of active transfers installed between the mixed air room and the bedrooms, as illustrated in Figure 40.

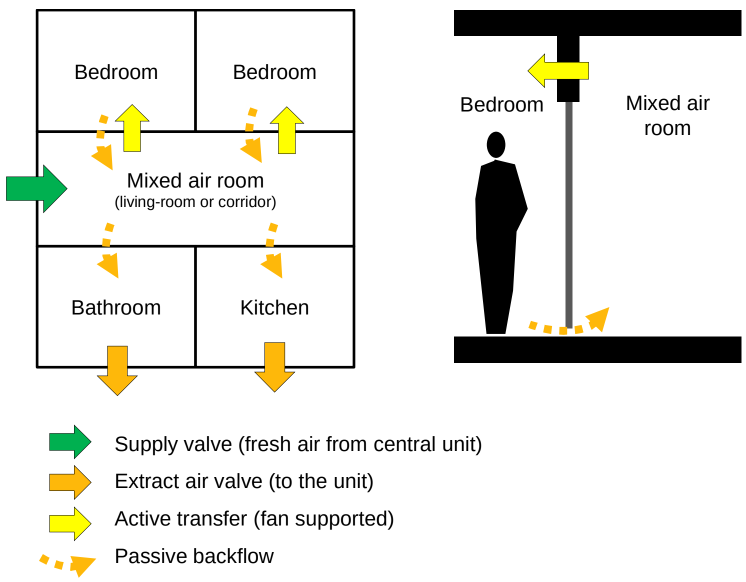


Figure 40: Illustration of the ventilation concept with active transfers in an apartment. Only one global supply is installed in the mixed air room (living room or corridor). The active transfers bring the fresh air into the bedrooms.

The active transfers can be installed either in the separation wall between the corridor and the bedroom or directly within the door leaf itself. The air from the bedrooms flows back through passive overflow openings (for example the door gap) into the mixed air zone. The air is extracted as usual through the kitchen and the bathroom with extract air valves connected to the central unit.

The saving potential of this concept was already recognized in 2010 by the town of Zurich, which is also facing large scale building refurbishment operations. A design competition to develop adapted products for active transfers was thus launched and lead to numerous solutions (Sprecher & Estevez, 2011). Several examples of non-residential buildings in which this concept was implemented (for example (Pfluger & Rothbacher, 2013)) confirmed the practicability of the concept.

Though, the ability of a systematic implementation in residential areas has not been surveyed yet. The factors that influence occupant comfort and air quality in rooms ventilated with active transfers need to be determined. Particularly, clear planning rules for the design of a ventilation concept with active transfers, which ensure comfort and air quality to the occupant are missing.

The following study aims at finding out the factors that influence air quality and occupant comfort in apartments ventilated with this concept. The key factors for the development of products especially adapted to renovation are also at focus in this part. Eventually guidelines are suggested to orientate the designer in the planning of the concept of ventilation with active transfers considering different floor plan configurations.

2. Influencing factors

In order to establish the factors that influence air quality and occupant comfort in an apartment ventilated with the concept of active transfers, a theoretical study was carried out on a typical three-room apartment, as illustrated in Figure 41.

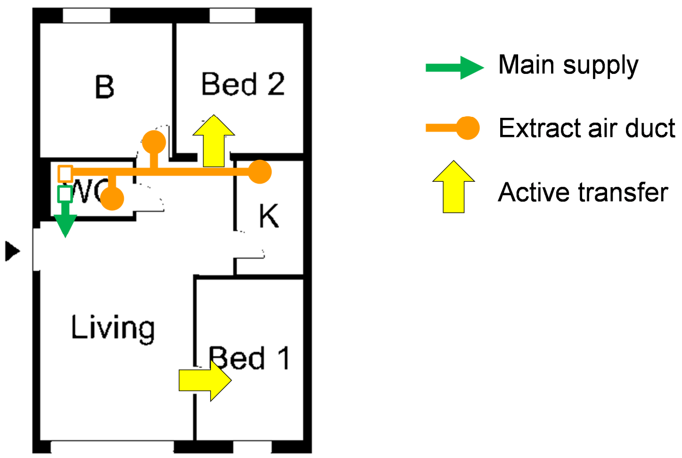
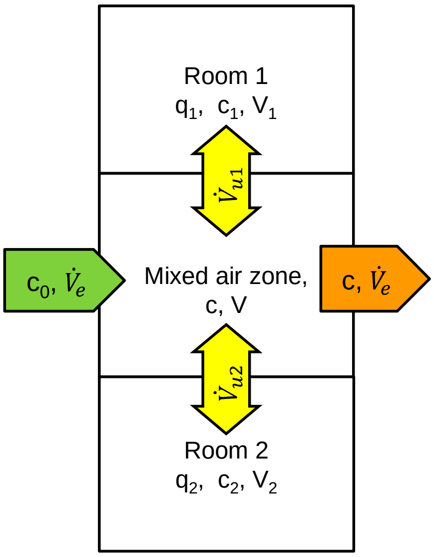


Figure 41: Typical Austrian housing situation used here as reference apartment.

The chosen apartment represents a typical Austrian housing situation. It is the same as the reference dwelling in (Rojas et al., 2015), in order to facilitate comparison.

2.1. Air quality

In a similar way to that in part 1, the reference apartment can be modelled with several zones in which the air is assumed as perfectly mixed, according to the results of (J. Schnieders, 2003) (see chapter 1, part .3.3.1). The surveyed zones of the model, flow paths and relevant physical parameters are illustrated in Figure 42.



q_1	CO_2 source in room 1 (two adults sleeping)
q_2	CO_2 source in room 2 (one child sleeping)
c	CO_2 concentration in mixed air room (living-room)
c_0	CO_2 concentration from outside air
c_1	CO_2 concentration in room 1
c_2	CO_2 concentration in room 2
$\dot{V}_{u1}$	air flow rate through active transfer to room 1
$\dot{V}_{u2}$	air flow rate through active transfer to room 2
$\dot{V}_e$	global air flow rate (supply or equally sum of extract)
V	air volume of the living-room
V_1	air volume of room 1
V_2	air volume of room 2

Figure 42: Model of a typical apartment in which the bedrooms are ventilated through active transfers (yellow double-arrows). The fresh air coming from the unit is brought in the living room (mixed air room) through a supply valve (green arrow). The air extracted through bathroom and kitchen, both connected to the mixed air room. The orange arrow symbolizes the sum of both extracts.

Infiltration or exfiltration to the outside are here neglected. Applying mass conservation law in the different rooms between time t and $t + \delta t$ lead to the following expressions:

In room 1 and 2:

$$m_{R1,2,CO2}(t+\delta t) = m_{R1,2,CO2}(t) + \dot{V}_{u1,2} \cdot \delta t \cdot \rho_{air} \cdot (c - c_{1,2}) + q_{1,2} \cdot \delta t \qquad (2.1)$$

With:

$m_{R1,2,CO2}(t+\delta t)$	mass of carbon dioxide in room 1 and 2 at time $t + \delta t$ [kg_{CO_2}]
$m_{R1,2,CO2}(t)$	mass of carbon dioxide in room 1 and 2 at time t [kg_{CO_2}]
$\dot{V}_{u,1,2}$	airflow rate through active transfer of room 1 and 2 [m^3/h]
ρ_{air}	density of air at 20 °C [kg_{air}/m^3]
$c_{1,2}$	carbon dioxide concentration in room 1 and 2 at time t [kg_{CO_2}/kg_{air}]
c	carbon dioxide concentration in room 1 and 2 at time t [kg_{CO_2}/kg_{air}]
$q_{1,2}$	source of carbon dioxide due to occupancy in room [kg_{CO_2}/h]

In the mixed air room:

$$m_{M,CO2}(t+\delta t) = m_{M,CO2}(t) + \left[\dot{V}_{u1} \cdot (c_1 - c) + \dot{V}_{u2} \cdot (c_2 - c) + \dot{V}_e \cdot (c_0 - c)\right] \cdot \delta t \cdot \rho_{air} \qquad (2.2)$$

With:

$m_{M,CO2}(t+\delta t)$ mass of carbon dioxide in room 1 at time $t+\delta t$ [kg_{CO_2}]

$m_{M,CO2}(t)$ mass of carbon dioxide in room 1 at time t [kg_{CO_2}]

$\dot{V}_e$ total supply and extract airflow rate in the apartment [m^3/h]

c_0 carbon dioxide concentration in the outside air [kg_{CO_2}/kg_{air}]

Considering the following relation between the air mass, air volume and CO_2 concentration:

$$m_{CO2} = c_{CO2} \cdot \rho_{air} \cdot V \qquad (2.3)$$

With:

m_{CO2} mass of carbon dioxide concentration in the room [kg_{CO_2}]

c_{CO2} carbon dioxide concentration in the room [kg_{CO_2}/kg_{air}]

ρ_{air} density of air in the room [kg_{air}/m^3]

V air volume of the room [m^3]

The progression overtime of carbon dioxide concentration in the mixed air room and in the bedrooms are described with the following system of differential equations:

$$\begin{cases} \dfrac{dc_1}{dt} = -\dfrac{\dot{V}_{u1}}{V_1} \cdot c_1 + \dfrac{\dot{V}_{u1}}{V_1} \cdot c + \dfrac{q_1}{V_1 \cdot \rho_{air}} \\ \dfrac{dc_2}{dt} = -\dfrac{\dot{V}_{u2}}{V_2} \cdot c_2 + \dfrac{\dot{V}_{u2}}{V_2} \cdot c + \dfrac{q_2}{V_2 \cdot \rho_{air}} \\ \dfrac{dc}{dt} = \dfrac{\dot{V}_{u1}}{V} \cdot (c_1 - c) + \dfrac{\dot{V}_{u2}}{V} \cdot (c_2 - c) + \dfrac{\dot{V}_e}{V} \cdot (c_0 - c) \end{cases} \qquad (2.4)$$

Thus the value of the concentration at steady state in each room is given by the equations:

$$c_{1,\infty} = c_0 + \frac{1}{\dot{V}_e \cdot \rho_{air}} \cdot [q_1 + q_2] + \frac{1}{\dot{V}_1 \cdot \rho_{air}} \cdot q_1 \qquad (2.5)$$

$$c_{2,\infty} = c_0 + \frac{1}{\dot{V}_e \cdot \rho_{air}} \cdot [q_1 + q_2] + \frac{1}{\dot{V}_2 \cdot \rho_{air}} \cdot q_2 \qquad (2.6)$$

$$c_{\infty} = c_0 + \frac{1}{\dot{V}_e \cdot \rho_{air}} \cdot [q_1 + q_2] \qquad (2.7)$$

With:

$c_{1,\infty}$	Final carbon dioxide concentration at steady state in room 1 [kg_{CO_2}/kg_{air}]
$c_{2,\infty}$	Final carbon dioxide concentration at steady state in room 2 [kg_{CO_2}/kg_{air}]
c_{∞}	Final carbon dioxide concentration at steady state in mixed air room [kg_{CO_2}/kg_{air}]

The following conclusions come from these expressions:

(1) Final carbon dioxide concentration in the bedrooms depends on two terms (beside the outside air concentration). The first one depends on global parameters (global airflow, sum of the sources). The second one depends on parameters of the zone (airflow rate through active transfer, source in the zone).

(2) The expression of the first term shows that carbon concentration in the room increases with higher total sources (q_1 and q_2) and lower global airflow rate, $\dot{V}_e$.

(3) The expression of the second term shows that carbon dioxide concentration in the room increases with lower airflow rate through the active transfer and with higher CO_2 source in the room.

(4) In case of high airflow rate through active transfer $\dot{V}_1$ and $\dot{V}_2 \gg \dot{V}_e$ the concentration in the room almost only depends on the first term of the equation, which means it only depends on the global parameter (sum of the loads, $q_1 + q_2$ and global airflow rate, $\dot{V}_e$).

(5) In case of high airflow rate through active transfer $\dot{V}_1$ and $\dot{V}_2 \gg \dot{V}_e$, the concentration tends to be the same in every room and equal to the final concentration in mixed air room. The air is almost perfectly mixed between the zones.

Numerical solutions to the system of differential equations can be found with the help of a Matlab script. Left side of Figure 43 illustrates the progression over time of carbon dioxide concentration in each room for an airflow rate through the active transfers at 55 m^3/h. On the right side the results are illustrated in case of high flow rate through the active transfers (500 m^3/h) which approximately correspond the situation when doors are open. In both cases, the global airflow rate is constant and set at a value of 120 m^3/h. The results confirm previous observations. On the left, side, the concentration in room 1 is higher because of higher CO_2 sources, which confirms the observation (3).

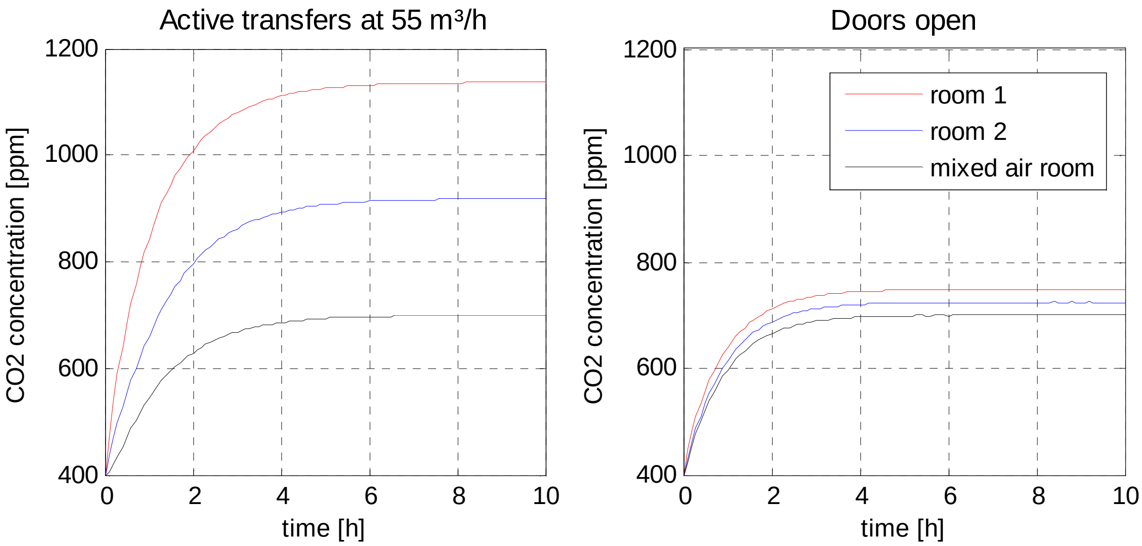


Figure 43: Numerical solutions of the system of differential equations for active transfers at 55 m³/h (on the left) and for a very high mixing between the zones (on the right), which approximately corresponds to the situation with open doors.

Systems with this typical $e^{-t/\tau}$ behaviour reach approx. 95 % of the final value after 3 times the time constant τ of the system. Several other tests show that the time constant depends on the global airflow and on the flow through the active transfers. Under typical conditions, the time constant varies between 1h (high airflow rates) and 2h (low airflow rate). It means that most of the time, 95% of steady state will be reached after a period from 3 to 6 hours.
We also observe that the concentration in the rooms at steady state decreases with higher airflow through the active transfers and tend to be the same in every room (right side of Figure 42), which confirms observation (2) and (5).

With this concept, air mixing between the rooms in the apartment should be maximized in order to improve global air quality. This can be achieved either when internal doors are left open or with increased airflow rate through the active transfers.

2.2. Air humidity and numerical model

The behaviour of air humidity it is a significant indicator for healthy and comfortable indoor air climate and must be also surveyed in apartments ventilated with active transfer concept.
The analytical method gave a first overview of the influencing factors on the dissemination of carbon dioxide source with constant sources. Though, the analytical model becomes very complex when the sources vary in time (occupant daily schedule) and include absorption behaviour, like it is the case for humidity.
In order to survey both factors simultaneously, the typical housing situation was modelled in CONTAM (NIST). This model was built on the basis of the validated CONTAM model in (Rojas-Kopeinig, Sibille, et al., 2012), with the same contaminant sources, distribution patterns and air-flow paths (see details in chapter 1, part 3.5). Each room of the apartment is represented with one zone of the model in which the air is assumed perfectly mixed. This

assumption relies on the results of (J. Schnieders, 2003) (see chapter 1, part 3.3). Figure 44 illustrates the selected floor plan and it model in CONTAM.

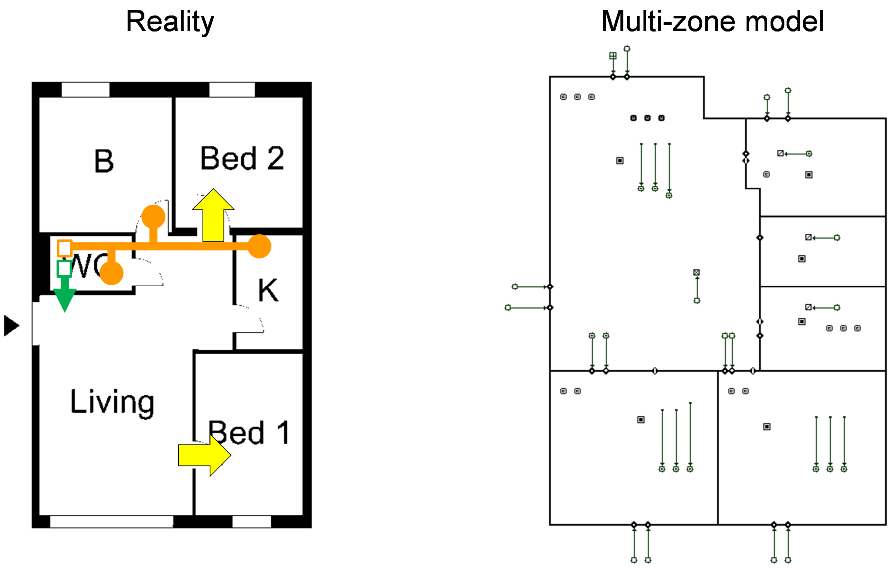


Figure 44: Floor plan and multi-zone model in CONTAM with ventilation concept with active transfers.

The active transfers were modelled as a flow path with constant volume flow. Simulations were performed over winter time (from 1st of December to 28th February), because it is the critical period concerning the risk of air dryness in the rooms. The simulations assumed standard occupancy pattern of a household with two adults and one child, as described in part 1.

Simulations were performed for varying global airflow rate $\dot{V}_e$ and fixed airflow rate through the active transfers at 70m³/h as well as in case of open doors.

Carbon dioxide concentration and humidity rate were evaluated in each bedroom and in the living room by occupancy according to the method related in part 1, using relative under- or overstepping of the target value (concentration over the target value of 1000 ppm for CO_2 and relative humidity under the target value of 30%).

The red line on Figure 45 shows the progression of the mean value of relative overstepping of the target value of the CO_2 concentrations in the different rooms by varying global supply airflow rate in the vestibule. The blue line represents the progression of the mean value of relative understepping of the target value relative humidity in the bedrooms and living room by varying global supply airflow rate in the vestibule. In black the sum of both values is represented. This value can be interpreted as the overstepping of the quality threshold of the indoor climate in the apartment by occupancy. The lower this indicator, the better the indoor is climate.

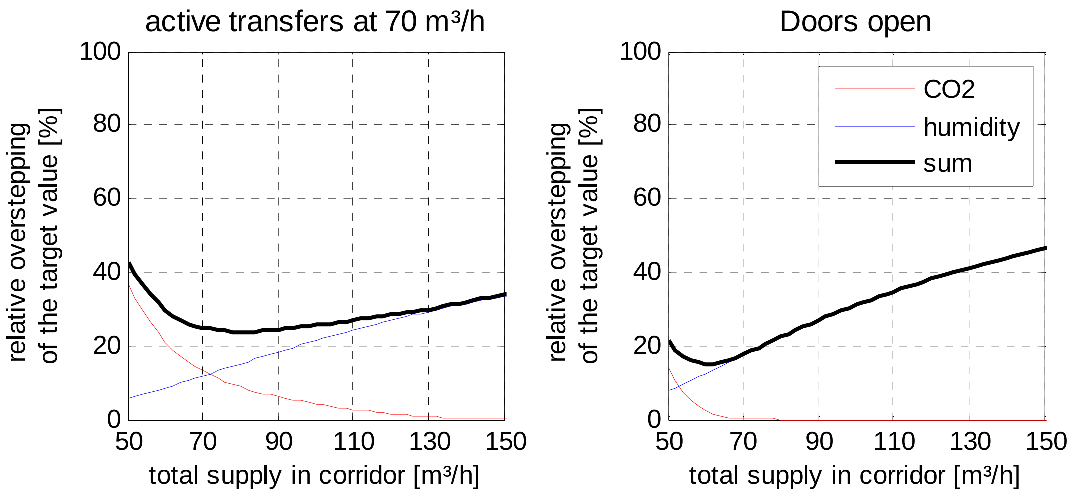


Figure 45: Relative deviation of the target values of carbon dioxide (1000 ppm) and humidity (30% relative humidity), as well as their sum in case of active transfers at 70 m³/h (left) and with open door (right) for varying global supply airflow rate in the vestibule.

On both diagrams, a minimum of this indicator can be observed. This minimum represents an optimum (or a compromise) between the air quality described by CO_2 concentration and air humidity. When doors are closed and active transfers operate at 70 m³/h, this minimum happens for a global airflow rate at approx. 80 m³/h. In case of open doors (the active transfers are switched off), this optimum takes places for a global supply airflow rate at approx. 60 m³/h. These observations lead to the following remarks:

(1) In case of open doors, the optimum at 60 m³/h confirms the results of (Rojas et al., 2015) for which the simulations were made on the basis of the same numerical model in CONTAM and assumptions.

(2) The range of optimal global airflow rate in case of open doors (60 m³/h) is very narrow, whereas in case of active transfers at 70 m³/h the optimal global airflow can vary ± 20 m³/h from 80 m³/h, without significant deterioration of the indoor climate. This is because the most significant humidity sources in the bedrooms and living room by occupancy are the occupants themselves. In case of closed doors (even with active transfers) a lot of humidity remains in the room. Thus the curve representing the relative lower deviation of humidity target value is less steep in case of ventilation with active transfers; thus the optimum range is thus wider.

(3) The optimal supply global airflow rate is higher in case of ventilation with active transfer than in case of open doors. This means that the lack of air mixing between the zones must be balanced by higher global airflow rate.

(4) The value of the sum of the relative overstepping of the target values (black line) at the optimal airflow rate is higher in case of ventilation with active transfers than in case of open doors. This means that in the case of ventilation with active transfers, the indoor air climate is globally worse than in the case with open doors. This is because the worse air quality due to less air mixing is balanced by higher global airflow rate which leads to dryer indoor air in winter. Even if a “compromise” can be found, it isn’t as satisfying as the case with open doors.

As a conclusion, the higher the airflow rate through the active transfer, the lower the global supply airflow rate in the mixed air room can be set. At the same time, keeping a low global airflow rate leads to better humidity rates in winter. Thus high performant products are needed for the active transfers,

The quality of indoor climate thus depends on the performance of the selected product for the active transfer. The next chapter focuses on the factors that influence the performance of a product and its acceptance from the occupant.

3. Product development

The previous chapter showed how significant the performance of active transfer is related to the indoor climate of the apartment. As mentioned in the introduction, some products are already available on the market; their performances vary between 60 and 70 m^3/h. In the frame of the European Union funded project “Sinfonia” (Smart INitiative of cities Fully cOmmitted to iNvest In Advanced large-scaled energy solutions) where more than 60 000 m^2 of social residential areas are being refurbished to a high level of energy performance, solutions are needed for the integration of the ventilation systems. The concept of ventilation with active transfers is thus an attractive alternative to traditional cascade ventilation. This context contributed to start the development of a product adapted to refurbishment with minimal installation work. This first development phase is based on the creation of a prototype. Measurements were made on this prototype in order to define the parameters that influence the performances of the product, including acoustic comfort and improved integration.

3.1. Product development

In the refurbishment project “Sinfonia” mentioned before, the apartments stay habited during the renovation operations. Thus the installation work like the drilling in the walls should be minimal. Particularly, some internal walls are load-bearing, which would require core drilling and produce much dirt and costs.
Thus, a solution for a product that can be integrated directly into the existing door without any drilling work was developed. A prototype was created based on the sketches in Figure 46 and fFigure 47 together with the company Pichler-Luft (J- PICHLER Gesellschaft m.b.h., Klagenfurt, A).

Figure 46: Sketch of the concept of active transfer integrated directly into the door.

Figure 46 shows the concept of the product that can be directly integrated into the existing door. The only work at the building site consists in cutting a slit at the top of the existing door to integrate the device and a door gap at the bottom to allow backflow.

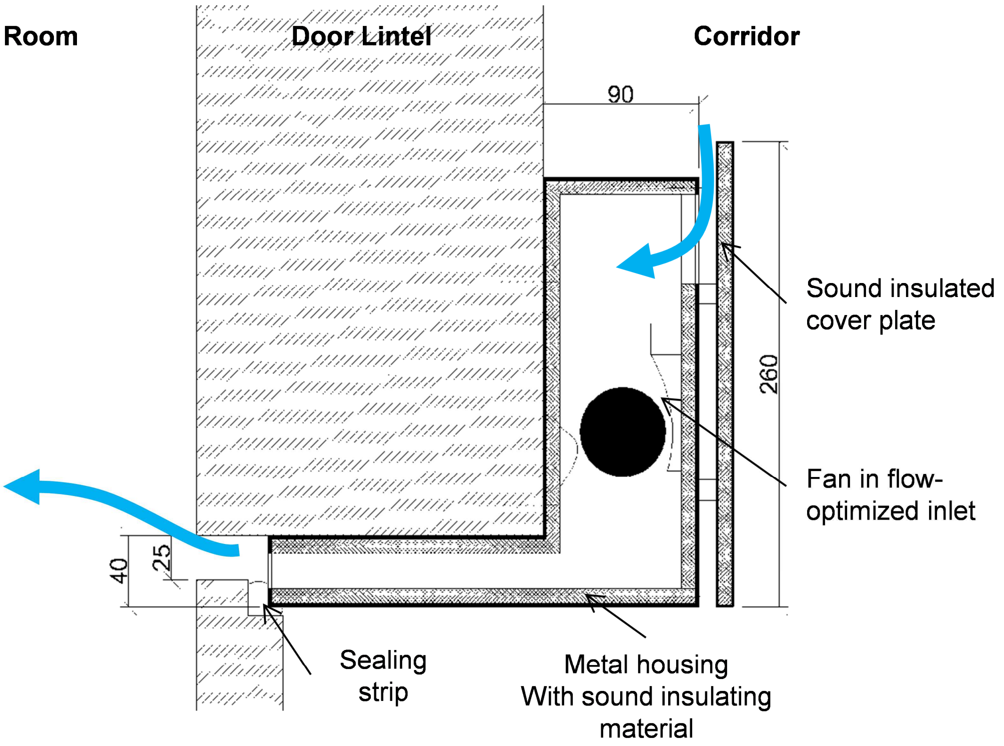


Figure 47: Sketch of a section through the prototype (adapted from prototype sketch from Pichler).

The prototype was installed into the door of a sample apartment from the real estate developer Neue Heimat Tirol (NHT Gemeinnützige Wohnbau Gmbh, Innsbruck, A), which was especially allocated for the measurements of the prototype. The pictures below show the prototype and the view from test room after installation.

Figure 48: Photographs of the prototype of active transfer (left). View from the room with the outlet of the active transfer (right)

The prototype was mounted on the door lintel in the vestibule and connected to electricity. In order to prevent any air short cut or sound transmission between the corridor and the room, the top of the door was covered with a sealing strip, as illustrated in Figure 47.

3.2. Measured performances

The performance of the prototype was measured on site. The airflow rate by several control voltages were measured four times each at the outlet. At the same time, the electric current and voltage for the running of the fan motor was measured in order to calculate the electric power consumption of the fan. The mean values of the measured performances are summarized in Table 8:

Control voltage	V	11	12	13	14	15
Airflow rate	m³/h	31	37	44	51	55
Electric power	W	0.99	1.2	1.3	1.54	1.8

Table 8: Measured performances of the prototype installed in the living room of the sample apartment.

The sound level in the room was also measured for different levels of control voltages. The sound level was measured at different points of the room. The resulting average sound levels were then A-weighted and the correction due to external noise according to (International Organization of Standardization, 2004) has been made. The measured reverberation time in the room was relatively high (average 1,4 s) because the room was completely empty of furniture. Thus the sound level values were evaluated for a reverberation time of 0,5 s which is a standard value for a bedroom or a living room with furniture.

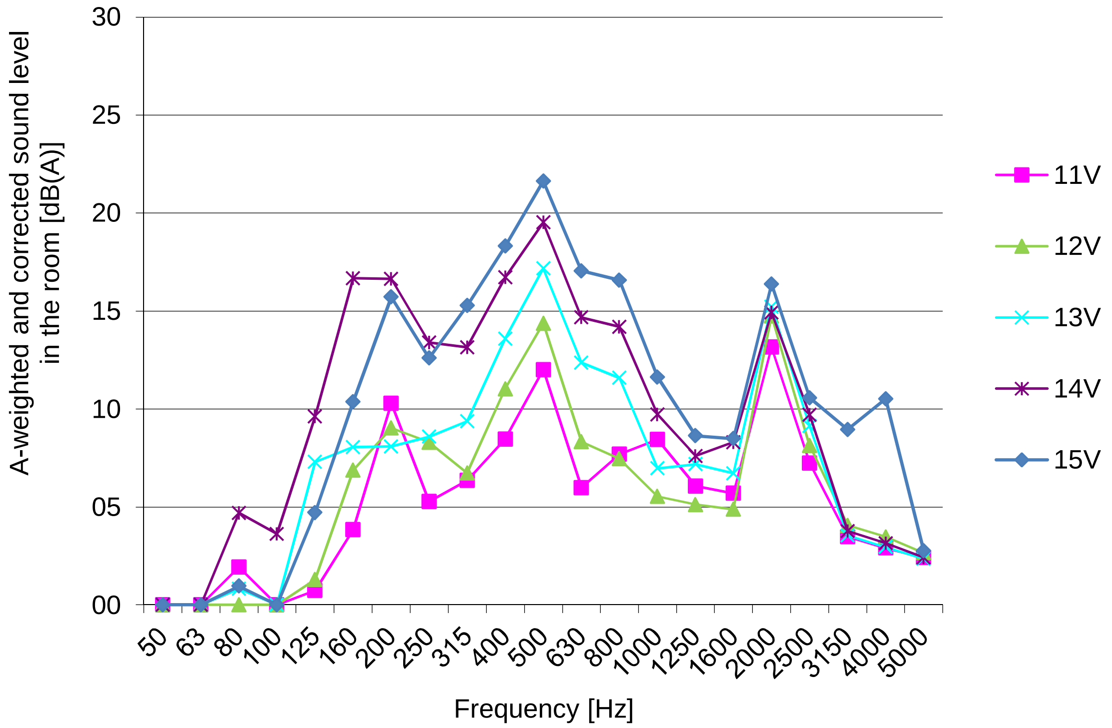


Figure 49: A-weighted and corrected (external noise and reverberation time) of sound level in the room for different values of control voltage

On Figure 49, two peaks, at 500 Hz and at 2000 Hz can be observed. Since this the intensity of the first peak (at 500 Hz) increases with the control voltage and thus with the airflow rate, it can be interpreted as an airflow noise. On the contrary, the intensity of peak at 2000 Hz is almost independent of the airflow. This noise is thus likely due to the vibrations of the structure which are transmitted to the room.

The average of all frequencies of the sound level in the room depending on the measured airflow rate are represented in Figure 50.

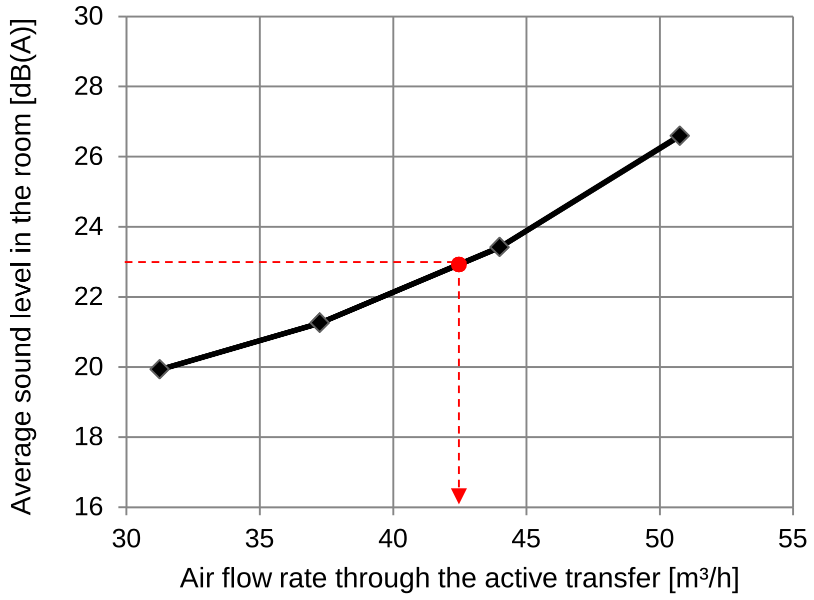


Figure 50: Graphic representation of the measured values of the sound level in the room (averaged, A-weighted and corrected) at different measured airflow rates.

According to the German standards, the sound level in a bedroom or living room in a ventilated apartment should not exceed 25 dB(A) (DIN 4109:1989-11, 1989). However, in order to ensure the acceptance of the occupant, a sound level in the room below 23 dB(A) is recommended (Greml, 2014). The diagram shows that, in this case, the active transfer should operate at max. 42 m³/h, in order to ensure the occupant comfort.
Designing the apartment with this product requires high global airflow rate to balance the lower flow rate of the active transfer. This means that the risk of air dryness in winter is relatively high and the global comfort to the occupant is worse than possible. The following chapter surveys optimization paths.

3.3. Optimizations and outlook

3.3.1. Optimizations paths

The optimization should target higher airflow rate through the fan and at the same time lower sound emissions into the room. A possibility to reduce the sound intensity peak at 500 Hz observed in Figure 49 would be for example to change the type of fan, from cross flow fan to an axial fan. They are generally quieter and would produce less noise related to airflow. The reduction of the intensity of the second peak at 2000 Hz can be achieved by improved integration that diminishes the propagation of vibrations. If axial fans are used, a variant of the product integrated into the wall could be also attractive. Indeed, according to the experience of several craft people, a drilled hole with diameter up to 150 mm can be easily made in an existing wall.

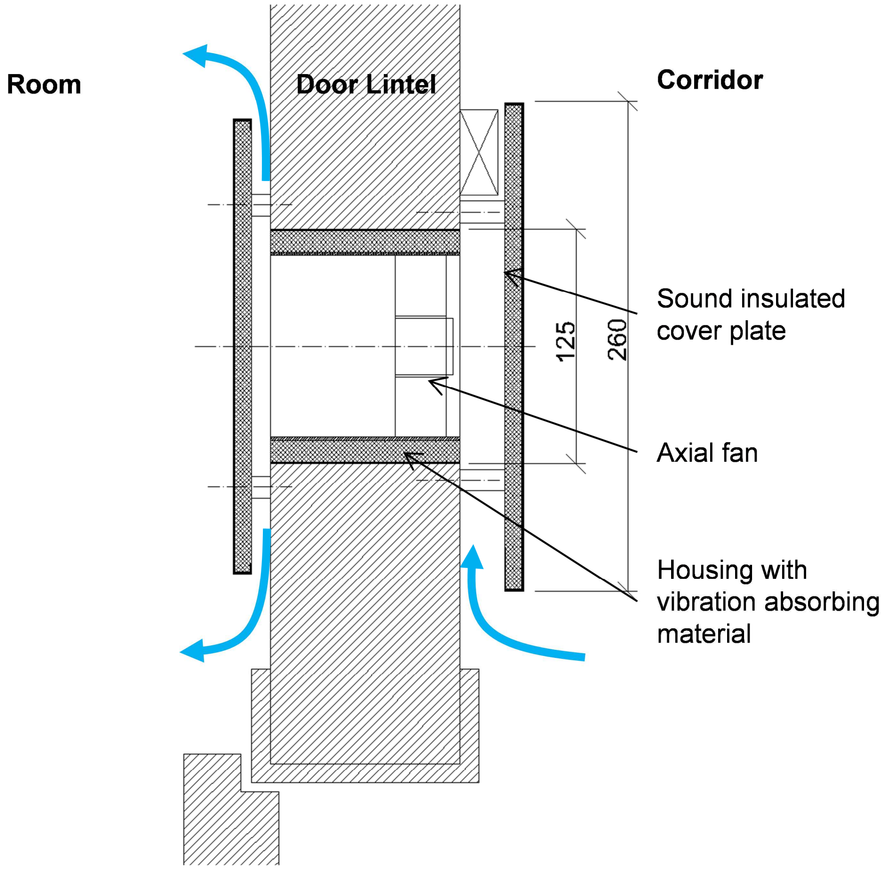


Figure 51: Sketch of a product with axial fans and simple integration in the door lintel.

In this case, two axial fans could be installed instead of the cross flow fan. The installation into the wall would also allow easily the attenuations of the vibrations from the fan to the room. Additional cover plates cover plates at the outlet (on room side) would also attenuate flow noise.

3.3.2. Passive backflow

The designed product does not integrate passive backflow possibility to the vestibule. Thus, the airflows back through the door gap, which must be consequently adapted. (Rojas-Kopeinig, Rothbacher, et al., 2012) recommends a pressure drop of max. 3 Pa for the overflow elements, in order minimize the risk of exfiltration due to overpressure in the room.
Based on the results of this study, Figure 52 compares the pressure drop through different door gaps (5mm to 15 mm) for a varying overflow air rates.

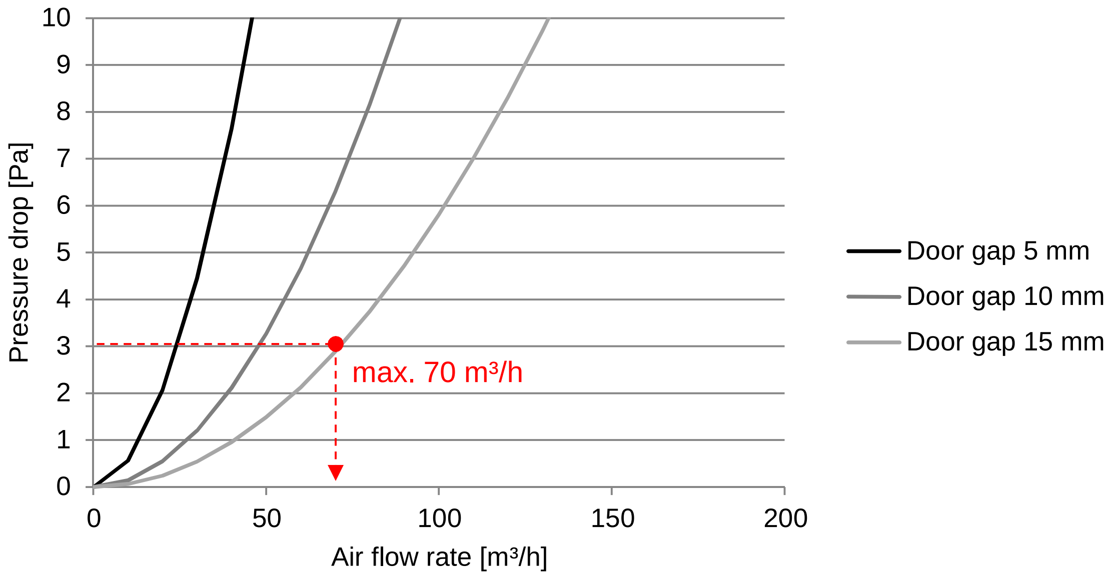


Figure 52: Pressure drop depending on airflow rate for a 85 cm-wide door with several heights of the bottom gap.

According to this diagram, an airflow rate of 42 m³/h through the active transfer (as recommended for the surveyed prototype in previous paragraph) would require a door gap of 10 mm. The diagram shows also that the maximum airflow rate for a pressure drop of 3 Pa with a door gap of 15 mm is 70 m³/h. Higher flow rates would lead to higher pressure drops and increase risk of exfiltration. Increasing the height of door gap would indeed reduce the pressure drop, but would be barely accepted by the user for aesthetic and comfort reasons (light and sound transmission).

Thus, for a ventilation concept with active transfers where the backflow occurs through door gap only, the airflow rate through the overflow should be limited at a value of 70 m³/h and a minimum door gap of 15 mm must be created. This result leads to the conclusion that the products in which the backflow is already integrated, and designed for the nominal flow through the active part, are preferable.

Indeed the cutting of the door gap is often not realized in practice because the information is rarely transmitted from the ventilation designer to the carpenter.

3.3.3. Outlook

In (Gilliand, 2015) the installation of high-efficiency ECM fans for the distribution of the air and heat into a passive house is reported. A split unit placed in the living room is used for air heating and cooling, additionally to the ventilation unit. The air is distributed into the rooms using a high-efficiency fan and ducts, delivering a flow of 200 m³/h. This concept adapted to a typical European apartment floor plan is illustrated in Figure 53.

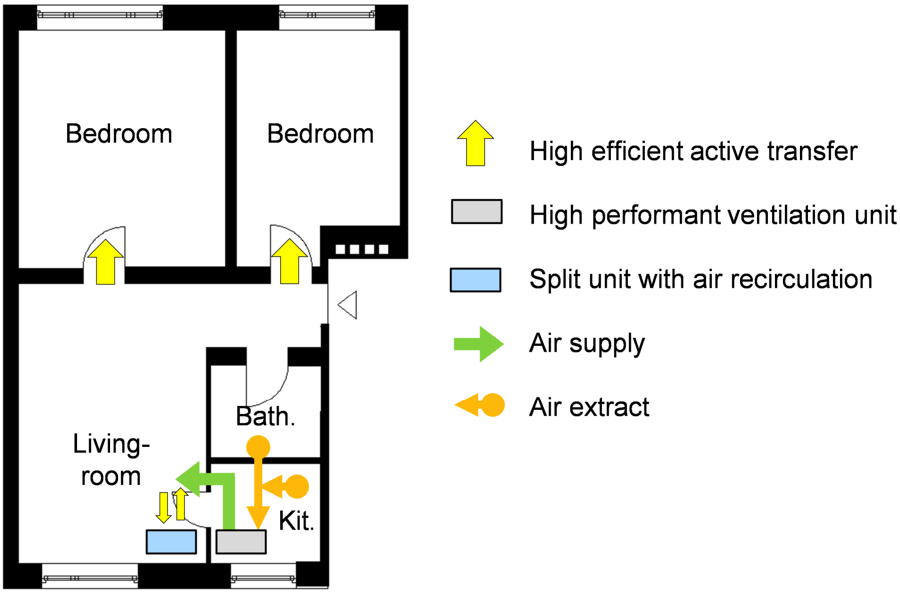


Figure 53: Schematic illustration of a ventilation, heating and cooling concept, using high-efficiency active transfers for distribution.

The development of an adapted product that achieves this range of airflow rate by tolerable acoustic comfort and simple installation would be very interesting.
Indeed, the required airflow rate through an active transfer between a living room and a bedroom to cover the heating load of the bedroom in a passive house (10W/m²) can be calculated as follows:

$$\dot{V} = P \cdot A \cdot \frac{1}{\Delta T} \cdot \frac{1}{c_p \cdot \rho_{air}} \qquad (2.8)$$

With:

P	heat load of the bedroom in a passive house 10 W/m²
A	area of a typical bedroom: 12 m²
ΔT	temperature difference between the living room and the bedroom: 2°C
c_p	specific heat capacity of the air: 0,27Wh/(kg.K)
ρ_{air}	density of air: 1,2 kg/m³

The resulting required air volume is:

$$\dot{V} = 176 \text{ m}^3/\text{h} \qquad (2.9)$$

Further development should thus target products that can transfer 180 m³/h while keeping the sound level in the room under 23 dB(A), and which can still be easily installed in a(n) (existing) wall. This way, active transfers can be used for the distribution of both fresh air and heating (or cooling) loads in the rooms of an apartment, and thus reduce dramatically the installation costs.

4. Numerical model and validation

Beside the performances of the prototype, measurements of carbon dioxide concentration in the rooms of the apartment were performed in order to validate the numerical model used for the simulations in part 1. Particularly, the validation of the two following assumptions is at stake:

- Assumption of well-mixed zones. In the theoretical model, the assumption of well-mixed zones is made. This assumption is based on the results of several studies for similar cases, (Jürgen Schnieders, 2003) and (Rojas & Pfluger, 2014). Though a validation in this particular case is preferable for further prognostics, based on this theoretical model.
- Assumption of the model for the active transfer. The CONTAM model "constant forced volume flow" was undertaken to model the flow path between the mixed air room and the bedroom with active transfer.

4.1. Measurements installation and results

The measurements were made between two rooms of the sample apartment, as described in Figure 54. A constant and defined source of carbon dioxide was set in the test room, simulating the presence of an occupant. Fresh air is supplied into the vestibule (mixed air zone) through a fan with defined constant airflow rate installed on the top of the entrance door. The door between the mixed air zone and test room is closed, the test room is thus only ventilated through the active transfer, which is installed in the door, as described in part 3.1. The air is extracted from the mixed air room with the same airflow rate as the supply (balance in the apartment) through a fan and duct leading to the outside.

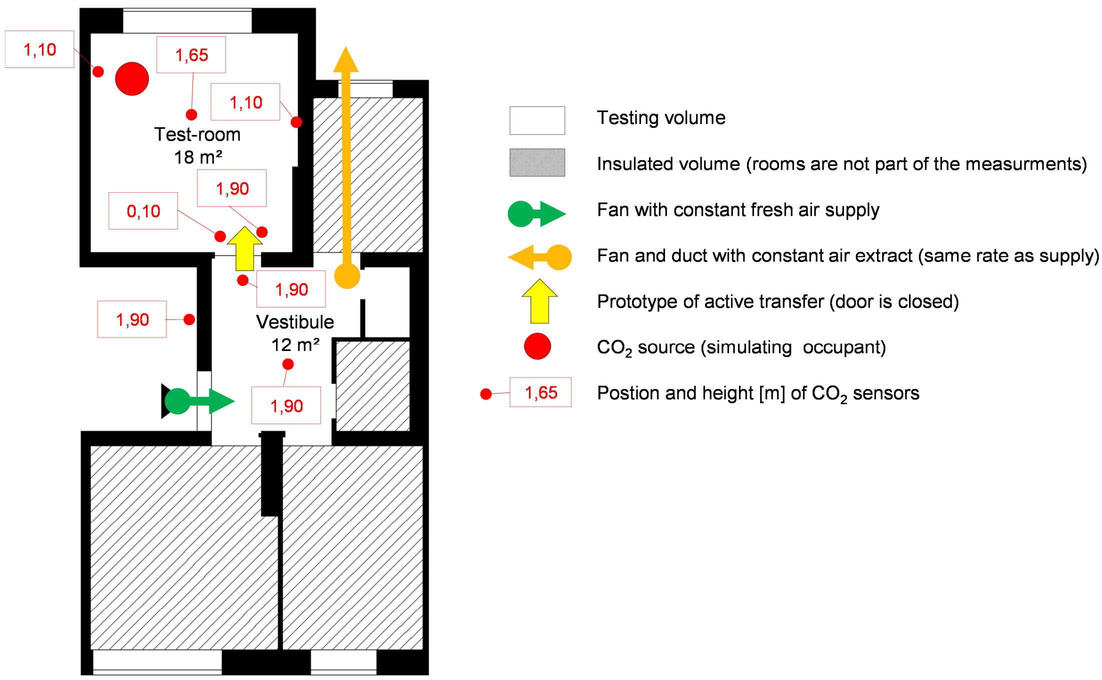


Figure 54: Test installation in for the measurement of the prototype. Experiment made with two fans without heat recovery (this is not a recommended installation for an energy efficient solution).

The behavior of carbon dioxide concentration in the test room and in the vestibule (mixed air room) was recorded at several positions in the apartment with the help of CO_2 sensors. The measurements were made to simulate several occupancy scenarios and settings of the active transfers. Doors and windows always stayed closed. The supply and return of mixed air zone stayed constant. Four scenarios were tested:

(1) CO_2 source at 0,3 L/min (one adult sleeping) in test room and active transfer off
(2) CO_2 source at 0,3 L/min in test room and active transfer operates at 55 m³/h
(3) CO_2 source at 0,65 L/min in test room and active transfer operates at 55 m³/h
(4) CO_2 source at 0,60 L/min in test room and active transfer operates at 31 m³/h

The progressions of carbon dioxide concentration in the several rooms over time for the four scenarios are illustrated in the diagrams below:

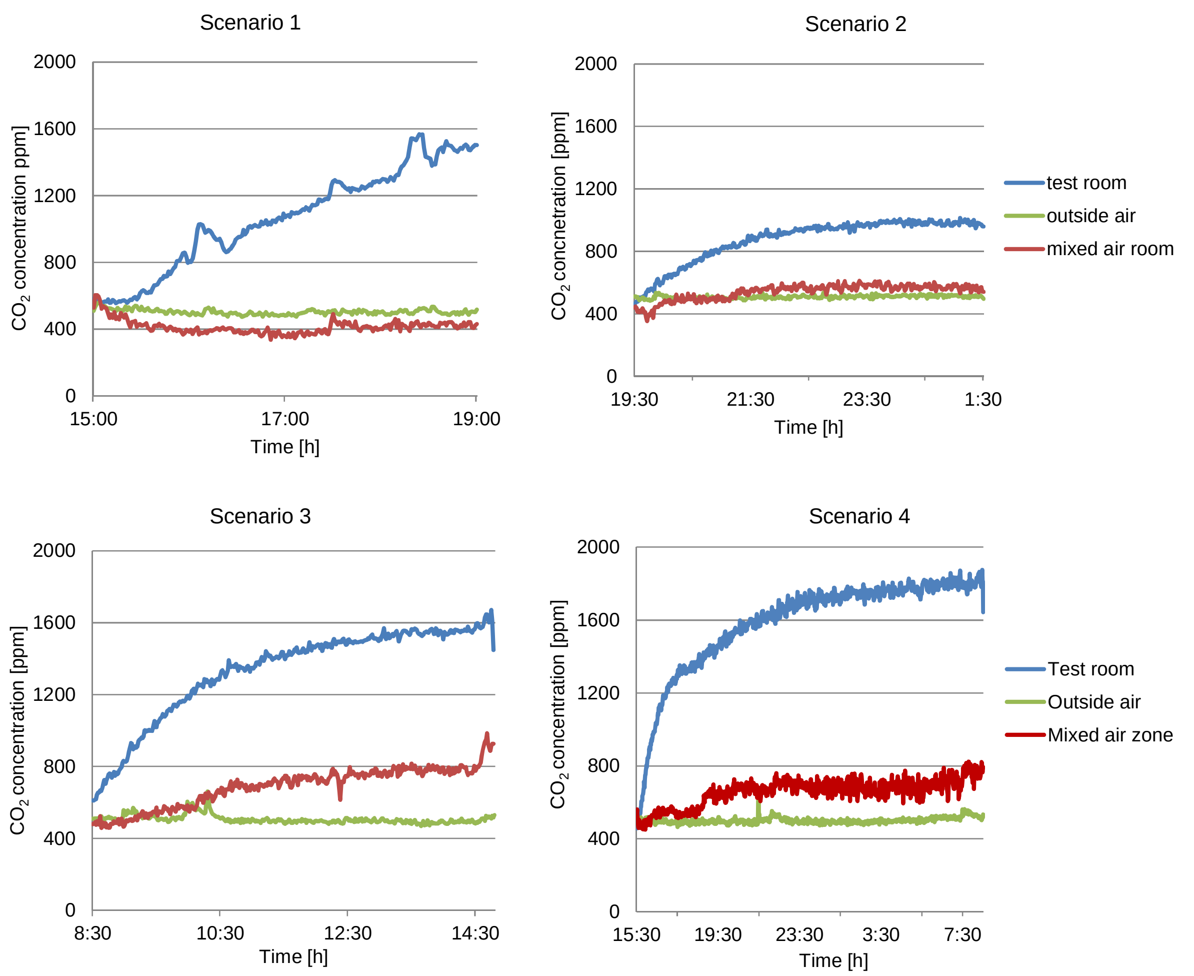


Figure 55: Progression of carbon dioxide concentration in the various zones (average of the measured points) for the four scenarios.

The almost linear raise of carbon dioxide concentration in the test room and stagnant concentration in the mixed air room in scenario 1 confirms that if the active transfer is off and the door is closed, there is almost no air transfer between the mixed air room and the test room. In this case, the test room is not properly ventilated. The CO_2 source has been set to the exhaling rate of one adult in the test room. After only four hours (half of a night period) carbon dioxide concentration has increased of more than 1000 ppm which is above tolerable threshold of IDA 4 according to (DIN EN 13779:2007-09, 2005). This result highlights the necessity of the active transfer to ensure ventilation of the bedrooms when no direct air supply is installed in the room.

The rising of carbon dioxide concentration in mixed air room and test room in scenario (2), (3) and (4) reveal the typical $e^{-t/\tau}$ behavior that has already been observed in the theoretical part of part 2.1 of this chapter. In scenario (2) and (3), the concentration in the test room reaches steady state condition after about 4 hours. The results also confirm that the concentration at “steady state” depends on the intensity of the sources. In scenario (4), carbon dioxide concentration increases very fast in the first two hours, which is understandable due to the high sources and low airflow through the active transfer. Though after two hours, the rise seems interrupted and becomes weaker even if a steady state also takes place afterwards. This break is probably due to an involuntary opening of the door between the test room and the mixed air room. Indeed, the concentration in the mixed air room also rises suddenly at this moment.

4.2. Validation of flow path model

In order to validate the model of the active transfer in the CONTAM model, the difference of carbon dioxide concentration between the test room and the mixed air room was calculated at each time step for the measurements and the simulation for the scenarios (2) and (3) as well as for the two first hours of scenario (4).

The results are presented in the diagrams below:

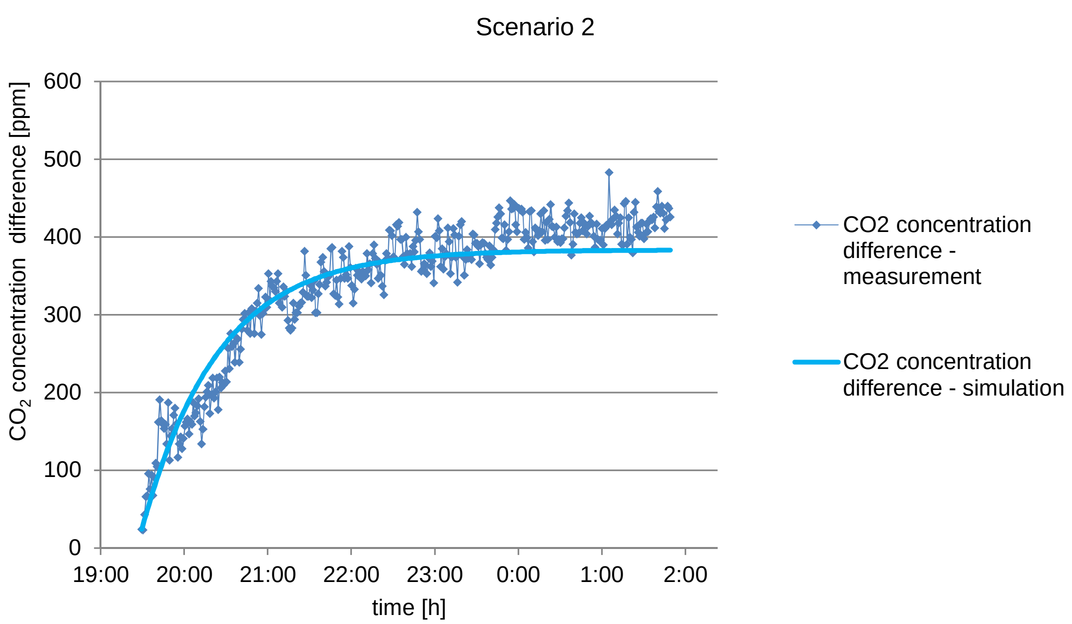


Figure 56: comparison between measurement and simulation for scenario 2.

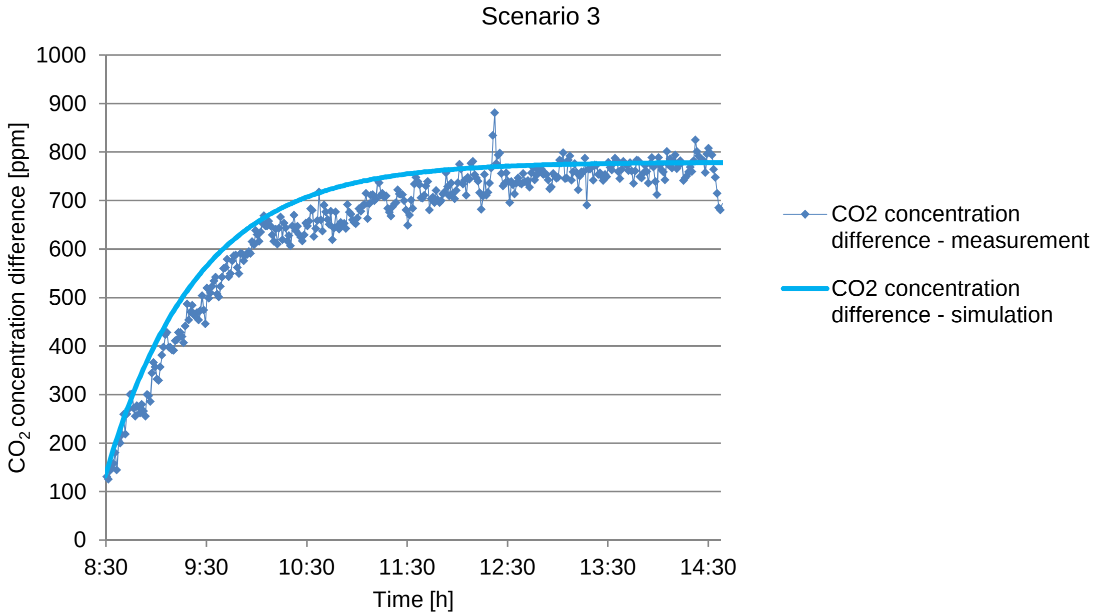


Figure 57: comparison between measurement and simulation for scenario 3.

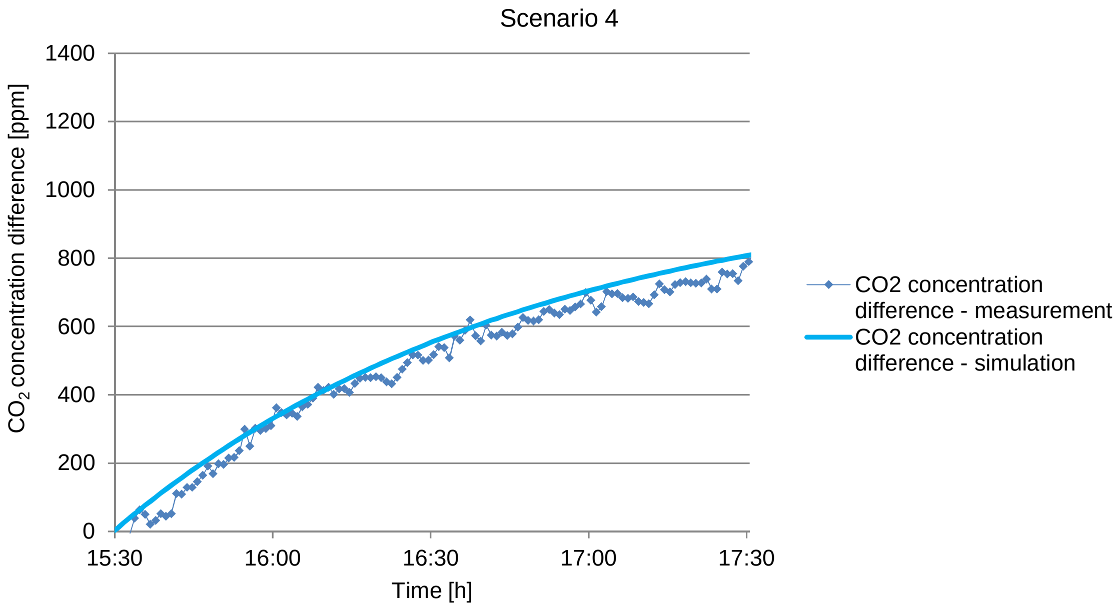


Figure 58: comparison between measurement and simulation for scenario 4.

The best matching for the three scenarios were found for a correction of the airflow rate of the active transfer of -10% of the measured value by 55 m³/h and of +10% of the measured value by 31 m³/h. This difference is probably due to imprecision by measurement technique of the airflow rate. For the scenario 4, no correction was made.

Nevertheless, the good correlation between the measurement and the simulation results lead to the conclusion that the used flow path model for the simulation of the active transfer in CONTAM is valid.

4.3. Validation of the assumption of well mixed zones

In order to evaluate how good the air mixing is inside the zones, a method based on the calculation of contaminant removal effectiveness is suggested here, based on the definition in(David & Mats, 1996).
Contaminant removal efficiency in a ventilated room with supply and extract air valve is defined as the ratio:

$$\varepsilon = \frac{CO_{2,EXH} - CO_{2,SUP}}{CO_{2,Occup} - CO_{2,SUP}} \cdot 100\ \% \qquad (2.10)$$

With:

$CO_{2,EXH}$ carbon dioxide concentration at the extract valve [ppm]

$CO_{2,SUP}$ carbon dioxide concentration at the supply valve [ppm]

$CO_{2,Occup}$ mean carbon dioxide concentration in the room [ppm]

According to this definition, average room concentration with complete mixing, $CO_2\ Occup$ is equal to (or less than) the concentration at the extract $CO_{2,EXH}$, and thus the efficiency, ε is equal or higher than 100%. In case of stagnation of the contaminant or of short-cut between the supply and the extract, the average concentration in the room ($CO_{2,Occup}$), is greater than the extract concentration, $CO_2\ EXH$ and thus the efficiency, ε is lower than 100%.
Contaminant removal efficiency was calculated for scenario 2 and 3 in the test room at almost steady state, 4 hours after the beginning of the measurement. The results are summarized in the table below:

	Average concentration in the room at almost steady state	Average standard deviation of the concentration	Contaminant removal efficiency
Scenario 2	954 ppm	12 ppm	119 %
Scenario 3	1509 ppm	32 ppm	109 %

Table 9: Summary of the measurement results for the average CO_2 concentration at steady state and for the contaminant removal efficiency in the test room.

The low values of standard deviation confirm that the period of 4 hours is a good approximation for steady state (concentration is almost constant). For both scenarios contaminant removal efficiency is higher than 100 %. This result confirms the assumption that the concentration is uniform in the test room.

The measurements of the prototype in the sample apartment confirmed the results coming out of the numerical model in CONTAM. The rest of the model (flow paths, sources etc.) has already been validated through numerous measurements in (Pfluger, Sibille, et al., 2013). Also the assumption of well-mixed zones has been validated again in the test room which is large enough to represent a bedroom or a living room.

These results confirm that the numerical model has been validated for the calculation of further prognostics for ventilation with active transfers.

5. Planning guidelines

Since the numerical model has been validated, it is possible to use it to make some prognostics about the adaptability of the ventilation concept with active transfer to different floor plans configuration or size. The use of simulation aims also at establishing a guideline to planers in order to help them designing this concept in the practice

5.1. Influence of floor plan configurations on the performances

The first step in the design of a ventilation concept with active transfers is the choice of the mixed air zone where the global supply air valve is installed. This zone should be chosen central to the apartment, with ideally only direct connections to the other rooms. This means that the mixed air zone will be most of the time a corridor or the living room.
Floor plan configurations that present a central corridor or a central living space are thus particularly well adapted to this ventilation type (Figure 59).

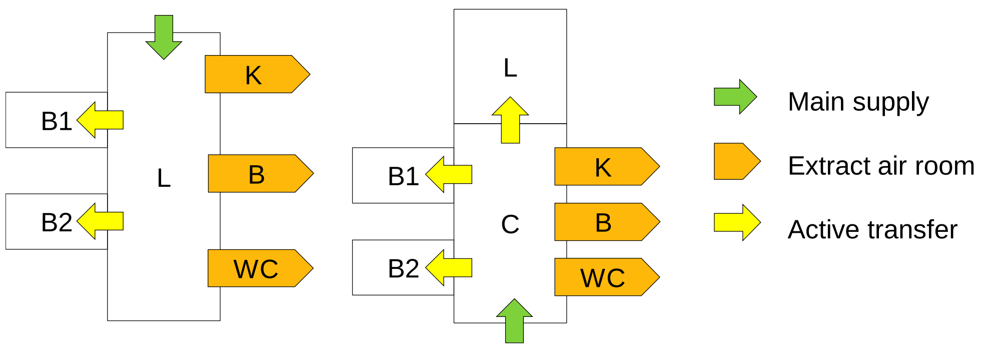


Figure 59: Two types of floor plans, well-adapted to ventilation concept with active transfers.

On the contrary, the floor plan configurations where the bedrooms and the extract air rooms are partially connected to the corridor and to the separated living room can be more problematic. Indeed, for these configurations two issues become apparent and may complicate the planning and realization of the concept:

- In some cases, the ventilation of some spaces may not be ensured as illustrated below:

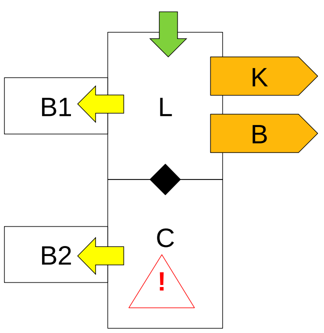


Figure 60: Floor plan configuration for which sufficient ventilation of the child's room (C) can be an issue

In this case, the control of the active transfer of the child's room must be thought out. Indeed, most of the time, the active transfer switches off automatically when the door is open (to save energy –see paragraph 3). Though here, assuming a child playing in his room with open door, but the separation door between the living space and the corridor stay closed, then the space formed by child's room and corridor may not be sufficiently ventilated. To prevent this situation, one possibility is to let the active transfer of child's room always on. If the configuration allows for it, the active transfer can also be placed, integrated into the wall between living room and child's room.

- In order to ensure good operation in the case where the active transfer is not directly connected to the mixed air room, the separating door should be designed to ensure optimal overflow. Indeed, high pressure drop at this place would impair the performance of the fans of the active transfers, and thus the air quality in the rooms.

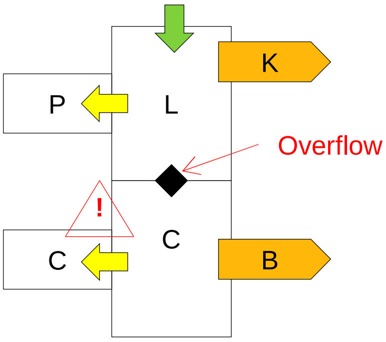


Figure 61: Floor plan configuration where the overflow between vestibule and living room should be well-designed to ensure the performance of the active transfer in the child's room.

The floor plan configurations where the kitchen is integrated into the living room are also problematic, because kitchen odors and contaminants may disseminate into the whole apartment due to the mixing caused by the active transfers (even if the bedroom doors are closed).

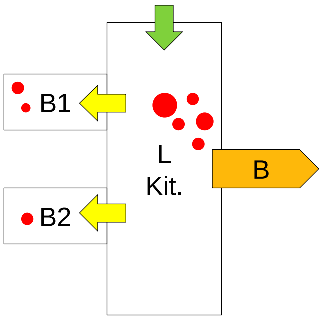


Figure 62: Example of configuration with kitchen integrated into the mixed-air room (living room). The active transfers support the dissemination of kitchen odors and contaminants into the bedrooms. An adapted control must be set to prevent this.

To prevent this effect, an adapted control system must be planed. For example the active transfers can automatically switch off when the kitchen hood is switched on and remain off one hour after the hood is off, so that the contaminants are evacuated from the mixed air room before the mixing with the bedroom occurs.

As a conclusion, the ventilation concept with active transfers can be applied to any type of floor plan. However, for some of them, special attention must be paid to the overflows and the control strategy of the active transfers.

5.2. Guidelines for the design

The following paragraphs describe two design strategies for the planning of ventilation with active transfers based on simulation results. Eventually, these results can be used by planners as a guideline.

5.2.1. Design with fixed airflow rates

A low-tech possibility to design the ventilation of an apartment consists in fixing the airflow through the active transfers as well as the global airflow rate in the mixed air room. The fixed airflow rates must be designed in order to optimize air quality and indoor air climate to the occupants.

In part 2.1 of this chapter, it was observed that the optimal global airflow that provides optimal indoor climate (air quality and humidity) depends on the performance of the selected active transfer. The higher the airflow through the active transfer, the less the global airflow rate must be set to reach the optimum between air quality and humidity. A lower global airflow rate (within the hygienic limits) also leads to a better indoor climate. Knowing the performances of the selected product for the active transfer, the planner must set the global airflow and dimension the ducts accordingly.

A set of simulations were performed to define the optimal global airflow depending on the performances of the active transfers for different kinds of floor plan configurations. The simulation models used derive from the model validated in part 4 of this chapter.

The following diagrams illustrate the results.

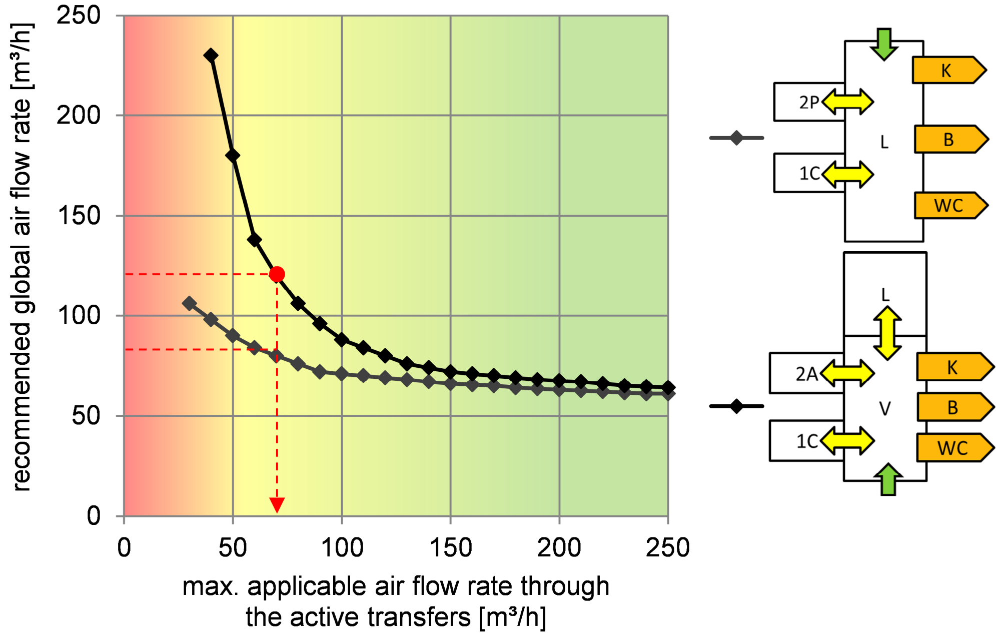


Figure 63: Map of the recommended global airflow rate according to the max. airflow rate through the active transfer for two types of floor plan configuration with standard occupancy pattern (two adults and one child).

With the help of simulations, it is possible to determine the value of global airflow rate that optimize the air quality and air humidity rate, for each value of the airflow rate through the active transfer. The values were reported in the map on Figure 63. The resulting curves allow definition of the recommended global airflow rate when knowing the maximal value of the flow through active transfer. This map can be directly used by ventilation planners: the first step is to define the maximal applicable airflow rate through the active transfer (x-axis). This is the maximal airflow rate that produces a sound level not higher than 23 dB(A) in the room. Indeed, even if the active transfer can actually deliver higher airflow rates, acoustic comfort must always be ensured.

Currently (at the time of writing) a typical value for a good product would be 70 m³/h. According to the map, the recommended value for the design of the global airflow rate is then:

- In case of a floor plan with central living room used as mixed air room: 80 m³/h
- In case of a floor plan with insulated living room and corridor used as mixed air room: 120 m³/h.

The required global airflow rates in the case of an insulated living room are higher. This is because the contaminant sources are higher in the living room and in this case it is ventilated only through the active transfer. A higher global airflow rate is thus required. The colors on the map give an indication of the average resulting quality of indoor climate in the apartment. Indeed, as seen in part 2.1, even if an optimum value can always be founded to

optimize air quality and air humidity, the overstepping of the thresholds defining the quality of indoor climate is more significant with low values of airflow through the active transfers. For 2-bedroom apartments the active transfers should be planned with flow rates higher than 40 m³/h.
With the same method, simulations were made for other kinds of apartment (1 bedroom to 3 bedrooms). Figure 64 and Figure 65 show the results maps.

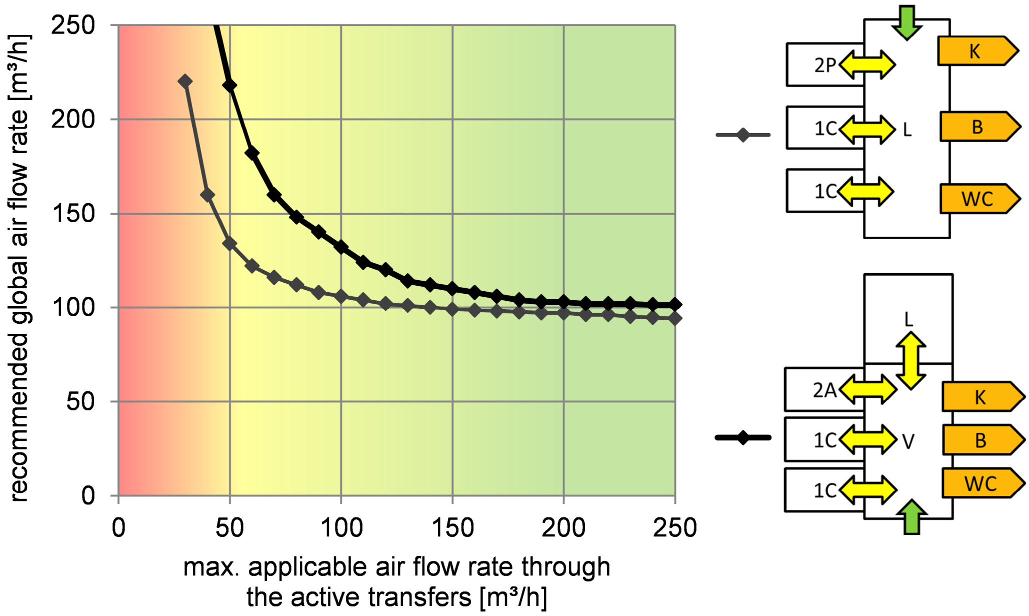


Figure 64: Map of the recommended global airflow rate according to the max. airflow rate through the active transfer for floor plan configurations with three bedrooms and an occupancy of two adults and two children.

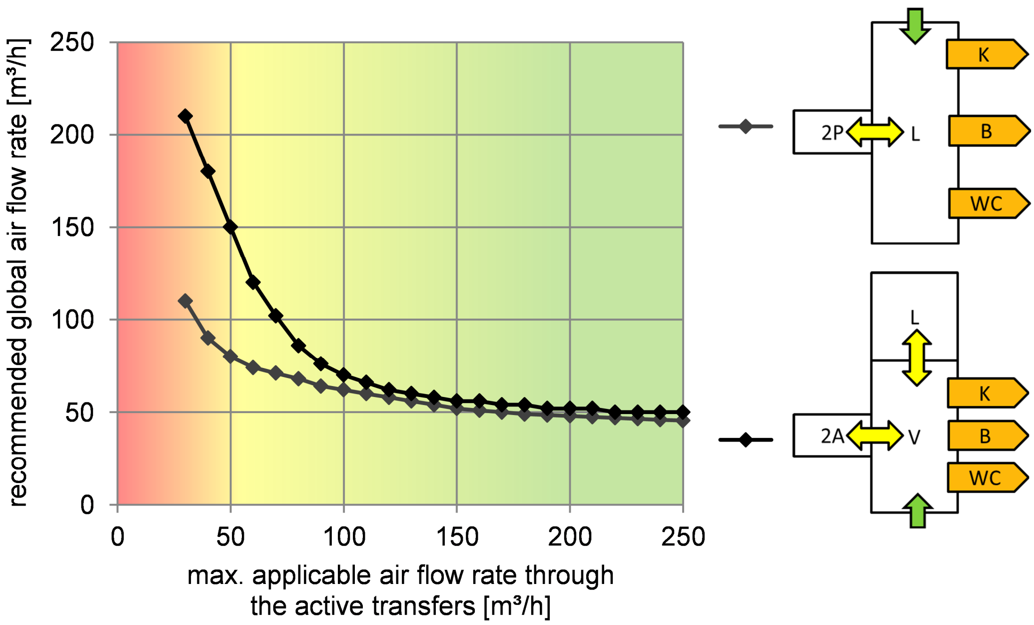


Figure 65: Map of the recommended global airflow rate according to the max. airflow rate through the active transfer for floor plan configurations with one bedroom and an occupancy of two adults.

These maps can also be used as guidelines for planners. The results for all the configurations show that for very high values of airflow rate through the active transfers (greater than 200 m³/h), when almost perfect mixing occurs between the zones, the optimal value for the global airflow rate is 20-25 m³/h per person. This observation confirm the results of (Rojas et al., 2015) about the recommended supply air rates in apartments.
The simulations were all performed for the climate of Innsbruck, where cold temperatures in winter increase the risk of dry air. In case of milder climates, the presented results can still be used. The increase of the airflow rate to balance poor performance of the active transfer will be in this case less problematic.

5.2.2. Design with fixed concentration in the mixed air room

Another possibility to plan a ventilation concept with active transfers is to set a target value of carbon dioxide concentration in the mixed air room. This can be realized easily with a usual CO_2 sensor used for demand-controlled ventilation placed in the mixed air zone and connected to the flow controller of the apartment.
The target value of CO_2 concentration in the mixed air zone depends on the performances of the active transfers and on the occupancy pattern. Simulations were made for a typical floor plan with two bedrooms and insulated living room.
The results are illustrated in Figure 66. The sum of the relative under- and overstepping of the target values of carbon dioxide concentration and relative humidity in the occupied rooms is represented for varying target concentration in the vestibule and airflows through the active transfers.

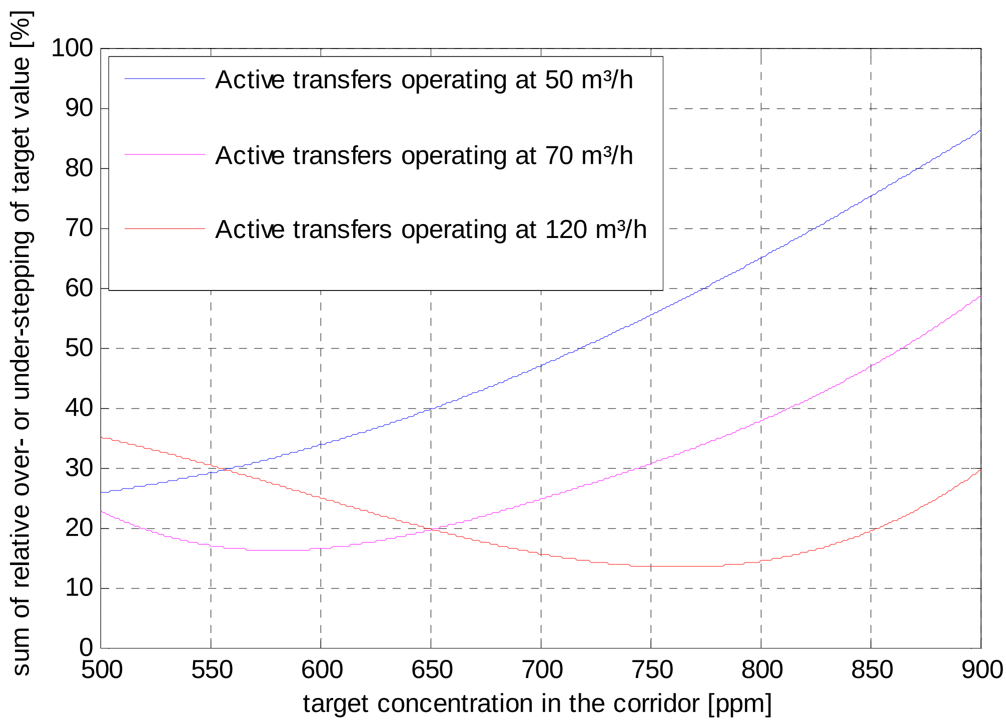


Figure 66: Average value over the two bedrooms and the living room of sum of the relative deviation of the target values, for varying target CO_2 concentrations in the mixed air room (corridor).

The results show an optimum for a concentration that depends on the performance of the active transfer.
For an active transfer that can deliver 70 m³/h (by max. 23 dB(A) sound level in the room), the target CO_2 concentration in the mixed air room (vestibule) should be set at 600 ppm to optimize air quality and humidity rate. In this case, this corresponds to an average value of 105 m³/h, which is lower than the recommended value in case of fixed airflow rates.
For an active transfer that can deliver 120 m³/h (by max. 23 dB(A) sound level in the room), the optimum is between 700 and 800 ppm, which means an even lower average value of global airflow rate and thus less energy consumption.

As a conclusion, in a ventilation concept with active transfers, controlling the global airflow rate with the CO_2 concentration in the mixed air room contributes a reduction in the electricity consumption of the whole system.

5.3. Electricity consumption

The results of the previous part showed that the concept with active transfer generally requires higher global airflow rate than cascade ventilation to ensure satisfying indoor quality to the occupant. Tough the increasing of global airflow rate leads to higher electricity consumption. In addition, the active transfer themselves are fan supported and increase as well electricity consumption.

5.3.1. Evaluation of the electricity consumption

The influence of the performance of the active transfers was surveyed by evaluating the electric consumption of the whole ventilation system in an apartment. The global airflow rate and the airflow rate through the active transfers were dimensioned according to the design map in Figure 63. The calculation was made assuming the air delivered by and returning to a central unit in the apartment with constant specific electric consumption of 0,40 Wh/m³. The active transfers are assumed with a specific electric consumption of 0,025 Wh/m³, which is the mean value of the products currently available on the market (2015).
The electricity consumption of the whole ventilation system is reported on Figure 67 depending on the applied airflow rate through the active transfers. This has been calculated for two floor plan configurations with 2 bedrooms, one with insulated living room (requires higher global flow rate and 3 active transfers) and one with living room as mixed air room (only two active transfers needed).

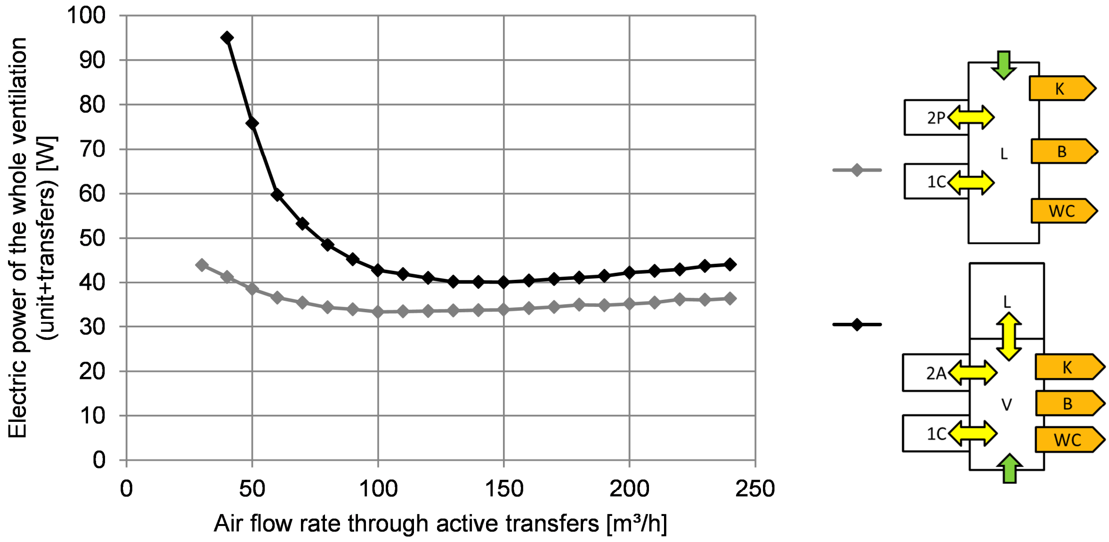


Figure 67: Electricity consumption of the whole apartment (two different configurations), depending on the applied airflow rate through the active transfers.

The results show that, globally, the higher the airflow rate through the active transfers, the lower the global electricity consumption. This is because the specific consumption of the central unit is largely dominant compared to the one of the active transfers. For active transfers set at 70 m³/h, the total consumption of the ventilation system in a 2 bedroom apartment with insulated living room (3 active transfers are needed) is about 53 W. In case of high airflow through active transfers (beyond 150 m³/h) the electricity consumption rises again slightly. This means that for the development of future products with high flow rates, a special attention still must be paid to the electrical consumption.

5.3.2. Optimization strategies

Optimization strategies can be adopted to reduce energy consumption and yearly costs.
As mentioned previously, one possibility is to use a door contact to switch off automatically the active transfer with the opening of the door. Indeed as sufficient mixing occurs when doors are open (see results of part 2.1), there is no need for active transfers.
Assuming that the doors are closed only 8 hours a day (overnight), the total energy consumption of an apartment with three active transfers operating at 70 m³/h can be reduced by 6 %.
It is also possible to reduce the airflow rate through the active transfer of the child's room (assuming only one child is sleeping). Indeed, the expression of the concentration in the rooms at steady state developed in part 1: show that the concentration in room 1 does not depend on the airflow rate of the active transfer of room 2. It is thus expected that reducing the airflow rate in the child's room has little influence on the air quality of the rest of the apartment. In order to evaluate the possible savings, the behavior of carbon dioxide concentration in the parent's room was simulated for varying airflow through the active transfer in child's room (global flow fixed at 80 m³/h and active transfer of parent's room at 70 m³/h). The simulations were performed for a 2-bedroom apartment with living room as mixed air room (Figure 68).

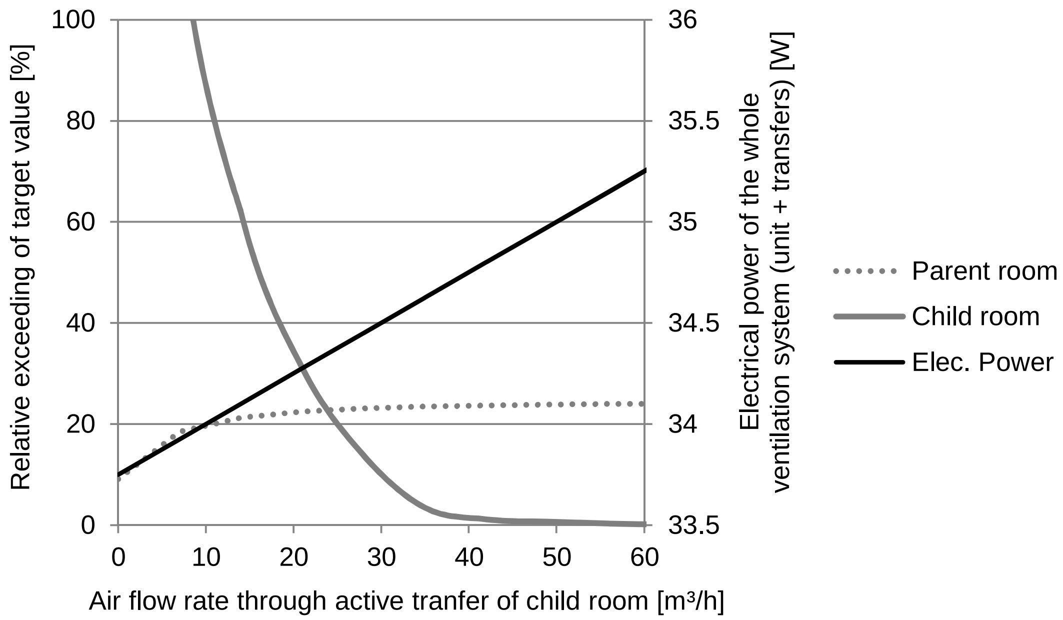


Figure 68: Relative exceedance of the target value in the bedrooms (left axis) and global electricity consumption of the ventilation system (right axis), for varying airflow rates in child's room and fixed global airflow rate and through the active transfer of the parent's room.

The results show that the airflow through the active transfer of the child's room can be reduced down to 25 m^3/h without impairing the air quality in parent's room. The air quality in child's room is then as good as in parent's room. Tough, this reduction does not allow significant savings on electric power (only approx. 1 W). Nevertheless, reducing flow rate through active transfer in child's room diminishes sound emissions improve thus the comfort of the occupant.

5.4. Comparison with cascade ventilation

The results of the previous chapter present ventilation with active transfer as a fungible alternative to cascade ventilation. The following paragraph suggests a comparison of the operating costs between both concepts for two typical renovation floor plans. In order to calculate accurately the energy consumption of each variant, the pressure drop through each supply and return branch has been evaluated. Usual products were chosen for the supply valves and were dimensioned according to the airflow rate. The resulting pressure drops derive from the technical data of the producer. The air ducts were also dimensioned according to the airflow rates. The calculation of pressure drop is detailed in Annex 3.
The results are presented in the table below with a suggestion of the ductwork for each situation. The results for active transfers are presented with current available products (2015) and also for the prognostic of more performant products available in the near future.

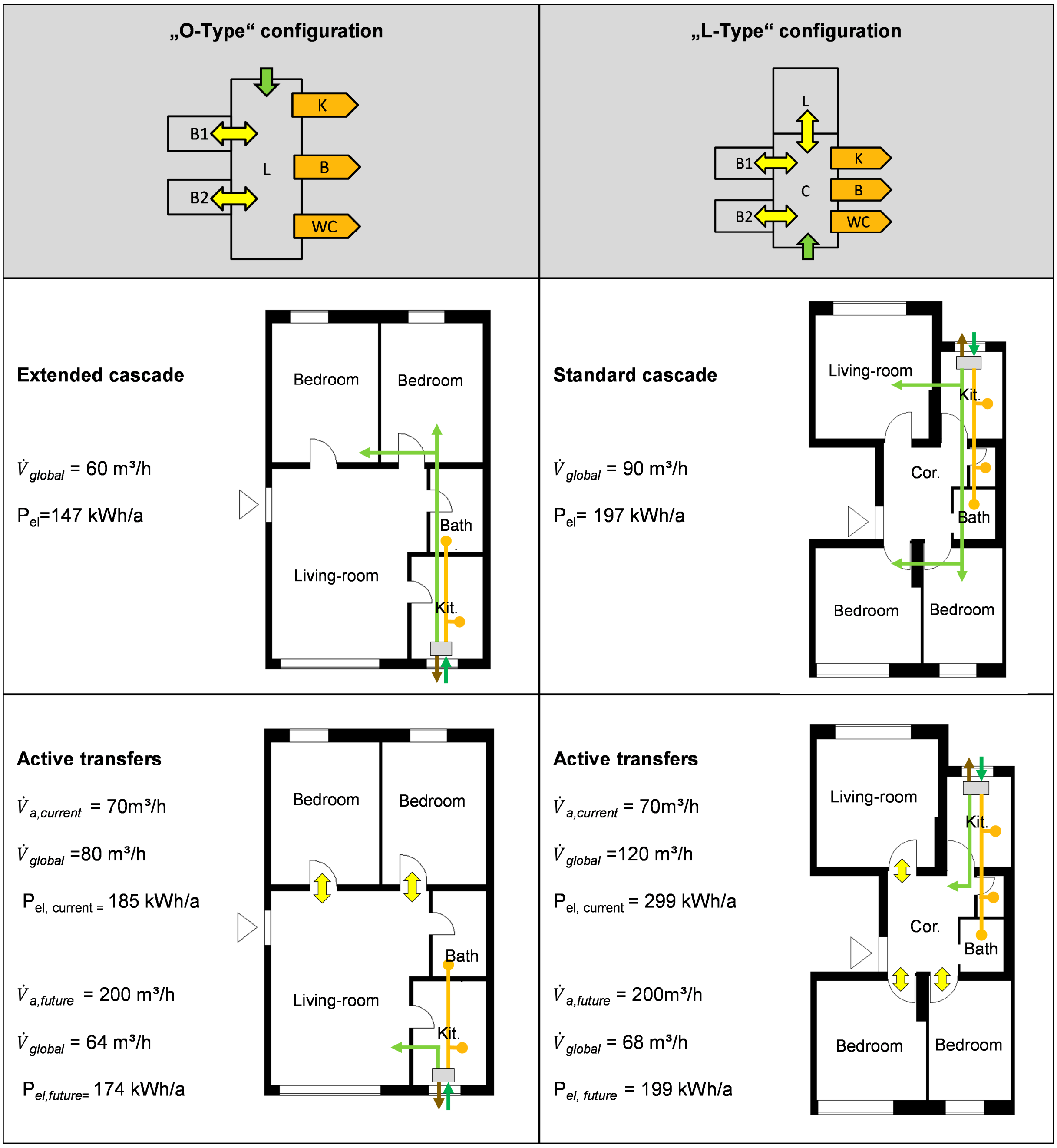


Figure 69: Results of the comparison between ventilation in cascade and with active transfers.

The results show that in the current situation (2015), cascade ventilation is more performant than the concept with active transfers. The electricity consumption is 20-30 % lower, depending on floor plan configuration. However, the solution with active transfers may be chosen to save investment and installation costs, for example in the case of renovation. With increasing performance of the active transfers, the electricity consumption tends to be the same as with cascade ventilation.

Particularly in case of floor plan configurations with insulated living room, (which is often the case in refurbishment areas), where the extended cascade ventilation is not applicable, the concept with active transfers is an efficient alternative to cascade ventilation with nearly the same electricity consumption.

6. Conclusion

In this part, the concept of ventilation with active transfers in dwellings was analyzed.
Simulation results on numerical models, as well as measurements on site have both shown that the feasibility of this concept relies on the performances of the products that should transfer high mixing airflow rates into the bedrooms, in order to provide a satisfying indoor climate. In fact, with high airflow rate through the active transfers, only a moderate increasing of the global flow rate in the mixed air room is needed to reach optimal quality of indoor air climate.
A numerical model was built to simulate the behavior of CO_2 concentration and humidity level in the rooms and was validated with measurements on site. This allowed for further simulations in order to make prognostics of the indoor climate with different kind of floor plan configurations ventilated with the concept of active transfers. The results were summarized in design maps that can be used as guideline for ventilation.
Considering the average performances of products currently available on the market (active transfers operating at 70 m^3/h) a global airflow of 80 m^3/h is recommended to achieve an optimal indoor climate in a dwelling with two adults and one child. The concept with active transfers can be regarded as fungible alternative to cascade ventilation in terms of indoor climate; however the electricity consumption is approximately 30 % higher than with cascade ventilation.
Since this concept requires only minimal installation of ducts in the apartment (only one main supply and extract ductwork), it is very attractive for renovation. Though there is still a lack of adapted products that combine simple installation (ideally without drilling the wall), good flow performances and quiet operating on the current market. This chapter explored therefore some paths for further product development. The next generation of products should target a transfer flow rate by 150 m^3/h by tolerable acoustic comfort. Such performance would allow not only very good air distribution in the rooms and minimal increasing of the global airflow (10 % to 20% depending on floor plan configuration), but would also allow the distribution of the heating and cooling loads into the bedrooms for a Passive House. The development of this concept is in fact the focus of the research project “SaLüH!” (Universität Innsbruck - AB Energieeffizentes Bauen, 2015).

Chapter 3

Development of a coaxial duct as outdoor air inlet and exhaust air outlet for ventilation units

1. Principle

Besides air distribution, the integration of the ventilation unit is also a central perspective of the cost reduction strategy. In the case of apartment-central ventilation concepts for multi-storey residential buildings, the installation of the unit is repeated many times. Simple, prefabricated systems are therefore very attractive. Most of the time, the apartment-central units are installed inside the building envelope. The inlet and exhaust air are guided through two core holes inside the building facade. In addition, these ducts must be insulated with diffusions resistant material in order to prevent heating losses and condensation at this place. Particularly in case of refurbishment, this installation work including the drilling of the wall is generally very laborious and expensive.
The use of a coaxial duct for outdoor air intake and exhaust air aims at reducing the costs and at saving space in the apartment. The objective is to create a high prefabricated product that facilitates the installation of apartment-central ventilation units. The construction principle is illustrated on Figure 70.

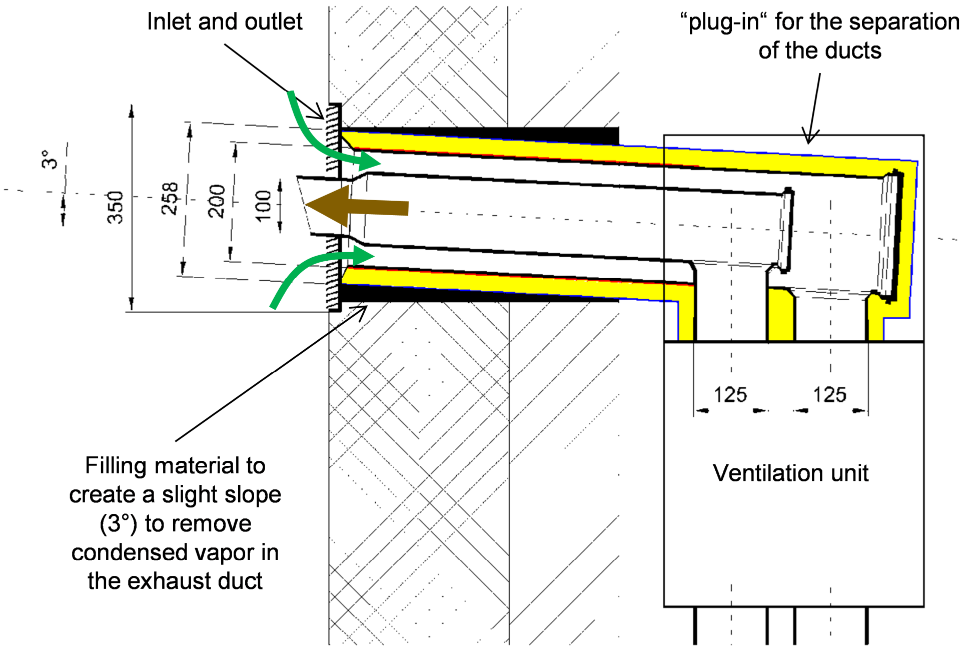


Figure 70: Sketch of the installation of the coaxial duct as outdoor air inlet and exhaust air outlet of the ventilation unit.

The drilling through the wall of the façade must be large enough to place the coaxial duct and allow a slight slope (approx 3°) to allow condensed vapor in the exhaust air duct streaming back to the unit.

This chapter describes several development steps of the coaxial duct and explores the technical feasibility of the different features that it includes. Dimensions, efficiency (no short between exhaust and intake, low pressure loss) and air defrosting have been considered in this development process.

The general design and the fitting dimensions of the coaxial duct have been defined in (Pfluger, Feist, & Hasper, 2013). Based on this work, sketches were made to design the integration of the different functions (insulation, condensed vapor removal, pre-heating element, inlet air grid and exhaust air nozzle etc.). Eventually, a prototype of the coaxial duct was delivered from firm Poloplast GmbH & Co KG (Figure 71).

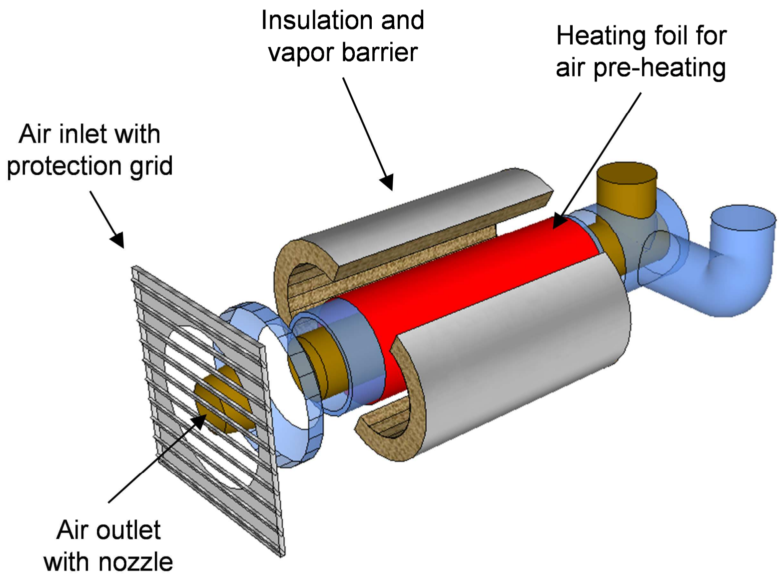


Figure 71: sketch of the different layers and assemblies (above) and prototype of the coaxial duct

The sketches in Figure 70 and Figure 71 show that the exhaust air (internal duct) is blown out of the duct through a nozzle. At the opposite, the outside air is taken nearby the facade through a protection grid and flows through the external duct in ring shape. For a good operation, the exhaust air should not be directly drawn again through the inlet grid (risk of short cut). This issue is at focus in the first part of this chapter.
The freezing of condensation in the heat exchanger of the unit must be prevented. The realization of pre-heating through a foil wrapped on the external duct will be therefore investigated in the second part of this chapter.
An alternative pre-heating strategy with an innovative system using heat-pipes is surveyed in the third part.

2. Metrological survey of the risk of short-cut

This chapter surveys the issue of short-cut between air exhaust and fresh air with several measurements made on the prototype. Amongst other, the design of the inlet grid and exhausted air nozzle influence the risk of such short cut. Different types of inlet and outlet constructions are therefore surveyed.

2.1. Measurement installation

Two kinds of protection grid and nozzle have been tested on the prototype.
The first protection grid has a standard design and is cut in the middle in order to place the exhaust air nozzle. The second grid type is a prototype that was especially produced for the coaxial duct in order to create an element which is completely integrated in the façade. The air gap for the air inlet has been designed to minimize pressure drop (5 Pa). Nozzle 1 (outlet for exhausted air) is shaped in a truncated cone with smaller diameter at the outlet in order to increase air speed at the end. Nozzle 2 has a specific profile which increases this effect. The four combinations are presented in Figure 72.

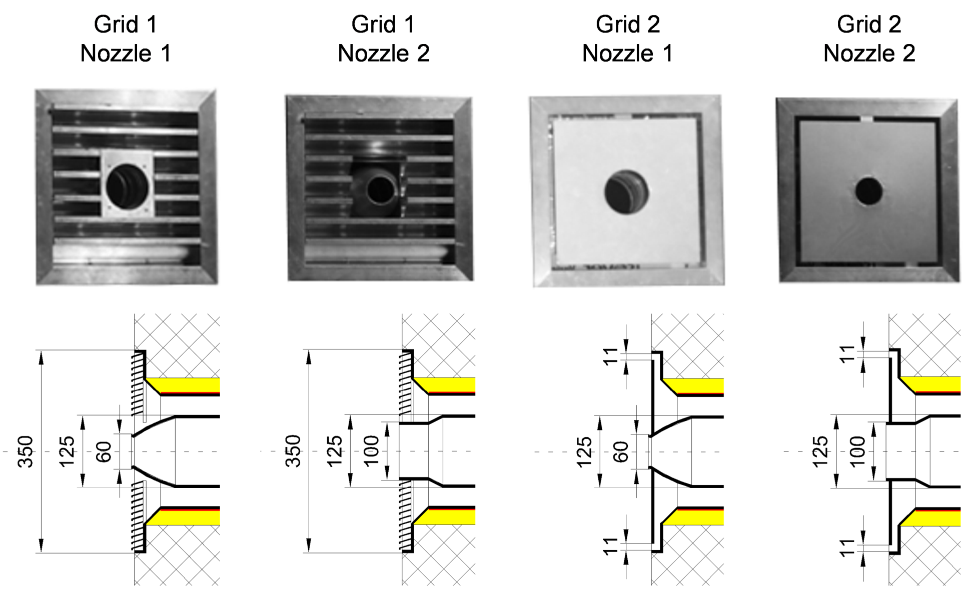


Figure 72: Combinations of grid and nozzle that have been surveyed. The yellow strip represents the insulation.

The prototype of coaxial duct was connected to a typical apartment ventilation unit with heat recovery. The airflow rate through the unit can be set up to 185 m³/h with 8 different levels. The measurements were driven for an airflow rate at 64 m³/h and 120 m³/h, which correspond to the recommended airflow rates of typical households (3 to 5 persons).

2.2. Visual test

The measurement installation has been placed into a testing hall with black background. The air extract of the unit was connected to a fog machine. By switching on the ventilation unit and the fog machine, the blowing of the exhaust air at the outlet could thus be observed. Especially, this experiment allowed the observation of potential short cut between outlet and inlet.

This experiment was performed and recorded with pictures and videos for the four combinations of grid with nozzle and for the two levels of airflow rate. The experience with grid 1 and nozzle 1 is shown on Figure 73.

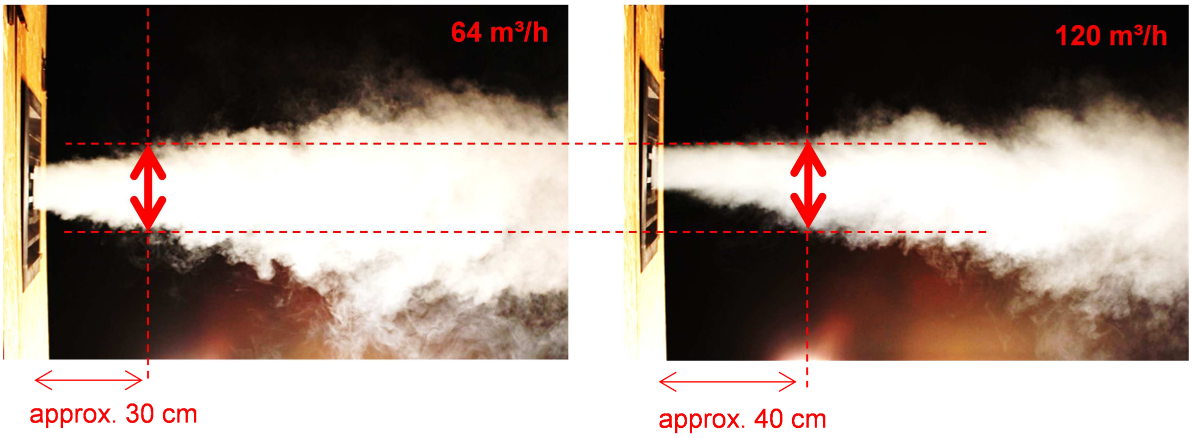


Figure 73: picture of the experiment for grid 1 and nozzle 1, for an airflow rate of 64 m³/h (left) and 120 m³/h (right). At an airflow rate of 64 m³/h, the outlet stream has a diameter of approximately 20 cm at a distance of approx. 30 cm and at a distance of approx. 40 cm in the case of 120 m³/h airflow rate.

With an airflow rate at 120 m³/h, the spreading of the stream and thus the risk of short cut is smaller than with an airflow rate at 64 m³/h.

In all the surveyed cases, no short-cut is visible. No significant difference is visible between the four combinations.

2.3. Measurement with tracer gas

In order to confirm these observations and quantify short cut rate for the different combinations, further experiments with tracer gas were performed. The objective is to determine the exact rate of air exhaust that is directly intaken again in the inlet for the four combinations of grid and nozzle.

The measurement installation was brought into real conditions. The grid was integrated into a wood panel, which was mounted into a window frame instead of a glass pane. The supply and extract of the unit are inside the test room and the inlet and outlet are outside. A sketch of the installation is shown on Figure 74.

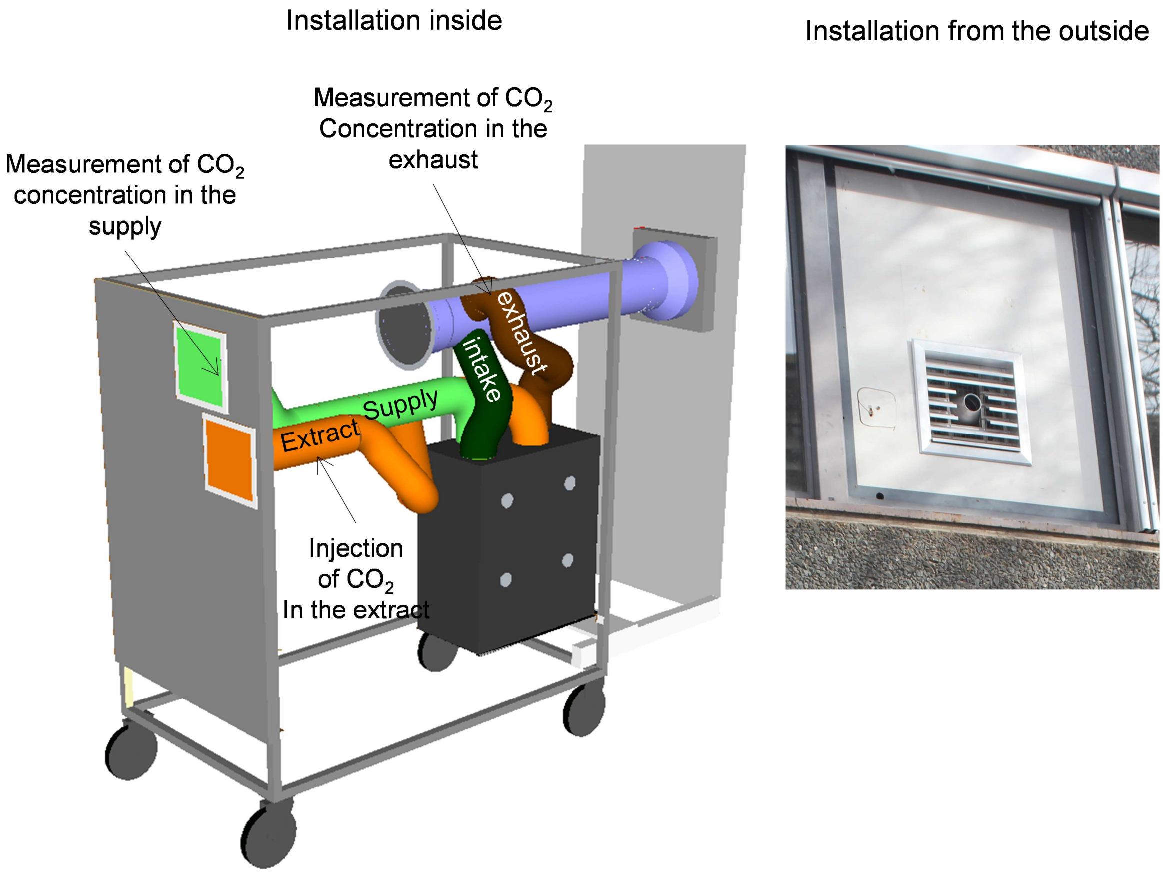


Figure 74: Sketch of the installation in the test room. The ventilation unit is mounted on a rolling frame structure (to be easily transported). The inlet grid is integrated into a wood panel that is mounded in a window frame. Carbon dioxide is injected in high concentration in the extract air. The concentration in the air intake duct is measured, thus the rate of short cut between outlet and inlet can be evaluated.

Carbon dioxide was used as tracer gas for this measurement. The measurement consists in injecting carbon dioxide in known concentration into the exhaust air and measuring the resulting concentration in the intake. This way, the rate of short cut can be evaluated. For practical reasons the injection was made in the extract and the measurement in the supply. This actually makes no difference to measuring in the exhaust and intake, since the tightness of the installation was tested and optimized prior to testing with the help of the fog machine.

Carbon dioxide has been injected into the extract air in order to reach a concentration of 40 000 ppm (measured not directly next to the injection to allow air mixing). Each combination of grid and nozzle has been measured for 10 minutes for both airflow rates. As the outside conditions can vary a lot, the following boundary conditions have been held for every measurement, in order to compare the results afterwards.

	Target value	Verification
Airflow rate	64 m³/h and 120 m³/h	Measured at the beginning of each measurement
CO_2 concentration in the extract and exhaust air duct	40 000 ppm	Measured at the beginning of each measurement
Wind speed outside	Max. 0.5 m/s	Measured at the beginning of each measurement
CO_2 concentration outside	Approx. 500 ppm and constant	Measured at the beginning of each measurement
CO_2 concentration inside	Constant during the measurement	Measured at the beginning and at the end of each measurement
Temperature outside	Almost the same for every measurements and above 0°C	Almost the same for every measurement
Temperature inside	Almost the same for every measurements	Almost the same for every measurement

Table 10: Summary of the boundary conditions for the measurements.

The following values were recorded during each measurement:

Measured quantity	Frequency of measurement
CO_2 concentration in the supply	Every Minute
Pressure drop between the exhaust air duct and the outside	Once during each measurement
Pressure drop between the outside air duct and the outside	Once during each measurement

Table 11: Summary of the measured quantities and their frequency of measurement.

2.4. Results

The airflows in the system can be modelled as in Figure 75.

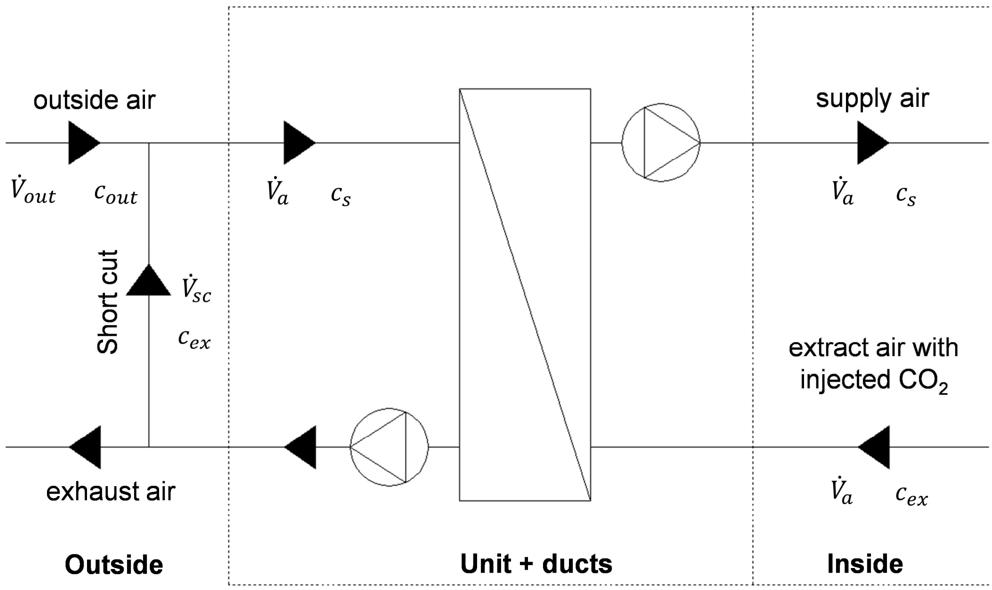


Figure 75: Schematic representation of the airflows in the system

The following expressions derive from the model:

$$\dot{V}_a = \dot{V}_{out} + \dot{V}_{sc} \tag{3.1}$$

$$\dot{V}_a \cdot c_s = \dot{V}_{out} \cdot c_{out} + \dot{V}_{sc} \cdot c_{ex} \tag{3.2}$$

With:

$\dot{V}_a$	set airflow rate (64 m³/h or 120 m³/h) flow through the unit and measured at the supply and extract [m³h]
c_s	carbon dioxide concentration measured in the supply duct [ppm]
$\dot{V}_{out}$	pure outside airflow rate [m³/h]
c_{out}	carbon dioxide concentration measured in the outside air [ppm]
$\dot{V}_{sc}$	short cut airflow rate [m³/h]
c_{ex}	carbon dioxide concentration measured in the extract air duct [ppm]

The amount of airflow rate that is cutting short from the exhaust into the intake can be derived from these expressions:

$$\dot{V}_{sc} = \frac{c_s - c_{out}}{c_{ex} - c_{out}} \cdot \dot{V}_a \tag{3.3}$$

We define short-cut rate with the expression:

$$\eta = \frac{\dot{V}_{\mathrm{sc}}}{\dot{V}_{\mathrm{a}}} \tag{3.4}$$

Thus

$$\eta = \frac{c_{\mathrm{s}} - c_{\mathrm{out}}}{c_{\mathrm{ex}} - c_{\mathrm{out}}} \tag{3.5}$$

The results from the experiments are summarized in the following table:

Grid type	Nozzle type	Airflow rate [m³/h]	C_{out} [ppm]	C_s [ppm]	Pressure drop in the intake duct [Pa]	Pressure drop in the exhaust duct [Pa]	η [%]
1	1	64	474	571	7.5	4.0	0.24
1	1	120	455	471	28.1	12.7	0.04
1	2	64	443	509	6.8	30.3	0.17
1	2	120	470	650	25.1	107.9	0.45
2	1	64	442	624	8.8	3.9	0.46
2	1	120	372	502	30.1	10.6	0.32
2	2	64	378	558	8.2	27.7	0.45
2	2	120	415	640	31.2	106.1	0.56

Table 12: Results of the tracer gas measurements of the short-cut rate between exhaust air and intake with coaxial duct.

The results show that short cut rate stays below 1%. The rate is even lower when the airflow rate through the unit is higher. These results confirm the observations made with the fog machine.
The results also show that the short cut rates with grid 1 (the standard one) are lower than with grid 2. Short cut rates are also lower with nozzle 2 (profile designed to increase speed at the outlet) than with nozzle 1. Though, pressure drop is significantly higher with the use of nozzle 2. Thus, the nozzle 1 is preferred because the increasing of pressure drop with nozzle 2 is disproportional to the slight reduction of short cut effect. As a conclusion, the variant with grid 1 and nozzle 1 is the best one.

Eventually the measurements showed that there is only a very limited risk of redrawing of the exhaust air into the intake duct with the coaxial duct. Nevertheless, as for standard installation (separated ducts), the integration of the coaxial duct into the façade must avoid spots that may influence unfavorable airflows and increase short cut risk (for example nearby corners).

3. Inlet air pre-heating with electric foil

For ventilation units without humidity recovery, a defrosting system is required in central European climates in order to prevent the freezing of condensation in the heat exchanger. Typically for a passive house certified ventilation units (with heat recovery rate above 85%) outside air temperature below -3°C must be pre-heated before entering into the heat-exchanger. The goal of this chapter is to survey the feasibility of air pre-heating though a 1m long electric heating foil wrapped on the air inlet duct.

3.1. Prototype of the heating foil

The design power needed for defrosting from -20°C (design minimal temperature) to -3°C (minimal temperature at the entrance of heat exchanger to prevent frost by 85 % heat recovery rate) can be calculated for a typical four persons household (120 m³/h) though the equation:

$$Q = \rho_{air} \cdot c_p \cdot (T_d - T_t) \cdot \dot{V} \tag{3.6}$$

With:

ρ_{air}	density of air (average temperature in the duct) [kg/m³]
c_p	specific heat capacity of air [J/(kg.K)]
T_d	design outdoor temperature [°C]
T_t	target temperature after pre-heating [°C]
$\dot{V}$	airflow rate through the duct [m³/h]

The necessary power for pre-heating is in this case 766W. In a previous theoretical study (Pfluger, Feist, et al., 2013) the resulting transferable heat power through the 1 m long heating foil wrapped on the external annulus duct is 903 W. This value is very significantly higher than in case of an air intake with standard 125 mm diameter duct (358 W) because the heat exchange surface of the annulus gap is higher. Coaxial duct is thus predestinated to this concept.
In order to confirm the feasibility of this strategy, such a heating foil has been prototyped and wrapped on the coaxial duct (Figure 76).

Figure 76: Left: heating foil wrapped on the prototype of a coaxial duct. Right: the whole duct is then wrapped by insulating and vapor impermeable material.

Measurements of this installation were performed in climate chambers to validate the calculation of the required heating load.

3.2. Required heating load

The whole installation (coaxial duct connected to the ventilation unit, as described in part 2.3) was installed in climate chambers as illustrated in Figure 77.

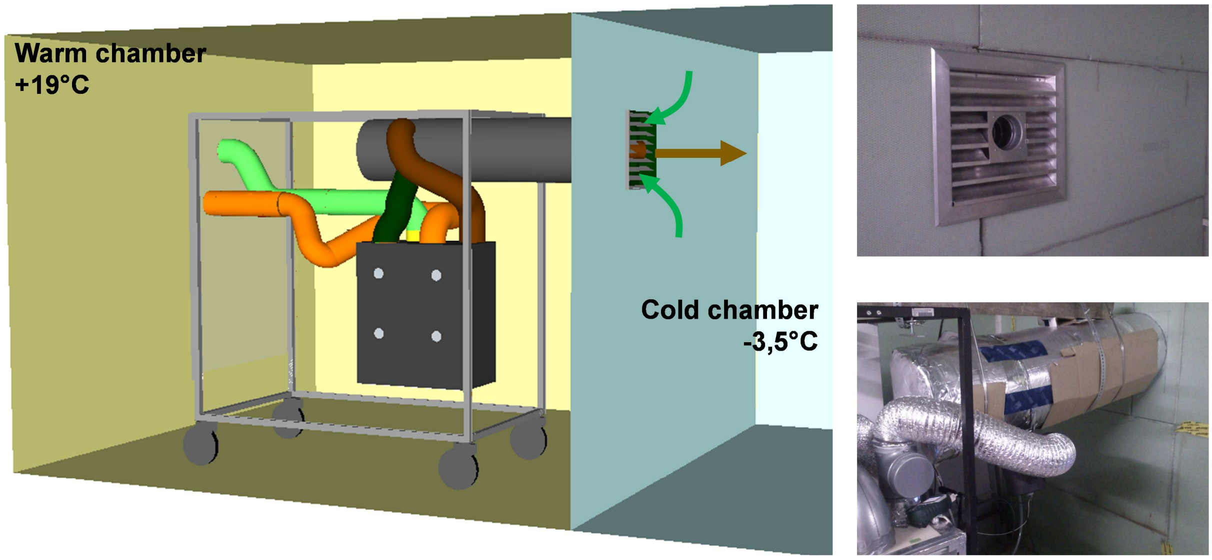


Figure 77: Measurement installation between the two climate chambers.

For technical reasons, it was not possible to set the temperature of the cold chamber under -3,5°C. The temperature of the warm chamber was set at 19°C.
Measurements were made over several hours for the three following scenarios:

- Airflow rate at 119 m^3/h and heating power to the foil at 394,8 W
- Airflow rate at 119 m^3/h and heating power to the foil at 293,4 W
- Airflow rate at 56 m^3/h and heating power to the foil at 143 W

The air temperature was measured at the intake (before heating) and before duct separation(after heating foil).
After steady state was established, the average temperatures at the several nodes were reported in the following table:

	airflow rate [m^3h]	Ta [°C]	Ti [°C]	TL [°C]	P [W]
Scenario 1	119	-3,35	18,92	6,08	394,8
Scenario 2	119	-3,42	18,89	3,88	293,4
Scenario 3	56	-3,63	19,00	4,58	143,0

Table 13: Summary of the three measured scenarios.

At the same time, a simple model of the heating transfers in the system was build up which is illustrated in Figure 78, using Beuken type electro-technical analogy.

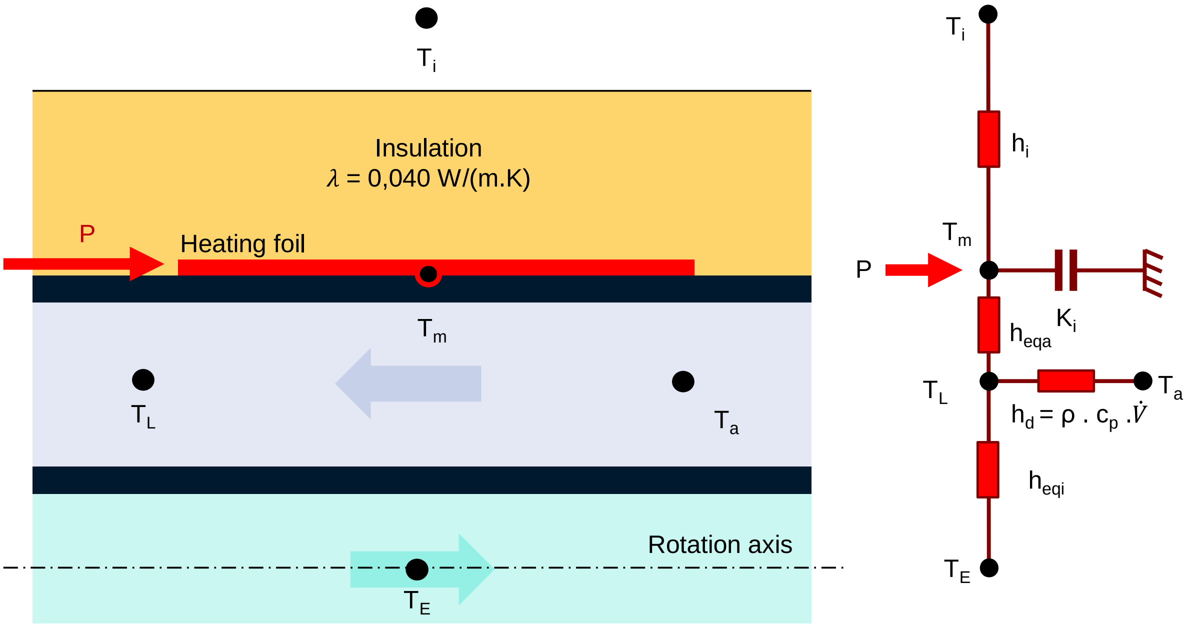


Figure 78: Left: sketch of a longitudinal section through the coaxial duct. Right: corresponding model of heat transfers in the section using electro-technical analogy. Heat flux is modelled through electric current and the temperature levels through electric potential.

Heat flow is modelled analog to electric current and the temperature levels analog to voltage.

With:

T_i	Air temperature inside (approx. 20°C) [K]
T_m	Temperature of the heating foil [K]
T_a	Air temperature at the inlet before pre-heating [K]
T_L	Air temperature after pre-heating
K_i	thermal capacity of the foil and the insulation layer [J/K]
P	heating power of the foil [W]
h_i	Combined thermal transmittance of the insulation layer with the heat transfer coefficient between the external surface and the inside air [W/K]
h_{eqa}	Combined thermal transmittance of the duct with the heat transfer coefficient between the internal surface of the external duct and the flowing air in the annulus gap[W/K]
h_{eqi}	Combined thermal transmittance of the duct with the heat transfer coefficient between the external surface of the internal duct and the flowing air in the annulus gap [W/K]
h_d	is defined through: $h_d = \rho \,.\, c_p . \dot{V}$, with:
ρ	density of air [kg/m³]
c_p	specific thermal capacity of air [J/(kg.K)]
$\dot{V}$	airflow rate [m³/s]

At node T_m of the system, the progression of temperatures in time is expressed through the equation:

$$P = h_i \cdot (T_m - T_i) + h_{eq} \cdot (T_m - T_L) + \frac{dT_m}{dt} \cdot K_i \quad (3.7)$$

At node T_L,

$$h_{eq} \cdot (T_m - T_L) + h_{eqi} \cdot (T_E - T_L) = h_d \cdot (T_L - T_a) \quad (3.8)$$

Thus, the progression of the temperature at the surface of the foil and of the air inside the duct can be expressed through the following system of equations:

$$\begin{cases} \frac{dT_m}{dt} = \frac{1}{K_i} \cdot \left[P - h_i \cdot (T_m - T_i) - h_{eqa} \cdot (T_m - T_L)\right] \\ h_d \cdot (T_L - T_a) = h_{eqa} \cdot (T_m - T_L) + h_{eqi} \cdot (T_E - T_L) \end{cases} \quad (3.9)$$

This system of equation was solved at steady state and the coefficients h_i, h_{eqa} , h_{eqi} and h_d were calculated in the conditions of the measurements using the equations developed in (Pfluger, Feist, et al., 2013).

The following graph (Figure 79) compares the calculated values of T_L obtained for varying input power P with the measured values.

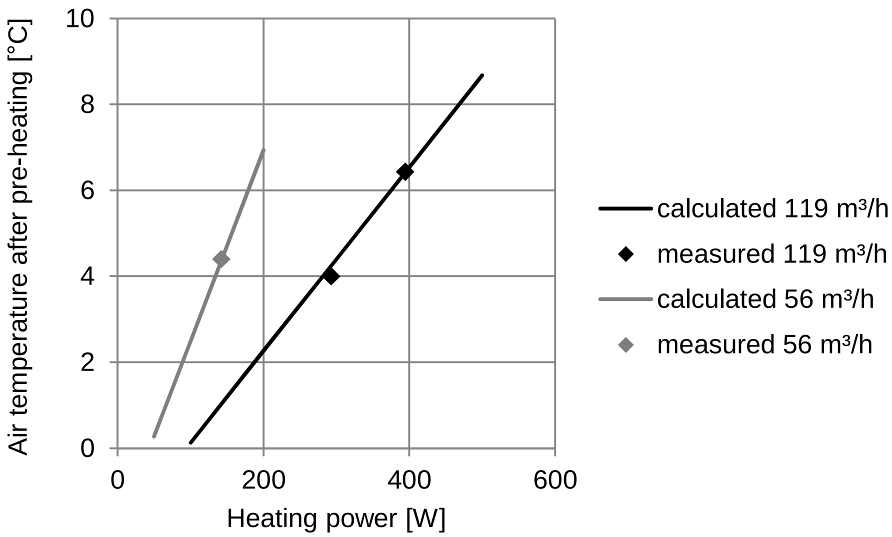


Figure 79: Air temperature after pre-heating foil for varying input power. Results through simulation model are compared to the measured values.

The comparison shows that the measured values are matching well with the calculated ones. The necessary heating power in the real conditions (pre-heating from -20°C to -3°C for an airflow rate of 120 m³/h), is 759 W, calculated with the model (in steady state conditions). It is slightly less than the theoretical value of 766 W calculated in (Pfluger, Feist, et al., 2013) because of the heat transmission from the internal to the external duct.

In fact, if we consider heqi→0 and hi→0 (perfect insulation) in equation (3.9), the theoretical value of 766 W results.
The transmission from the internal duct to the external duct contributes to the pre-heating of the air. Though, this transmission should be limited; if the exhaust air with 0°C and approx. 100 % relative humidity is in contact with the cold duct wall with approx. 20°C, there is a risk that the condensed water freezes in the internal duct. If this happens for a long time period, the ice may impair airflow and produce high pressure drops in the internal duct. The internal duct should be thus insulated with a high efficient material, for example with areogel (lambda 0,012 W/K.m).

3.3. Optimization of the electrical consumption

In reality, the outside air temperature in the defrosting season varies over day and night time. When the temperature reaches the threshold for defrosting (here assumed at -3°C) the pre-heating system switches on. A control of the heating power is possible through the measurement of the outside air temperature at the entrance of the unit, which is T_L in the model Figure 78. The energy consumption for defrosting will depend on the chosen control strategy and on the accuracy of its setting.
The goal of this chapter is to evaluate the energy consumption of the prototyped defrosting system. The method for this is to run simulations on the theoretical model on Figure 78 for a typical outside temperature profile and test several control strategies on the heating power. For this purpose a first validation of the model under dynamic conditions is needed.

3.3.1. Measurements

For this, the whole measurement installation was installed in real conditions with varying outside air temperature. The coaxial duct was integrated into the wood panel of the window frame exactly as for the measurement of short cut risk in part 2.3. The coaxial duct is thus directly connected to the outside air.
The heating power is controlled with the outside air temperature with a hysteresis cycle. For this the command voltage of the heating source and the temperature sensor of outside air were connected to a LabView (“LabVIEW 2014 - National Instruments”) interface. During measurement time, the outside air temperatures were varying between 10 and 20°C. The threshold values for the hysteresis controller were thus set at 14°C (start of the pre-heating) and 18°C (stop of the pre-heating). The heating power was set constant at 800 W and the airflow rate at 50 m³/h.

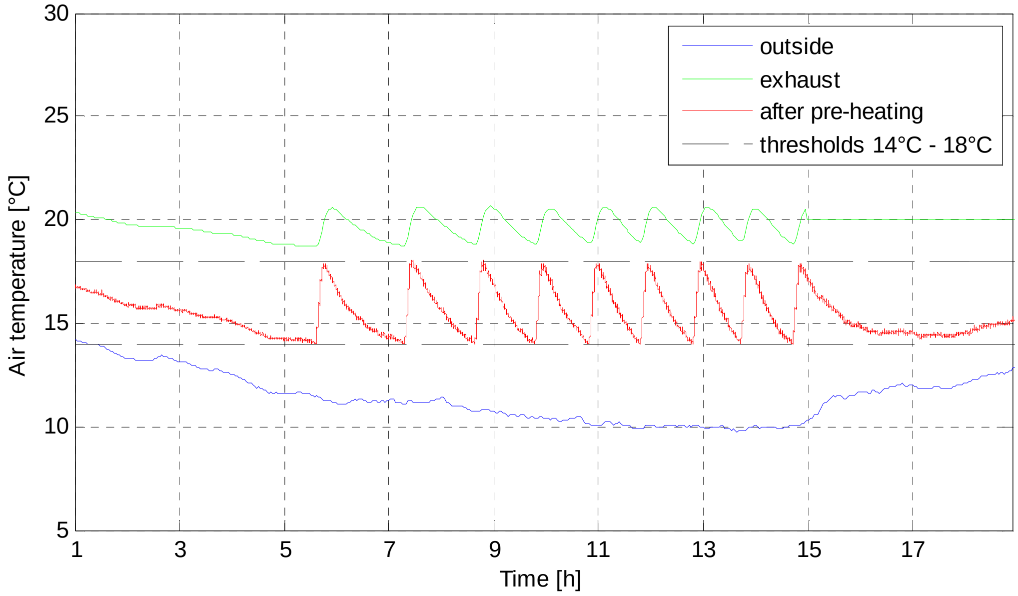


Figure 80: Measured temperatures outside and after pre-heating with hysteresis controller with lower threshold at 14°C and upper threshold at 18°C.

The measurement results show the operating of the hysteresis controller. While the outside temperature falls below 14°C, the heating power is delivered through the foil and the air warms rapidly up to 18°C. After reaching this value, the heating source is switched off. The outside air cools slowly with the heating foil. It takes approximately two hours until the air reaches again the lower threshold and the process starts again.

3.3.2. Validation of the model

The differential equations deriving from the model in part 3.2 of this chapter were formatted in a Simulink (Mathworks, 2015) model. The model in Simulink includes the control of the heating source with hysteresis with the same threshold values as in the measurement. The profile of the measured outside air temperature and of the temperature of the exhausted air was input in order to simulate the profile of the temperature in the duct as in the measurement. The simulation results compared to the measurements are presented in Figure 81.

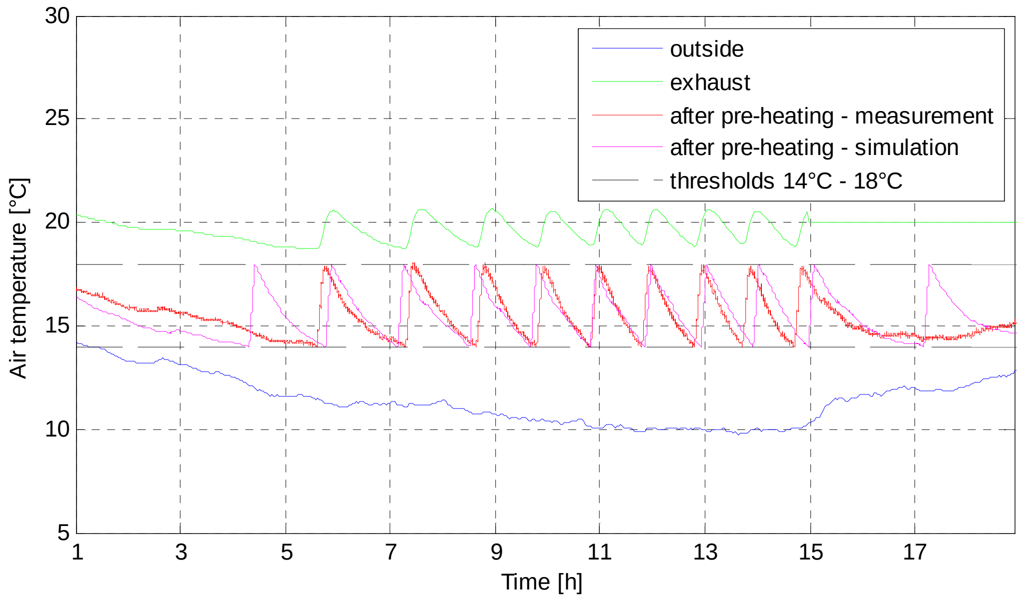


Figure 81: Measurement and simulation results for inlet air-pre heating controlled with hysteresis.

The value of K_i needed to be increased in order to fit the simulation results to the measurements. In fact, K_i which represents the thermal capacity of the construction was first calculated based on several literature data with 17 kJ/K. Though, it was observed in the measurements that the construction stores the heat of the foil more than this first guessed. A better fit appears for Ki = 22 kJ/K. The diagram shows that in the measurement, at the beginning of the process, the air temperature cools slower as in the simulation. Thus the heating process begins earlier in the simulation. This effect can be attributed to thermal bridges in the envelope of the coaxial duct. The coefficient h_i may be in reality of the measurement higher than calculated.
The evolution of the exhaust air temperature shows that the heat is also transmitted to the internal duct. This confirms the need for an insulation layer between the two ducts.

3.3.3. Prognostics

The Simulink model was used to make prognostics about the energy consumption of the pre-heating concept. For these simulations, an insulation layer made of 1cm aerogel between the two ducts was assumed. The coefficient h_{eqi} drops below 1 W/K; this term can thus be neglected. The prognostics were made for a typical winter in Vienna, Austria with an outside air temperature profile undertaken from Meteonorm database (Jan et al., 2014). The heating power was set at 778 W (value calculated in part 3.2). Typically the control of the heating load for defrosting is based on the temperature of the exhaust air, which should not drop below 0,5°C to avoid any frost in the heat exchanger. The model was thus extended with a typical ventilation unit with 85% heat recovery that has an electric power of 0.30 Wh/ m^3. The temperature of the exhaust air is given through the equation:

$$T_{exh} = T_{ext} \cdot (1 - \eta) + \eta \cdot T_L + \frac{P_{el}}{\rho \cdot c_p} \quad (3.10)$$

With:

T_{exh} air temperature at the exhaust (after heat recovery) [°C]
T_{ext} air temperature at the extract (before heat recovery) [°C]
T_L air temperature at the inlet (outside air after pre-heating) [°C]
η heat recovery rate of the unit [%]
P_{el} specific power consumption of the unit [Wh/m³]
ρ density of air [kg/m³]
c_p specific thermal capacity of air [J/(kg.K)]

The simulation on the Simulink model for the given temperature profile was performed and the total energy consumption for defrosting over a year was thus calculated. Three different control strategies were tested, considering an airflow rate of 60 m³/h (3-persons household).

Control type	Yearly electrical consumption
Hysteresis set temperatures lower: 1°C upper 2°C	36,6 kWh/a
Hysteresis set temperatures lower: 0.5°C upper 0.6°C	20,2 kWh/a
Proportional controller with target value 0.5°C	24,3 kWh/a

Table 14: summary of the tested control strategies and corresponding yearly electrical consumption.

The results underline that an accurate control strategy has a significant influence on the electrical consumption of the system. A fine tuning of the controller allows more than 30 % savings. In addition, the amount of energy used for defrosting with electricity (10% to 20 % of the electrical consumption of the ventilation unit) also highlights the necessity of more performant strategies.

The next chapter therefore explores an alternative defrosting strategy using heat pipes in order to save further energy and costs.

4. Inlet air pre-heating with heat pipes

An alternative strategy to electric defrosting surveyed in previous part uses the concept of heat-pipe.

4.1. Principle and previous studies

Heat-pipes or thermosiphons allow heat transfer without the use of a pump. The operating principle is illustrated in Figure 82.

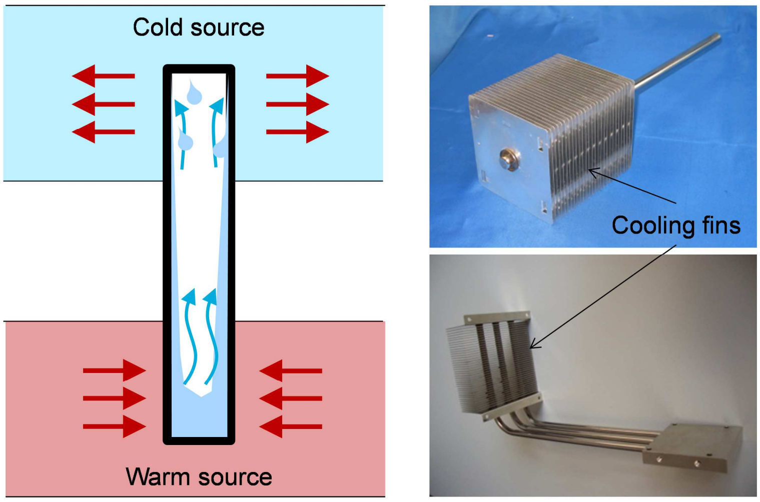


Figure 82: Principle of operating of a heat pipe (left). Heat pipes with cooling plates (source: DAU GmbH & Co KG).

The refrigerant fluid inside the pipe is heated through the warm source, evaporates and moves to the other end of the pipe. There, the evaporated fluid transfers its heat content to the cold source and condenses. The fluid thus moves again to the warm side, either with gravity (thermosiphon) or through capillarity action (heat-pipes) and the cycle starts again.
In (Pfluger, 2014), the use of this principle for defrosting has been theoretically surveyed, as well as the expected savings life cycle cost for a central unit. In fact, the operating of the heat-pipe does not require any direct electrical connection (in case of pre-heating as surveyed in previous part) or any pump (as it is the case for the defrosting of central units which are connected to hot water boiler with an additional pump). The connection principle is illustrated on Figure 83.

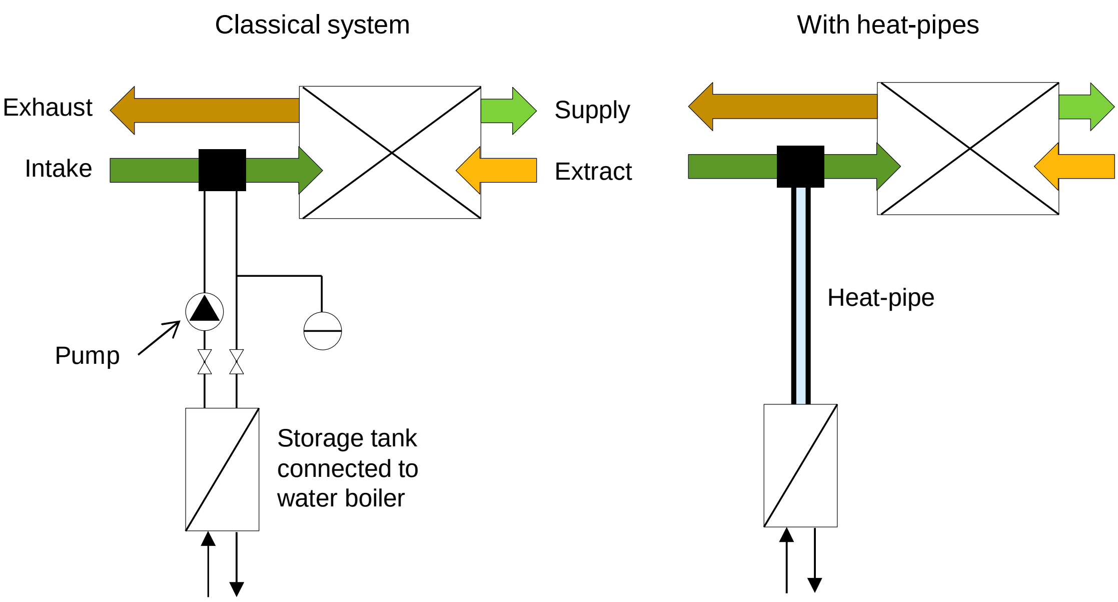


Figure 83: Sketch of the connection of the hot water tank to the defrosting heat exchanger, with a classical system (left) and with heat-pipes right).

The objective of the next paragraphs is to establish the feasibility of defrosting using heat – pipes. For this purpose, a prototype was ordered and measurements were made to validate a simulation model.

4.2. Measurements

A prototype of heat pipes designed for the transfer of the heating load for the defrosting of an apartment wise unit was delivered from the firm DAU GmbH & Co KG (Miba Group) (Figure 84). The heat-pipes are filled with water in low pressure.

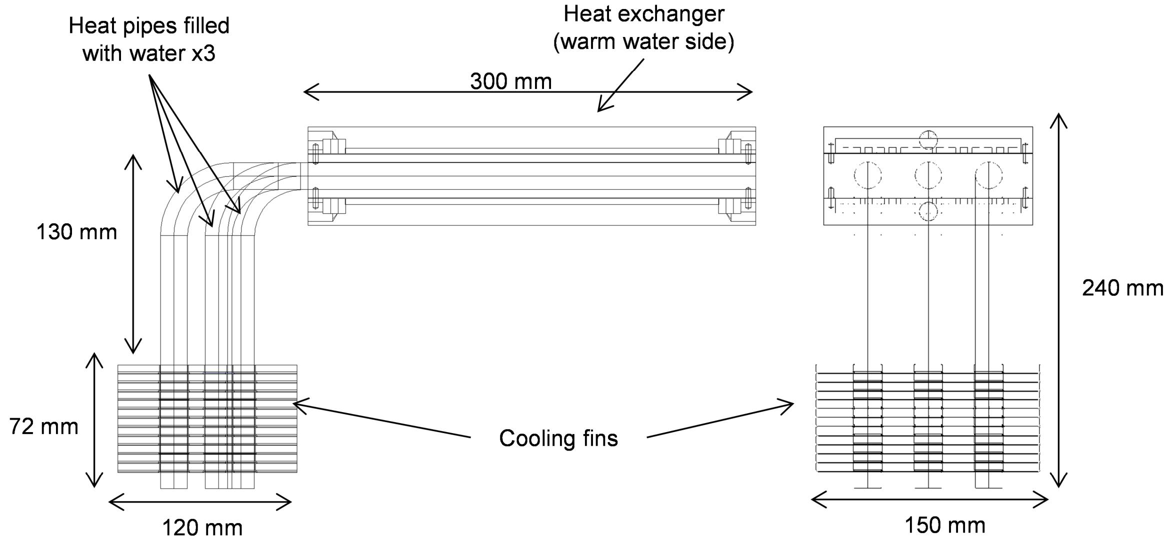


Figure 84: Construction drawing of the prototype of the heat pipes for the measurements (source: firm DAU).

The prototype has been integrated into a measurement installation delivered from the firm J. PICHLER Gesellschaft m.b.H., as illustrated on Figure 85.

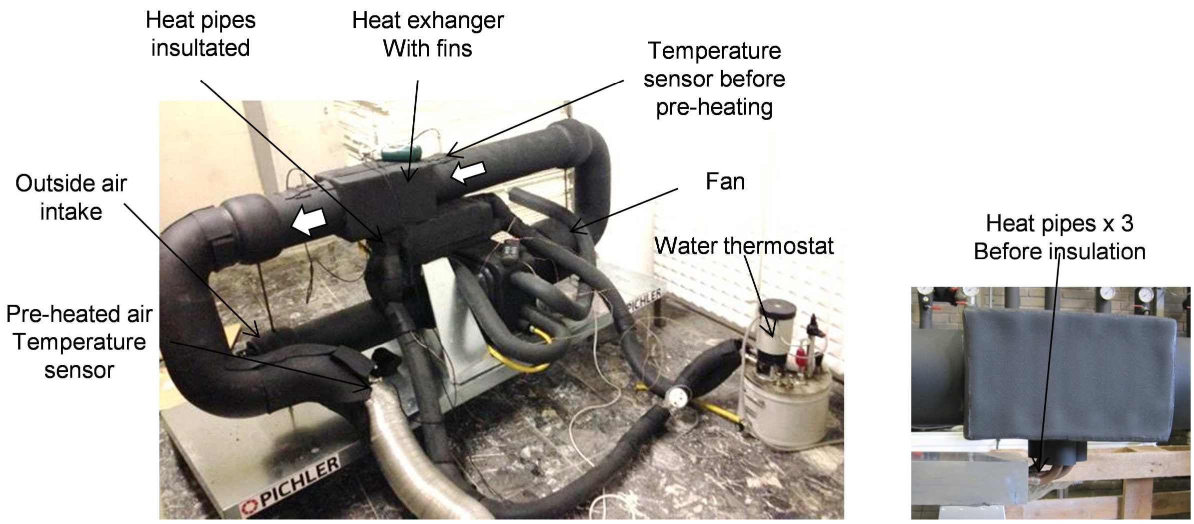


Figure 85: Measurement installation of the prototype of the heat exchanger with heat pipes.

The fan draws the outside air into the duct. The airflow through the cooling fins of the heat-pipe inside the heat exchanger air and warms up. The temperature of the air is measured immediately before and approximately one meter after the heat exchanger with the heat pipes.
The heat pipes receive the heat from warm water connected to a thermostat. The temperature of the water is measured before and after the heat-pipe. The water mass flow and airflow rates are measured at each measurement point. The whole system (including the heat-pipes) was insulated with diffusion-resistant material and installed in a room with air temperature at approx. 21°C. The measured points are reported in annex 1.
The transmitted heat flux from the water (warm source of the heat-pipes) to the heat-pipes and from the heat-pipes to the air was calculated for each point, using the equation:

$$Q_{air} = \rho_{air} \cdot c_{p,air} \cdot \dot{V}_{air} \cdot \Delta T_{air} \tag{3.11}$$

$$Q_w = \rho_w \cdot c_{p,w} \cdot \dot{V}_w \cdot \Delta T_w \tag{3.12}$$

With:

$Q_{air\ or\ w}$	transmitted heat flux from heat-pipes to air or from water to heat-pipes [W]
$\rho_{air\ or\ w}$	density of air or of water (for air: 1,20 kg/m³, for water 1000 kg/m³)
$c_{p,air\ or\ w}$	heat capacity of air or of water (for air: 1005 J/(kg.K), for water 4182 J/(kg.K))
$\dot{V}_{air\ or\ w}$	flow rate of air or of water [m³/s]
$\Delta T_{air\ or\ w}$	temperature difference [K]

Ideally, the heat transferred from the water to the heat pipe should be equal to the heat transferred from the heat-pipe to the air. In the diagram on Figure 87 the heat flux transmitted from the heat-pipes to the air and the measured increasing of the air temperature are represented in function of the heat-flux from the water to the heat-pipes.

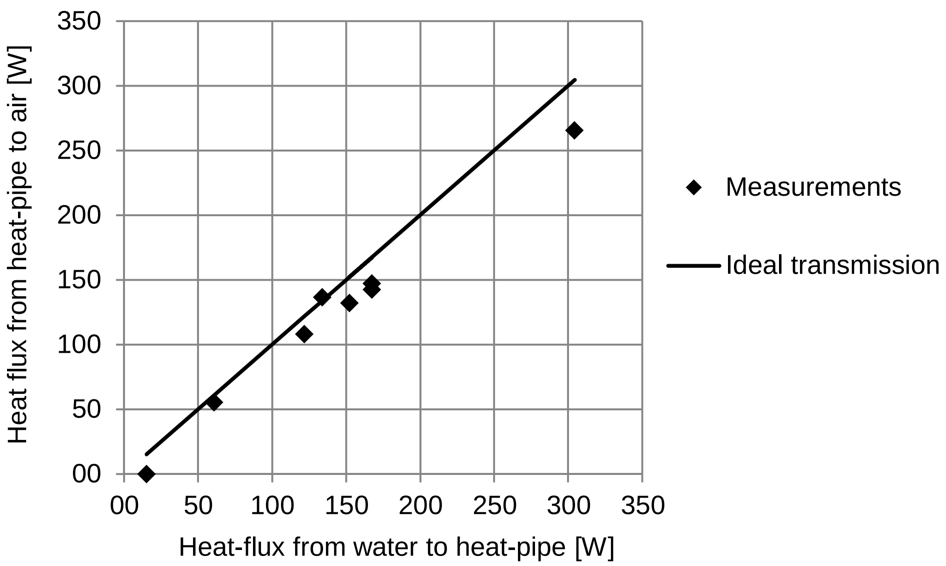


Figure 86: Heat flux from the heat pipes to the air, depending of the heat flux from the water to the heat pipes, both calculated with the measured values of temperature and flow. The line represents the ideal transmission (no heat losses).

The left diagram on Figure 87 shows that almost the whole heat flux from the water to the heat-pipe is transmitted to the air. The ideal behaviour with perfect insulation (no heat loss) is represented with the line on Figure 86.
This behaviour also explains the increase in the air temperature with the heat flux transmitted to the water to the heat-pipes (input heat flux). Indeed, in case of perfect insulation, we have:

$$Q_{air} = Q_w \qquad (3.13)$$

Hence,

$$\rho_{air} \cdot c_{p,air} \cdot \dot{V}_{air} \cdot \Delta T_{air} = Q_w \qquad (3.14)$$

Thus,

$$\Delta T_{air} = Q_w \cdot \frac{1}{\rho_{air} \cdot c_{p,air} \cdot \dot{V}_{air}} \qquad (3.15)$$

Thus, at constant airflow rate, the temperature increasing is directly proportional to the input heat flux, Q_w. This linear behaviour is represented by a trend line on the right side of Figure 87.

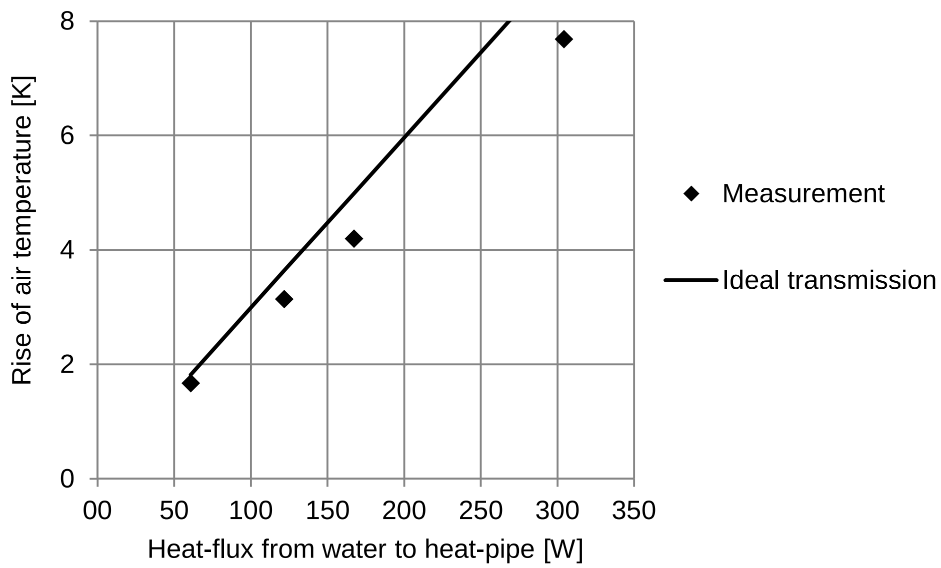


Figure 87: Measured increasing of air temperature for varying measured heat flux from water to heat pipes, at constant airflow rate (approx. 100 m³/h).

The measurements were made for different water temperatures in the thermostat (26°C, 31°C, 36°C, 39°C and 49°C). At water temperature 26°C it was observed that no heat transmission occurs between water and air (no temperature difference on both sides). This is because the temperature is too low to allow the evaporation of the water inside the heat-pipe.

4.3. Model validation

In (Pfluger, 2014) a model of the heat transfer with the heat-pipes connected to the ventilation unit with heat recovery was built in the Engineering Equation Solver (EES, F-Chart software) software. The diagram window is presented in Figure 88.

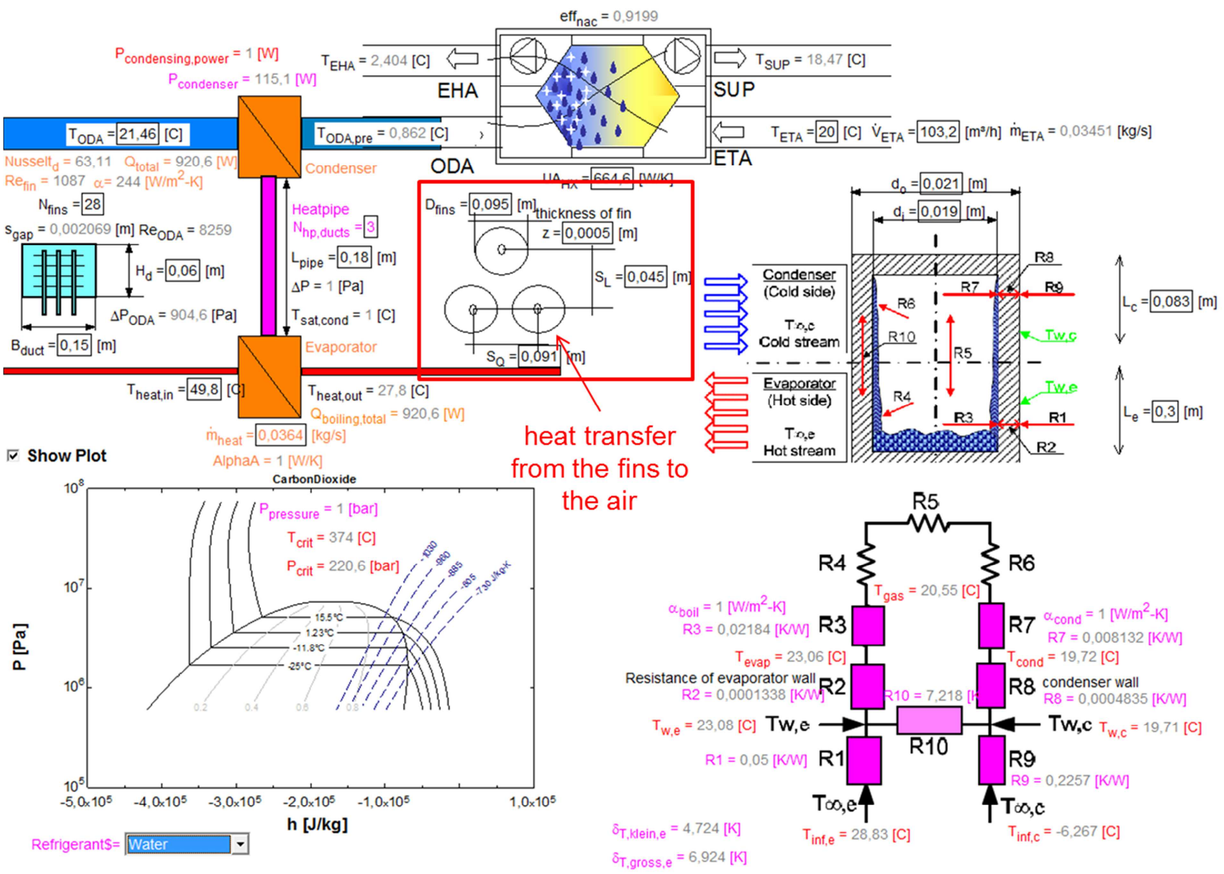


Figure 88: Screen-shot of the model of the heat transfer through the heat pipes, connected to the air intake of a ventilation unit with heat recovery in EES.

This model was adapted in order to the measurement installation. Particularly, description of the heat transfer in the heat exchanger from fins to the cold air was modelled with three circular fins, for which the cooling behaviour is described in (von Böckh & Wetzel, 2009), pp 102-104. According to this description, the heat transfer coefficient depends on the efficiency of the heat transfer from the heat pipe to the fin, which is given by:

$$\eta_{Ri} = \frac{\tanh X}{X} \tag{3.16}$$

With:

$$X = \varphi \cdot \frac{d_a}{2} \cdot \sqrt{\frac{2 \cdot \alpha_a}{\lambda \cdot s}} \tag{3.17}$$

With:

φ Correction factor for circular fins
d_a External diameter of the heat pipe [m]
α_a Heat transfer coefficient at the surface of the fin [W/m².K]
λ Conductivity of the fin [W/m.K]
s Thickness of the fin [m]

The correction factor for circular fins is expressed through the equation:

$$\varphi = (\frac{D}{d_a} - 1) \cdot \left[1 + 0{,}35 \cdot ln \frac{D}{d_a}\right] \quad (3.18)$$

With:
D Diameter of the fin [m]

The air and water temperatures, as well as the air and water flows were entered for the several measurement points. The air and water temperatures after pre-heating, as well as the heat flux at both sides of the heat-pipes were calculated by the simulation program. Then, the simulations and measurement results were compared. The diameter of the transfer discus was slightly adapted to reach an optimal fit with the measurements.
The comparison between measurement and simulation results is summarized in Figure 89 and Figure 90.

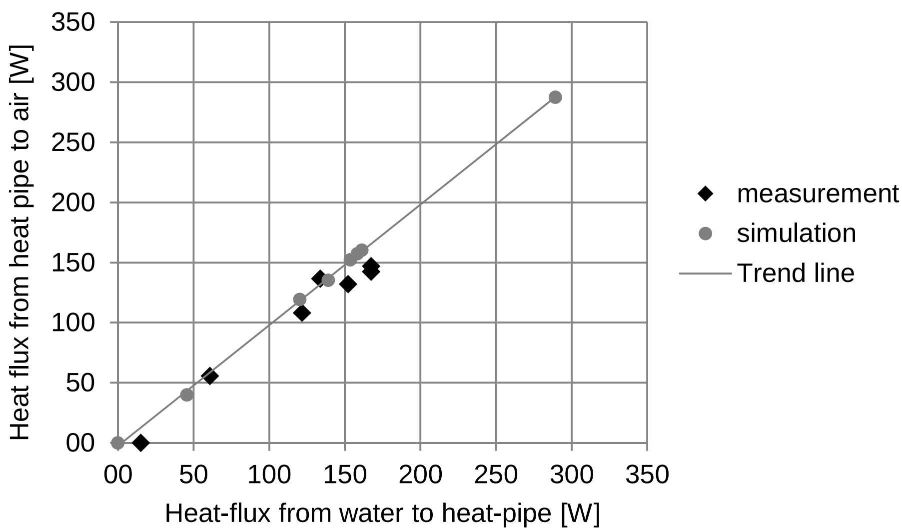


Figure 89: Heat flux from the heat-pipes to the air (output) depending of the heat flux from the water to the heat pipes (input), calculated with the measured values and with the simulation results.

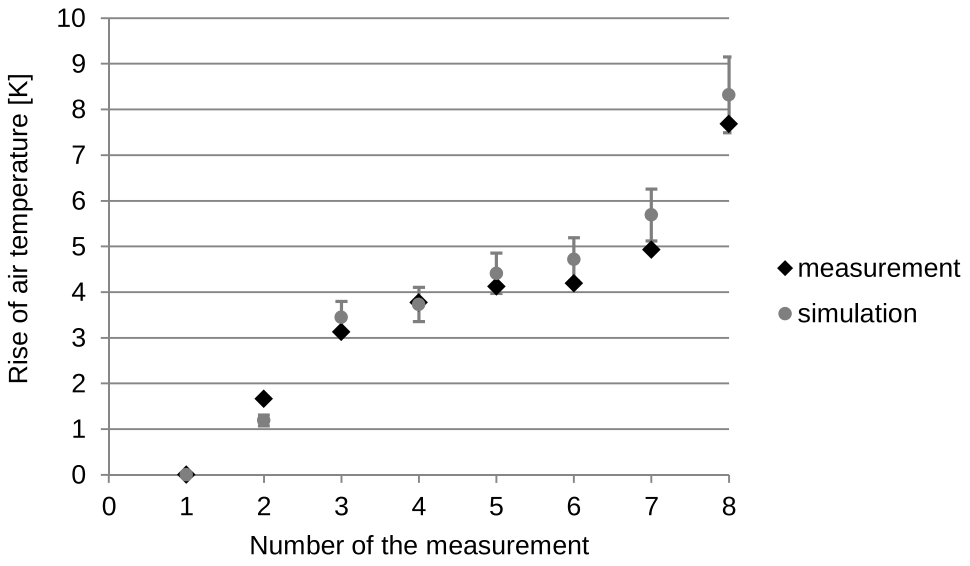


Figure 90: Report on the increasing of the temperature for the various measurement points: comparison of the measurement and simulation results. The error indicators represent 10% error.

The results show that the simulated data are close to the measurements. An error of maximum 10 % is observable by almost all the points.
This error is due to measurement inaccuracy, particularly for the measurement of the water flow rate. These results allow the validation of the model. It is used in the next part to make some prognostics on cases which are closer to reality (outside air temperature by -15°C).

4.4. Conclusion

The validated model is used to calculate the required water mass flow in order to reach air temperature above 0°C at the air exhaust. Simulations were performed for an apartment-central unit with 100 m³/h and that has 95% heat recovery for varying outside air temperature. The results are summarized in Figure 91.

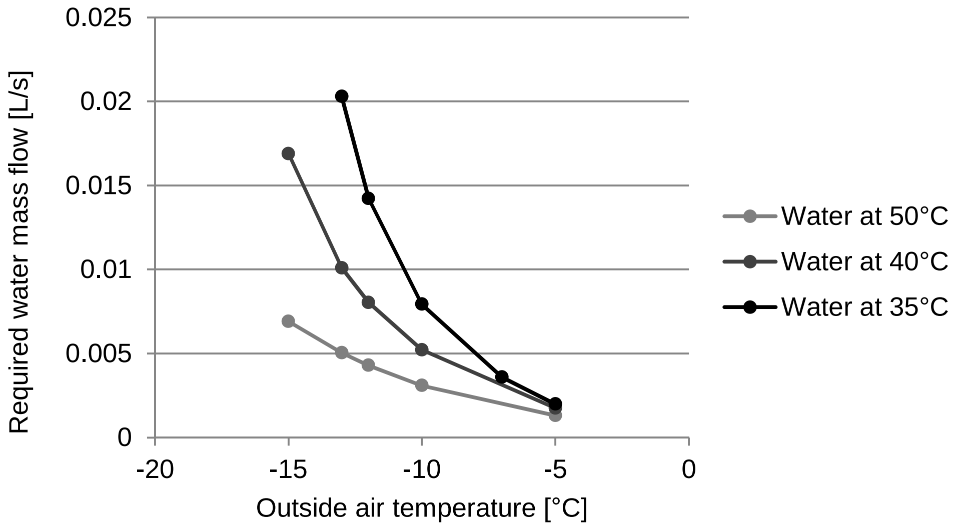


Figure 91: required water mass flow at several supply flow temperature to reach 0,5 °C at the air exhaust for varying outside air temperatures (assumed an airflow rate of 100 m³/h through an apartment-central unit with 95% heat recovery).

The results show that depending on the temperature of the water source and the outside air temperature, the required mass flow varies between 0,002 L/s and 0,02 L/s. Water with only 35°C or 40°C is sufficient for the operation of the heat pipes. This strategy can thus be used in combination with a heat pump.

5. Conclusion

The focus of this part was to survey the feasibility of integrating the air inlet and outlet ducts of an apartment-central unit into a prefabricated coaxial duct. Based on existing previous studies, constructions drawings were made and a prototype was ordered. Visual tests and measurements with tracer gas on the prototype were performed to survey the issue of short cut between exhaust air and intake. Both analyses showed that the risk of redrawing of the exhaust air through the inlet grid is very little (less than 1 %), regardless of the products used for the outlet nozzle and the air intake grid. The survey rather pointed out the issue of pressure drop through the exhaust nozzle, which should be minimized in order not to increase the operating cost of the unit.

Since a defrosting strategy is required for the installation of units without humidity recovery in central Europe, a concept with a wrapped heating-foil on the intake duct was surveyed. This concept is particularly attractive for coaxial ducts because the intake duct is also the external one: its diameter is larger than in usual constructions, thus a higher heat transfer surface is available. Measurements were driven with a prototype of the heating foil wrapped around the coaxial duct and allowed a validation of the model of the heat transfers. At steady state, the results confirm that a minimum heating load of 766 W is necessary to warm up the air from -20°C to -3°C for an airflow rate of 120 m³/h. The heating load must be increased, depending on the quality of the insulation of the system. In addition, a thin insulation layer between the two ducts is recommended in order to prevent the freezing of condensation in the exhaust air duct.

Further measurements and simulations with different control strategies allowed making some prognostics about the energy consumption of this defrosting concept in a typical central European climate. The results showed that an optimized tuning of the control strategy allows for up to 30 % savings in the yearly energy consumption for defrosting.
As alternative to electric defrosting, a strategy using heat-pipes to transfer the energy from a warm source (for example warm water with 40°C) to the air intake duct was surveyed. This principle is attractive because it does not require any direct electric energy or any pump. Measurements on a prototype of heat exchanger with heat pipes were made in order to validate the theoretical model. The results confirmed that this principle is fungible for the air defrosting of an apartment-central unit, and can be combined with any domestic hot water system.

General conclusion

The research work developed in this dissertation responds to the need for simple installations and practicable planning tools, in order that the investment and operating costs of ventilation with heat recovery in residential buildings can be reduced.

As it has been demonstrated by the findings in the first part of this document, the concept of extended cascade ventilation simplifies air distribution in apartments, and leads at the same time to a significant reduction in operating costs (approx. 25 %). The analysis of the feasibility of this concept for each type of floor plan configuration has enabled the establishment of precise guidelines for designers, which is interactive and freely accessible online under the link: http://www.phi-ibk.at/luftfuehrung/ .

In addition, design rules for the realization of a “duct-free” supply air distribution concept with active transfers have been established. The results show that with the current range of available products (airflow rate through the active transfers at 70 m³/h) a global airflow of 80 m³/h is recommended for a three-room apartment in order to reach a similar quality of indoor climate than with cascade ventilation. The analysis of the associated electrical consumption showed however that this concept still consumes approximately 30 % more electricity with currently available products than cascade ventilation. Nevertheless, this strategy appears extremely promising for the distribution of heating and cooling loads via air in apartments. Product development must therefore focus on increasing the airflow rate (target value 150 m³/h), while keeping sound emissions low and facilitating integration within existing constructions.

Eventually, the survey and development of an optimized integration of the air intake and air exhaust in a coaxial duct of an apartment-central unit eliminated the issue of short cut between air exhaust and intake (less than 1%). The feasibility of integrating frost protection via an electric foil or using heat pipes was also confirmed.

Through simplified integration, ventilation with heat recovery tends to become more affordable to investors in residential areas. Indeed, some of the developed strategies are today either planned (active transfers) or already constructed (extended cascade ventilation) in real building projects. However, the experience gained from project planning shows that the implementation of ventilation systems with heat recovery in residential areas is today still an important financial issue. This gives rise to the question of which perspectives to follow for further cost reduction.

A first response appears by the observation of the evolution of the cost of ventilation units in the past years. At the beginning of production, important research and development efforts lead to elevated costs. However, with the amount of units sold, a learning effect takes place and the costs decrease. This pattern is typical for many industrial products and is called the ”learning curve” (Jung, 2014). The following equation gives an example of such a typical evolution:

$$K(p) = K_0 \cdot L^{log_2(\frac{p}{p_0})}$$

With:

$K(p)$	the cost of one piece when p pieces are sold [€]
K_0	the cost at beginning [€]
L	the learning rate [%]
p	the number of pieces sold [pc.]. p can be described as a function of time.
p_0	number of piece sold at the beginning [pc.]

Typically, for ventilation with heat recovery in residential areas, the learning curve would appear as in Figure 92.

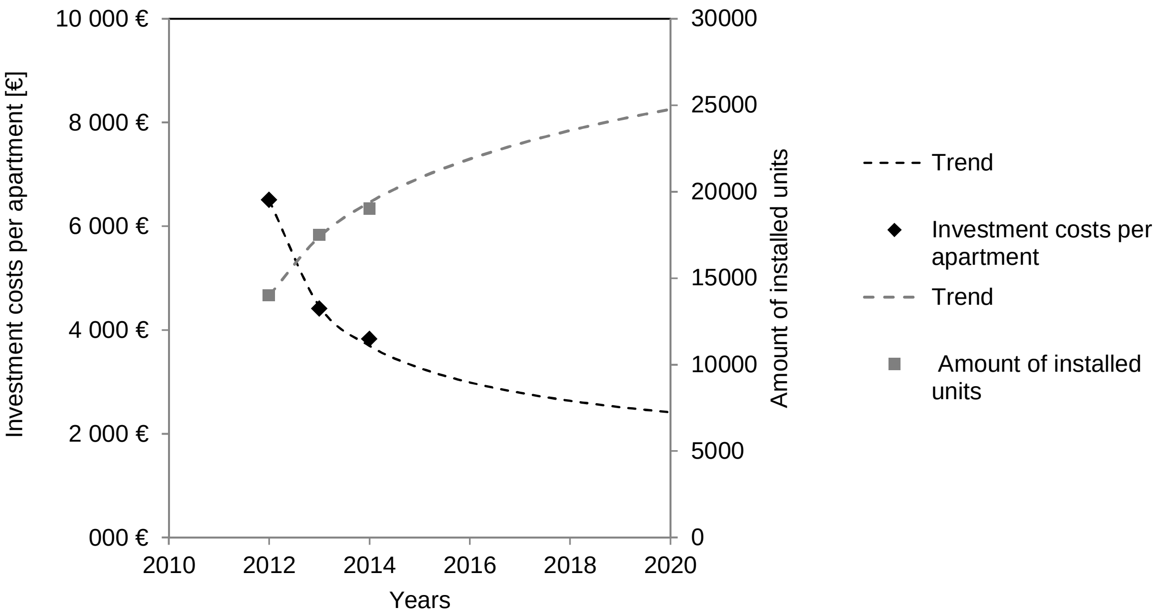


Figure 92: Classical pattern of cost evolution with learning effect applied to ventilation with heat recovery. The costs data derive from several producer and building owner data in the past three years. The behavior of the sold quantities derive from statistical data (Komfortlüftung Verband, 2015).

The observation of this curve leads to the following statements:

(1) The significant reduction of the investment costs per apartment unit observed in the past years confirms that the technology and planning knowledge are nowadays mature for large-scale implementation of highly efficient ventilation with heat recovery in residential areas.

(2) Innovation efforts in terms of low-tech strategies, integrated and pre-fabricated design must continue to be exerted to make ventilation with heat recovery more attractive, and thus increase the quantities sold.

(3) The development of design tools is vital in increasing the learning effect and thus reducing the costs.

(4) A wider spreading of this system can also be achieved with wisely applied funding programs. For example, a funding rate that would make high efficiency ventilation system as expensive as other, lower performance solutions would support building owners in their investments. An annually decreasing funding rate would support this effect.

(5) If the trend continues, investments costs of 2000€ per apartment can be expected by 2020. In this case, the implementation of high efficiency ventilation will no longer be a financial issue.

A second perspective for further cost reduction is offered by the observation of life cycle costs compared to the annuity of the investment.

The results of such an analysis for a residential building in Vorarlberg, Austria (building with 18 apartments) offer a typical example. The analysis was driven by several assumptions regarding the durability of the ventilation unit (Figure 93).

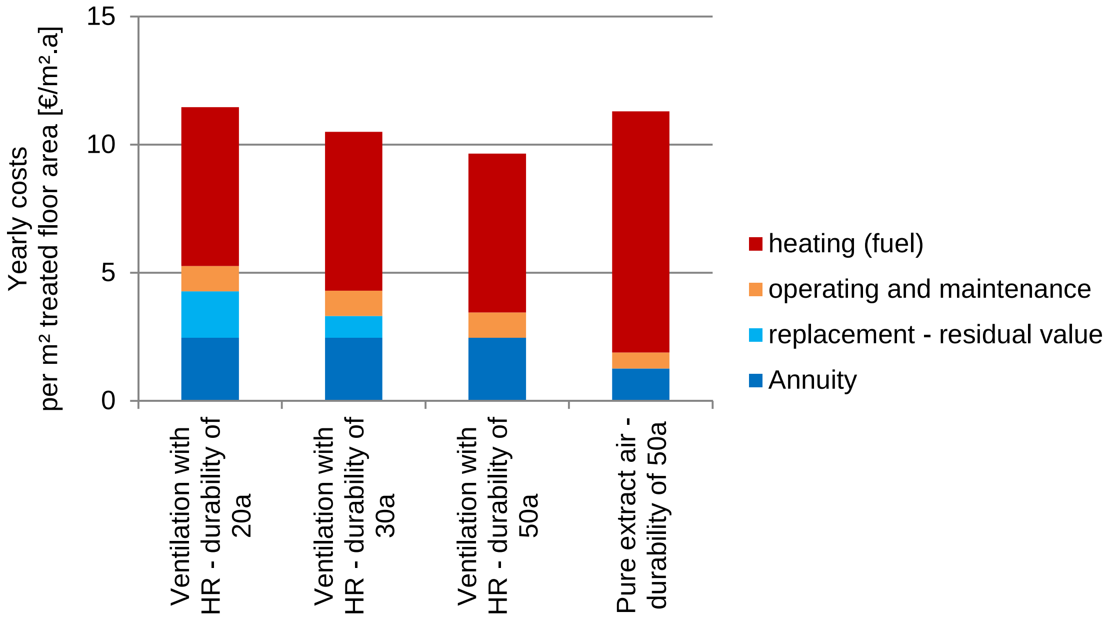


Figure 93: Investment, operating and heating costs of ventilation in a passive house over 50 years for varying durability of the ventilation unit. The investment, heating and operating costs are adapted from (Sibille & Malzer, 2015) and calculated with the EconCalc application. Maintenance costs derive from (Schöberl & Hofer, 2011).

The observation of this diagram leads to the following conclusions:

(1) Assuming a durability of 50 years of the ventilation unit rather than the generally assumed 20 years, the total costs over 50 years are reduced by 16 %. The installation of ventilation with heat recovery in dwellings is relatively new and it is thus hardly possible to precisely determine their durability. However, the experience gained from work on a number of apartment buildings, where ventilation was installed for over 25 years, tends to show a low frequency of replacement.

(2) Even if the ventilation system with heat recovery needs to be replaced after only 20 years (worst case), it is still as economical as a pure extract air ventilation that

would have a durability of 50 years! Moreover, the installation of ventilation with heat recovery provides a more comfortable and healthier indoor climate to the occupants. The heat recovery system also saves more than one third of the heating energy, which represents in this case more than 6 tonnes of emitted CO_2 every year (for the 18 apartments).

These observations lead to further research perspectives in the field of high performance ventilation in residential areas. First, low-tech systems that can be easily integrated in buildings, particularly in refurbishment should be further developed. In addition, corresponding planning tools should be systematically provided in order to facilitate the implementation of innovative solutions. Eventually, the operation of ventilation in residential areas must be further surveyed in order to better define the needs of occupants, and to optimize the durability of the systems.

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Annex 1

Calculation of the internal pressure drop in the unit:

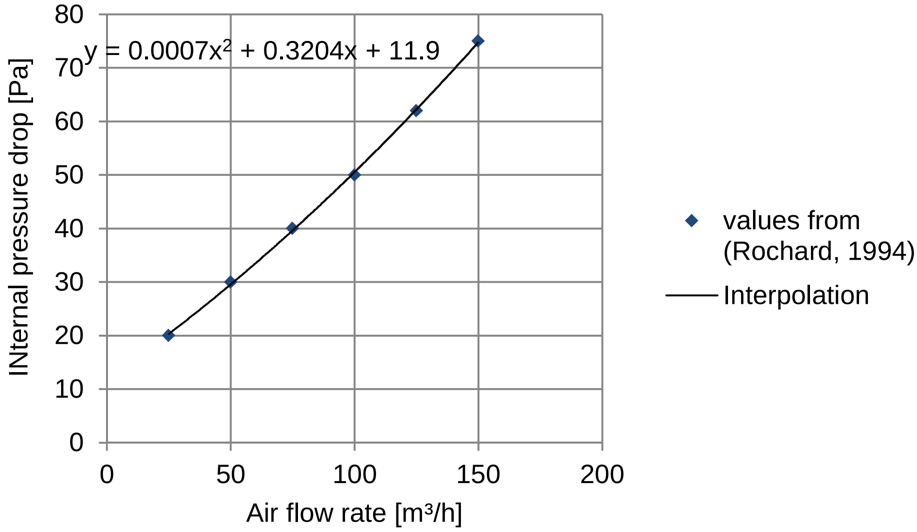

Figure 94: Internal pressure drop in the unit depending on the airflow rate. The curve is interpolated from the values in (Rochard, 1994).

Airflow rate through the fan [m³/h]	Internal pressure drop in the unit [Pa]
50	30
60	34
70	38
90	46
110	56

Table 15: Resulting internal pressure drop inside the ventilation unit for the surveyed examples.

Annex 2

Detail of pressure drop and electrical consumption of the unit in the apartments:

		Metal spiral pipes		Semi-rigid ducts	
Apartment A1		**standard cascade**	**extended cascade**	**standard cascade**	**extended cascade**
Max. pressure drop in supply branch	Pa	31	28	27	27
Max. pressure drop in extract branch	Pa	18	18	32	32
Internal pressure drop	Pa	46	34	46	34
Total Pressure drop supply	**Pa**	**77**	**62**	**73**	**61**
Total Pressure drop extract	**Pa**	**64**	**52**	**78**	**66**
Airflow rate	m³/h	90	60	90	60
Specific power supply fan	Wh/m³	0.13	0.15	0.13	0.15
Specific power extract fan	Wh/m³	0.12	0.13	0.13	0.15
Electric power of the unit	W	22.5	16.8	23.4	18
Electricity consumption over year	**kWh/a**	**197.1**	**147.2**	**205.0**	**157.7**
Electricity costs over year	€/a	33.5	25.0	34.8	26.8

		Metal spiral pipes		Semi-rigid ducts	
Apartment A2		**standard cascade**	**extended cascade**	**standard cascade**	**extended cascade**
Max. pressure drop in supply branch	Pa	24	35	30	46
Max. pressure drop in extract branch	Pa	16	8	32	24
Internal pressure drop	Pa	38	30	38	30
Total Pressure drop supply	**Pa**	**62**	**65**	**68**	**76**
Total Pressure drop extract	**Pa**	**54**	**38**	**70**	**54**
Airflow rate	m³/h	70	50	70	50
Specific power supply fan	Wh/m³	0.14	0.17	0.14	0.18
Specific power extract fan	Wh/m³	0.13	0.15	0.14	0.16
Electric power of the unit	W	18.9	16	19.6	17
Electricity consumption over year	**kWh/a**	**165.6**	**140.2**	**171.7**	**148.9**
Electricity costs over year	€/a	28.1	23.8	29.2	25.3

		Metal spiral pipes		Semi-rigid ducts	
Apartment A3		**standard cascade**	**extended cascade**	**standard cascade**	**extended cascade**
Max. pressure drop in supply branch	Pa	35	32	30	28
Max. pressure drop in extract branch	Pa	20	16	48	41
Internal pressure drop	Pa	56	46	56	46
Total Pressure drop supply	**Pa**	**91**	**78**	**86**	**74**
Total Pressure drop extract	**Pa**	**76**	**62**	**104**	**87**
Airflow rate	m³/h	110	90	110	90
Specific power supply fan	Wh/m³	0.14	0.13	0.14	0.13
Specific power extract fan	Wh/m³	0.13	0.12	0.15	0.14
Electric power of the unit	W	29.7	22.5	31.9	24.3
Electricity consumption over year	**kWh/a**	**260.2**	**197.1**	**279.4**	**212.9**
Electricity costs over year	€/a	44.2	33.5	47.5	36.2

Table 16: Calculation of the total pressure drop in the supply and extract branches in every surveyed variant. It derives the specific power of the fan and the electrical consumption of the unit. The calculation of the yearly electricity costs is made with 0,17 €/kWh.

Annex 3

Pressure drop through the supply air valves for the surveyed situations:

Airflow rate at the supply valve	Chosen product for the supply valve	Pressure drop at outlet (according to technical data)
30 m³/h	Wall diffuser Type CTVK – 125 mm (J. Pichler)	15 Pa
64 m³/h	Sound insulating wall chamber with diffuser (Schako – Klima Luft) Type R-DSC-402– 1000 mm	15 Pa
68 m³/h	Sound insulating wall chamber with diffuser (Schako – Klima Luft) Type R-DSA-VD1– 1000 mm	10 Pa
80 m³/h	Sound insulating wall chamber with diffuser (Schako – Klima Luft) Type R-DSC-401– 1000 mm	10 Pa
120 m³h	Sound insulating wall chamber with diffuser (Schako – Klima Luft) Type R-DSC-4-401– 1000 mm	25 Pa

Table 17: Pressure drop at the supply for the surveyed situations, with various types of diffuser.

Maximal pressure drop through the authoritative supply and return branches of the surveyed situations:

Situation	Active transfers 200 m³/h x 3	Active transfers 200 m³/h x 2	Active transfers 70 m³/h x 3	Active transfers 70 m³/h x 2	Standard cascade	Extended cascade
Global airflow rate [m³/h]	68	64	120	80	90	60
Max. dP supply [Pa]	11,4	15,8	29,0	11,8	20,6	17,4
Max. dP extract [Pa]	12,7	12,3	17,0	12,5	14,5	11,5
Internal dP [Pa]	37	35	60	42	46	34
Specific power consumption of both fans [Wh/m³]	0,26	0,26	0,27	0,25	0,25	0,28
Elec. power of the unit [W]	17,7	16,6	32,4	20,0	22,5	16,8
Yearly consumption of the unit [kWh/a]	155	145	284	175	197	147
Yearly consumption of the active transfers [kWh/a]	44	29	15	10	0	0
Yearly total consumption [kWh/a]	199	174	299	185	197	147

Table 18: Maximal pressure drop through the authoritative supply and return branches of the surveyed situations.