Comparison of three residential ventilation systems in practical operation

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Abstract. Three mechanical ventilation systems widely used in Swiss apartment buildings were investigated experimentally. The first system is the Central Bidirectional ventilation (CBi), where each dwelling is equipped with an AHU, supply air in bedrooms and extract air in wet rooms. In the second one, the Centralized Unidirectional ventilation (CUn), each dwelling is equipped with a unidirectional ventilation unit, extract air in wet rooms and outdoor air transfer devices in bedrooms. In third system bedrooms and living rooms are equipped with non-ducted Decentralized Ventilation Units (DVU), additional the wet rooms are served by independent extract air fans. The three ventilation systems were investigated in a total of 33 flats in 17 apartment buildings, with a total of 98 supply air rooms and 86 extract air rooms. Multiple products were represented in all systems. The cleanliness of the ventilation systems was assessed visually and the frequency of filter changes was queried.

With few exceptions, the hygienic condition was good to satisfactory. In 80% of the CBi systems and DVU's, filters were changed at least once a year. In the CUn systems, this was done only half as often. The air flows were measured in all rooms as found. Then the filters were changed and the ventilation components were cleaned. Finally, all airflows were measured again. The values in the as-found and clean condition were compared with the requirements of the Swiss standards. Overall, the CBi systems proved to work quite stable and robust. The supply air flow rate was 6% lower in the as-found conditionthan after cleaning. For the other two systems, significant reductions in supply air flow rates dueto clogged filters and devices were observed as well as significant imbalances. One conclusion is that CUn and DVU systems would require significantly more filter changes and cleaning to ensure the same reliable operation conditions as the CBi system. For the CBi, the specific electric power input was determined and compared with measurements in projects carried out 9 and 12 years earlier. The SPI was about one third lower than in the older projects, which was interpreted as product improvements.

Keywords. Residential ventilation. Bidirectional ventilation unit. Unidirectional ventilation unit. Non-ducted ventilation unit. Specific power input (SPI).
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1. Introduction

In Swiss apartment houses with continuous running mechanical ventilation, three systems are widely spread:

Central Bidirectional Ventilation (CBi)
Each flat is equipped with a ducted bidirectional air handling unit (AHU) with heat recovery. Bedrooms were served with supply air. Extract air is removed from bathrooms, toilets and kitchens. No supply or extract air is required in the air transfer zone, even if it contains a living space.

Figure 1 shows a simplified scheme of the system.

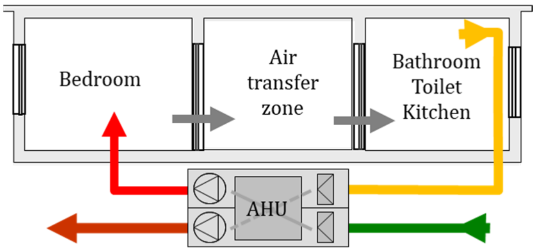


Fig. 1 – Scheme of the CBi system

Central Unidirectional Ventilation (CUn)
Only extract air is mechanically conveyed. For this each flat is equipped with a ducted unidirectional ventilation unit. Alternatively, a central extract air fan serves several or even all flats of an apartment house. Outdoor air is suck in the bedrooms through outdoor air transfer devices (OTD). Figure 2 shows a simplified scheme of the system.

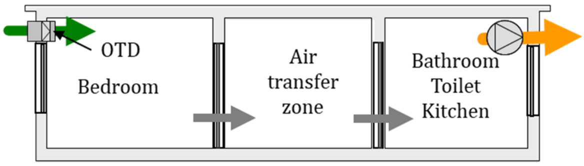


Fig. 2 – Scheme of the CUn system (OTD: outdoor air transfer device)

Decentralized Ventilation Units (DVU)
Bedrooms and living rooms are equipped with non-ducted bidirectional AHUs with heat recovery, the so-called Decentralized Ventilation Units (DVU). Typically, bathrooms and toilets are served by additional exhaust fans. Mostly each wet room has his own exhaust fan, which is switched on only during or after the use of the bath or toilet respectively. Less often a central extract air fan with continuous operation is used. Figure 3 shows a simplified scheme of the system.

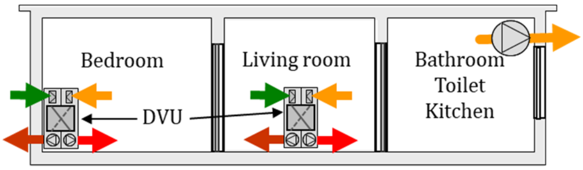


Fig. 3 – Scheme of the DVU system (DVU: non-ducted decentralised ventilation unit)

All three systems are dealt in the old Swiss standard for residential ventilation, the SIA 2023 [1] and the new standard SIA 382/5 [2]. A main area of application for the systems is residential buildings designed according to the Swiss Minergie energy label. Hints, recommendations and specific Minergie requirements for these systems are available in the brochure 'Gute Raumluft' [3] and the Minergie application guide [4]. All publications are available in German, French and Italian.

For owners, planners and operators of residential buildings it is relevant to know the strengths and weaknesses of ventilation systems in practical operation. On the one hand, this is a basis for system evaluation and, on the other hand, it helps to take the right preventive measures for optimal operation. Further, the authorities also have an interest in this information so that the requirements and funding measures can be targeted. Therefore, in 2017 the Conference of the Energy Offices of the Eastern Swiss Cantons launched a project for the investigation of systems CUn and DVU. In 2019 an analogue project for the CBi system was added. The final report of the first project has been published in 2019 [5] and for the second project in 2021 [6].

2. Research method

The aim of the projects was to compare the practical operation of the three ventilation systems on an equal basis. The dwellings for the investigation had been selected so that in each ventilation system products from different manufacturer are represented. Additionally in one housing estate maximum 3 flats were chosen. Finally the objects had to be located in different parts of the main Swiss settlement area, the Swiss Plateau. Table 1 shows selected data from the three ventilation systems.

Tab. 1 – Selected data of the investigated systems

Description	Number in the system		
	CBi	CUn	DVU
Flats	11	13	9
Housing estates	7	6	5
Products	4	4	2
Supply air rooms	29 [a]	26 [a]	[b]
Supply air transfer devices	40	42	16 [c]
Extract air transfer devices	44	31	19

a without rooms in transfer zone, like living rooms
b not recorded, only selected units were measured
c number of selected units

First, the air flow rates of all supply and exhaust air devices were measured in each flat as found. Secondly, the easily accessible parts of the ventilation systems were cleaned, and the filters replaced. At the same time, the hygienic condition was visually assessed. By questioning the caretakers or the residents, it was ascertained how often the filters are changed and when the last filter change took place. Finally, all air flow rates were measured in the clean condition. In both sates the measured air flow rates were compared with the requirements of the Swiss standards. The imbalance of the flat as-found and in the cleaned state was determined and the influence on the efficiency of the heat recovery was calculated.

In the project with the CBi systems, the specific power input (SPI) was evaluated and compared with projects carried out about 10 years earlier.

3. Results

3.1 Maintenance

In the CBi and DVU systems, about 80 % of the flats had a maintenance contract or the filters were changed by the caretaker once or twice a year. In the CUn system, filters were changed at least once a year in only about one-third of the outdoor air transfer devices (OTDs). For another third, this took place about every two years and for the rest every three or more years. Overall, maintenance was less well organised for the CUn systems than for the other two.

After the filters, the outside air grilles were the most heavily soiled components in all ventilation systems. Overall, the soiling was only hygienically sensitive in 20% of the OTD and in one CBi system with a removed extract air filter. However, the clogging led to additional pressure losses, especially in the OTDs and DVUs, which in some cases massively reduced the air volume flows (for data see the following chapters).

3.2 Air flow rates of the CBi systems

Figure 4 shows the ratio of the measured supply air flow rates of the entire flat in the found and cleaned state, compared with the required minimum of the standard SIA 2023. Since all dwelling were built before 2021 this standard was relevant and not SIA 382/5. For commissioning, a tolerance of 10% for the total air flow rate (of the entire flat) is permissible. 9 out of 11 flats with the system CBi met the total supply air flow of the old Swiss standard both, in the found and the cleaned state. The new standard SIA 382/5 typically requires about 25% lower minimum values. It can be said for the total supply air flow rate, all flats comply with SIA 382/5.

Besides a minimum total air flow rate of the dwelling, SIA 2023 and SIA 382/5 require a minimum supply air flow rate of 30 m^3/h for each supply air room. For commissioning, for this value a tolerance of 15% is permissible. This means a measured supply air flow of 25.5 m^3/h meets the standards. Figure 6 shows for the CBi system the cumulative frequency of rooms with a supply air volume flow below a certain value. Graphs are shown for the found and the clean state.

In the found state 24% of the supply air rooms didn't fulfil the standards. In the clean state the number is 28%. Figure 6 shows that the air volume flow rates generally slightly increased as a result of cleaning. In one flat, which was found with the extract air filter removed, a readjustment of all air volume flows took place, which led to a reduction in 3 supply air rooms. The reason for too low air flow rates (below the lower tolerance) was in about half of the cases bad adjustment. The rest were intentionally undersized, despite the requirements of the standard.

3.3 Air flow rates of the CUn systems

Analogous to Figure 4, Figure 5 shows the ratio of the measured total air flow rates of the flats with the CUn systems in the found and cleaned condition, compared to the required minimum of the SIA 2023 standard.

In the found state only 5 out of 13 flats met the minimum total supply air flow rate of the old Swiss standard. Even in the clean state, only 6 out of 13 comply. With the new standard SIA 382/5 6 flats in the found state and 8 in the clean state would comply. Analogous to Figure 6, Figure 7 illustrates the cumulative frequency of the supply air flow rates in the rooms with the CUn system.

In the CUn system, two thirds of the supply air rooms were equipped with a single OTD. In none of these rooms did the supply air flow rate meet the minimum requirements of the standards. In the remaining supply air rooms, two OTDs were installed. As found, 33% of these rooms did not meet the lower tolerance limit of the standard. In the cleaned state, the value was 13%.

3.4 Air flow rates of the DVUs

For the DVU system the total air flow rate of a dwelling is not relevant, because each room is ventilated individual. Analogue to Figure 6, Figure 8 illustrates for the 16 measured DVUs the cumulative frequency of supply air flow rates in the rooms.

In the as-found condition, 69% of the DVUs did not meet the lower tolerance of the air flow rate of the standard. In the cleaned condition, 56% did not meet the requirements.

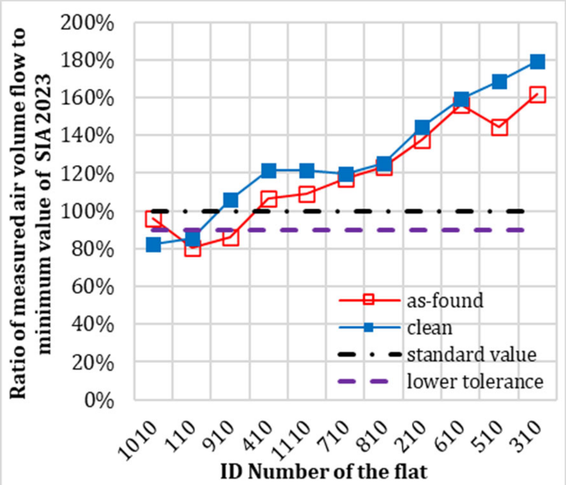


Fig. 4 – Ratio of the measured air flow rates of the flats with a CBi system compared to the requirements of the SIA 2023 standard.

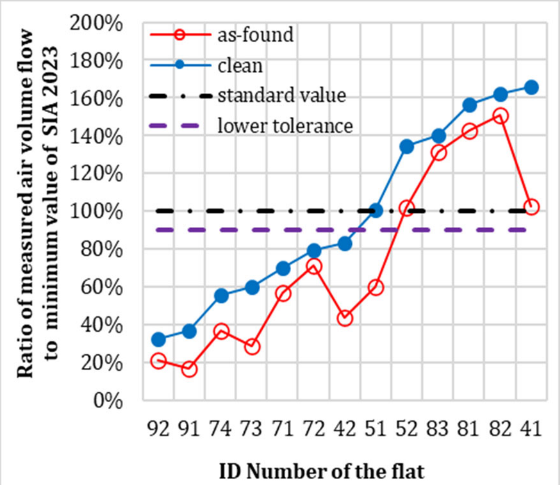


Fig. 5 – Ratio of the measured air flow rates of the flats with a CUn system compared to the requirements of the SIA 2023 standard.

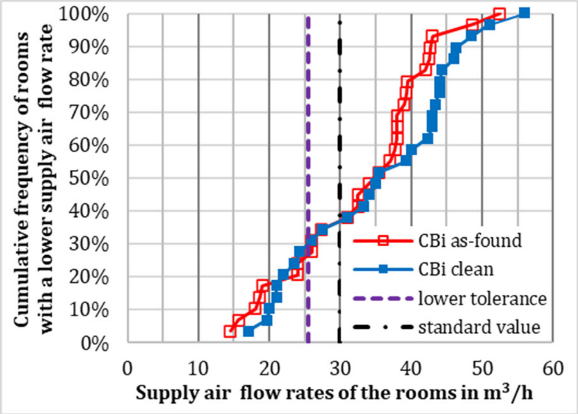


Fig. 6 – Cumulative frequency of supply air flow rates in rooms with the CBi system

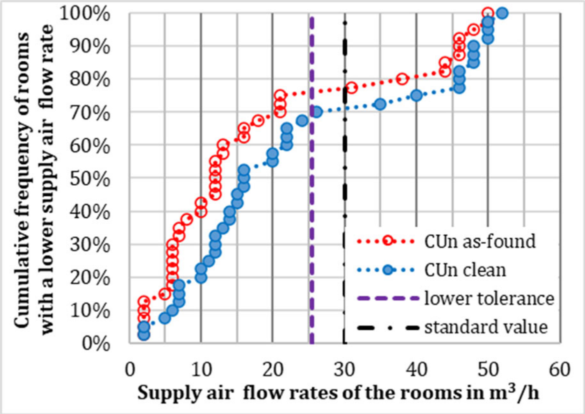


Fig. 7 – Cumulative frequency of supply air flow rates in rooms with the CUn system

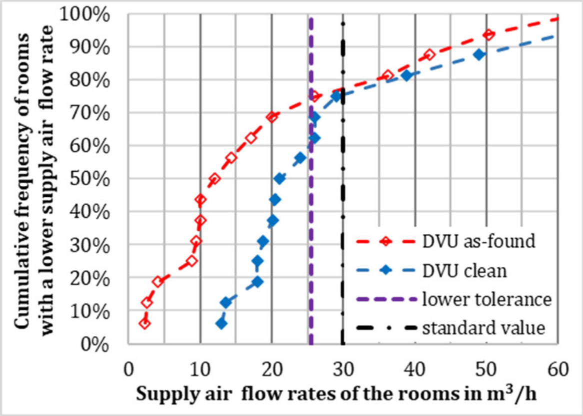


Fig. 8 – Cumulative frequency of supply air flow rates in rooms with DVUs

3.5 Comparison of air flow rates

Table 2 shows the comparison of the measured air flow rates of the three systems. The upper value is the mean value. The values below in brackets show the range between the minimum and maximum measured value.

Tab. 2 – Comparison of the measured air flow rates of the three ventilation systems

Description	CBi	CUn	DVU
Whole flat: Ratio of the measured air flow rate in clean state to the minimum value of SIA 2023	mean 129 % (82 ... 179 %)	mean 80 % (27 ... 167 %)	a
Supply air rooms only: air flow rate in clean state	mean 35 m^3/h (17 ... 56 m^3/h)	mean 24 m^3/h (2 ... 52 m^3/h)	mean 28 m^3/h (9 ... 64 m^3/h)
Ratio of the air flow rates in supply air rooms in the found state to the clean state	mean 94 % (76 ... 143 % b)	mean 83 % (38 ... 105 %)	mean 70 % (13 ... 98 %)

a For DVU, only single rooms are assessed
b Highest value: The exhaust air filter was removed in the found state.

3.5 Imbalance

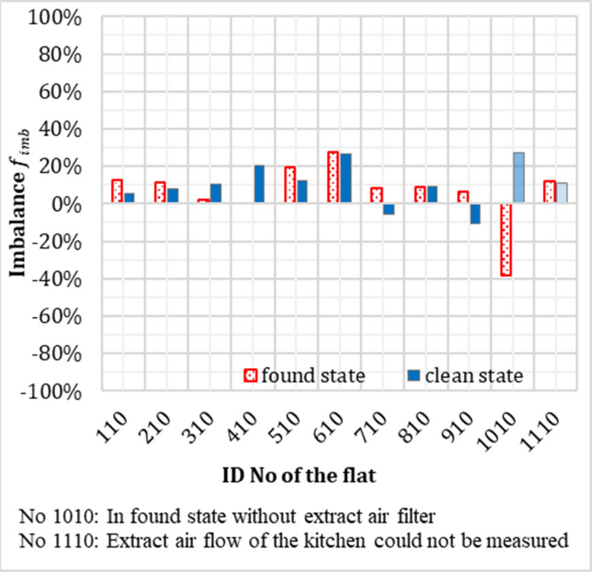
The imbalance is the difference between supply and extract air mass flow divided by the higher of the two values. This can be calculated according to Equation (1):

$$f_{imb} = \frac{q_{m,sup} - q_{m,ext}}{max(q_{m,sup}; q_{m,ext})} \qquad (1)$$

where $q_{m,sup}$ is the supply air mass flow rate and $q_{m,ext}$ is the extract air mass flow rate.

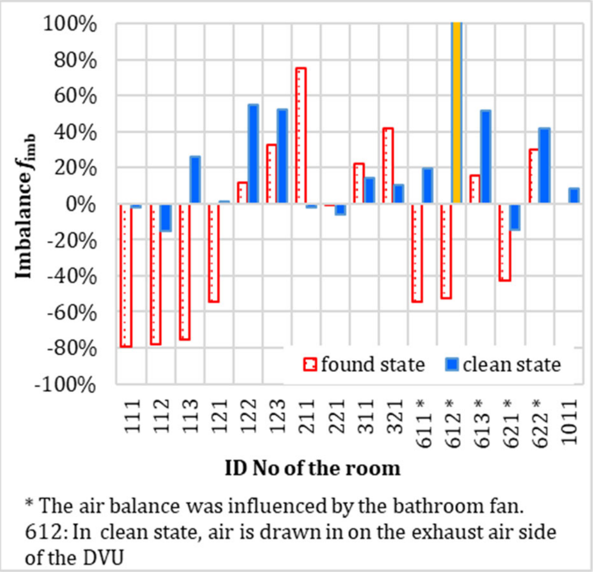
Regardless of whether the value is positive or negative, any imbalance reduces the benefit of heat recovery. Furthermore, there is additional infiltration or exfiltration and thus higher ventilation heat losses.

Figure 9 shows the imbalance for the CBi systems in the found state and the clean state. In 9 of the 11 flats it was possible to take measurements for the calculation of the imbalance.



No 1010: In found state without extract air filter
No 1110: Extract air flow of the kitchen could not be measured

Fig. 9 – Imbalance in the flats with CBi system



* The air balance was influenced by the bathroom fan.
612: In clean state, air is drawn in on the exhaust air side of the DVU

Fig. 10 – Imbalance in rooms with DVUs

In flat No 1110 the extract air transfer device in the kitchen was not accessible. In No 1010, the system was operated without extract air filter in the found state. In the clean state both filters (outside air and exhaust air) were used again. This flat therefore had a large negative imbalance (-38%) in the found state. After inserting the filters and cleaning there was a positive disbalance of 27%.

The mean value of the amount of the imbalance was 12% in both the found and the clean state. In 5 flats, the amount of the imbalance was below 10%, which can be described as a good value. In 2 other flats it was 10 to 20%. In the flats 410, 610 and 1010, an adjustment would be recommended due to the amount of imbalance of higher than 20%.

Figure 10 shows the imbalance for the DVUs in the found state and the clean state. In half of the cases the cleaning and filter replacement led to a clear reduction of the amount of imbalance. However, in five cases the value was higher after cleaning and filter replacement, then in the found state. In 3 cases (No 123, 613 und 622) an imbalance was part of the system design, for a reduction of the sound power level of the DVU. In No 611 to No 622 additional exhaust fans, which could not be switched off by the occupants, influenced the imbalance. In No 612 the exhaust fan of the bathroom caused such a strong negative pressure that after cleaning the outdoor air was sucked through the extract air side of the DVU into the flat.
It's to mention during the measurements for the determination of the imbalance neither strong wind nor high temperature differences was present.

For the evaluation of the impact of the imbalance to the energy efficiency of the heat recovery (HRC), the model shown in Figure 11 is used. Thereby, a room is equipped with a ventilation unit, which runs with imbalance. The difference between the extract air mass flow rate $q_{m,ext}$ and the supply air mass flow rate $q_{m,sup}$ is equal with the air mass flow rate of infiltration $q_{m,inf}$ or exfiltration. In the following, only the infiltration is shown. However, the result, the influence on the energy balance, is the same with infiltration or exfiltration.

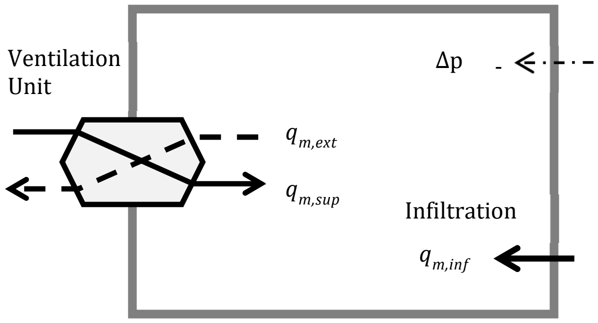


Fig. 11 – Scheme of the model for the influence of imbalance

As quality grade for the impact of the imbalance to the energy efficiency of the heat recovery (HRC) the definition 'system efficiency' is introduced. The system efficiency is the heat gain of the HRC, in relation to the heat losses of a fictional ventilation system without HRC and with an air mass flow rate, which is equal to air mass flow rate of the balanced ventilation unit. With this definition, the system efficiency can be expressed as in Equation (2):

$$\eta_{sys} = \eta_{HRC} \cdot (1 - |f_{imb}|) \tag{2}$$

where η_{HRC} is the energy efficiency of the HRC with imbalance, and f_{imb} is the imbalance according to Equation (1).

The conversion of the energy efficiency of the HRC with a mass flow ratio of 1 to the energy efficiency with imbalance can be calculated with the NTU model e.g. as described in VDI Heat Atlas [7]. For commercially available ventilation units, the model for counterflow heat exchangers can be used with good reliability. Figure 12 shows the system efficiency η_{sys} as function of the amount of the imbalance based on calculation according to the mentioned source [7]. The energy efficiency of the HRC with a mass flow ratio of 1 (symbol $\eta_{1:1}$) is the parameter.

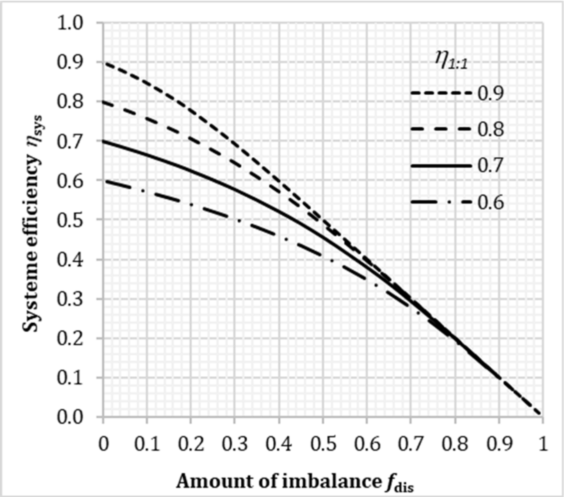


Fig. 12 – System efficiency η_{sys} as function of the imbalance f_{imb} , for different energy efficiencies of the HRC with a mass flow ratio of 1 ($\eta_{1:1}$)

With the DVU system, in addition to the imbalance in normal operation, there is a reduction in energy efficiency in mixed operation mode when the extract air fans in bathrooms and toilets are switched on and cause an additional increased imbalance. Furthermore, for both systems CBi and DVU the frost protection mode can reduce the energy efficiency. Table 3 shows the system efficiency of CBi and DVU systems including imbalance, mixed mode (only DVU) and frost protection. The later two reductions are estimated according to the project report about the practical operation of CUn and DVU systems [5]. The values for frost protection are based on average European climate. In Table 3 the reduction of the system efficiency due imbalance is calculated on base of the average measured imbalance in found state and clean state. Since for CBi systems the imbalance was the same on both states, there is only one column for this system.

3.6 Specific power input of CBi systems

Table 4 shows the comparison of the measured specific electrical power input (SPI) of CBi systems from the measurements of the current project [6] and of two older studies [8] and [9]. The SPI is defined as the electrical power input at design conditions divided by the air flow rate (average of supply and exhaust side). Although no statistically relevant statement is possible due to the small number of AHUs measured, the values can be considered representative for the period under investigation. In all measurement series, widespread AHU types of market leaders were well represented.

Tab. 3 – Estimation of the energy efficiency of CBi and DVU systems with consideration of imbalance and defrosting

Description	System and state		
	CBi [a]	DVU as-found	DVU clean
Average of the amount of the measured imbalances	0.12	0.42	0.21 [c]
Efficiency of heat recovery at mass flow ratio of 1($\eta_{1:1}$)	0.70 … 0.80	0.70 … 0.80	0.70 … 0.80
Reduction of energy efficiency by measured imbalance	0.04 … 0.05	0.17 … 0.24	0.08 … 0.10
Reduction of energy efficiency by additional imbalance caused by mixed mode with extract fans in bathrooms	[b]	approx. 0.05	approx. 0.05
Reduction of energy efficiency by defrosting function	0.00 … 0.03	0.00 … 0.03	0.00 … 0.03
Net annual energy efficiency	0.63 … 0.75	0.45 … 0.51	0.54 … 0.65

a Since for CBi the imbalance was the same on both states, there is only one column for this system

b The CBi system do not have additional fans in bathrooms

c without No 612

Tab. 4 – Comparison of the specific electrical power input (SPI) of CBi-systems from different studies

Reference	Period of investigation	Number of units in study	Specific electrical power input (SPI) in W/(m^3/h)			
			state	average value	minimum value	maximum value
[8]	2007, 2008	6	n.a. [a]	0.59	0.30	1.03
[9]	2011	11	n.a. [a]	0.47	0.29	1.09
[6]	2019, 2020	6	as-found	0.39	0.26	0.51
			clean	0.35	0.22	0.44

a No details on state of filter and soiling of components recorded in this study

As a general rule, it can be stated that the SPI values have improved by about one third in the last 10 years.

The results in [6] show that in average a reduction of the SPI of 13% is reached by cleaning. This result includes an increase of the total airflow rate by 7% and a reduction of the electrical power input of 5%. Figure 13 compares the measured SPI with the product specification at the external reference pressure difference of 50 Pa, as it is required from the European ecodesign regulation [10]. Additionally the target value and the limit value of the Swiss standard SIA 382/1:2014 [11] are shown as bench mark.

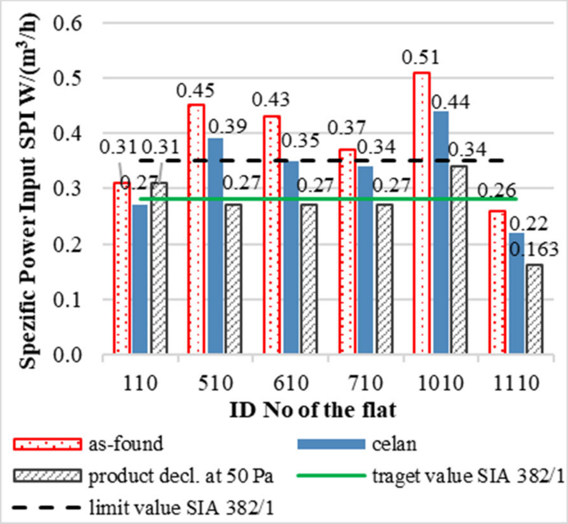


Fig. 13 – Specific electrical power input (SPI) of CBi systems measured in [6], as-found and in clean state. Comparison with target and limit values of SIA 382/1 and the product specifications at 50 Pa.

In [8] an important finding was that the internal pressure losses of the AHUs and the air duct network should be reduced to improve the SPI. The reduction of the SPI between the studies [8] and [6] of 41% for the average SPI in the cleaned state and of 57% for the maximum value suggests that such improvements took place in between. The difference between the average value to the minimum value of the SPI in the cleaned state (37%) and the encountered difference to the values stated by the product declaration at 50 Pa suggests that considerable improvements of the SPI are still possible.

4. Conclusion

With CBi systems, the air volume flow rates required by the Swiss standard were typically well achieved or exceeded in the supply air rooms and the entire flats. For the air volume flow rate of the flats, a tendency towards oversizing is observed, which mainly stems from the fact that supply air is blown in unnecessarily in living rooms that are located in the air transfer zone.

CUn systems did not achieve the air volume flow rates required by the standards in most cases. There is a tendency here to undersize. A major reason for this is probably that two OTD per room would typically be required for to meet the minimum value of the Swiss standard. However, for reasons of aesthetics, sound insulation, thermal comfort and possibly also costs, only one OTD is usually installed.

With DUVs, the required air flow rate in the rooms is slightly undercut on average. However, it should be noted that in 12 (with mainly newer designs) of the 16 units examined, on average only about half of the required supply air flow rate was available. The result that the mean value across all units is close to the standard value is due to the fact that the other 4 units (3 of which were old designs) delivered significantly higher air flow rates.

The ratio of the measured air flow rate in the found and in the clean state tells us how stable or robust the systems and ventilation units are in practical operation. Here the CBi systems obviously perform better than the other two systems. This can also be interpreted to mean that CUn systems (especially the OTDs) and DVUs should be maintained more frequently than CBi systems so that they have comparable stability.

Any imbalance reduces the energy benefit of the heat recovery and can lead to undesirable air flows in terms of building physics and hygiene. Here, too, the CBi systems perform significantly better than the other two. In particular, with the CBi systems the mean values, but also the extremes, are comparatively close to each other in the found and clean state, which again indicates a stable and robust operation. In the case of CUn systems and DVUs, it is astonishing to see the high imbalances that were determined in the found state, and how the imbalances increased due to the clogging.

5. Acknowledgment

The authors would like to thank the Conference of the Energy Offices of the Eastern Swiss Cantons for initiating the projects, the technical exchange, and the financial support.

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The datasets analysed during the current study are available in [5] and [6]
https://www.endk.ch/de/dokumentation/studien