A systematic approach to assessing indoor air quality of long term care facilities

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M. te Kulve, M.G.L.C. Loomans, E.R.C.M. Huisman, H.S.M. Kort. A systematic approach to assessing indoor air quality of long term care facilities. Gerontechnology 2017;16(4):224-238; https://doi.org/10.4017/gt.2017.16.4.004.00 Not much is known about the favourable indoor air quality in long term care facilities (LTCFs), where older adults suffering from dementia live. Older adults, especially those who suffer from dementia, are more sensible to the indoor environment. However, no special requirements for the indoor air in long term care facilities exist. Due to the decrease in cognition function, it is hard to evaluate comfort and health in this group. Nevertheless, infectious diseases are a persistent problem. Based on literature an assessment methodology has been developed to analyse LTCFs to determine if differences in building characteristics and Heating, Ventilation and Air Conditioning (HVAC) systems influence the spread of airborne infectious diseases. The developed methodology is applied in seven long term care facilities in the Netherlands. After that, the methodology has been evaluated and its feasibility and applicability are discussed. From this study, it can be concluded that this method has potential to evaluate, compare LTCFs, and develop design guidelines for these buildings. However, some adjustments to the methodology are necessary to achieve this objective. Therefore, the relation between the indoor environment and infection risk is not yet analysed, but a consistent procedure to analyse this link is provided.

Keywords: indoor air quality, infection prevention, older adults, well-being

Introduction

The number of older adults in the world is increasing rapidly[1]. This goes together with sensory changes and increased risk of age related diseases like dementia[2]. Frail older adults suffering from dementia often need institutional care and therefore live in long term care facilities (LTCFs). In these facilities, they spend most of their time indoors (95%)[3]. Additionally, older adults, especially those who suffer from dementia, have an altered sensitivity to indoor environmental parameters[2]. Since the physical environment directly influences health and wellbeing, careful attention to the indoor environment in LTCFs is desirable. The indoor air quality, contaminations, and pollutants as well as temperature, influence the health of occupants in a room[4]. Indoor environmental standards are based on the perception of average people whereas older adults are known to have a different sensitivity of the physical environment[5-7]. However, there are no special requirements for elderly care facilities[8], while the sensitivity to the indoor environment is even larger for older adults coping with dementia and who live in these care facilities[2]. Therefore, we aim to set up a systematic approach to defining favorable conditions for LTCFs.

Little is known about the current indoor climate in LTCFs, although the effect of the physical environment on the health and well-being of patients has been proved to be important[9]. A study in care facilities in Portugal showed that the indoor concentration of CO_2, tVOC, O_3, and PM10 all exceeded the limits due to insufficient ventilation[3]. A second study found that the mean PM2.5 of 22 elderly care centres was above international reference level during both summer and winter[10]. According to Aminoff[11] poor indoor environmental conditions may have a role in the suffering of people with dementia. By adjusting the indoor environment to the needs of the residents, it is expected they put less demand on the professionals working in the LTCFs.

The study of Bae and Park[6] confirmed in line with previous studies, that older adults are more likely to be affected by air pollution. Indoor air pollution can cause among others cardiorespiratory diseases and asthma[12]. Also overheating in buildings goes together with health effects. This is especially important in nursing homes because older adults are at risk to high temperature[13]. On the other hand, cold temperatures may potentiate respiratory tract infections[10]. Apart from the fact that a poor indoor air quality can cause health problems, air can also transfer pathogens of airborne diseases. The study of Li et al[14] emphasized the need for an investigation on the impact of indoor air onto the spread of airborne infectious diseases, as little is known about the impact of airflow patterns on infectious disease propagation.

The transmission of infections is complex, and controlling the infections, especially at the psycho geriatric (PG) departments of LTCFs is hard because residents can freely interact with each other and live close together. In addition, staff and visitors have an easy access to the ward. Older adults are more at risk to an infectious disease[15]. This is due to the fact that advanced age is related to a declining immune system and a weakened host defense. Illness is often recognized after it has already spread, because of subtle presentation of the infection. However, delays in diagnosing and treating infections increase the risk of transmission within the facility[16]. Besides, it is hard to apply restrictions for residents because they do not comprehend the situation[15]. Therefore, prevention of infections and outbreaks in LTCFs is important.

There are many studies that suggest that an insufficient amount of ventilation contributes to the spread of airborne diseases but no minimum ventilation rate is known[17]. The reason for the little evidence is first of all due to the large number and interacting factors that contribute to the transmission of the infections and the fact that the (airborne) evidence of the airborne infection rapidly disappears once the infection period is over. So, the influence of the ventilation impact is often too difficult to be quantified[14]. The airborne route will become more important when the other routes are blocked. Still, it is not known how much reduction of the contaminant concentration is required, to achieve a measurable reduction in disease transmission[18]. The contribution of the airborne route compared to the contact route is yet to be defined due to its complexity. Although there is not much evidence, the contact route is assumed as being the most important. Beggs[19] concluded that the contribution of the airborne route is likely to be greater than expected due to the movement of contaminated persons, though contact spread is the principle route of most infections.

Additionally, a poor indoor air quality can also contribute to a weakened host as it influences the healing process, recovery, and well-being[7]. Apart from the state of dementia, these individuals are a weakened host that makes it more likely for infectious agents to invade[25]. So apart from airborne transmission, the indoor air quality may also play another role in the infection by weakening the defense mechanism of individuals.

Based on an airborne infections disease risk model, filtering (particularly MERV 13-16 filters) was estimated to reduce the risk of infectious diseases compared to equivalent outdoor air ventilation[23]. Li et al[14] concluded that there is sufficient and strong evidence that demonstrate an association between ventilation and air movements in buildings and the transmission spread of infectious diseases indoors. Brankston et al[20] also state that control of airborne transmission requires control of airflow through ventilation. Building characteristics should be taken into account as well, as they affect bacteria, fungi, temperature and relative humidity measured in elderly care centres[10].

We can conclude that older adults suffering from dementia have different needs concerning the indoor environment and that they are at risk of infectious diseases. Still, there are no specific guidelines for the design of these indoor environments where older adults suffering from dementia live. This is probably due to the lack of knowledge about the desired conditions. Therefore, there is a need to define appropriate requirements for LTCFs. The objective of this study is to provide a systematic approach to developing design guidelines for the indoor climate in LTCFs and to benchmark these buildings. The systematic approach should be able to assess the indoor air quality in LTCFs and its effect on the spread of airborne infectious diseases. This paper describes the development of a systematic approach that can be used to set up indoor climate guidelines, which should reduce the transmission of airborne agents in LTCFs and with that the occurrence of infectious diseases in such facilities.

Method

In the current study, a systematic approach has been developed to evaluate and compare LTCFs. This approach is based on the scheme illustrated in *Figure 1*, which shows the relation between on one hand the building and indoor air quality and on the other hand outbreaks of infections and health & comfort. As shown in *Figure 1*, the building characteristics may influence as well the contact as the airborne transmission. The building also affects the indoor air quality; indoor environment measurements may reveal the contri-

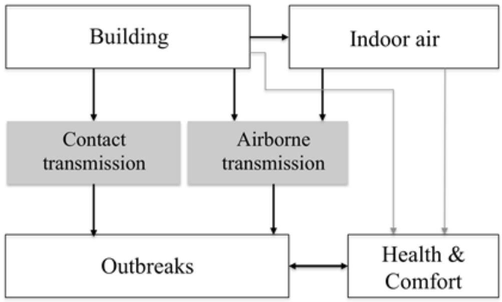


Figure 1. Scheme factors influencing airborne transmission in LTCFs

bution of the indoor air quality to airborne transmission. General health and comfort aspects are also incorporated because the indoor air quality has an impact on these as well and with that the potency for developing an infectious disease. To deduce the role of indoor air in the transmission of infections, the four "categories" in the scheme will be analysed systematically.

Literature search / define contributing parameters
To define the variables that play a role in the outbreak of infectious diseases, a literature search was done to find contributing factors to transmission. The objective of this literature search was not to provide a thorough literature review but to find the building and indoor air parameters that influence the transmission of airborne infections. Also parameters to measure and compare outbreaks of infections in LTCFs were of interest. The electronic databases that were used are Scopus, Science Direct, Google Scholar, Psychinfo and the database Eindhoven University of Technology. The search terms that were used are a combination of 'Dementia' or 'Psycho Geriatric' or 'PG patients' or 'Elderly Care' and 'Indoor Climate' or 'Air Quality' or 'Indoor air' or 'Design Guidelines' or 'Healing Environments' or 'Physical Environment' and 'Spread of disease' or 'Airborne diseases' or 'Indoor Air Quality' or 'Scabies' or 'influence' or 'Skin flakes' or 'Mites' or 'Transmission' or 'Elderly care' or 'Long term care facilities' or 'Psychotherapy' and 'Behavioural problems' and 'Assessment' and 'Treatment' and 'Systematic Review'. Additionally, references found in publications were used. In total, out of 37 articles identified, results of 13 articles were used. Titles and abstracts were used to determine whether the papers included relevant information concerning the spread of airborne diseases, influencing factors of transmission, indoor air quality in LTCFs and the sensitivity of older adults to indoor air quality.

Systematic approach
The selected publications have been used to define the parameters that might contribute to the transmission of airborne infectious diseases. These parameters are listed in *Table 2*. For each of these parameters it has been defined whether it contributes to the airborne and/or contact route and its reference(s) are added. To compare the outbreaks of infections in different LTCFs, the size, frequency, type, period and duration of the outbreaks were defined as parameters. For health and comfort, a list of variables has been composed as well. These are incorporated into a set of questions for the health care professionals. The set of questions include work schedule and activity related questions, questions about the general feeling of health, comfort, and control over the indoor climate. The Health Optimisation Protocol for Energy-efficient Buildings (HOPE) study[26] has been used to set up the structure of the evaluation of the building characteristics.

Application and evaluation of the systematic approach
To verify whether the systematic approach is suitable to analyse the relation of indoor air and the outbreaks of infections, it was tested in seven LTCFs in the Netherlands. This was done at the psycho geriatric (PG) department of the tested LTCFs. The buildings needed to be at least three years old to be included in the study, so the history of infectious diseases could be analysed. The basic characteristics of the buildings that were studied are indicated in *Table 1*.

Design of the systematic approach

The scheme presented in *Figure 1*, resulted in a systematic approach to evaluate LTCFs, with the purpose to analyse the relation between the indoor air quality and the outbreaks of infectious diseases. This approach consists of two checklists and a semi-structured interview to evaluate the building. The defined parameters of the indoor air quality have been used to set up a measurement plan. For the comparison of the outbreaks in LTCFs, the history of infections is used, taking parameters from literature. The general health and comfort variables are incorporated in a questionnaire. In *Figure 2*, an overview of the evaluation instruments is illustrated. The systematic evaluation approach consists of four parts as illustrated in *Figure 2*. Each is described and explained below.

Systematic approach
Building & HVAC evaluation
As illustrated in *Figure 2*, the evaluation of the building characteristics consists of three parts: the building characteristics (via checklist), the Heating Ventilation and Air Conditioning (HVAC) systems (via checklist) and the use of the buildings (via interview). Detailed information on the checklists and questionnaire is found in the (digital) supplementary material. The checklists on both building characteristics (for example ad-

Table 1. Basic characteristics of the LTCFs participated in study

Building	Year built	Operable windows	Mechanical ventilation	Nr of residential groups	Nr. PG patients	Size [m²] (PG - department)
A	1985	Yes	Balanced	14	84	4440
B	2010	Yes	Balanced	6	36	1710
C	1998	Yes	Balanced	2	64	2780
D	2004	Yes	Balanced	9	72	2115
E	1992	Yes	Mechanical exhaust, natural supply	4	80	2820
F	2008	Yes	Balanced	4	38	1360
G	1978	Yes	Balanced	15	90	3300

dressing outdoor conditions, building structure and material use) and HVAC systems (for example addressing natural/mechanical ventilation, humidity management, contaminant source control and maintenance) have been composed to evaluate characteristics that were found in literature to play a role in the transmission of diseases. The checklist can be filled out at the location of the building. *Table 2* indicates hypothesized connections of the building characteristics to the transmission routes and with that to the spread of infectious diseases. Technical information from drawings and descriptions e.g. information about the indoor air supply and exhaust, design ventilation rates, floor plan and lay-out are needed for both checklists. Airflow measurements are also part of the checklist of the HVAC systems. A semi-structured interview, which takes around 30-60 minutes, with a team manager of the PG department, should provide for the desired information about the use of the building.

Indoor air measurements

The indoor air measurements assume temperature, relative humidity, and CO_2 concentration measurements are performed in a living room and two bedrooms per LTCFs. The position in the room is chosen taking into account the behavior of the resident and in approval with their caregivers. The measurement period is set at one month, with a measurement interval of 10 minutes. An Eltek data logger with three sensors (GW47) were used to measure temperature (accuracy: ± 0.5˚C (5 to 40˚C), resolution: 0.1˚C), relative humidity (accuracy: ± 2% (10 to 90%), resolution: 0.1%), and CO_2 (accuracy: ± 50 ppm + 3% of measured value (0-5000 ppm) resolution: 1 ppm). Particulate matter measurements are performed during one day with an interval of one minute. These measurements were obtained using a Remote 2014 Airborne particle counter by Lighthouse; it counts particles with a size smaller than 10, 2.5, 0.7, and 0.5 µm. Outdoor conditions are obtained from nearby meteorological and environmental measurement sites.

Assessment size/frequency of the outbreaks of infections

To compare the frequency, size and duration of an outbreak of an infection, parameters are defined that describe the occurrence of infections over the past 5 years. This information needs to be requested at the LTCF. When the information is not available at the site the information can be requested at the municipal health services from the corresponding region.

Comfort and health evaluation

The indoor air quality and the building characteristics also play an important role in comfort and health of the building occupants e.g. Wolkoff[27]. Therefore, a questionnaire has been set up to evaluate the perception of comfort and general health aspects of the health care professionals of the PG departments of LTCFs[26]. Detailed information on the health and comfort questionnaire is found in the (digital) supplementary material.

Analysis of data

Results of the building analyzes

An overview of the results for all buildings is developed to provide insight in the current situation in the PG departments of LTCFs. First, the data type of all questions has been defined. Depending on the measurement level, the data is analyzed. For ratio and interval data boxplots are made (*Figure 3a*). The minimum and the maxi-

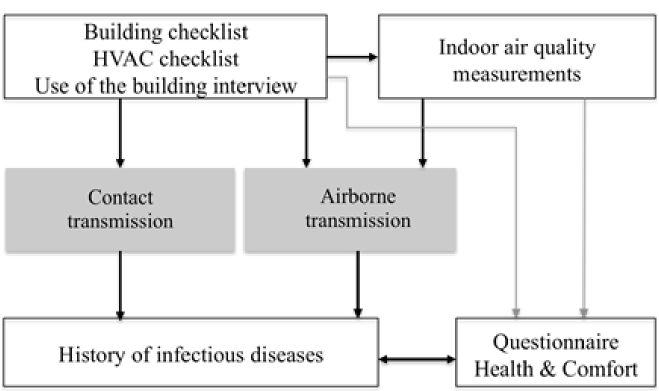


Figure 2. Scheme evaluation tools

Table 2. Parameters

Variable influencing infections	Which is influenced or characterized by:	Transmission		Reference	Questions in Building Checklist	Questions in HVAC Checklist	Physical measurements	Interview Use of building
		Airborne	Contact					
Ventilation		Airborne		Li et al, 2007 [14]; Cole and Cook, 1998 [34]; WHO 2009 [17]; ASHRAE, 2012 [18]; Nielsen 2013 [23]; Eames et al, 2009 [21]				interview
	Ventilation rate	Airborne		Li et al, 2007 [14]; WHO 2009 [17]; Nielsen, 2013 [23]		05; 13-19	CO_2	
	Air flow direction	Airborne		Li et al, 2007 [14]; Eames et al, 2009 [21]		03		
	room pressure differentials	Airborne		ASHRAE, 2012 [18]		21		
	personalized ventilation	Airborne		ASHRAE, 2012 [18]		21		
	displacement	Airborne		ASHRAE, 2012 [18]		21		
	Natural vs mechanical ventilation	Airborne		Seppänen and Fisk 2002 [35]		01; 02; 04		
Temperature		Airborne		Cole and Cook, 1998 [34]		40-46	indoor temperature	interview
	Heating	Airborne		Cole and Cook, 1998 [34]		07; 08		
	Remaining a constant temperature	Airborne			38-46	50-52		
Humidity		Airborne		Cole and Cook, 1998 [34]; Noti et al, 2013 [22]		22; 47-49	RH	
	Lack of moisture control	Airborne		Wargocki et al, 2002 [4]		23; 24		
Air cleaning		Airborne		ASHRAE, 2012 [18]; Cole and Cook, 2009 [34]		06; 10		
	Filtrations	Airborne		ASHRAE, 2012 [18]; Eames et al, 2009 [21]		30; 31		
	UV filtration	Airborne		ASHRAE, 2012 [18]		32		
	Air disinfection	Airborne				33		
	PM	Airborne					PM10; 2.5; 0.7; 0.5µm	
	0.5-5.0 µm droplets	Airborne		Cole and Cook, 2009 [34]			PM2.5; 0.7; 0.5µm	
	0.3-10 µm bacterial cells	Airborne		Cole and Cook, 2009 [34]			PM10; 2.5; 0.7; 0.5µm	
	0.02-0.30 µm viruses	Airborne		Cole and Cook, 2009 [34]			not possible	
	Maintenance:	Airborne		Wargocki et al, 2002 [4], Salonen et 2013 [36]		35-37		
	Clogged filters	Airborne				33		
	Contaminated ducts	Airborne				34		
Building materials		Airborne	Contact	Norbäck, 2009 [7]	21; 22; 24; 25; 27; 28; 30; 31			
	Mold growth	Airborne	Contact		35; 36; 37			
	Condensation	Airborne	Contact		32; 33			
	Floor coverings	Airborne	Contact		20; 23; 26; 29			
	Age of building and materials	Airborne	Contact		01; 02; 03; 04			
Contaminant source control		Airborne		Norbäck, 2009 [7]				
	Source pollution reduction	Airborne			34			
	Location of outdoor air intakes	Airborne				20; 25-29		
	Outdoor concentrations	Airborne		Norbäck, 2009 [7]	15; 16; 17; 18; 19			
Physical contact		Airborne	Contact	Li et al, 2007 [14]				
	Sharing facilities	Airborne	Contact		07; 12; 13			interview
	Seperation	Airborne	Contact	Garibaldi, 1999 [16]	05; 06; 14			interview
	Space per person	Airborne	Contact	Li et al, 2007 [14]	08; 09; 10; 11			

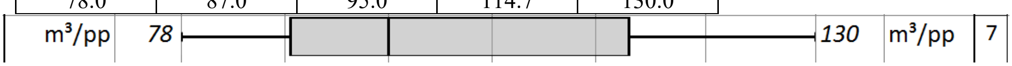
mum of this boxplot are defined from the data of the investigated buildings. Boxplots are displayed horizontally, the least favorable condition at the left, and the most favorable condition at the right. This is done from the point of view of preventing the spread of airborne infectious diseases. The number of buildings that are included in this analysis is indicated at the right of the graph. From the variables with an ordinal measurement level, similar boxplots are made from the range of possible answers (multiple choice) and shown in (*Figure 3b*). The minimum value is the least favorable condition, and the maximum value is the most favorable condition. Horizontal bars, as shown in (*Figure 3c*), are used to show the results of the binominal and nominal data. The bars represent the percentage of the investigated buildings for which this answer is applicable. The data of the questionnaires of all locations (N=95) have been put together. The use of the buildings is measured on the basis of an interview. The answers were processed using a data sheet to order the information. This structure was used to compare the use of the buildings, similarities and differences are discussed for each of the categories: general, residential groups, activities, control over the indoor climate and about the protocol in case of an outbreak.

Ranking buildings
For each building, the results of the evaluation are compared with the other investigated buildings. The score of a variable for one building is indicated with a grey bar in the boxplot *Figure 4* bottom. This bar indicates the score of that building is in quadrant 4 of the boxplot. The buildings are ranked to the quadrant the score is *Figure 4* top. This indicates how well the building scores compared to the other investigated buildings. The score does not imply that a building with a score of "1" is, in any case, good and a score of "4" is bad. Due to the lack of guidelines and reference no optimum can be defined yet. The ranking is used to find the effect of differences between buildings and its effect on health and comfort. This allows benchmarking of facilities on the specific issues monitored.

Comparing buildings
Radar plots are used to give a quick overview of all scores of the different LTCFs. *Figure 5* shows examples of the radar chart for two of the investigated LTCFs. Radar charts for all seven LTCFs investigated are attached in *Appendix I*. The radar consists of three parts, (I) the building, HVAC characteristics and physical measurements, (II) the outbreaks of infectious diseases, and (III) comfort and health. Each category consists of different parameters represented at the axes of the chart. It gives a quick insight into which aspects the building scores good or bad and helps to find possible correlations between those three. Variables are assigned to the parameter that they influence. Each variable is used only once. If one of the variables, which are included in the score of one parameter at the axis, is unknown, the average of the other variables is used to determine the score. The percentage of answered questions is indicated for each axis. The scores range from 1 to 4 (*Figure 4*). The score from 1-4 is from the best 25% (score 1) of the investigated buildings till the worst 25% (score 4) of the rated build-

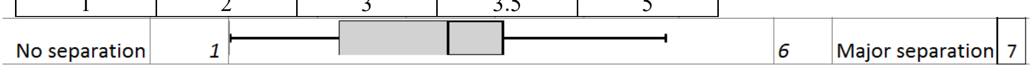
A) Example ratio and interval data: *What is the average space (m^3) per resident?*
From the obtained data, the following values can be calculated and a boxplot can be made.

Min	Q1	Median	Q3	Max
78.0	87.0	95.0	114.7	130.0



B) Example ordinal data: *How are different residential groups separated?*
1 = Corridor open; 2 = Corridor with closed doors; 3 = Corridor open and different floor levels; 4 = Corridor closed and different floor levels; 5 = Different floor levels; 6 = Different buildings
From the obtained data, the following values can be calculated and a boxplot can be made.

Min	Q1	Median	Q3	Max
1	2	3	3.5	5



C) Nominal data: *What type of control system is there for the mechanical ventilation?*

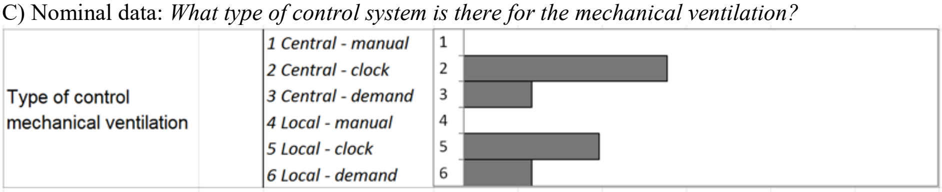


Figure 3. Examples boxplots and graph to give an overview of the results

	1st quadrant	2nd quadrant	3rd quadrant	4th quadrant
Score	**4**	**3**	**2**	**1**
	Least 25%			Best 25%

Example: What is the average space (m^3) per resident? Answer building X: *125 m^3/pp.*

Within 4th quadrant so a score of 1 is assigned to this building for this variable (right side of graph)

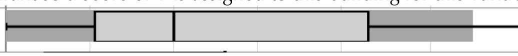
m³/pp *78*

130 m³/pp 125.0 1

Figure 4. Schedule and an example of assigning scores to the buildings

ings. The value "0" is assigned when a parameter could not be calculated because less than 75% of the answers are known. The percentage behind the parameters represents the amount of answered questions. A score of 5 indicates that the parameter does not meet the requirements of the building legislation.

The first part of the radar is composed using a selection of the building and indoor air related parameters and consists of six axes: (1) General building characteristics, (2) Contaminant source control, (3) Building materials, (4) Ventilation, (5) Maintenance and air cleaning, and (6) Temperature & humidity. Each axis consists of different variables. The list of variables connected to an axis is found in *Appendix II*. Because the contribution of each of these variables is unknown, no weighting factor has been applied. The second part of the radar indicates the scores of three parameters referring to the outbreaks of infections. Perceived health and comfort scores are shown in the third part. Information from the personal questionnaires used for this ranking is provided in *Appendix II*. These are the results of the questionnaire for the investigated building. The chart should give a quick insight into the aspects for which a building has good or bad scores and helps to find possible correlations between the three categories.

Applying these radar charts, possible relations can be found and further analyzed. By sorting the buildings, for example, on the frequency of infections, patterns in the building and HVAC characteristics might be observed. These possible

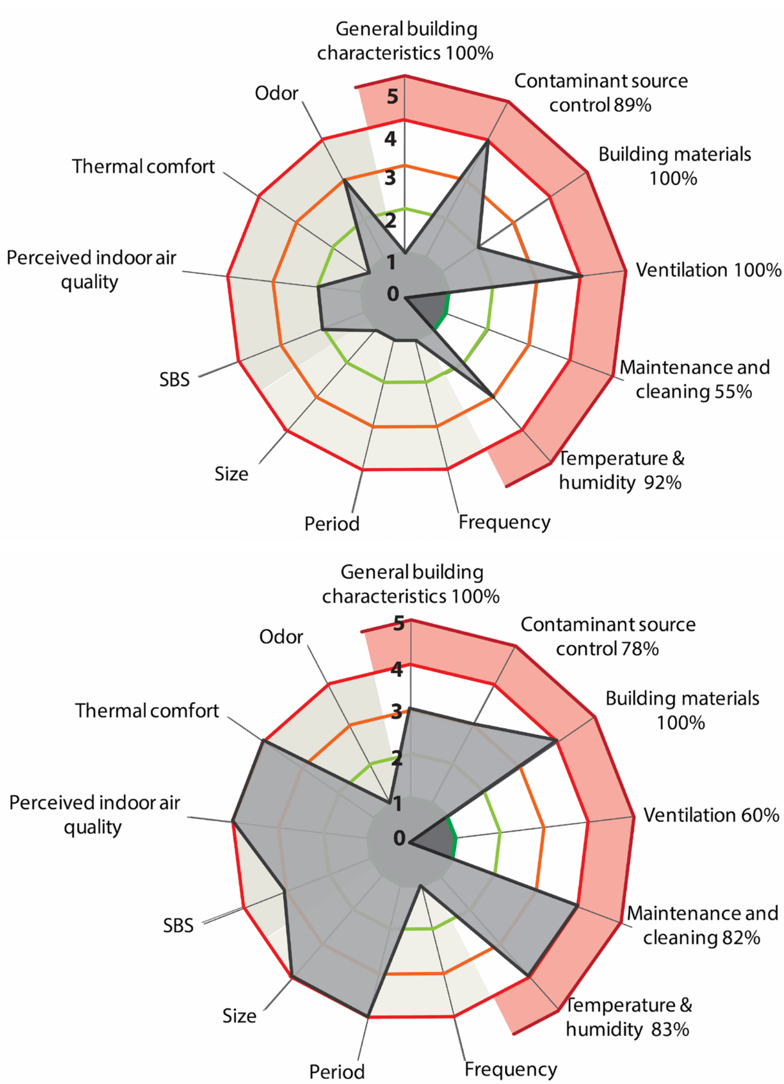


Figure 5. Radar chart for two of the investigated LTCFs

relations can then be further analyzed depending on the data.

Development of the design guidelines

Because there are many contributing factors, a large sample size is required to find correlations. Therefore, a methodology that can be applied in many LTCFs is necessary to find the important contributors to the transmission of airborne infections. By using the approach as a system to store information about the building and its indoor environment as well as a tool to find the relations among the building characteristics, indoor air quality and its effect on the transmission of infections, a large sample size can be achieved. When a sufficient large sample size is obtained, the information stored in the systematic approach can then be used as a basis to derive correlations and define specific design guidelines for LTCFs. The assessment procedure may be repeated for individual LTCFs at a predefined time interval to assure up-to-date performance over the life-time of the LTCF.

Testing the systematic approach

As described in the method section, the systematic approach was tested in seven LTCFs in the Netherlands. It was possible to execute the checklists, interviews, and observations, which needed to be done at the location of the LTCF, in one day. For some parameters it was not possible to obtain reliable information or no information was found at all. An interview of 30-60 minutes with a team manager of the PG department was planned to give insight in the use of the building, the general activities during the day and their locations. Indoor air measurements were placed for a time span of approximately 40 days, as described in 3.1.2. These measurements were only carried out at two locations due to the availability of measurement equipment. Information about the outbreaks of infections from the past 5 years was requested at the health care facilities participating in the research. However, it appeared that LTCFs only register this information during an outbreak. When the infection is over this information is not saved. From only one health care facility this information was directly accessible. Because health care facilities are mandatory to report when someone suffers from a notifiable disease or when there is an unusual number of sick people with diarrhea, jaundice, skin diseases or other diseases of infectious nature[28], the municipal health services from the corresponding regions were contacted for the requested information. However, some municipal health services were not willing to give this information and the completeness of the obtained information differed. For filling out the questionnaire, a time period of two weeks was given, this resulted in a response from 7 to 21 participants per LTCF.

Discussion

Evaluation of the systematic approach

The aim of the systematic approach is to analyze if differences in building characteristics, HVAC systems, and use, influence the spread of airborne infectious diseases. Therefore, data from a significant number of buildings, with a variety of characteristics, is required to obtain enough power to determine the role of the indoor air in the transmission of airborne infections. This current approach is intended to structure this information. Additionally, it should give an overview of the current buildings and rank these; the structure should facilitate a comparison between buildings. The advantage of using this tool is that successful interventions in one building can be addressed and this knowledge can be used and applied in other buildings. Because this systematic approach is also used to store the information about the buildings, it is dynamic. New buildings, renovations, and new technologies will keep it up to date and should raise the quality of the desired outcome of the performance indicators. Below is discussed whether the systematic approach succeeds in this objective and how it possibly can be improved.

Availability and reliability of the information

To perform the systematic approach at a LTCF, assistance is necessary from different employees, which need to be willing to participate and put time and effort into finding the required information that is not frequently used. This appeared to be a factor that makes it difficult to find facilities that want to collaborate in the research and to get all the desired information from the LTCF. A change in the management and control of the building related data is necessary to make the information better accessible and comparable. If this information would be stored systematically, for example using the developed technique, it will also provide useful information to the facility mangers: it will give them insight in the quality of the building and its effect on comfort and health. Preferably this would be done at all LTCFs so it can be used for comparison and as a benchmark for LTCFs.

The reliability of the obtained information depends on the knowledge of the people who provided the information and the availability of documentation. Information provided from the interview is based on the experience, knowledge, and interpretation of that person. Some health care organizations are not willing to give information about the history of infections because they doubt the comparability of the available information. Although infectious diseases have to be reported at the municipal health services, conform the Dutch Health Law Article 26 "Reporting institutions"[29], there is no uniform structure on how this information is stored. The rules can be interpreted in various ways, the quality and consistency differ and therefore it is hard to compare the data. This is also confirmed by the municipal health services. The manner of registration by the LTCF is not prescribed by the government, neither is the method of registration of the municipal health services[29]. If we want to determine factors contributing to the spread of airborne infections, a systematical way of data collection is necessary, to rank and score the buildings on the parameters of the outbreaks of infectious diseases. A remark should be made that contamination does not always lead to an infection, but that an infected person is a source and carrier of the infection. Independently of this systematic approach, it is recommended that a more uniform system to structure this data is able to compare outbreaks in different LTCFs and to study whether interventions are effective. Currently, this specific information as available at LTCFs lacks consistency and agreement towards each other.

Contributions variables, weight factors and/or hierarchy

This approach of the building assessment has been developed from the point of infection prevention. So, the parameters and the scores have been defined to reduce transmission. Perceived health and comfort are also evaluated because these are affected by indoor air as well. However, favorable conditions for health and comfort are not necessarily the same.

The parameters at the axes of the radar charts consist of (a selection of the) different variables investigated. The impact of each of these variables is yet unknown. In the current analyses, the contribution of the different variables that have been defined, are divided into different categories in which their contribution is assumed to be the same. The average of the variables is used to calculate the score of one parameter. To give insight into the scores of the variables within one parameter, sub radars can be made of these scores. Based on these sub radars, it can be discussed whether the average, median, trimmed mean, modus etcetera is the best representatives for calculating the score of the parameters in the radar chart. The analyses of the sub radars and median versus average scores can be used to give more insight into how the hierarchy should be applied. When there are large differences within the sub radars, hierarchy and weight factors probably will become more important.

More research is needed to find out whether weighting factors or a hierarchy should be applied in this analysis. This can, for example, be done using the Delphi method[30], the "ranking type" Delphi[31] or the Analytic Hierarchy Process[32]. These methodologies are intended to structure the variables based on their importance in the contribution of the transmission of airborne infections. In this analysis, possible interactions should be taken into account as well.

Reliability / Contributing variables

From the parameters in the radar chart that are derived from more than one variable, at least 75% of the variables are necessary to calculate the parameter. When fewer variables are known the parameter gets a score of "0". This value is chosen because the scoring interval is 25%. The nominal variables cannot yet be incorporated in the radar chart. So, for example air movement, which is important according to the literature study, is not included in the scores. To include this variable, it needs a higher measurement level. This means that the air movement will have to be quantified or different types of air movements need to be defined, and arranged from least to most favorable type. For the contribution of the indoor air quality on the transmission of infections by weakening the defense mechanism of individuals, it is unfortunate that the perceived health is hard to evaluate for the residents. Methods that could be applied are an observational study and/or an interview with health care professionals on their experience about health, well-being and behavior of the residents. However, these methods are time consuming.

In the current in-situ analyses the temperature, relative humidity, and CO_2 concentration were only measured at two locations. These measurements, however, are integral parts of the building assessment and therefore should be performed in every building analyzed. These measurements make the evaluation more performance based and support the validation of the model. Requirements can be added to the descriptive variables to ensure comparability. Currently, only maintenance, the year the building was built and renovations take the quality of the systems (for a small part) into account.

The starting point of the current model is the role of the building characteristics and the indoor air quality. There are certainly more factors that play a role in the prevention of outbreaks and the indoor air quality. Related to the prevention of outbreaks cleaning regime and frequency has to be considered as well as the compliance to the hygiene protocols by the professionals. The proposed approach could, of course, be extended with these parameters.

Further development

To fulfill the objective of the systematic approach adjustments are required. The Design Research Methodology (DRM) can be used to structure this development[33]. In addition, the sample size of the participating LTCFs should be enlarged. Most preferable would be to include buildings on the basis of the number of outbreaks, to ensure variance. However, as previously described, it is not possible to obtain this information. When the model has been validated, relations between on one hand the building characteristics and HVAC systems, and the other hand the spread of infectious diseases and health and comfort of health care professionals can be analyzed. When more information is available about the desired conditions and the effect of the building and HVAC characteristics, design criteria for the buildings can be established and integrated in the model. Finally, it can be applied in all LTCFs to structure the building and HVAC characteristics to define their positions compared to others. This should result in defining effective interventions or design guidelines to improve the indoor air quality and reduce the number or size of outbreaks of infectious diseases.

There are still some aspects that limit the applicability of this approach. First of all, a more unambiguous and structural way to collect data about the history of infectious diseases is needed. Information about the HVAC systems is sometimes hard to find, because data is not stored. This issue confirms the relevance for a systematic approach to store such information. Also, indoor air measurements need to be performed at more buildings to obtain better insight in the indoor air quality. The evaluation technique itself needs to include the nominal variables in the scores. Application of weight factors and hierarchy is required but need further research. This is supported by an increased sample size.

Conclusion

This research was performed to provide a systematic approach to develop design guidelines for the indoor climate in LTCFs in relation to spread of infectious diseases. An evaluation tool has been designed to evaluate building characteristics, HVAC systems, indoor air quality, the outbreaks of infectious diseases and health and comfort in LTCFs. Only little information and guidelines are available about the favorable indoor environmental conditions in LTCFs and not much is known about the current indoor air quality. Therefore, the developed systematic approach does not define criteria yet but it ranks, compares the buildings, and gives an overview of a sample of buildings.

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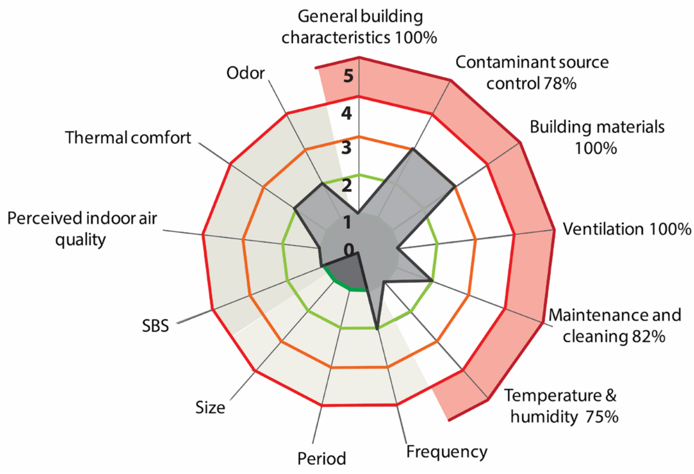
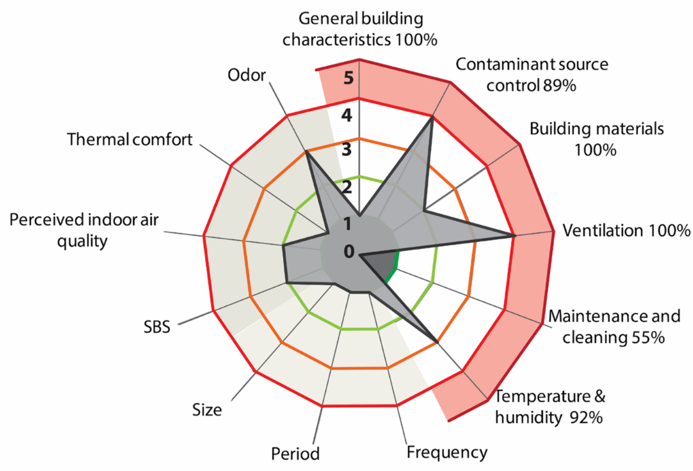
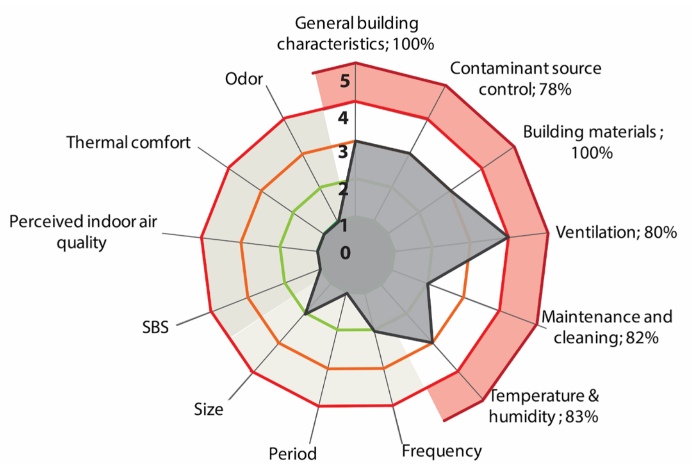
Appendix I. Radar charts for each long term care facility



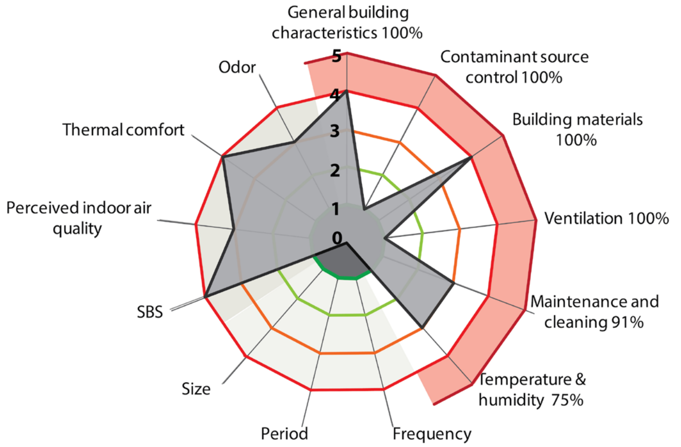
Long term care facility A



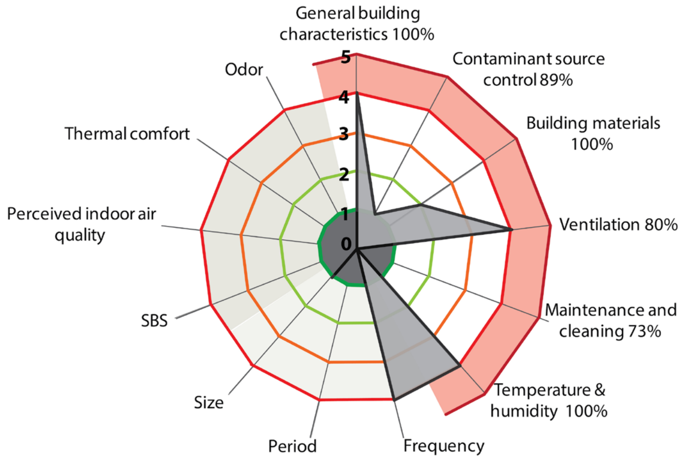
Long term care facility B



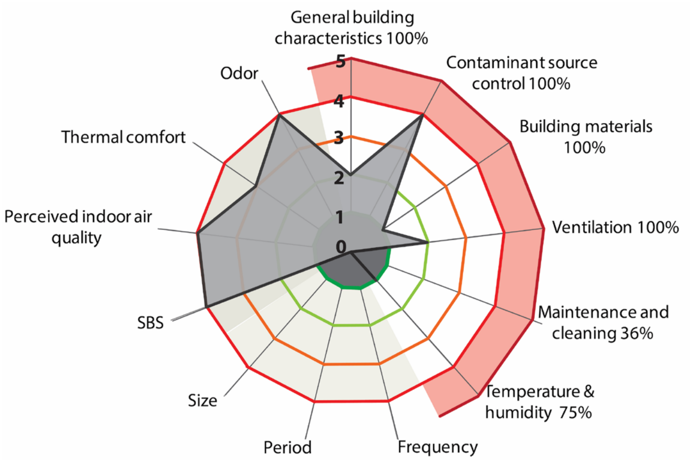
Long term care facility C



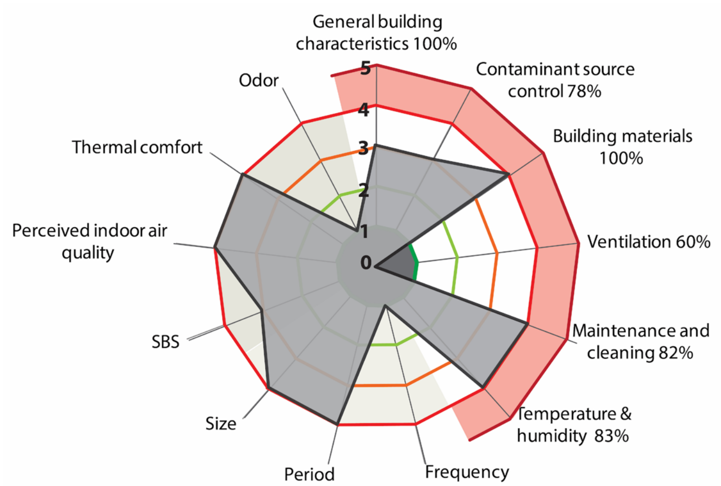
Long term care facility D



Long term care facility E



Long term care facility F



Long term care facility G

Appendix II. Connection radar chart axes to investigated variables

1. Building characteristics and HVAC characteristics

General building characteristics

The score of the "general" characteristics of the building consists of:

- Age of buildings and materials, this score is average of:

- B#01 Year built
- B#02 Year conversion of building (if not applicable: year is year built)
- B#03 Year refurbishment (if not applicable: year is year built)

- Space per person, score is average of:

- B#10 Average m2 per person
- B#11 Average m3 per person

- Separation residents, score is average of:

- B#05 Number of floor levels
- B#06 Number of residential groups
- B#14 Separation groups

- Sharing facilities, score is average of:

- B#07 Number of residents in one group
- B#12 Average number of bathrooms per person
- B#13 Percentage with one persons room

Score "General"= ranking of the average score of (Age of building and materials; Space per person; Separation residents; Sharing facilities)

Contaminant source control

The score of the "outdoor conditions" characteristics of the building consists of:

- B#15 Location
- B#16 Outdoor pollutants

Radiation, this score is average of:

- B#17 Radon
- B#18 TV radio
- B#19 Mobile phone

- Position ventilation intake, this score is average of:

- HVAC#26 Position intake
- HVAC#27a + b Distance exhaust
- HVAC#28a + b Distance cooling towers
- HVAC#29 Nr. of potential pollutant sources close to intake

Score "Contaminant source control" = ranking of the average score of (Location; Outdoor pollutants; Radiation, Position ventilation intake)

Building materials. The score of the "building materials" of the building consists of:

- Material ceiling, score is average of:

- B#21 Ceiling living room
- B#24 Ceiling kitchen
- B#27 Ceiling bedroom
- B#30 Ceiling corridor

- Material floor, score is average of:

- B#20 Floor living room
- B#23 Floor kitchen
- B#26 Floor bedroom
- B#29 Floor corridor

- Material walls, score is average of:

- B#22 Walls living room
- B#25 Walls kitchen
- B#28 Walls bedroom
- B#31 Walls corridor

- Condensation

- B#32 Material window frames
- Binom: + B#33 Condensation on windows
  + B#35 Visible mould growth
  + B#36 Damp spots on walls, ceiling or floors
  + B#37 Visible air leaks in the structure

Score "Building materials" = ranking of the average score of (Material ceiling; Material floor; Material walls; Condensation)

- Ventilation. Air exchange rate, this score is average of:
- HVAC#01 Operable windows
- HVAC#13b Design ACH living room
- HVAC#14b Design ACH bedroom
- HVAC#17a Measured ACH living room
- HVAC#19a Measured ACH bedroom

- Air cleaning, this score is average of:
- HVAC#30a Filtration pre
- HVAC#30b Filtration main
- Binom: + HVAC#31 UV (binomial data)
 + HVAC#32 Air disinfection (binomial data)

- Maintenance, this score is average of:
- HVAC#33 Frequency replacement filters
- HVAC#34 Frequency cleaning supply air ducts
- HVAC#35 Frequency supply air devices
- HVAC#36 Frequency cleaning exhaust air devices

- PM concentration, this score is average of:
- 10 μm average (measurements)
- 2.5 μm average (measurements)
- 0.7 μm average (measurements)
- 0.5 μm average (measurements)

- Temperature and humidity management. Remaining a constant temperature, this score is average of:
- B#38 Structure roof
- B#40 Structure external walls
- B#42 Structure internal walls
- B#43 Structure floors
- B#39 thermal resistance roof
- B#41 Thermal resistance external walls
- B#44 Thermal resistance floor
- B#46 Percentage glazing
- Binom: + HVAC#51abcd Solar shading (binomial data)
 + HVAC#42 HVAC (binomial data)
 + HVAC#43 Glazing (binomial data)

- Heating and cooling, this score is average of:
- Binom: + HVAC#07 Heating in AHU (binomial data)
 + HVAC#08 Cooling in AHU (binomial data)
 + HVAC#44 Temperature controlled by the system (binomial data)

- Humidity management, this score is average of:
- HVAC#22Humidification and dehumidification
- Binom: + HVAC#23 Water droplet eliminators (binomial data)
 + HVAC#24 Maintained to collect condensed water (binomial data)
 + HVAC#47 Humidity controlled by the system (binomial data)

The binominal data within one category has been combined to determine a score. For each health care facility the number of positive answers at these questions are summed. The results of that summation has been treated like the other ordinal data to create a boxplot. From these results a score of each building can be defined, depending on the quartile the result is in.
- B#01 means: question 01 from the building checklist.
- HVAC#30 means: question 30 from the HVAC checklist.

2. Outbreaks of infectious diseases
Score "Frequency" = ranking of the score of frequency of outbreaks (number of outbreaks per year over the investigated period)

Score "Period" = ranking of the score of period of outbreaks (average number of days per outbreak)

Score "Size" = ranking of the score of size of outbreak (average number of persons [resident + professional] per outbreak)

3. Comfort and health
Score "Odor" = ranking of the score of (score odor [summer/winter] – PQ#39)

Score "Thermal comfort" = ranking of the score of (average % thermal acceptability [summer/winter] – PQ#30)

Score "Perceived Indoor air quality" = ranking of the score of (average % air quality acceptability [summer/winter] - PQ#36)

Score "SBS" = ranking of the score of (average #PSI5 symptoms/person [summer/winter] - PQ#12+#13)

PQ#01 means: question 01 from the personal questionnaire.