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Abstract. The outdoor air pollution and the insufficient hygiene of HVAC systems often result in low indoor air quality. The World Health Organization estimated that 50% of indoor biological contamination comes from the air-handling system; the air filters are sources of pollution due to the accumulation and proliferation of bacteria on the surface. Furthermore, the presence of indoor contaminants can have a negative impact on the health and well-being of the occupants, who spend about 80% of their time indoors. To guarantee a better indoor air quality and a lower health risks, a new concept of biocidal filtration has been introduced. The present paper shows the results of a literature review aimed at exploring how to integrate the health effects on building occupants into the economic benefits of an antibacterial filter. The research focuses on costs and benefits produced by the application of an antibacterial filter, comparing it with a traditional one. Two methods were applied for the assessment; the Cost Benefit Analysis and the Monte Carlo Simulation. The results suggested the goodness of the economic investment on biocidal filter and showed how it allows to achieve benefits in term of energy savings and health for the different analysed case studies.

1 Introduction

The indoor air quality directly affects occupants' health and well-being. Indeed, a damage indoor environment is linked to an increase in Sick Building Syndrome (SBS) symptoms, respiratory diseases, sick leave, and to a decrease in comfort and productivity. As ASHRAE guidelines [1] stated, people spend about 80–90% of their time in enclosed spaces. For this reason, it results necessary to monitor and to optimize the indoor environmental quality (IEQ). In addition, in the revised Energy Performance of Buildings Directive (EPBD, 2018 [2]) new requirements were set, including the importance to assure proper indoor environment in order to optimize health, indoor air quality and comfort levels. The revised EPBD underlined the need to consider not only the energy efficiency of a building, but also the indoor environmental quality, and the health and well-being of the occupants. In order to achieve a good IEQ it is essential to design air filter and Heating, Ventilating and Air Conditioning (HVAC) system [3]. However, the insufficient hygiene of HVAC often results in the low quality of indoor air. The World Health Organization (WHO) [4] estimated that 50% of indoor biological contamination comes from the air-handling system. In addition, several studies discovered that HVAC system is the main source of pollution in indoor spaces [5, 6, 7]. As a matter of fact, traditional air filtration not only can reduce the outdoor to indoor transport of pollutants, but it also can improve the health and comfort of occupants and their productivity [8]; at the same time, it can be a source of pollution due to the bacterial material accumulated on the surface. To reduce bacterial growth in air filters is necessary to introduce antimicrobials agents that allow to decrease the level of biocontamination in the treated air [9]. In this way, the replacement of a traditional filter with a biocidal one is investigated. In detail, the purpose of the present paper is to show the result of a literature review aimed at exploring how to integrate the health effects on building occupants into the economic benefits of the biocidal filter. The study was developed toward the consultation of papers and books related to occupant health and by using Standards concerning indoor environmental comfort. The paper focuses on four main sections; the first one contains some qualitative and quantitative features of the biocidal filter and its bactericidal capacity on respiratory diseases. Section two aims at analysing the methodologies used to estimate the costs and the benefits of the examined air filters. Section three concerns the application of the methods described in the previous section to the different analysed case studies. Finally, the fourth section shows the results of the economic evaluation and the implementation of the model with a probabilistic approach.

1.1 Bactericidal filter capacity on respiratory diseases

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The biocidal air filter examined is characterized by rigid pockets, a high particulate filtration (F7 according to UNI779 [10]) and a certified efficacy of antibacterial power (ePM1=50% according to EN 16890 [11]). Compared to a traditional filter, the main difference consists in the presence of an additional decontamination from airborne microbiological agents (bacteria, moulds, viruses, algae). In detail, the bactericidal capacity of the filter has been evaluated on two bacteria: Staphylococcus Aureus (Gram-positive) for which has emerged an abatement capacity of 98%, and Escherichia Coli (Gram-negative) for which has shown an abatement of 53% after 16 hours, until 90% after 24 hours of contact with the filter [12].

The research focuses on the main respiratory diseases, pneumonia and meningitis, due to these tested bacteria. The economic benefits of antibacterial filter on the human health were estimated by computing both direct costs, related to hospitalization and antibiotic treatments, and indirect costs, identified with the loss of working days (Section 3.3 – table 4 and 5).

They are described below the main features of pneumonia and meningitis, the incidence of Staphylococcus Aureus and Escherichia Coli in the respiratory diseases, and the bactericidal capacity of the biocidal filter to remove both bacteria.

The pneumonia is a disease of the respiratory system caused mainly by bacterial infections. Based on the epidemiological criteria, it can be divided in Community-Acquired Pneumonia (CAP), contracted outside the hospital environment, and Hospital-Acquired Pneumonia (HAP), developed at the hospital whose clinical symptoms occur after 48 hours from the hospitalization [13]. Bacterial pneumonia is associated with Gram-positive (Streptococcus pneumoniae and Staphylococcus aureus) and Gram-negative bacteria (Hemophilus influenzae, Moraxella catarrhalis, Pseudomonas aeruginosa, Klebsiella pneumoniae and Escherichia coli). In detail, the CAP is characterized by 4% of S. Aureus and by 2% of E. Coli; the abatement capacity of the biocidal filter is 4% and 2% respectively. The hospital pneumonia identifies 13% of S. Aureus and 8% of E. Coli; in this case the bactericidal filter capacity is equal to 8% and 13% respectively.

The meningitis is an inflammation process that affects the membranes covering the brain and spinal cord and it can be caused by a viral or bacterial infection. The bacterial meningitis requires an immediate hospitalization treatment due to its fatal brain damage (100% of patients are treated in hospital). As pneumonia, it can be divided in Community-Acquired Meningitis (CAM) and Hospital-Acquired Meningitis (HAM) [14]. Both are influenced by 10% of S. Aureus and 6% of E. Coli; the abatement capacity of biocidal filter are equal to 10% and 6% respectively. This disease may affect a wide range of people independently on the age; infants, children, adults and also the older people. The following analysis focuses only on the meningitis costs that characterized the office, the hotel and the hospital rooms (Table 6). Whereas school and gymnasium are not considered, because the meningitis related to infants and children are not characterized by the presence of the bacteria mentioned earlier and therefore are out of scope.

2 Methods

2.1 Components financial feasibility

The financial feasibility of a project, or product, is usually evaluated through approaches that take into account only the costs as parameters of the evaluation. The Life Cycle Cost (LCC) technique is defined by ISO 15686-5:2008 [15] as a tool for decision support during the design phase. The LCC approach makes it possible to determine the overall cost of a project, taking into account the entire life cycle [16]. The scales of application of the LCC can be different; from the evaluation of the individual components of a complex system, to an entire project. One of the purposes of the LCC can be the evaluation of alternative solutions that present different investment, management and maintenance costs. By distinguishing the different cost items mentioned, the LCC formula is as follows (Equation 1):

$$LCC = C_i + \sum_{t=0}^{N} \frac{C_g + C_m}{(1+r)^t} \mp V_r \left(\frac{1}{(1+r)^N}\right) \quad (1)$$

where C_i is the investment cost, C_g the running costs, C_m the maintenance costs, t the year when the cost occurs, N the number of years of the whole period considered. Around this purely financial concept, different techniques were arose introducing sustainability awareness in the evaluation: Life Cycle Assessment (LCA), Life Cycle Sustainable Assessment (LCSA), Social Life Cycle Assessment (SLCA). These recent developments have made it possible to change the paradigm of energy system evaluation, shifting the concept of energy efficiency towards socio-economic efficiency.

2.2 Evaluation of co-benefits

Increasingly, the attention of scientific research is moving towards an integrated assessment that considers not only financial aspects, but also socio-economic ones. The externalities inclusion makes it possible to determine an overall assessment, considering both tangible and intangible effects arising from a project [17, 18, 19]. In this study, the impacts generated by the installation of a biocidal filter compared to a traditional one in terms of reduction of health effects are mainly assessed. If the financial evaluation is carried out by LCC method, as indicated in Section 2.1, the Cost Of Illness (COI) technique could be used to evaluate the benefits generated in health terms. The COI method evaluates benefits as avoided costs. In accordance with the methodology, the effects can be clustered in direct, indirect and intangible costs. The direct costs cover expenditures for resources provided for the prevention and treatment of the same pathology and related diseases, specialist visits, haematological and serological tests, diagnostic control procedures, supportive drug therapies and hospitalizations. Indirect costs are attributable to production losses due to absence from work by the subjects affected. Lastly, intangible costs are associated to psychosocial effects, such as suffering, and discomfort caused by the disease. In the COI approach, direct costs are estimated according to a bottom-up approach, multiplying the epidemiological data related to a disease with the costs of hospitalization, medication and disease management arising from the literature. For the calculation of indirect costs, reference was made to the Human Capital Approach (HCA) [20], which bases the calculation of costs since loss of productivity at work. The intangible costs are those very difficult to be expressed in a monetary value. To estimate these costs, approaches based on revealed preferences techniques are used, which through surveys capture the consumers' willingness to pay to avoid certain negative effects. In this research, we will focus on the evaluation of direct and indirect avoided costs, omitting intangible ones.

2.3 Cost-benefit analysis framework

Increasingly, economic evaluation has been applied in studies on health care and in the medical context, recording an increase in scientific literature [21, 22]. In this context, economic assessment can be defined as the comparative analysis of alternative actions in terms of costs and consequences, with the aim of improving resource allocation efficiency and maximizing results. Economic analysis is the main purpose of considering both benefits and costs. Several methods of economic evaluations have been tested in medicine; Cost-Minimization Analysis (CMA), Cost-Benefit Analysis (CBA), Cost-Utility Analysis (CUA). In this study, the CBA approach was chosen as the basic framework, combined with the Cost of Illness (COI) method [23]. According to [24], CBA is an analytical technique that is used in investment decisions in order to assess the welfare changes attributable to alternative projects and to select the most profitable in terms of the society's convenience. CBA is developed through subsequent steps as follows: 1) identification of costs and benefits of the project; 2) estimation of the monetary values; 3) distribution of the estimated costs and benefits over the time and construction of the cash flow; 4) definition of the discount rate; 5) calculation of the performance indicators. With specific reference to the performance economic indicators, the Benefit/Cost ratio (B/C) is used in this study [25]. B/C is calculated dividing the sum of the discounted incremental benefits flows by the sum of the discounted incremental costs flows (Equation 2), obtaining a dimensionless ratio:

$$\frac{B}{C} = \frac{\sum \frac{B_a - B_b}{(1+r)^t}}{\sum \frac{C_a - C_b}{(1+r)^t}} \tag{2}$$

where B_a is the benefits flows on the program a, where B_b is the benefits flows on program b, C_a is the costs flows of program a, C_b is the costs flows of the program b, r is the discount social rate and t represents the time. The B/C ratio aims to establish a clear relationship between monetary investment to achieve one project rather than another, and the return of impacts, translated into monetary terms.

3 Application

3.1 Case studies

Different case studies are analysed: office, hotel and school building, school gym and hospital rooms. First, to define the number of occupants in each case study the minimum air flow rates required by the UNI 10339 [26] are analysed. Subsequently, assuming the use of the medium-sized for both the biocidal and traditional filter, the following scenarios reported in Table 1 are established.

Table 1. Different case studies analysed.

Case Study	Minimum air flow rate	Number of occupants
Office	11 l/s per person	67
Hotel	11 l/s per person	67
School	5 l/s per person	150 (140 students; 10 teachers)
School gym	16.5 l/s per person	45 (43 students; 2 teachers)
Hospital Rooms	11 l/s per person	67

3.2 Estimate of costs

The Life Cycle Cost (LCC) of a filtration system includes the initial investment and maintenance, the energy consumption cost and the total cost for disposing the filter. It can be defined as follow (Equation 3):

$$LCC_{total} = I_{investment} + LCC_{energy} + LCC_{maintenance} + LCC_{disposal} \tag{3}$$

In this paragraph the global cost calculation of the biocidal filter is analysed, comparing it with a traditional one. The input data for both filters are shown in the following table (Table 2) [8]. Table 3 presents the annual costs for each component; only investment and energy costs are different for the two filters considered.

Table 2. Input data used in the analysis.

Input Data	
Parameter	**Assumed value**
Interest rate	6%
Air flow	1 m³/h
Running time	6,000 hours (1 year)
Fan efficiency	50%
Energy Cost	0.10 €/kWh (increasing 5% per year)
Calculation Period	10 years

Table 3. Annual costs for each filter.

	Antibacterial Filter	**Traditional Filter**
Investment Cost	200 €	80 €
Maintenance Cost	40 €/year (no price increase)	
Disposal Cost	4 € (increasing 5% per year)	
Energy Cost (*1)	156 €	244 €
Initial - final pressure	70 -250 Pa	80-450 Pa (*2)
Average pressure drops (*3)	130 Pa	203 Pa

(*1) The energy cost for one year is calculate as follow: [(Air flow) ✕ (Average pressure drop) ✕ (Running time) ✕ (Energy cost)] / [(Fan efficiency) ✕ 1000] [8]
(*2) From EN 779:2002 [27]
(*3) The average pressure drops for both antibacterial and traditional filter is calculated as follow: $p_{initial} + (p_{final} - p_{initial})/3$ [8]

Annual energy, future maintenance and disposal costs during the useful life of the installation are discounted at the present value. In this way, the correction factor (CF) is determined as following formula (Equation 4):

$$CF = [1 + (i - p)]^{-n} \quad (4)$$

where n is the number of years, i represents the interest rate and p the price increase (in the case of replacement cost p=0). The sum of these factors, calculated for each year, gives the total factor used to determine the total discounted costs.

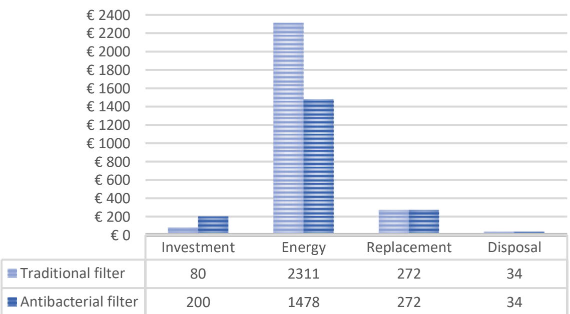

Fig. 1. Discounted costs for each filter.

Figure 1 shows the incidence of each discounted cost. It is evidence that the energy cost for air filters is the most dominant factor of an LCC calculation (about 71% for antibacterial filter and 86% for traditional one). From this comparative analysis the antibacterial filter has a higher investment cost but at the same time a higher energy saving due to the lower fall in average pressure. Maintenance and disposal costs remain unchanged for both filters.

3.3 An integrated CBA model to support decision making in HVAC system

A probabilistic COI model is developed in order to estimate an aggregate measure of the economic burden associated with respiratory diseases related to pneumonia and meningitis, in terms of direct and indirect costs. The Staphylococcus Aureus and other infectious agents of Gram-negative bacterial origin, Escherichia Coli, are the main responsible for the CAP and HAP (Section 1.1). [28] has estimated that 9 adults in 1000 per year and 11-16 children per 1000 per year get CAP pneumonia. Treatment of CAP pneumonia may require treatment based on antibiotic intake (outpatient treatment) or may require hospitalization for a range of cases ranging from 8% to 51%. Pneumonia involves a large number of hospitalizations, which commit significant financial resources to National Health Services (NHS), as shown in Table 3. The duration of the hospital therapy requires 10 days and demands different treatments according to the evaluation of clinical severity. In Italy, about 50% of pneumonia in adults falls into complications (CC) requiring more expensive treatments [29].
From 5 to 10 cases of HAP occur every 1000 people admitted to hospital. Unlike CAP pneumonia, HAP also affects patients aged under 17, with an incidence of 17%. This involves an extension of the hospitalization period. The hospitalization rates of cases of meningitis are lower than those of pneumonia, recording 3-6 cases per year for every 100,000 inhabitants.
From 1 to 6 cases per year, every 500-1000 hospitalized persons are likely to be suffering from meningitis. Staphylococcus Aureus and other Gram-negative bacteria are responsible for cases of meningitis. The treatment required for meningitis is hospitalization, for an average duration of 10 days. Hospitalization periods determine indirect impacts that the COI method takes into account in the evaluation. The most obvious impact is the absence of work, which can be translated as expenditure for the national providential system.

Table 4. Parameters for direct health costs associated with pneumonia and meningitis [30, 31, 32].

Direct costs per patient	**€**
Cost of antibiotic treatment to cure pneumonia (*1)	37.50
Cost for outpatient management for pneumonia	182
Cost of hospitalization for pneumonia with complications (CC) for adults (> 17 years old) per day	3,558
Cost of hospitalization for pneumonia without complications (CC) for adults (> 17 years old) per day	2,291
Cost of hospitalization for pneumonia for adolescent (< 17 years old) per day	1,948
Cost of hospitalization for meningitis per day	8,067

(*1) Antibiotic cost (6.50 €) and chest radiography cost (15.50 €, to be considered twice)

Epidemiological data are the starting point for the COI analysis. Through an estimate of the number of individuals suffering from the pathology under examination, the resources consumed by patients in terms of hospitalization and/or outpatient care are estimated to determine the average annual cost for each individual and the total annual cost. The model was implemented with data deriving from a systematic review of the available literature (Table 4). The direct costs for the hospitalization and antibiotic treatments are calculated following the formula (Equation 5):

Direct costs = Medical treatment cost $\times$ Abatement capacity $\times$ Period spent $\times$ Morbidity events (5)

where the Medical treatment cost is equal to the cost of antibiotic or hospitalization, the Abatement capacity is the biocidal filter capability to reduce bacteria responsible for pneumonia and meningitis, and the Period spent reflects the time spents in the place where the filter is installed, in terms of days of work, days of stay, study days and so on, and Morbidity events represent the disease cases in the investigated case study.

Table 5. Parameters for indirect costs associated with workers' productivity [33, 34].

Indirect costs per patient	€
Average gross daily wage worker in the tertiary sector [33]	125
Average gross daily wage worker in public administration (school) [34]	97.54

The indirect costs consider the days of work lost due to admission to hospital treatment. The method used is the HCA, following the formula (Equation 6):

Indirect costs = Daily salary $\times$ Hospitalization days $\times$ Morbidity events (6)

where the Daily salary corresponds to the wage for different workers according to case studies, Hospitalization days represent the average period of hospitalization to carry out the treatment. The parameters for the estimation of indirect costs are summarized in Table 5. For each patient, the average annual salary corresponds to € 27,500 for the case study of the office, hotel and room of hospitalization, while € 19,996.27 for educational buildings, equivalent on average to a daily fee of € 125 and € 97.54 before taxes, respectively. The daily wage is given by the average annual income divided by working days per year (equal to 220 effective days for the tertiary sector, 365 effective days for hotel, and 205 days for school). For the estimation of indirect costs, it is assumed that all subjects were in the productive age and employed. In the office, hotel, and hospital rooms, the indirect costs are calculated by referring to the value of the days lost by the patient. While, in the case of school buildings, such as the classroom and the gymnasium building, being the assessment based on cases of pneumonia on children, the indirect impacts are calculated as teachers' work performance not received by the students. For each case study, the direct and indirect avoided costs due to pneumonia are calculated and, where applicable, due to meningitis (Table 6).

Table 6. Total direct and indirect costs per case study.

Case Study	Costs due to pneumonia [€]	Costs due to meningitis [€]
Office	74.70	7.69
Hotel	123.99	12.76
School	28.05	-
School gym	10.39	-
Hospital Rooms	627.00	797.78

In the CBA, the energy savings resulting from biocidal installation are considered. They are determined as the difference between the energy costs (Table 3) of traditional filter and those of the antibacterial one.
Once calculated costs and benefits, it is possible to set the analysis following the CBA framework. The first step is to distribute the costs and benefits identified, considering a calculation period of 10 years. The discount rate chosen is equal to 2%.

4 Discussion of the results

To consider the intrinsic variability of the data used to implement the model, a probabilistic approach is used. The CBA analysis is joined with Monte Carlo simulation, in order to calculate a series of possible realizations of the phenomenon under examination, in a probabilistic way. The analysis consists in considering, for each parameter identified in the different sources, a minimum, average and maximum value in a triangular distribution. Furthermore, the distributions were analysed performing 200 interactions in order to obtain interval estimates of the main epidemiological and economic data.

Table 7. Monte Carlo simulation results.

Case Study	B/C minimum value	B/C maximum value
Office	14.31	21.93
Hotel	18.41	30.35
School	11.82	13.11
School gym	10.23	10.59
Hospital Rooms	113.40	215.90

Table 7 shows the results obtained from Monte Carlo simulation. The case study that obtains the greatest benefits in terms of abatement of the bacteria responsible for pneumonia and meningitis turns out to be the hospital rooms. This is mainly motivated by the prolonged hospitalization of patients. Thus, avoided production costs would be higher than in other case studies. Figure 2 presents the variation of B/C ratio according to the variation of the variables' values for the office case study.

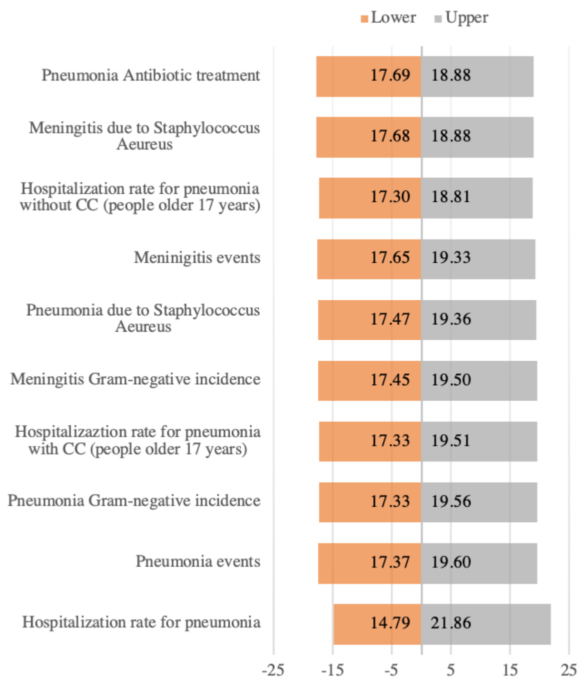

Fig. 2. B/C ratio from Monte Carlo simulation for the office case study.

The hospitalization rate for pneumonia is the main statistical parameter capable of generating the highest level of variation in the estimate of the B/C ratio. Indeed, the oscillation of this parameter between 8% and 51% involves high variations in direct and indirect costs, varying the B/C between 14.79 to 21.86. The frequency of events related to pneumonia is the second most relevant parameter; if the maximum value of 10 cases per 1000 inhabitants is assumed, the B/C reaches a value equal to 19.60; if we assume that the parameter takes the minimum value of 8 cases per 1000 inhabitants, the B/C is 17.37.

Conclusions

An integrated CBA model to evaluate an innovative antibacterial filter for HVAC system is proposed. The framework integrates financial and economic parameters in order to assess the socio-economic efficiency of the system component [35]. In particular, a detailed literature review is performed to investigate the health benefits that arising from biocidal filter installation. An epidemiological analysis is proposed in this research in order to establish the number of potential patients diagnosed with pathologies related to meningitis and pneumonia in various case studies. To estimate the benefits in terms of avoided costs, the COI approach is applied. According to the COI method, the study makes it possible to calculate the economic burden absorbed by the diseases, estimating a direct annual cost sustained by the NHS. With reference to indirect costs, the COI estimated the loss of productivity in monetary terms following the HCA. From the point of view of financial analysis, the calculation of energy savings achieved is considered [36, 37]. The model confirmed the importance of installing filtration measures in community settings to reduce the health effects of pneumonia and meningitis. In all the case studies analysed, the antibacterial filter provides benefits that exceed the costs incurred compared with a traditional filter. In particular, the antibacterial filter is efficient in the hospital, where the frequency of diseases related to pneumonia and meningitis is frequent. In conclusion, this work results to be an efficient reference tool for decision makers in HVAC systems problem to understand the economic aspects generated by the installation of an antibacterial filter in different community and hospital environments. This study presents some limitations. Being the model based on survey data from the existing literature. Unfortunately, there is no data on the national level of all the cost and epidemiological data referring to pneumonia and meningitis. However, a systematic review of the literature, rigorously conducted following international guidelines, allowed to identify the most recent sources. To address this problem, Monte Carlo simulations are conducted to take into account the heterogeneity of the different data available, and obtaining results based on intervals include the unofficial sources used. Furthermore, the intangible costs incurred by patients are not taken into account in this evaluation. The future research perspectives aim at the implementation of the model of further avoided indirect and intangible impacts thanks to the installation of biocide filters [38, 39]. Further development foresees the simulation of additional scenarios in different fields of application.

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