PREPRINT: Costola D, Blocken B, Hensen JLM. 2009. Overview of pressure coefficient data in building energy simulation and airflow network programs. Building and Environment. In press.

Overview of pressure coefficient data in building energy simulation and airflow network programs

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Abstract

Wind pressure coefficients (C_p) are influenced by a wide range of parameters, including building geometry, facade detailing, position on the facade, the degree of exposure/sheltering, wind speed and wind direction. As it is practically impossible to take into account the full complexity of pressure coefficient variation, Building Energy Simulation (BES) and Air Flow Network (AFN) programs generally incorporate it in a simplified way. This paper provides an overview of pressure coefficient data and the extent to which they are currently implemented in BES-AFN programs. A distinction is made between primary sources of C_p data, such as full-scale measurements, reduced-scale measurements in wind tunnels and computational fluid dynamics (CFD) simulations, and secondary sources, such as databases and analytical models. The comparison between data from secondary sources implemented in BES-AFN programs shows that the C_p values are quite different depending on the source adopted. The two influencing parameters for which these differences are most pronounced are the position on the facade and the degree of exposure/sheltering. The comparison of C_p data from different sources for sheltered buildings shows the largest differences, and data from different sources even present different trends. The paper concludes that quantification of the uncertainty related to such data sources is required to guide future improvements in C_p implementation in BES-AFN programs.

Keywords: wind pressure coefficient, building energy simulation (BES), airflow network (AFN); ventilation; heat, air, moisture transfer model (HAM); infiltration; model intercomparison; building envelope

1 Introduction

Air infiltration and ventilation have a profound influence on both the internal environment and the energy needs of buildings [1]. Air flow through the building envelope is also an important factor influencing building heat loss and moisture transfer [2]. Wind is an important driving force for infiltration and ventilation. Wind pressure is therefore an important boundary condition for a wide range of models, from building component heat, air and moisture (HAM) transfer models to airflow network (AFN) programs, which are either used as a stand-alone program or coupled with building energy simulation (BES) programs [3-6]. Wind pressure on the building envelope is usually expressed by pressure coefficients (C_p), which are defined as follows:

$$C_P = \frac{P_x - P_0}{P_d} \quad ; \quad P_d = \frac{\rho \cdot U_h^{\,2}}{2} \tag{1}$$

where P_x is the static pressure at a given point on the building facade (Pa), P_0 is the static reference pressure (Pa), P_d is the dynamic pressure (Pa), ρ is the air density (kg/m^3) and U_h is the wind speed, which is often taken at building height h in the upstream undisturbed flow (m/s).

In the past, the impact of C_p on BES results was studied using sensitivity analysis, identifying C_p as one of the main sources of uncertainty in BES-AFN models [7,8]. The reasons are the high uncertainty associated with C_p values, and the fact that several performance indicators, e.g. energy consumption, thermal comfort and mould growth, are often very sensitive to the air change rate, which depends on C_p. Hensen [9] described the difficulty to perform an accurate evaluation of C_p. Further studies, especially on the development of analytical models for C_p prediction [10,11], have not been able to overcome the difficulties in obtaining reliable C_p values without using costly wind-tunnel experiments. In this sense, Tuomaala [12] stated that "there is no reliable and effective method for evaluating the value of wind pressure coefficients for complex cases." The difficulties in obtaining reliable C_p data for BES-AFN can be explained by the wide range of influencing parameters, including building geometry, facade detailing (e.g. external shading devices, balconies), position on the facade, sheltering elements (e.g. buildings, trees), wind speed, wind direction and turbulence intensity.

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To the knowledge of the authors, there is no overview of C_p data in BES-AFN programs. The purpose of the present paper therefore is to provide such information together with a comparison of data from different data sources. This overview can be useful for the development and validation of AFN, BES and building envelope HAM models, for ventilation, infiltration and indoor air quality studies, for documentation for building certification programs and for the development of new models for C_p prediction.

The paper is structured as follows. Section 2 describes the BES and AFN programs that are included in this overview, as well as the method used for their selection. The sources of C_p data are classified in primary and secondary sources. Primary sources provide data for a specific building and take into account most of the parameters that influence the C_p data. The term secondary sources is used in this paper to describe those sources that were generated based on primary sources. Data from primary sources is, in general, more accurate than data from secondary sources, but the cost to obtain them is also higher. Section 3 provides a brief overview of the primary sources: full-scale measurements, reduced-scale wind-tunnel tests and computational fluid dynamics (CFD) simulations. Sections 4 to 6 describe the secondary sources in detail. A large number of secondary C_p sources exist, which have different aims and characteristics. Databases of C_p values are the most common secondary source. Those databases, which are collection of C_p data, are present in several books and standards, and they provide data for a limited set of generic building configurations. Another secondary source are the analytical models, where primary data has been used to derive general equations to predict C_p. Section 7 presents comparisons of the values from each data source for the simple case of a cubic building, to demonstrate the differences between them. Finally, the main conclusions are provided in section 8.

2 BES and AFN programs

This section mentions the programs included in the present overview. It is not the intention of this selection to be complete; rather the purpose is to have a sample of programs that represents the state of the art in commercial and academic BES and AFN modelling. The selection of BES programs was based on the recent work by Crawley et al. [13]. Their paper resulted from the collaborative work of several research groups dealing with BES, and contrasts capabilities of 20 BES programs. From those 20 programs, 7 included a fully implemented and coupled AFN [13], which requires C_p data. Stand-alone AFN tools also represent an important reference for the present paper. Firstly because some of them are coupled with BES tools, e.g. Trnsys and COMIS [14], and secondly because they may include the most advanced features which will then be implemented in BES tools. To the knowledge of the authors, the most recent review of AFN tools was published in 1999, comparing 14 AFN programs [15]. From those, 3 programs claimed to have some data on C_p: AIOLOS, COMIS and Nitecool. From this list, AIOLOS and COMIS are included in the present overview. CONTAM is also mentioned in [15], but at that time the version "Contam 96" did not have any C_p data. The present version (CONTAMW 2.4b) does include C_p data, and is therefore also included in the present overview. Table 1 lists the selected programs and the documentation used as reference for this paper. In all the cases, the "Help" available in the program interface was also considered as source of information. Note that this set is certainly small compared to the amount of existing BES tools, but that it is considered representative for a general overview about the topic.

3 Primary sources

Primary sources are considered to be the most reliable C_p data sources. Most of the tools listed in Table 1 clearly state in their documentation the possibility and the way in which user-defined C_p data, which is most often obtained from primary sources, can be inserted and used, In this section, a brief description of the main primary sources is provided, focusing on their advantages and disadvantages.

3.1 Full-scale measurements

On-site full-scale measurements at real building facades provide the most representative description of C_p. In those measurements, there is no need to reproduce boundary conditions, no scaling issues, and no physical models to be adopted. However, full-scale measurements are complex and expensive, and are therefore mainly used for validation purposes. Early full-scale experiments, e.g [25], used sensors with high uncertainty for the pressure measurements, such as manometers, and for the wind speed, such as cup anemometers. More recent experiments using ultrasonic anemometers and pressure transducers provide a large amount of high-quality data about the pressure at the building facade. Raw data from full-scale measurements are sometimes available at the web site of research centres, e.g http://www.wind.ttu.edu/Research/FullScale/WERFL_4th.php.

In many of the past experiments, the building is relatively unsheltered, so the approaching wind flow can be easily measured [26-28]. The definition of proper boundary conditions is a main constraint when full-scale experiments are used for validation purposes. Many of the existing data cannot be used for validation purposes due to the lack of information on the approaching wind flow [29]. In the urban environment, where many nearby obstructions are present, defining a good reference measurement location constitutes a main challenge, and this type of experiments is less commonly found in the literature. Despite the problems associated with reference measurements, on-site full-scale experiments are always useful to gain insight in the pressure variation across the building facade. In structural design, not only the spatial variation across the facade, but also the temporal variation resulting from turbulence is very important. However, for ventilation and infiltration studies, the effects of turbulence on the temporal variation of C_p are often neglected [30,31].

It is commonly assumed that C_p is independent of the wind speed. This is considered to be true when the flow around the building is Reynolds number independent and not significantly influenced by thermal processes. For bluff bodies with sharp edges, the first assumption is generally valid even for low velocities because of the high Re numbers in building aerodynamics. The second assumption is not necessarily true for low wind speeds, because the mean wind speed as well as turbulence can be significantly influenced by solar radiation [32] and the related small-scale and large-scale buoyancy processes, including thermal stratification. This point is less relevant for structural engineering aerodynamics, because there the focus is generally on strong winds under neutral atmospheric stability. However, infiltration and ventilation studies have to deal with the entire range of wind speeds. Full-scale experiments conducted to assess the uncertainty in C_p prediction for natural ventilation indicated very scattered values for low wind speeds [33]. The solution adopted was to discard all values where the reference wind speed was lower than 4 m/s from the analysis [33]. This solution clearly compromises the applicability of the results for a large range of situations with low wind speed.

The uncertainty in the measurements, which can be determined according to ISO [34], is rarely object of detailed analysis. C_p is a derived quantity; therefore it demands measurements of several quantities: pressure on the facade, reference wind speed, and strictly speaking also air temperature and atmospheric pressure to obtain the air density. Measurement uncertainty for each of these parameters will contribute to the resulting C_p uncertainty, not only because of the sensor uncertainty, but also because of other sources, such as the measurement protocol. The combined uncertainty of full-scale measurements is important because it provides the limit of accuracy when these data are used for validation purposes.

It can be concluded that full-scale experiments are the primary data source that provides the most representative information; however the use of these experiments for BES-AFN is restricted to research and validation purposes. Full-scale experiments should also focus on urban environments and on low wind speed conditions, for which the analysis of pressure coefficient data is particularly challenging. Also measurement uncertainty requires further attention.

3.2 Wind-tunnel measurements

Wind-tunnel experiments are generally considered the most reliable source of pressure data for buildings in the design phase. Structural engineering uses custom wind-tunnel experiments to assess the wind loads on a specific building, considering geometry, immediate surroundings and appropriate approach-flow profiles of mean wind speed and turbulence. The use of wind-tunnel measurements to provide BES input data however is limited due to cost, time and know-how involved in this type of experiments.

In the first half of the 20th century, knowledge on wind flow around buildings was mainly obtained using wind-tunnel experiments [35]. In this early stage, the use of laminar or low-turbulence uniform approach flows was common, and the deficiencies of this technique for modelling processes in the atmospheric boundary layer (ABL) were not identified for many years. Later, the comparison between wind-tunnel results and full-scale measurements highlighted the importance of the ABL wind speed profile and the higher ABL turbulence, and it incited the development of boundary-layer wind tunnels [25]. Nowadays, wind-tunnel modelling to determine pressure on buildings is widely practiced [29]. However, wind-tunnel experiments, as any laboratory measurements, demand special care. A common exercise, carried out by 12 institutions, compared the wind-tunnel results for the simple case of an isolated cube, for 3 wind directions [36]. Figure 1 shows the mean result from the wind-tunnel experiments by the 12 different laboratories and the overall range of results. The variation is less for the windward surface, while the roof and the leeward surface exhibit larger differences. The variation in the results stresses the importance of quality assurance procedures in wind-tunnel testing. Some possible explanations for the variation in the results were mentioned by the authors, such as "statistical variability of the data themselves as well as those introduced by the measurement equipment; physical variability of the flow due to different simulation methods, in particular regarding the structure of the simulated turbulence; different judgement on the time and geometric scales imposed by a given wind-tunnel flow; imperfections of the model, pressure tapping and tubing; imperfections of the software used for the data analysis; and finally, human error, lack of accuracy and ability must not be forgotten." [36].

Recently, a comparison between reduced-scale wind-tunnel experiments and on-site full-scale measurements was performed for the same isolated cube case as the common exercise [37]. The results from this comparison show an overall underestimation of the C_p at the side and leeward surfaces by the wind-tunnel experiments (see thick solid line in Fig. 2). New wind-tunnel experiments were conducted in the same study [37], with special attention being paid to the high-frequency part of the turbulence spectra. These new results are also shown in Figure 2, for two tests with slightly different boundary conditions (see two thin dashed lines). These are in better agreement with the full-scale data, even though the full turbulence spectra, and consequently the turbulence intensity profiles, were not reproduced in the wind tunnel.

Similar to the full-scale experiments, uncertainty in wind-tunnel measurements is seldom reported in accordance to the guidelines of ISO [34].

Based on the sample of studies provided in this section, it can be concluded that wind-tunnel experiments present specific challenges. The quality of wind-tunnel results is directly affected by the history of calibration in the wind tunnel, quality assurance procedures, and the know-how of the personnel involved in the test set-up and execution.

3.3 CFD

CFD has been used to study air flow around buildings for more than 30 years [38], while simulations focused on wind pressure on the building facade emerged about 20 years ago [39-42]. Those studies were clearly exploratory, with no direct application in building design or industry. In the next years, the application of CFD strongly increased due to improvements in computer performance, price reduction, and the availability of commercial CFD software. Stathopoulos provided a clear picture of "past achievements and future challenges" in Computational Wind Engineering (CWE) in a paper from 1997 [43], which is still equally valid today in many respects. The paper expresses concern about the misuse of CFD for problems that cannot be approached using this technique, which is still the case today considering the lack of validation in many CFD applications. The review indicates some areas for improvement in the future. The list is reproduced below [43]: "(a) Numerical accuracy by using higher-order approximations coupled with grid independence checks; (b) Boundary conditions, which depend on the specific problem under consideration so that they require good physical insight and high level of expertise; and (c) Refined turbulence models although ad hoc turbulence model modifications are unlikely to perform well beyond the specific flow conditions for which they have been made." [43]. It can be said that the advances in these aspects have been less pronounced than the increase in CFD use by practitioners and researchers. Numerical accuracy, including grid independence analysis, is not reported in many applications, and are not part of the editorial policy of many journals. Concerning the boundary conditions, the definition of inlet profiles is often still simplified, especially with regard to the turbulence structure in Reynolds-averaged Navier Stokes (RANS) models. In transient simulations, such as those using Large Eddy Simulation (LES), inlet conditions are more sophisticated, but also more demanding. The proper use of wall functions for the solid boundary at the floor of the computational domain also proved to be a source of concern [44-46]. It is accepted that LES can provide good results for C_p and for related natural ventilation problems, while RANS simulations provide less accurate results [47-49]. Just as in wind-tunnel modelling, quality assurance in CFD is imperative. In this respect, it is noted that important collaborative research efforts in recent years have led to extensive guidelines to increase the accuracy and reliability of CFD modelling for wind flow in urban environments [50,51].

Despite the vast increase in the application of CFD to study the wind flow around buildings, it is not common practice to use it as source of custom C_p data for BES simulation. The main reasons are the required level of expertise and the high cost of these simulations, both in terms of computational resources and user time, when compared to the BES simulation itself. Part of those limitations can be overcome in the future by the integration of pre-processing and post-processing between BES and CFD, together with clear guidelines for such simulations. IES<VE> is the only BES tool that at present includes a prototype of this integration, but in the present state it is less useful, due to the limited number of options for the CFD simulation, limited grid options and lack of integration in the post-processing stage. However, it does indicate a possible direction to improve the use of CFD as source of C_p data.

4 Secondary sources: General aspects

When primary data sources are not available, secondary sources provide low-cost data for infiltration and ventilation studies. Table 2 presents a list of the secondary sources implemented in the BES and AFN programs mentioned in Table 1, where different labels are used to indicate the level of implementation. "x" refers to full implementation, meaning that all data from the source are implemented in the BES-AFN program. "p" indicates that only part of the data source is implemented. "r" refers to the fact that the source is not implemented in the program, but that the program documentation refers to the data source from which the C_p values can be obtained by the user. Finally, "?" means that data from a certain source is implemented but that it is not clearly mentioned in the documentation which source was used. Therefore, we identified the most likely source based on the C_p values and the nomenclature used in the program, and added this information in the table. Concerning building height, data for low-rise buildings is more often implemented than data for their high-rise counterparts. Concerning the data source, data provided by AIVC is included in 7 out of the 10 programs included in this paper. Note that despite the large amount of wind tunnel data published, only two databases are used in the programs: the so-called AIVC database [1,15] and the ASHRAE Handbook - Fundamentals [52]. Analytical tools are less frequently included than databases, at least in BES programs. Only two BES programs provide full implementations of the analytical models "CpCalc+" or "Swami and Chandra", while AFN programs require the use of third-party tools, i.e. the analytical model is implemented in another program and not inside the AFN program (see indication with "r" in Table 2). Note that for CONTAMW, the Swami and Chandra model is not implemented as such, but instead some results of this model were previously calculated, and these data have been provided in the program. The equations proposed by Swami and Chandra [53] are labelled as "analytical tool", but they are in fact much simpler than CpCalc+ or C_p Generator. Each of the of secondary data sources in Table 2 is discussed in the next sections.

5 Secondary sources: Databases

C_p databases are compilations of C_p data from one or more sources, where the data is classified according to some parameters, such as building shape and orientation to the incident wind. C_p databases are widely available, particularly for the calculation of wind loads on structures. Wind load standards often provide C_p values for unsheltered buildings with simple geometries, to be used when custom wind-tunnel experiments are not available. A similar approach, i.e. with simple geometries for mostly unsheltered buildings, is used in C_p databases available in the ventilation and infiltration literature, e.g. the AIVC database [1] or the data in the ASHRAE Handbook [52], which are described below.

5.1 AIVC

The Air Infiltration and Ventilation Centre (AIVC) has been an international reference in the subject since its inauguration in 1979. It is an annex running under the "Energy Conservation in Buildings and Community Systems (ECBCS)" of the International Energy Agency (IEA). In 1986, after a workshop about wind pressure coefficients promoted by the AIVC [54], a compilation of C_p data was published as part of a comprehensive guide [1], which quickly became an important reference in the ventilation field due to its concise and straightforward character. This publication presents tables with data for low-rise buildings, and figures with vertical profiles for high-rise buildings. Note that the term "low-rise buildings" is used for buildings with up to 3 storeys, which seems to imply that higher buildings are classified as "high-rise". The tables (for low-rise buildings) were compiled based on a combination of several studies, while the profiles (for high-rise buildings) were reproduced from a single publication [55].

The data for low-rise buildings is based on the compilation of wind-tunnel data published in the workshop [54], and seven other bibliographical references, e.g. [55,56], but the method that was used to convert the wind-tunnel data to the database is not mentioned. The C_p database for low-rise buildings consists of tables with surface-averaged data, for rectangular floor plans and for 3 shielding levels: exposed, semi-sheltered (surrounding obstacles with half of the building height), and sheltered (surrounding obstacles with the same height as the building). The data are provided for wind direction sectors of 45°, for the wall of a square floor plan building and for the long and short walls of a rectangular (1:2) floor plan building. The exact building height and the width to height ratio are not mentioned. For the facades, only the averaged value over the whole surface is provided. For the roof of the low-rise buildings, three types of averaged data are provided: a surface-averaged value, a value for the "rear" and a value for the "front" part of the roof. For each one of them, data is provided according to different roof pitch angle: lower than 10°, between 11° and 30° and higher than 30°. Some details about the data for low-rise buildings are not included in the publication. For the sheltered cases, the spacing between the building and the surroundings obstacles is not mentioned. No information is provided about the wind profile used in the wind-tunnel tests that provided the data. The publication correctly contains several warnings regarding the use of the data for low-rise buildings. The first page mentions that "the intention of these data sets is to provide the user with an indication of the range of C_p values which might be anticipated for various building orientations and for various degrees of shielding." [1] All the other pages contain an explicit warning: "Caution: Approximate data only. No responsibility can be accepted for the use of data presented in this publication." [1]. Despite the mentioned careful and modest purpose of the low-rise building C_p database, it has been extensively reproduced, however generally without reproduction of the warnings, by later AIVC publications [15,57,58] as well as by other publications on building performance [3,24,59]. The database is currently in use for the scientific community, e.g. [60]. Often, the confidence that is expressed in this database seems to exceed the intention of the original publication. This is most likely due to the scarcity of C_p data, and – in spite of the limitations of this secondary data - it should be noted that, in absence of primary data, this approach was probably the best choice

Concerning the AIVC data for high-rise buildings, no effort was made to compile tables based on several wind-tunnel tests, and only the data from one source were reproduced in the AIVC publications [1,57]. In the first publication [1], the data are presented as vertical C_p profiles for two wind directions, 0° and 45°, in relation to the normal to the longer face of the building (e.g. Fig. 3a). This angular discretization is commonly used for square floor plan buildings, but in this case the floor plan has an aspect ratio of 1.5:1 [57], which might lead to misinterpretation by the user. The model used in the wind-tunnel tests, at a scale of 1:400, has dimensions W x L x H = 0.11 x 0.076 x 0.23 m^3, which represents 44 x 30.4 x 92 m^3 in full scale. Data is presented for 4 different shielding levels, characterised by different heights of the surrounding obstructions: 1/6, 1/4, 1/2 and the same height as the height of the building. The comment provided to contextualize these data mentions that it is "showing the vertical dependency of pressure coefficients for tall buildings", which seems to indicate that the qualitative aspect was a priority, rather than the quantitative one. The use of vertical profiles for the high-rise building data might lead to misunderstandings, because in some cases the "vertical dependency" is not the main aspect in the C_p distribution over the surface. Figure 3 presents an example of a vertical C_p profile [1] and the C_p distribution over the same surface for the same experiment [57]. The figure represents a windward facade with a wind attack angle of 45°, and the profile is based on the average of the three values at the same level. The surface distribution shows a clear vertical dependency of C_p, but it also shows a horizontal dependency which is as pronounced as the vertical one for this specific surface and wind attack angle. This dependency is omitted in the vertical profiles, like the one in Figure 3. More recent AIVC publications do not include reproduction of the profiles or surface distributions for high-rise buildings, and present only the data for low-rise buildings [15,58]. The reproduction of the high-rise building data by others is also less common, e.g. [61], and it is used merely to exemplify the complex distribution of C_p over the surface.

5.2 ASHRAE

The ASHRAE Handbook of Fundamentals [52] is not a ventilation-oriented document like the AIVC publications, so it only presents condensed information about C_p in the chapter dedicated to airflow around buildings. Different from the AIVC low-rise building database, the ASHRAE Handbook only reproduces data from primary sources, rather than compile data from different publications in a single database. The publication provides data for low-rise and high-rise buildings, presenting surface-averaged C_p data as well as examples of the distribution over the surface. For the surface-averaged data, which are in fact used in BES-AFN programs, the building geometries are simple rectangular prisms with four different floor plan aspect ratios, and data are presented for wind attack angles from 0° to 180°.

An important difference between the AIVC and the ASHRAE data is the attention given to sheltering/obstruction effects: ASHRAE does not present data for sheltered buildings, although it provides correction factors for the reference wind speed based on sheltering factors. As in the AIVC database, there is no information about the wind profiles used in the experiments.

6 Secondary sources: Analytical models

Analytical models consist of a set of equations to calculate C_p for a specific building configuration [10,11,53,62,63]. They represent a user-friendly way to access the large amount of empirical data used in the model formulation. Analytical models for C_p prediction were developed based on wind-tunnel and full-scale experiments. They aim to provide C_p data for a broader range of building configurations, considering obstructions, the effect of different wind profiles and the C_p variation across the facade.

Analytical models were generally developed using regression techniques to analyse a large amount of C_p data. A particular approach was used by Allen [62], who applied harmonic analysis to wind tunnel data. The result of analytical model development is a function where the C_p value depends on the set of parameters considered in the regression, e.g., floor plan aspect ratio, width to height ratio, position at the facade, position and size of the surrounding buildings, aerodynamic roughness length and wind direction. The applicability of the derived functions depends on the quality and extent of the C_p experimental data used in the regression, as well as on the parameters considered in the analysis. Regarding the experimental data, several authors [10,53] point to the lack of data for complex building shapes such as L-shape or U-shape. Regarding the parameters, two considerations are important. Firstly, the available data guide the parameterization, because the chosen parameter needs to be covered by the range of experiments. So, some parameters cannot be considered because of lack of data. Secondly, there is a trade-off between precision and complexity. More precise equations tend to demand more parameters, but the increment in the precision does not necessarily justify the use of very complex formulae. The choice of which parameters to include in the regression analysis can be made based on sensitivity analyses. Note that none of the models presented here provide information on the uncertainty associated with their predictions. For some of them, correlation coefficients are provided, but it is not possible to calculate the prediction uncertainty using only this value. In the following sections, the main features of three analytical models are presented.

6.1 The model by Swami and Chandra (1988)

The model proposed by Swami and Chandra [53] provides one simple equation for low-rise buildings and another for high-rise buildings. The low-rise building equation is presented below, as an example. It provides a surface-averaged value for the facade:

$$NC_p = \ln[1.248 - 0.703 \cdot \sin(\theta/2) - 1.175 \cdot \sin^2(\theta/2) + 0.131 \cdot \sin^3(\theta/2) + 0.769 \cdot \sin^4(\theta/2) + 0.07 \cdot G^2 \cdot \sin^5(\theta/2) + 0.717 \cdot \sin^6(\theta/2)] \quad (2)$$

where NC_p is the normalized pressure coefficient. G is the natural logarithm of the floor plan aspect ratio (ratio of the width of the wall under consideration to the width of the adjacent wall) and θ is the wind attack angle. NC_p is equal to one when the wind is orthogonal to the surface. It is therefore necessary to know a priori the surface-averaged C_p value for wind orthogonal to the surface. For this value, the model suggests $C_p = 0.6$, but it indicates that the value can vary from 0.19 to 0.91, depending on the wind profile, building height, roof pitch and floor plan aspect ratio. The model calculates C_p for buildings with a rectangular floor plan. Sheltering effects are not considered in detail; a shielding correction factor is proposed, to be applied directly to the calculated flow rate. This shielding factor is independent of the position, number, size and type of possible ventilation openings. The equation for low-rise buildings only provides surface-averaged C_p. The decision to neglect the variation of C_p over the surface was based on earlier studies [56,64], which focused on infiltration calculations assuming cracks that are homogeneously distributed over the building facades. This assumption however is not valid for many ventilation calculations, and may also be invalid for some infiltration calculations. The equation has two parameters: wind direction and building floor plan aspect ratio, and has a correlation coefficient of 0.8. This result is good, considering the broad range of data analysed, including data from buildings with different heights and different roof pitch angles, and the fact that these parameters are not used in the analytical model. The equation for high-rise buildings does not provide surface-averaged values but includes the position at the facade as an additional parameter. Correlation coefficients for this equation are not provided.

6.2 CpCalc+ (1992)

CpCalc+ [10] was developed within the COMIS workshop [4] with the intention to provide C_p values for sheltered buildings, which can not be obtained with the model by Swami and Chandra [53]. Compared to Swami and Chandra's model, additional experimental data were used to take into account sheltering effects, and also new parameters were added, such as the power-law exponent of the mean wind-speed profile, the plan area density, the relative building height to the surrounding buildings, the width to height aspect ratio and the position at the facade. The plan area density is defined as the ground surface area covered by buildings to the total ground surface area. Sheltering effects are considered indirectly, using the "plan area density", rather than taking into account the individual sheltering effects by each building. In order to allow for the higher number of parameters, a parametrical approach was used, based on successive independent corrections for each parameter. This approach creates a much more complex model, based on several tables with coefficients for each correction. The author mentions that the methodology is the main result, rather than the equations themselves. This is due to the lack of complete and high-quality experimental data, which is considered the main obstacle for a more comprehensive analysis.

6.3 C_p Generator

The C_p Generator has been developed in the last 30 years to "predict the wind pressure coefficients, C_p, on the facades and roofs of block shaped buildings" [11]. The tool is a web-based application (http://cpgen.bouw.tno.nl), developed by the Dutch institution TNO. The C_p Generator has a similar approach and similar capabilities as CpCalc+, predicting point values on the facade and also on the roof, dealing with low-rise and high-rise buildings with user-defined dimensions (length-width-height) and taking into account the effects of the surrounding terrain by wind-speed profile corrections. The main improvement, compared to the other analytical models, is the way in which sheltering is taken into account. The model considers discrete block-shaped obstructions instead of the neighbourhood plan area density. Unfortunately, the model was not developed in the English language. A comparison between C_p Generator results and data from on-site full-scale experiments on two particular low-rise building, in terms of C_p differences between positions at the building facade, shows that they "are closer to reality than simulations carried out with C_p values from the AIVC tables"

[33]. Nevertheless, they show large deviations compared to experimental data obtained for the same building, for some points and wind directions.

7 Comparison of C_p data features

Table 3 is a summary of the characteristics of each of the secondary sources described in the previous sections. It also compares these characteristics with those of primary sources. The first conclusion is that none of the databases or analytical methods can handle the effects of site topography (hills, valleys, …), building facade detailing or inform about the uncertainty of the provided data. Another feature that is similar in most data sources is the size of the wind direction sectors. In most sources, the user can choose any wind attack angle. Only the AIVC database has a fixed angular discretization in 45° intervals (for low-rise buildings) and 90° intervals (for high-rise buildings). The variation across the facade and sheltering effects are treated in different ways by each of the data sources listed in Table 1. These aspects are discussed in more detail in the subsections below.

7.1 Variation across the facade

Table 3 shows that only the analytical methods can fully take into account the variation across the facade. However, most BES programs only include database values (see Table 2). In order to analyse the importance of the variation across the facade, some comparisons are made here. A suburban environment is chosen for this comparison, and the corresponding wind-profile parameters for the analytical models are obtained in the program documentation of each model. A power-law wind-speed profile exponent (α) of 0.22 was used for CpCalc+, while an aerodynamic roughness length (z_0) of 0.5 m was used for C_p Generator. Note that the other models do not take the type of surrounding terrain into account. For the AIVC database and the model by Swami and Chandra for low-rise buildings, only surface-averaged values are used in the comparisons, because those data sources do not provide values for specific points at the facade. Figure 4 presents the data for three points on the facade of a low-rise cubic building (10x10x10 m^3). The data from the different sources show a similar pattern. Figure 4a shows that the maximum deviation in C_p for the middle point is 0.4, which might be considered high, given the simple building geometry. For the lower left corner (Fig. 4b; x = 1 m, y = 1 m), the deviations go up to 0.5. For the top right corner (Fig. 4c; x = 9 m, y = 9 m), deviations go up to 0.4. Note that especially in Figure 4c, as opposed to Figures 4a and b, predictions by CpCalc+ and Cp Generator are in good agreement with each other, and predict values that are considerably lower for the windward facade than the surface-averaged values from AIVC and Swami and Chandra. Figure 4d shows the differences between the C_p values at the three different positions compared with the surface-averaged values of the AIVC, clearly indicating considerable deviations for every wind angle of attack. This confirms the statement by Feustel et al. [65], the use of surface-averaged values was one of the main motivations for the development of analytical methods, as “From experience we know that wall-averaged values of C_p usually do not match the accuracy required for air-flow calculation models.”

7.2 Sheltering effects

Table 3 shows that most of the data sources can partially model the sheltering effect by buildings, however the techniques used for it are very different. Table 4 details the method used by each data source to take into account the sheltering effect. Seven methods are distinguished, which can be classified into three main approaches, A, B and C, as indicated in Table 4. Approach A consists of the direct use of wind-tunnel results (method 1) or of the parameterization of the geometry of the obstacles (methods 2 and 3) It demands more information about the obstacles but the sheltering effect is better taken into account. This approach is adopted by 7 of the 10 of the programs. Approach B consists of using correction factors based on general classifications about the geometry of the surrounding obstacles. These correction factors are either applied to the C_p value itself (method 4), to the calculated flow rate (method 5) or to the (reference) wind speed (method 6). It is used by three of the programs. Approach C consists of using the data from the leeward building surface to provide data for the sheltered windward surface (method 7). It is used by one program. Note that IES uses approach A for low-rise and approach B for high-rise buildings. Also for other programs, more methods can be used, depending on the data source implemented or used by the program. For example, COMIS can be used with either method 1, 2 or 3, depending on the data source adopted. The seven methods in Table 4 are described in detail below, and some results are compared at the end of this section.

Method 1 uses C_p results from wind-tunnel experiments with obstructions around the model, as in the AIVC database. This is certainly the most adequate solution to take the sheltering into account because the geometry and position of each obstruction is reproduced in the experiment. However, this information is highly case specific, and databases like AIVC can reproduce only a few configurations. Moreover, in the AIVC database there is no information about the distance between the model and the surrounding buildings, which can affect directly the C_p results. Method 2 uses parameters to describe the surrounding area. For example, in CpCalc+, these are the neighbourhood density and the ratio of building height to the height of the surrounding buildings. This method is in some way an improvement compared to AIVC because the parameters can be used to describe a large range of surrounding configurations. However, the surroundings are considered homogeneous, which is rarely the case in reality. Method 3 uses parameters to describe each discrete obstruction. In Cp Generator, these are the position and the size of each of the obstructions. This method is very similar to method 1, but the description of the discrete surrounding obstruction(s) is restricted by the parameters chosen by the developers, e.g. C_p Generator only considers rectangular prisms as obstructions. Also in this case there are clear advantages of analytical models compared to databases. For instance, C_p Generator can handle any obstacle configuration while the AIVC database only gives results for a few configurations. Methods 1 to 3 (approach A) try to take into account the specific impact on the C_p value, instead of adopting a stronger simplification like the other methods listed in Table 4. Method 4, based on correction factors applied on C_p, adopts different assumptions depending on the program. IES <VE> adopts the AIVC database, but the data for high-rise sheltered buildings do not comply with the original source. Data analysis reveals that constant correction factors (0.66 and 0.33) are applied to the data for fully exposed buildings to obtain values for semi-exposed and sheltered buildings respectively. The documentation does not mention this procedure. Tas uses correction factors based on the relative building height, i.e. the height of the building to that of the surrounding buildings [19]. SUNREL adopts correction factors according to five levels of sheltering, which are taken from values that were obtained to be applied directly on the flow rate, rather than on C_p. Methods 5 and 6 are not implemented in any of the programs in this paper. Method 7 refers to an option provided in Tas to "designate all apertures of a given type *sheltered,* which has the effect as treating the apertures as though they were on the leeward side of the building. This feature may be used to treat apertures which face into an enclosed courtyard, and are thus not subject to the wind pressures experienced by an exposed aperture" [19]. Note that all methods consider a uniform sheltering correction for all points at the building facades, while in reality the extent of sheltering can be different for different parts of the facade.

In order to present the different results obtained using the discussed methods, the same building and facade positions as in section 7.1 are used, but now this building is considered to be surrounded by similar buildings in an infinite regular array with a horizontal spacing of 10 m, i.e. equal to building height. The results are shown in Figure 5. While the AIVC data display only a small variation of C_p values with the angle of attack, the analytical methods provide very different results as a function of this angle. This might seem logical, given the effect of channelling of wind flow through the building group and the complex structure of building wakes interacting with each other. The correction factors on C_p were applied to the AIVC data for the unsheltered building, and in spite of the different techniques used in each program, their results are approximately the same. The results obtained using correction factors on C_p show good agreement with the AIVC data for the sheltered building on the windward facade, while the leeward facade shows higher differences. The use of data from the leeward facade to model the sheltered effect was also demonstrated using the AIVC data for the unsheltered building, and the results do not follow the same trend of the other data source, as expected. Considering all the data sources on Figure 5, the range of the results is wide, implying high uncertainty associated with C_p values for sheltered buildings. Figure 5 only considers sheltering by neighbouring buildings, but several low-rise buildings, such as L-shape or U-shape buildings, can provide shelter to themselves [53]. In those cases, the uncertainty might be even higher.

8 Conclusions

Pressure coefficients on building facades are influenced by a wide range of parameters. As it is practically impossible to take into account the full complexity of C_p variation, BES-AFN programs generally incorporate it in a simplified way. This paper has provided an overview of wind pressure coefficient (C_p) data in building energy simulation (BES) and air-flow network (AFN) programs. 7 BES programs and 3 AFN programs were considered. A distinction has been made between primary sources of C_p data, such as full-scale measurements, reduced-scale measurements in wind tunnels and computational fluid dynamics (CFD) simulations, and secondary sources, such as databases and analytical models. The main conclusions are:

1. Secondary data sources are most often used in BES-AFN programs.
2. Wind-tunnel experiments are the most common primary data source, while at present CFD is only rarely used. In the future, it might become an important source of C_p data, as a stand-alone tool or even integrated into BES-AFN programs.
3. Databases are the most common secondary data source in BES. Analytical tools are rarely found in BES programs, but commonly indicated as a data source in the documentation of AFN programs.
4. Pressure coefficients from different data sources, for the same building in the same conditions, show large variations, even for simple configurations like fully exposed cubic buildings (differences up to

0.4). Variations for data for sheltered buildings and for points near the facade corners can be considerably higher (differences up to 1.0). The same applies to complex building geometries, which are not included in existing secondary databases.

5. The lack of information about the uncertainty associated with the values provided by each data source raises questions about the accuracy of buildings performance simulations based on these data. Therefore, the quantification of those uncertainties using empirical data for a broad range of cases is an important topic of future research.
6. This overview has been limited to only 7 BES and 3 AFN programs. While many other valuable programs exist, the present sample is considered as a representative sample in terms of pressure coefficient data sources. These 10 programs were selected based on earlier, more general comparative work.
7. This overview may be used to guide future efforts in the development of BES, AFN and building envelope HAM programs. It can also assist future studies dealing with ventilation simulation, particularly those focused on the impact of C_p values and/or data sources in the overall simulation uncertainty

Acknowledgements

This research is funded by the "Institute for the Promotion of Innovation by Science and Technology in Flanders" (IWT-Vlaanderen) as part of the SBO-project IWT 050154 "Heat, Air and Moisture Performance Engineering: a whole building approach". Their financial contribution is gratefully acknowledged.

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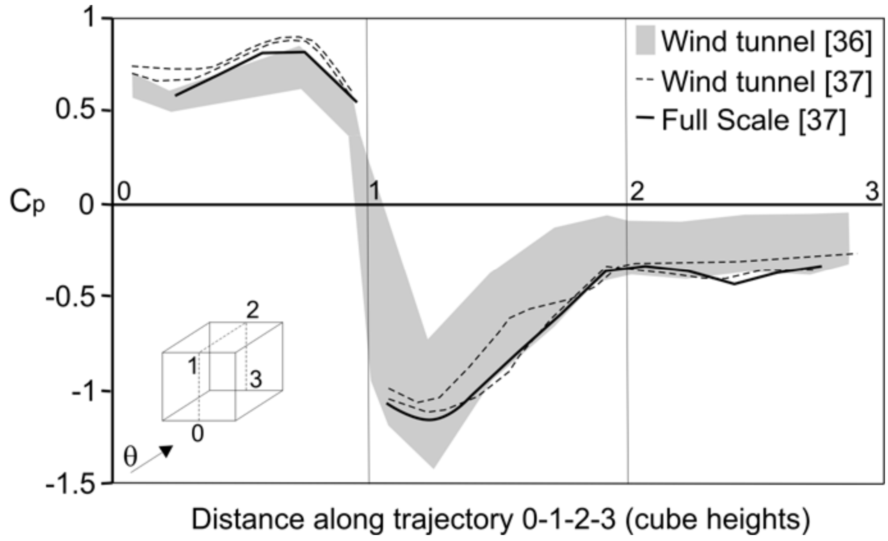

Figure 1. Comparison of different wind tunnel experiments, after [36].

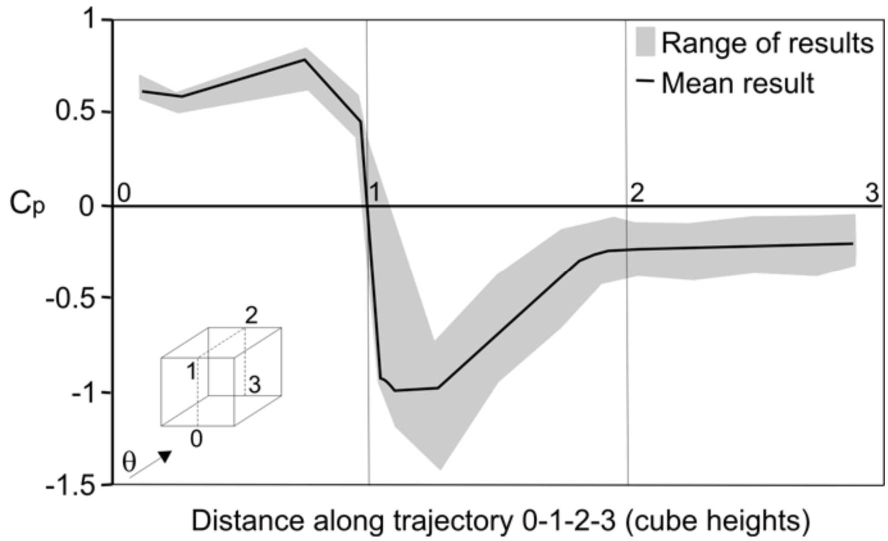

Figure 2. Comparison of different wind tunnel experiments with full scale results, after [36,37].

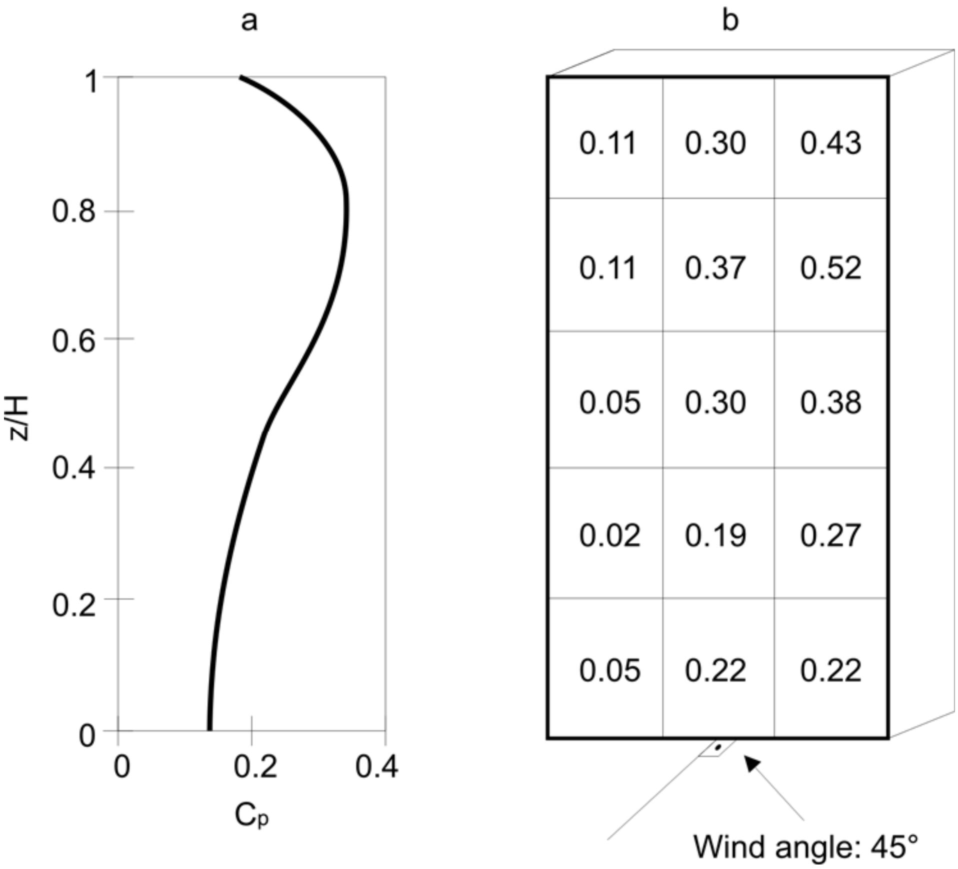

Figure 3. Example of (a) vertical profile of C_p values for a high-rise building surface [1], and (b) the corresponding C_p distribution over the surface [57].

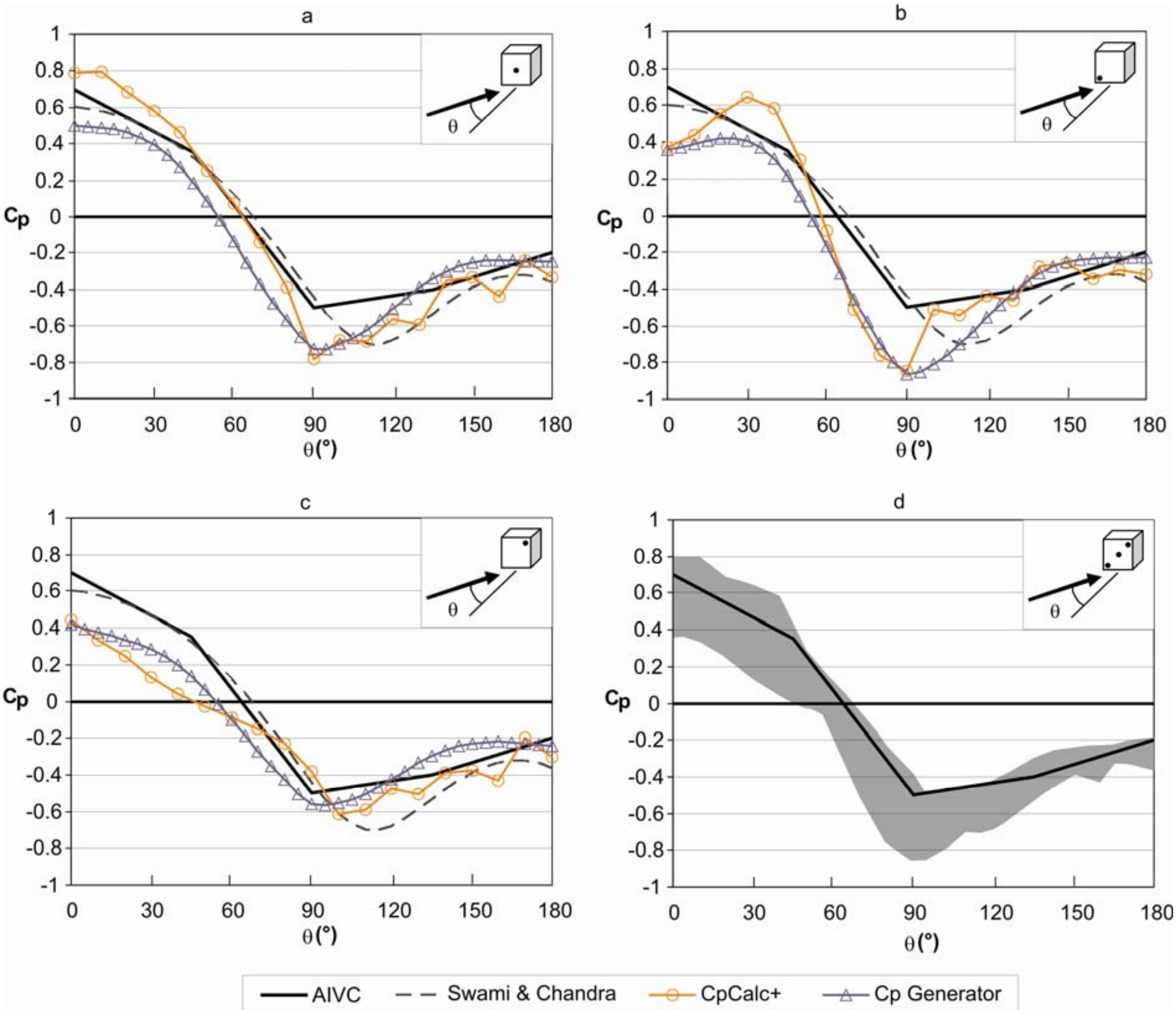

Figure 4. C_p for an unsheltered low-rise cubic building as function of wind angle of attack (θ): (a) middle of the facade; (b) lower left corner; (c) upper right corner; (d) range of data for the three points.

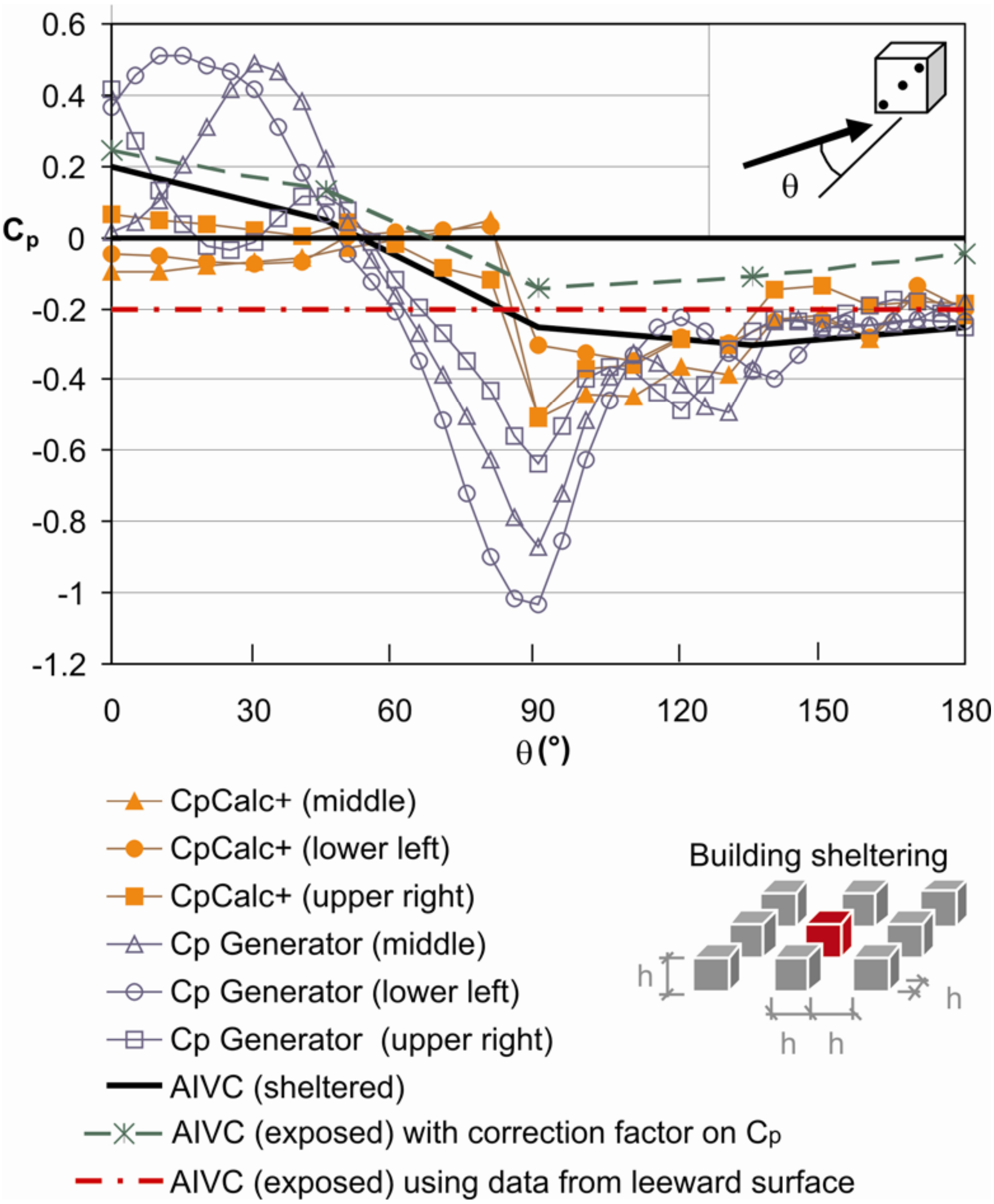

Figure 5. Sheltered building: C_p from different sources, and different points at the facade.

Table 1. BES and AFN programs considered in the overview.

Program	Type	Version	Documentation
ESP-r	BES	11.3	[3;9;16]
EnergyPlus		2.0.0.025	[17]
IES <VE>		5.6	[18]
Tas		9.0.5	[19]
BSim		4.6.7.12	[20;21]
IDA ICE		3.0 (15)	*
SUNREL		-	[22]
CONTAMW	AFN	2.4b	[23]
AIOLOS		1.0	[24]
COMIS		3.2	[4;14]

* no external document available, the “help” function was used to gather information.

Table 2 . List of secondary sources (C_p database and analytical models) implemented in the BES and AFN programs that are mentioned in Table 1.

		ESP-r	EnergyPlus	IES <VE>	Tas	BSim	IDA ICE*	SUNREL	CONTAMW	AIOLOS	COMIS
Database											
AIVC	Low-rise	x		x		p			p	?	?
	High-rise			p	p					?	?
ASHRAE	Low-rise										
	High-rise		x						?		
Analytical model											
Swami & Chandra	Low-rise		x					p	p		
	High-rise										
CpCalc+		x								r	r
Cp Generator									r		r

x – Implemented
p – Partially implemented
r – Not implemented in the program, but the C_p data source is indicated in the program documentation.
? – Not clearly mentioned in the documentation.

* contains no data source, only refers to external data sources

Table 3. Summary of features of databases and analytical models

	Primary sources	AIVC		ASHRAE		Swami & Chandra		CpCalc+	Cp Generator
		Low-rise	High-rise	Low-rise	High-rise	Low-rise	High-rise		
Topographic effects	x								
Building configuration (complex building geometry and facade detailing)	x								
Information on uncertainty	x								
Wind attack angle	x	p	p	x	x	x	x	x	x
Effect of surrounding terrain (smooth, rural, suburban, urban)	x							x	x
Variation across the facade	x		p				x	x	x
Sheltering effect by buildings	x	p	p	p	p	p	p	p	p

x – Fully able to model
p – Partially able to model

Table 4. Methods to model sheltering effects

Approach	Method	ESP-r	EnergyPlus	IES <VE>	Tas	BSim	IDA ICE	SUNREL	CONTAMW	AIOLOS	COMIS	Data source
A	1: Wind-tunnel experiments	x		x		x	x		x	x	x	AIVC
A	2: Parameters to describe the surrounding area	x								x	x	CpCalc+
A	3: Parameters to describe each obstruction								x		x	Cp Generator
B	4: Correction factor on C_p			x	x			x				
B	5: Correction factor on flow rate											Swami & Chandra
B	6: Correction factor on wind speed											ASHRAE
C	7: Copy data from the leeward facade				x							