Optimization of a solar chimney to enhance natural ventilation and heat harvesting in a multi-storey office building

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Optimization of a solar chimney to enhance natural ventilation and heat harvesting in a multi-storey office building.

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I would like to dedicate this study to my parents, who are the invisible heroes of my accomplishments this far.
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Abstract

This study explores the applicability and potential benefits of a solar chimney (SC) in a prototype multi-storey office building in the Netherlands. Dynamic performance simulations in the BPS program ESP-r are the basis for the analysis. Calibration and validation of the SC model were based on measurements in a small-scale test set-up (height: 11m, depth: 0.25m). The full-scale SC model has a height of 50m. Sensitivity analysis (SA) and optimization of the SC design were performed with respect to the annual energy harvested in the SC and the annual fan energy savings achieved. Harvested energy was found most sensitive to the length of the SC and the short-wave absorptivity of the walls, while fan savings to the length and depth of the cross section. The depth of the SC was found so influential in the case of fan savings because the area of the inlet opening (where most pressure losses were found to occur), was assumed the same as the SC’s cross section area. The glazing type and thermal mass were also found influential for both harvested energy and fan savings but to a lesser extent. Optimization indicated that the highest value for length, depth and absorptivity and the minimum value for the thermal mass would maximize both performance indicators. Given that the higher the depth –for a given length– the lower the pressure losses at the inlet opening of the SC, the maximum value for depth found in optimization should be translated as a requirement to minimize the pressure losses at the inlet opening. This requirement could also be accomplished by other means, and not necessarily by increasing the area of the opening. Analysis of the flow via CFD is considered more appropriate to indicate an optimum depth for the SC channel. Robustness analysis offered a general overview on the complexity of the controls (e.g. fans, dampers) required in case windows are to be opened.
1

Introduction

The exploitation of sustainable energy sources to cover the functional demands of buildings (for heating, ventilation, cooling, etc.) can contribute to significant energy savings and thus to alleviation of the current environmental, economical and social problems related to conventional energy practices. Passive (natural) ventilation of buildings is a successful means to save energy otherwise consumed for mechanical ventilation and possibly cooling. Solar chimneys (SC) are passive elements that make use of the solar energy to induce buoyancy-driven airflow and naturally ventilate the building.

A SC differs to a conventional chimney in that at least one wall is made transparent; solar radiation enters the chimney through the glazed part and heats up the walls. The temperature of the air inside the SC channel rises due to heat transfer from the walls and if the temperature difference between the air in the SC and the building is high enough, then the stack effect drives the air from the interior of the building into the SC to be exhausted at its top. The exhaust air is replaced by fresh air through openings or other paths in the building, and natural ventilation is accomplished. Performance of the SC is primarily described by the induced ventilation flow rates; in case heat harvesting is also of interest, air temperature in the channel is the other important performance indicator. Integration of a solar chimney in a building is possible in many ways (Figure 1.1[a-d]), e.g. as part of the south-facing façade (or the façade where maximum solar availability applies, [c]), on the roof (also known as ‘roof solar chimney’, [b]), in the place of a conventional chimney or as extension of a double façade (usually for multi-storey buildings [a&d]). The geometry of the SC channel is described by its height, length and depth. The elements of the SC are presented in Figure 1.2; the terms indicated in the figure will be used in the following sections to refer to the solar chimney’s parts and geometrical features.

![Figure 1.1 Possible ways of SC integration to a building.](image)

While the applicability and performance of the SC has been widely studied in single-floor or single-zone buildings experimentally (e.g. Khedari et al. 2000, Hirunlabb et al. 1999), numerically (e.g. Ho Lee and Strand 2009, Rodrigues et al. 2000) and analytically (e.g. Bassiouny and Koura 2008, Afonso and Oliveira 2000), integration in multi-storey buildings...
Passive ventilation of a five-storey building was found feasible in the study by Letan et al. (2003). Numerical simulations were performed with commercial CFD software assuming steady-state temperature and velocity fields and summer conditions. Air was supplied to the floors through a northern duct and was exhausted directly to the SC duct located on the southern side of the building; the SC-induced airflow rates decreased with floor level because the stack height decreased: the higher the level, the lower the airflow rate. At the top floor level (5th floor) airflow was close to zero and overheating occurred, while acceptable thermal conditions were accomplished for all other floor levels. The authors argued that extending the SC above the rooftop level by one storey height would improve the situation, but mechanical ventilation would still be required for the top floor.

Ding et al. (2005) investigated a prototype eight-storey office building with an atrium on the northern side and a double-skin façade on the southern side, which extends to an SC channel above the roof height. Reduced scale experiments and CFD simulations were again employed in this study. Here as well the airflow rates got lower with floor level and the suggestion that the SC is at least two-storey high was made.
Ventilation of a four-storey building (total height of 12m) via buoyancy-induced flow in a double-skin façade channel was studied by Gan (2006) using CFD analysis. Although not an SC channel was studied here, the double-skin façade works in a similar way, with the difference of more symmetrical heating of the two glass skins. Flow rates decreased from bottom to top: for a cavity width of 0.4m, 34% and 17% of the total flow was induced at the bottom and top floor respectively. These floor-to-floor variations were significantly reduced when photovoltaic panels (PV) were integrated at the outer skin of the façade.

Punyasompun et al. (2009) performed small scale experiments for a three-storey building under the Bangkok climatic conditions and developed a simplified model that could be used for designing a ‘multi-solar chimney building’. They tested two possible ways of SC integration; one where each floor had a separate SC channel (i.e. outlet openings at every floor), and one where the floors were connected to a common SC channel, extending from bottom to top floor (i.e. one outlet opening at the top of the channel). The latter proved to perform better and induced higher airflow rates through the floors. These studies have demonstrated the additional complexity and challenges posed by integrating an SC system with a multi-storey building, indicating the need for further research on various related topics.

Integration of a SC in a large-scale building project is a site-specific and building-specific problem, such that it is imperative that the design is based on performance estimations under dynamic conditions and for the specific building, climate and surroundings. Such performance estimations can be cost-effectively achieved via numerical modeling in building performance simulation (BPS) tools: dynamic thermal and airflow simulations for the SC-building system can be performed and the feasibility, potential benefits as well as possible improvements of the design can be explored. The need for such an approach will continue to grow, as more attention is drawn to the SC concept within the building industry; the Manitoba Hydro Place (2009) being an example of a large-scale real-time application of the SC concept (Figure 1.3 left) in a climate responsive energy efficient office building located in Canada. With a height of 115m, length of 15.5m and depth of 2.85m, the solar chimney integrated in this building is utilized as a natural ventilation element in the summer and as a heat recovery device in the winter. Another highly innovative, climate-neutral building project under the name ‘Kameel van de Noord’ (‘Camel of the North’, Amsterdam) is currently under way, which also utilizes the concept of the SC. It is evident that the SC concept can be successfully implemented -together with other ‘green’ technologies- in buildings opting to promote sustainability. As goals of ‘zero-energy’ or ‘climate-neutral’ buildings are becoming more popular and new experience is gained every day, it is very likely that the SC technology will become common practice in the coming years. Further research on solar chimneys is even more significant in anticipation of this development.

The present study explores the integration of a SC in a prototype multi-storey office building in the Netherlands. It forms part of a broader project under the name ‘Earth, Wind & Fire’, concerning the exploitation of solar, geothermal and wind energy in a prototype building. Performance evaluations will be performed in the BPS tool ESP-r and results will be used for sensitivity analysis (SA), design optimization and robustness analysis of the coupled SC-building system. The aim and applied methodology are presented in brief in the next section.
1.1 Aim and Applied Methodology

The aim of this study is the investigation of the applicability and optimization of a solar chimney to enhance natural ventilation in a multi-storey office building in the Netherlands.

To achieve the aim of the project we envisaged the research methodology which involves the following stages (Fig. 1.4):

1. Calibrating and validating the ESP-r model of the solar chimney with the available measurements data from the small-scale test set-up.
2. Choosing and modeling the prototype office building where the large-scale SC is intended to be used and perform relevant calculations (e.g. ventilation requirements).
3. Performing Sensitivity Analysis (SA) for the large-scale SC design and for the following parameters: length, depth, short-wave absorptivity and long-wave emissivity, insulation thickness and thermal mass of the back and side walls, glazing type and glass percentage of the glazed wall. The performance indicators for the SA are (i) the annual harvested energy (i.e. the air enthalpic gains in the SC) and (ii) the annual fan energy savings.
4. Multi-objective optimization of the SC design to maximize: (i) the air enthalpic gains in the SC that could be recovered and used for e.g. heating purposes and (ii) the fan energy savings.

1 The test-setup is located in Mook, the Netherlands and measurements are performed in the context of the EWF project, under the responsibility of Peutz.
5. Testing the robustness of the final optimized design using the model of the SC coupled to the model of the prototype building (e.g. influence of operating windows) and making recommendations.

The modeling and simulations of the SC and the building are performed in ESP-r. For the SA and optimization stages the freeware program Simlab (SIMLAB 2009) and the commercial software modeFRONTIER (ESTECO, version 4.2.1) are used respectively. The following chapters present the above methodology and corresponding results in detail. It is the scope of this report to include only the new knowledge acquired and to concentrate on the results analysis and discussion.

Figure 1. 3 Schema of the applied research methodology.
Calibration & Validation of the SC Model

2.1 Introduction

In order to confirm that the ESP-r model of the SC can adequately predict its performance, it is necessary to calibrate and consequently validate the model. Measurement data from a small-scale SC test setup will serve the calibration and validation of the model; the former will be based on one-hour data assuming steady-state conditions and the latter will be based on whole day data thus assuming dynamic conditions. With calibration certain parameters of the thermal and airflow network in ESP-r are fine-tuned to best represent the actual performance of the system. Validation will offer confidence in the model's dynamic predictions. The procedure is performed for the small-scale SC model which replicates the test-setup SC where measurements are performed. The scalability of this model to predict the performance of the full-scale SC is discussed at the end of this chapter.

A detailed description of the procedure can be found in (Gontikaki and Trcka, 2010). A summary of the applied methodology and results analysis is presented here for brevity reasons.

2.2 Calibration

Calibration concerns both the thermal and airflow network of the model. With respect to the former, the objective is to select an appropriate correlation for the estimation of the convective heat transfer coefficients \( h_c \) \( \text{Wm}^{-2}\text{K}^{-1} \); with respect to the latter, the objective is to select an appropriate airflow component and to fine-tune certain of its input settings. The model used for calibration is an exact representation in terms of geometry and construction of the test-setup SC (Peutz, 2009). Figure 2.1 shows the model's geometry, zones division and airflow network. Calibration results for the thermal and airflow network are presented below.

2.2.1 Thermal Network Modeling Issues

From the available correlations in ESP-r the ones developed to account for buoyancy-driven airflow in open vertical channels were chosen, i.e. the Molina & Maestre and the Bar-Cohen & Rosenhow correlations (Beausoleil Morrison, 2000). Simulations in which all other model settings were kept constant and the \( h_c \) correlation was changed between the two mentioned above, indicated no difference in predictions of the two model variants. The Molina & Maestre was chosen to be used. This correlation was also compared against the default correlation used in ESP-r (Alamdari & Hammond) and was found to give more promising results for the specific problem (see 2.2.3.1).
2.2.2 Airflow Network Modeling Issues

Among the two airflow components initially selected to be tested (orifice and general flow conduit component), the general flow conduit component was chosen as a more realistic approach of the SC channel's geometry and flow characteristics. This section will refer only to the calibration of the model using this type of component.

The equation describing the flow through the general component is:

$$m = A \frac{\rho \Delta p}{\sqrt{\frac{fL}{D} + C_i}} \left[ \frac{kg}{s} \right]$$  \hspace{1cm} (2.1)

where $A$ the opening area, $\rho$ the air density, $\Delta p$ the pressure difference, $f$ is the frictional factor, $L$ is the conduit length, $D$ is the hydraulic diameter and $C_i$ the local dynamic loss factor. The input data required for this component are $A$, $L$, $D$, $C_i$ and $k$, where $k$ is the absolute wall roughness of the duct. From the above, $A$, $L$ and $D$ are determined by the geometry of the SC and for $k$ a reasonable value is selected equal to 1 mm\(^1\); thus calibration will consist of fine-tuning the $C_i$ factor of the components.

\(^1\) Model predictions were found insensitive to roughness variations; between roughness of 1mm and 10mm a 2% difference in air temperature predictions was found.
It is noted that due to restrictions imposed by the program, calibration was conducted for one-hour timeslots assuming steady-state conditions. The timeslots corresponding to different measurements days that were considered in calibration are presented in Table 2.1 along with some climatic data and the measured air temperatures at bottom and top of the SC.

Table 2.1 Climatic data & measured air temperatures at the bottom and top of the SC for the time-slots considered in calibration.

<table>
<thead>
<tr>
<th>No.</th>
<th>DATE</th>
<th>Timeslot</th>
<th>Avg. Solar radiation I [W/m²]</th>
<th>Avg. Wind speed w [m/s]</th>
<th>Air temperature T_{air} [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>inlet (0.25m)</td>
</tr>
<tr>
<td>1</td>
<td>15/12/09</td>
<td>10:00-11:00</td>
<td>276.0</td>
<td>2.20</td>
<td>19.5</td>
</tr>
<tr>
<td>2</td>
<td>15/12/09</td>
<td>12:00-13:00</td>
<td>416.7</td>
<td>1.30</td>
<td>21.0</td>
</tr>
<tr>
<td>3</td>
<td>15/12/09</td>
<td>13:00-14:00</td>
<td>380.7</td>
<td>1.31</td>
<td>21.0</td>
</tr>
<tr>
<td>4</td>
<td>15/12/09</td>
<td>14:00-15:00</td>
<td>285.5</td>
<td>1.76</td>
<td>20.4</td>
</tr>
<tr>
<td>5</td>
<td>15/12/09</td>
<td>15:00-16:00</td>
<td>91.9</td>
<td>1.36</td>
<td>20.1</td>
</tr>
<tr>
<td>6</td>
<td>08/01/10</td>
<td>11:00-12:00</td>
<td>188.5</td>
<td>0.79</td>
<td>17.4</td>
</tr>
<tr>
<td>7</td>
<td>15/04/10</td>
<td>12:00-13:00</td>
<td>328.5</td>
<td>1.15</td>
<td>22.1</td>
</tr>
<tr>
<td>8</td>
<td>15/04/10</td>
<td>13:00-14:00</td>
<td>367.2</td>
<td>1.19</td>
<td>22.6</td>
</tr>
<tr>
<td>9</td>
<td>15/04/10</td>
<td>14:00-15:00</td>
<td>362.3</td>
<td>1.29</td>
<td>22.5</td>
</tr>
<tr>
<td>10</td>
<td>18/03/10</td>
<td>12:00-13:00</td>
<td>396.4</td>
<td>0.84</td>
<td>24.2</td>
</tr>
</tbody>
</table>

The applied methodology for each timeslot can be outlined as follows (see Fig. 2.2):

- Processing of measurement data to use as input in the model. Surface temperatures (for the opaque and glass walls) and pressure difference along the SC channel (between bottom and top) will be used.
- Perform a simulation assuming an initial value for the C_{i} of the components.
- Compare the model’s output to corresponding (also processed) measurement data and readjust the C_{i} until a satisfactory agreement is accomplished; an agreement between the measured and predicted values of the air temperatures and mass flow in the SC channel is required.

It is noted that with respect to air temperature agreement the statistical measure of R^{2} is used; for every simulation run the predicted values of the air temperature in the zones is compared to the corresponding measured values and R^{2} is determined. The R^{2} takes values between 0 and 1 with 1 being the perfect agreement, i.e. that predictions and measurements fully coincide. For the agreement of mass flow rates, an error bandwidth of ±40% (is assigned to the measured value; agreement is found as long as the predicted value falls within the error range. This error is based on velocity measurements at a later stage of the project where velocity was measured at eight (instead of two as is the case in the timeslots considered) points across the section; the velocity between the different points was found to vary by a maximum of 40% (Peutz, 2010). A short section on the processing of the data follows.
2.2.2.1 Processing of measurement data

As stated earlier, the measurement data to be used as input are surface temperatures and pressure difference in the SC while air temperatures and mass flow rate are the data to be compared with the model’s output. It is noted that surface temperatures are measured at all walls at four heights (0.5/4.0/7.5/9.5m), mass flow rate is derived by velocity measurements in two points across the section and at four heights (0.5/4.0/7.5/9.5m), air temperatures are measured at nine points distributed across the section and at four heights (0.25/4.0/7.5/11.0m) and the pressure difference is measured between two points located at 0.50m and 11m respectively (Baharvand, 2010).

Processing of the measured data involved:

- Averaging over one hour the data provided in 10 minutes intervals.
- Area averaging of the air temperature measured at nine points assuming the averaging scheme shown in Fig. 2.3.
- Trend-line fitting of the temperature measurements (at four heights) to derive data at heights corresponding to the model’s zone heights. In most cases the surface temperature of the backwall was fitted with an exponential line \( y = a \cdot e^x \) while the air temperatures were a linear equation of height \( y = a + b \cdot x \) with \( a, b \) being parameters of the functions).
• Assuming a value for the surface temperature of the model's top zone, that is above the highest measurement point located at 9.5m. Surface temperature of zone 9 (9.8-11.0m) was assumed to be 75% of that estimated for zone 8 (8.7-9.8m).
• From the air temperature distribution along the height of the SC (estimated by the equation of the fitting curve) the hydrostatic pressure difference between bottom and top of the SC was calculated; this value was added to the measured pressure difference and the sum was assigned as boundary condition to the model.

![Figure 2.3 Air temperature measurements area averaging scheme.](image)

2.2.3 Calibration Results
For all timeslots but one\(^2\), the \(C_i\) value was found to be either 0.6 or 1.0. Since the \(C_i\) value of the airflow components is necessarily a fixed value in ESP-r simulations were performed for all timeslots with a \(C_i\) of 0.6 and 1.0. For these simulations' results and all timeslots, air temperature agreement is presented in Table 2.2 and mass flow agreement in Table 2.3. The timeslots in the latter table are indicated only by their number for brevity. Figures 2.4 & 2.5 present the measured and predicted air temperatures for timeslots 3 and 5 and for \(C_i=1.0\); these timeslots present the highest and lowest \(R^2\) respectively for this \(C_i\) value and can thus serve as an indication of how \(R^2\) is translated in absolute differences between data.

Figure 2.5 presents the results for the timestep of 15/12/09 10:00-11:00 when the Molina & Maestre and when the Alamdari & Hammond \(h_c\) correlations are used. The figure supports the decision to use the Molina & Maestre correlation as more appropriate for the specific problem (see §2.2.3.1).

\(^2\) For timeslot No.2 the \(C_i\) that gave the best results was found to be 2.5.
Table 2.2 Air temperature agreement expressed by $R^2$ for all timeslots and for Ci equal to 0.6 and 1.0.

<table>
<thead>
<tr>
<th>No.</th>
<th>DATE</th>
<th>Timeslot</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$C_i=1.0$</td>
</tr>
<tr>
<td>1</td>
<td>15/12/09</td>
<td>10:00-11:00</td>
<td>0.92</td>
</tr>
<tr>
<td>2</td>
<td>15/12/09</td>
<td>12:00-13:00</td>
<td>0.71</td>
</tr>
<tr>
<td>3</td>
<td>15/12/09</td>
<td>13:00-14:00</td>
<td>0.97</td>
</tr>
<tr>
<td>4</td>
<td>15/12/09</td>
<td>14:00-15:00</td>
<td>0.90</td>
</tr>
<tr>
<td>5</td>
<td>15/12/09</td>
<td>15:00-16:00</td>
<td>0.27</td>
</tr>
<tr>
<td>6</td>
<td>08/01/10</td>
<td>11:00-12:00</td>
<td>0.81</td>
</tr>
<tr>
<td>7</td>
<td>15/04/10</td>
<td>12:00-13:00</td>
<td>0.30</td>
</tr>
<tr>
<td>8</td>
<td>15/04/10</td>
<td>13:00-14:00</td>
<td>0.80</td>
</tr>
<tr>
<td>9</td>
<td>15/04/10</td>
<td>14:00-15:00</td>
<td>0.41</td>
</tr>
<tr>
<td>10</td>
<td>18/03/10</td>
<td>12:00-13:00</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Table 2.3 Mass flow agreement for all timeslots and for Ci equal to 0.6 and 1.0.

<table>
<thead>
<tr>
<th>Timeslot</th>
<th>ESP-r predictions</th>
<th>Value</th>
<th>Error range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$m_{pred}$ [kg/s]</td>
<td>$m_{meas}$ [kg/s]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_i=1.0$</td>
<td>$C_i=0.6$</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.76</td>
<td>0.93</td>
<td>0.55</td>
</tr>
<tr>
<td>2</td>
<td>0.77</td>
<td>0.96</td>
<td>0.54</td>
</tr>
<tr>
<td>3</td>
<td>0.76</td>
<td>0.94</td>
<td>0.63</td>
</tr>
<tr>
<td>4</td>
<td>0.73</td>
<td>0.91</td>
<td>0.58</td>
</tr>
<tr>
<td>5</td>
<td>0.69</td>
<td>0.85</td>
<td>0.62</td>
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<tr>
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<td>0.68</td>
<td>0.84</td>
<td>0.73</td>
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<td>0.63</td>
<td>0.60</td>
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<td>0.54</td>
<td>0.66</td>
<td>0.57</td>
</tr>
<tr>
<td>9</td>
<td>0.53</td>
<td>0.64</td>
<td>0.59</td>
</tr>
<tr>
<td>10</td>
<td>0.60</td>
<td>0.73</td>
<td>0.58</td>
</tr>
</tbody>
</table>
$C_i = 1.0$, $R^2 = 0.97$

Figure 2.4 Measured and predicted air temperatures in the SC for $C_i = 1.0$ and for the timeslot with the highest $R^2$ (15/12/10 13:00-14:00).

$C_i = 1.0$, $R^2 = 0.27$

Figure 2.5 Measured and predicted air temperatures in the SC for $C_i = 1.0$ and for the timeslot with the lowest $R^2$ (15/12/10 15:00-16:00).
Figure 2.6 Predicted air temperatures for different $h_c$ correlations and $C_i$ values for the 15/12/10 10:00-11:00 timeslot.

2.2.3.1 Results Analysis

The following conclusions can be drawn from the calibration procedure:

- The fact that different $C_i$ values were found to perform best between the various timeslots is an indication that the model cannot predict the performance of the SC equally well at all times. This is reasonable considering the complexity of the flow characteristics in a naturally ventilated duct and the various parameters affecting the flow which cannot be taken into account (e.g. downdraught effects) or were chosen to be neglected in the model (e.g. wind).

- Given the various measurement uncertainties (including both sensor inaccuracies and measuring inaccuracies) and errors introduced by processing of the data, the calibration results are considered satisfactory. For $C_i$ equal to 1.0, mass flow predictions are always within the estimated valid range. When $C_i$ is fixed at 0.6 a good air temperature agreement is found, while in the first four timeslots the mass flow value predicted exceeds the upper limit of the valid range. In both cases ($C_i = 1.0/0.6$) low air temperature agreement was found for the timeslots of 15/4/10, but it is partially attributed to a large error in processing of the measurements' data. For example the parabolic profile taken by the predicted air temperatures, as opposed to the linear profile of the measurements (see Figures 2.4 & 2.5) is explained by the

---

3 The $R^2$ of the trendline used to calculate the surface temperatures to be used as input in the model was $\sim 0.70$; in all other cases $R^2$ was above 0.90.
parabolic profile of the trendline\(^4\) for the surface temperature measurements which is used to calculate the input in the model.

- The Molina & Maestre (or the Bar-Cohen) \(h_e\) correlation is more appropriate than the default correlation of Alamdari & Hammond used in ESP-r for the specific type of problem. It can be seen in Figure 2.6 that when the former is used, good agreement is found for a \(C_i\) of 1.0 while if the latter was to be used, a \(C_i\) of 5.0 would be required, leading to extremely low values of the mass flow, in some cases out of the lower valid limit of measurements.

### 2.2.3.2 Scaling issues

According to the calibration results a value for the local loss factor ranging from 0.6 to 1.0 would be appropriate for the components of the SC shaft. These numbers are translated into a range for the losses per meter in the SC of 0.71-1.18 Pa/m. In the full-scale 50m SC this would result in 35.5-59.0 Pa, which is even higher than the losses of the entire building (estimated at \(\sim 42.8\)Pa, see Chapter 3). The geometry and materials (e.g. very low roughness of the aluminium and glass) of the SC do not support the findings of such high losses; it is thus assumed that the pressure loss over the inlet opening is included in the measured pressure difference between bottom and top of the chimney. This assumption is supported by the low position of the pressure meter at the SC bottom\(^5\) which does not guarantee that the total pressure loss of the inlet is measured; actually measurements indicate a close to zero pressure loss through the inlet, which goes against common logic.

Under the scope of the above, for the validation study that follows but also for the full-scale application of the model the total dynamic pressure losses assumed to occur in the SC shaft will be assigned to the inlet opening only, whereas for the components of the SC a local loss factor of zero and a reasonable roughness value (e.g. 1mm) will be selected. Thus, instead of a \(C_i\) value of 0.6 or 1.0 assigned to the ten individual components comprising the SC shaft, a value of 6 (10x0.6) or 10 (10x1.0)\(^6\) will be assigned for the inlet opening. It should be highlighted that the modified model according to the above, will give the same simulation results for air temperatures and mass flow rates as the model initially used.

### 2.3 Validation

In the validation study, whole day simulations are performed and results are compared to measurements in the same way as in the calibration procedure. The input in this case is only the climate file (based on on-site measurements) while all parts of the physical model (i.e. flow in the measurement room) are included in the model, as opposed to the model used for calibration where only the SC shaft was considered. Table 2.4 summarizes the differences between the calibration and validation approach.

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\(^4\) In all timeslots the measured surface temperature at 4.0m is the same or even less than the one at 0.5m, resulting in a parabolic profile.

\(^5\) The height difference between the meter at the inlet and the one inside the shaft is \(-0.30\)cm

\(^6\) This value is derived from the equality \(10^4(C_{i,0.6} \cdot 0.5 \cdot \rho \cdot v^2) = C_{\text{opening}} \cdot 0.5 \cdot \rho \cdot v^2\); the inlet opening has the same dimensions as the SC thus \(v \text{ [m/s]}\) is the same through the components and the opening. The difference in \(\rho\) is negligible, thus \(C_{\text{opening}} = 10^4 C_{i,0.6}\).
2.3.1 Validation Results

Validation was performed for the days 15/12/09, 08/01/10, 18/03/10 and 15/04/10. Validation results regarding air temperature are presented in Figures 2.7-2.10; the figures include the predicted and measured temperatures for the top zone of the SC (i.e. zone nine, height from 9.8m to 11m) and the range of the measurements error (estimated at ±3.5°C). The estimation of the air temperature measurements error was based on preliminary CFD calculations in a SC channel of the same geometry and for a heat flux equal to 400W/m² (Peutz, 2009). The corresponding graphs for mass flow agreement are not presented for brevity reasons; it is noted that the predicted values always fall within the ±40% error.

Table 2.4 Comparison of calibration and validation approach.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Calibration</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose</strong></td>
<td>Calibrate airflow component</td>
<td>Gain confidence in dynamic predictions of the calibrated</td>
</tr>
<tr>
<td><strong>Model</strong></td>
<td>Only the SC shaft</td>
<td>All parts of the test set-up</td>
</tr>
<tr>
<td><strong>Assumptions</strong></td>
<td>Solar transmission is not modeled/ wind is neglected</td>
<td>Solar transmission is modeled/ wind is neglected</td>
</tr>
<tr>
<td><strong>Simulation period &amp; conditions</strong></td>
<td>One hour timeslots/steady-state</td>
<td>24hrs period/dynamic conditions</td>
</tr>
<tr>
<td><strong>Input</strong></td>
<td>Surface temperatures/ ΔP bottom-top of SC</td>
<td>Climate file</td>
</tr>
</tbody>
</table>

Hours from 9am to 5pm are included in the figures, i.e. the ones with most solar radiation during the day. Figures 2.11 and 2.12 present the direct normal solar radiation intensity and the outside wind speed (multiplied by 10) during the hours 7am to 8pm of the days considered for validation of the model.
Figure 2.7 Validation results for 15/12/09 – Air temperatures at the top zone of the SC channel.

Figure 2.8 Validation results for 08/01/10 – Air temperatures at the top zone of the SC channel.
Figure 2. 9 Validation results for 18/03/10 – Air temperatures at the top zone of the SC channel.

Figure 2. 10 Validation results for 15/04/10 – Air temperatures at the top zone of the SC channel.
Figure 2.11 Direct normal solar radiation intensity for the validation days.

Figure 2.12 Wind speed during the validation days.
2.3.2 Results Analysis

The following general comments can be made regarding the validation results:

- The air temperature predictions lie within the uncertainty range of the measurements in most cases. An overestimation of the air temperature above the upper valid limit is found for most hours of 15/4/10, for which the calibration results were also the poorest (for the three timeslots considered). For some hours of 08/01/10 air temperatures also fall outside the upper uncertainty limit, but it can be argued that the low values and the highly irregular pattern of the solar radiation intensity during that day (see Figure 2.15) can cause model instabilities.

- The climatic conditions are believed to have a high influence on the accuracy of the model's predictions, and while solar radiation is taken into account in the model, the wind is neglected and that can be an important source of error. In the case of 15/4/10 wind speed is consistently high during all hours considered for validation; an underpressure at the outlet of the SC due to this wind could cause higher flow rates and thus lower air temperatures than the model would predict (see Figure 2.10). On the other hand, for the 15/12/09 when good agreement is found between air temperature measurements and predictions the wind speed is consistently low, actually the lowest among all days.

- In most cases the predicted air temperature at 9am falls over the upper valid limit, while agreement is established at 10am. This is probably due to the very low or even zero solar radiation intensity values at this hour. In the 'absence' of the input variable (solar radiation) that drives the thermal mechanisms in the SC, the error introduced by the initial simulation conditions can be dominating (see 2.3.3).

In order to have a complete appreciation of the uncertainties and possible sources of error in the validation procedure, a discussion section follows which summarises all relevant information.

2.3.3 Discussion

The validation results presented above have not taken into account several sources of uncertainties. More specifically:

- The estimation of the measured air temperature values are subject to instrumentation errors, averaging scheme errors and trendline fitting errors. The uncertainty estimated here (error of ±3.5°C) does not include these errors.

- Instrumentation errors of solar radiation and outdoor air temperature measurements are also not included.

- Uncertainties of physical material properties are not taken into account (e.g. uncertainty of short wave absorptivity of the aluminium layer, visible transmittance of the glazing, etc).

Model prediction errors introduced by:

- Neglecting wind.

- Assuming that the total solar energy entering the zones is absorbed solely by the backwall; shading by side-walls is also neglected.

---

7 This simplification was imposed by program restrictions; insolation between zones could not be calculated due to the use of fictitious surfaces for the zones' top and bottom surfaces.
• Assuming that flow occurs during all hours whereas in the test set-up the system is shut down during the night hours; this could cause higher start-up temperatures for the surfaces of the walls during the early hours of the day, which could explain the air temperature over-estimation at 9am for all days.
• Uncertainties of the model’s parameters and predictions.

Some of the aforementioned errors could be accounted for, but this would only improve the already satisfactory validation results (model’s predictions would always fall within the larger uncertainty ranges); since confidence in the model is already gained with a conservative error estimation there is no need to proceed with a more elaborate estimation.

2.4 Conclusions

Calibration indicated that the general flow conduit component chosen to represent the SC channel manages to predict the system’s performance quite accurately; a roughness value of 1mm and zero local losses are assumed for the components. An appropriate local loss factor value between 6 and 10 was found for the opening of the SC, assuming it has the same dimensions as the chimney’s cross section. The Molina & Maestre algorithm for convective heat transfer has been adopted as the most promising. Validation has shown a good match between measurements and predictions, even with various sources of uncertainty being neglected in results presentation. The validation results confirmed that the SC model in ESP-r can be used with confidence for simulating the performance of the SC. A full-scale SC model with the components’ settings found via calibration will be used in the following stages of the study.
3

Case Study

3.1 Introduction

This study aims at investigating the applicability of a SC system in a multi-storey office building in the Netherlands. To this purpose, a building that would serve as the case study needs to be selected. The SC design and the functional requirements of the integrated system are determined by certain features (e.g. geometry, ventilation demand) of the case study building, thus before advancing to the next steps of the research, a description of the building is offered.

The case study is inspired by the Vertigo building of the faculty of Architecture at the Eindhoven University of Technology (TU/e) campus, in the Netherlands (Figure 3.1). It is noted that the case study considered is only a simplification of the actual building; the number of floors, the floor height and the raw dimensions of the floor plan are only preserved. The case study building is modeled in ESP-r. In the following, with the term ‘building’ its model equivalent is implied. The building’s geometry, ventilation requirements, duct calculations and airflow network modeling in ESP-r are presented in the following sections.

![Figure 3.1 The Vertigo building in TU/e Campus.](image)

3.2 Geometry

The floor plan of the building is rectangular with dimensions of 43.2*32.4m (floor surface area is ~1400m²). The total height of the building is 49.5m, with nine floor levels of 5.5m height each (Figure 3.2). As stated earlier, the number of floors and their height are taken as is in the actual building. The internal layout of the floors is kept simple, with the floors being internally divided into six office areas and a central corridor; the internal floor layout and office zones dimensions can be seen in Figure 3.3. Every floor is assumed to have the same internal layout. The internal layout is
arbitrary and is chosen so that no more complexity than necessary is included; a certain level of realism is however sustained through the modeling of the separate office zones. Since thermal performance predictions are not of interest to this study, other geometry features of the floors e.g. windows will only be modeled as openings for the airflow network, wherever required in robustness analysis.

Figure 3. 2 Wireframe image of the prototype building.

Figure 3. 3 Wireframe image of the floors' internal layout (top view).
3.3 Ventilation requirements

The required ventilation rate is assumed 4 ACH\(^1\); for the calculation of the air volume of the office zones a floor height of 3m instead of 5.5m is taken into account (this height was considered in ventilation calculations of the actual building). Table 3.1 presents the required supply volume per zone, floor and building. Each floor requires 3.63m\(^3\)/s, which for the whole building amounts to ~32.7m\(^3\)/s.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Air Volume [m(^3)]</th>
<th>ACH</th>
<th>Volume flow rate [m(^3)/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW/SE/NW/NE</td>
<td>476.28</td>
<td>4</td>
<td>0.529</td>
</tr>
<tr>
<td>E/W</td>
<td>680.40</td>
<td>4</td>
<td>0.756</td>
</tr>
</tbody>
</table>

Ventilation required per floor: \(4 \times 0.529 + 2 \times 0.756 = 3.628\) m\(^3\)/s

Ventilation required for the building: \(9 \times 3.628 = 32.65\) m\(^3\)/s

3.4 Duct design

The duct network of the building consists of a supply section and an exhaust section. The terms used here to describe the various ducts of the network will be used consistently in the chapter to refer to the corresponding ducts. Figures 3.4 and 3.5 work complementary to the description of the network given below, with the former representing the entire network of the building and the latter the internal network of the individual floors. In the figures the lines represent the ducts and the nodes the starting and ending points of the ducts (i.e., junctions or points where ducts of different sizes connect). Nodes are labeled with a letter followed by a number; the letters are abbreviations for supply, exhaust and floor; the number represents the floor level. Whenever the letter f is used instead of the floor number i.e. s(f), a reference is implied to all the corresponding ducts irrespective of the floor.

A main supply duct is located on the northern side and runs vertically from the top to the bottom floor (s0-s9-...-s1); at every floor level secondary ducts diverge from this main duct (e.g. s6-s6', s9-s9' etc) to supply the air required in every floor to ventilate the office zones. The terms 'supply duct' and 'floor supply duct' will be used to refer to the main supply duct and the diverging secondary ducts (see Figure 3.4). An internal supply network runs inside every floor which supplies air to the office zones; the zone of the centrally located corridor is not supplied with fresh air. The term 'internal duct' will be used to refer to the ducts of the main supply section of the floor network; the secondary ducts diverging from the main section to ventilate the zones will be called 'zone ducts' while all ducts comprise the 'floor network' (see Figure

\(^1\) ACH stands for Air Changes per Hour and is the total volume of air supplied into a space within an hour as a fraction of the space’s volume. The volume flow in m\(^3\)/s is derived by: \(V_{air}=ACH \times V/3600\).
3.5). It is noted that the floor network begins at junction $s'(f)$ where the *internal ducts* diverge from the *floor supply duct* and ends at node $f(f)$ which represents the corridor (see figure). Air from the zones is exhausted to the corridor via openings; a duct exhausts the air of the corridor to the main exhaust duct (on the southern side; this duct will be called 'floor exhaust duct'; the main exhaust duct will be referred to as 'exhaust duct'. The part of the network consisting of the *supply, floor supply, floor exhaust* and exhaust ducts will be referred to as the 'main network', as opposed to the *floor network*. The airflow paths for the 1st, the 6th and the 9th floors are presented in Figure 3.4; e.g. for the 6th floor the airflow path follows the nodes $s0-s9-s8-s7-s6-s6'-f^*6-e6-e1-SC-e0$. It should be noted that the node $f^*(f)$ in the figure is only a schematic reduction to one node of the whole floor network shown in Figure 3.5. In Figure 3.5 the floor supply and floor exhaust ducts are also included for clarity even though they are not part of the floor network as defined here.

The SC will be connected with the exhaust duct at ground level (floor 1); a fan located at the bottom of the SC will ensure that the volume flow through the building is constant and equal to $32.65 \text{ m}^3/\text{s}$. The fresh air is supplied in the supply duct at height of 50m and is exhausted at the top of the SC. Due to the fan, the ventilation system is considered hybrid$^2$.

\[\text{Figure 3.4 Schema of the main airflow network.}\]

$^2$A system relying completely on the SC would not be able to induce the required ventilation rate at all times, due to its dependency on the varying climatic conditions. A fan is used to comply with the constant ventilation requirements of the office building.
Prior to modeling the airflow network in ESP-r, the network's components (ducts, dampers, etc.) need to be dimensioned. The method of 'equal friction' is employed to that purpose. This method aims at balancing the network so that each airflow path has the same losses; this practically ensures that the desired volume flow is admitted through all and zones of the building. The steps of the equal friction method are presented below in summary:

1. Calculation of the required volume flow through each duct of the network and estimation of its length.
2. Choice of the air velocity in each duct. In the supply and exhaust ducts 5m/s is selected; in all the rest 2m/s.
3. Derivation of the duct dimensions (cross section area $A_m^2$ and hydraulic diameter $D_h [m]$) based on volume flow and air velocity in the duct.
4. The friction and dynamic losses in each duct are calculated based on the friction factor $f [Pa/m]$ and the dynamic loss factors $C [-]$ of each duct.\footnote{For ducts in diverging junctions 'Table SD5-Wye, 45 Degree, Diverging' (2009, 21.49) and for those in converging junctions 'Table ED-5 Wye, 45 Degree, Converging' (ASHRAE 2009, 21.34) was used to calculate $C$. The friction chart in ASHRAE 2009, 21.8 is used for estimation of $f$.}
5. For every airflow path the sum of the friction and dynamic losses is calculated and the path with the highest losses is found; dampers are placed in all other paths to impose the additional pressure loss required so that the path has losses equal to the highest losses found. Thus all paths result to have the same pressure losses and the system is balanced.
The above procedure is conducted separately for the main network and the floor network. The air temperature is assumed to be 18°C in all ducts of the supply section and 20°C in the ducts of the exhaust section. In the final building design of the EWF project, a ‘Climate Cascade’ will be the equivalent of the supply duct and it will condition the incoming air to 18°C (Bronsema, 2009).

Tables 3.2 and 3.3 present the dimensions of the ducts in the main and floor network respectively. The ducts are labeled after their start and end nodes. The diameter of the ducts is adjusted according to the flow in order to maintain the same velocity. The geometry of the exhaust duct is that of the supply duct only reversed, i.e. e9-e8=s2-s1 etc. while the sections of the floor network running on the west and the east sides are symmetrical, since the internal layout of the zones is also symmetrical.

Table 3.2 Dimensions of the main network ducts.

<table>
<thead>
<tr>
<th>Duct label</th>
<th>Length [m]</th>
<th>Volume [m³/s]</th>
<th>Flow [m²]</th>
<th>Diameter [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply ducts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s0-s9</td>
<td>2.25</td>
<td>32.66</td>
<td>6.53</td>
<td>2.88</td>
</tr>
<tr>
<td>s9-s8</td>
<td>5.50</td>
<td>29.03</td>
<td>5.81</td>
<td>2.72</td>
</tr>
<tr>
<td>s8-s7</td>
<td>5.50</td>
<td>25.40</td>
<td>5.08</td>
<td>2.54</td>
</tr>
<tr>
<td>s7-s6</td>
<td>5.50</td>
<td>21.77</td>
<td>4.35</td>
<td>2.35</td>
</tr>
<tr>
<td>s6-s5</td>
<td>5.50</td>
<td>18.14</td>
<td>3.63</td>
<td>2.15</td>
</tr>
<tr>
<td>s5-s4</td>
<td>5.50</td>
<td>14.52</td>
<td>2.90</td>
<td>1.92</td>
</tr>
<tr>
<td>s4-s3</td>
<td>5.50</td>
<td>10.89</td>
<td>2.18</td>
<td>1.66</td>
</tr>
<tr>
<td>s3-s2</td>
<td>5.50</td>
<td>7.26</td>
<td>1.45</td>
<td>1.36</td>
</tr>
<tr>
<td>s2-s1</td>
<td>5.50</td>
<td>3.63</td>
<td>0.73</td>
<td>0.96</td>
</tr>
<tr>
<td>Floor supply ducts</td>
<td>2.00</td>
<td>3.63</td>
<td>1.81</td>
<td>1.52</td>
</tr>
<tr>
<td>Exhaust ducts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e9-e8</td>
<td>5.50</td>
<td>3.63</td>
<td>0.73</td>
<td>0.96</td>
</tr>
<tr>
<td>e8-e7</td>
<td>5.50</td>
<td>7.26</td>
<td>1.45</td>
<td>1.36</td>
</tr>
<tr>
<td>e7-e6</td>
<td>5.50</td>
<td>10.89</td>
<td>2.18</td>
<td>1.66</td>
</tr>
<tr>
<td>e6-e5</td>
<td>5.50</td>
<td>14.52</td>
<td>2.90</td>
<td>1.92</td>
</tr>
<tr>
<td>e5-e4</td>
<td>5.50</td>
<td>18.14</td>
<td>3.63</td>
<td>2.15</td>
</tr>
<tr>
<td>e4-e3</td>
<td>5.50</td>
<td>21.77</td>
<td>4.35</td>
<td>2.35</td>
</tr>
<tr>
<td>e3-e2</td>
<td>5.50</td>
<td>25.40</td>
<td>5.08</td>
<td>2.54</td>
</tr>
<tr>
<td>e2-e1</td>
<td>5.50</td>
<td>29.03</td>
<td>5.81</td>
<td>2.72</td>
</tr>
<tr>
<td>Floor exhaust ducts</td>
<td>2.00</td>
<td>3.63</td>
<td>1.81</td>
<td>1.52</td>
</tr>
</tbody>
</table>
Table 3.3 Dimensions of the floor network ducts.

<table>
<thead>
<tr>
<th>Duct Label</th>
<th>Length [m]</th>
<th>Volume Flow [m³/s]</th>
<th>Cross section [m²]</th>
<th>Diameter [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal ducts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>s()-NE &amp; s()-NW</td>
<td>12.2</td>
<td>1.81</td>
<td>0.91</td>
<td>1.07</td>
</tr>
<tr>
<td>NE - E &amp; NW-W</td>
<td>15.1</td>
<td>1.29</td>
<td>0.64</td>
<td>0.90</td>
</tr>
<tr>
<td>Zone ducts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E - zoneSE &amp; W-zoneSW</td>
<td>17.7</td>
<td>0.53</td>
<td>0.26</td>
<td>0.58</td>
</tr>
<tr>
<td>NE-zoneNE &amp; NW-zoneNW</td>
<td>1.5</td>
<td>0.53</td>
<td>0.26</td>
<td>0.58</td>
</tr>
<tr>
<td>E-zoneE &amp; W-zoneW</td>
<td>1.5</td>
<td>0.76</td>
<td>0.38</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Table 3.4 presents the calculations for the airflow paths of the floor network (one for each zone); in the same way the main network calculations are conducted but will not be presented for brevity reasons. Initially the airflow path with the highest pressure loss is found (see table, path to SE/SW with 10.35Pa) and the dampers’ sizes are consequently determined for the rest of the paths, so that all paths have the same pressure loss (e.g. for path to NE/NW 2.35=10.35-8.00Pa). It is implicit that the dampers are positioned at the zone ducts, so that the loss is imposed on the corresponding zone’s flow path.

Table 3.5 presents the local dynamic loss factors (C_i) found for the ducts of the main network. Table 3.6 presents the total pressure losses found for the nine airflow paths (one for each floor) and the dampers’ sizes to balance the network. These dampers are positioned at the floor supply ducts.

Table 3.4 Equal friction method calculations for the airflow paths of the floor network.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>s()-NE &amp; s()-NW</td>
<td>12.2</td>
<td>0.10</td>
<td>2.05</td>
<td>1.22</td>
<td>4.96</td>
<td>6.18</td>
<td>6.18</td>
<td>6.18</td>
<td>6.18</td>
</tr>
<tr>
<td>NE - E &amp; NW-W</td>
<td>15.1</td>
<td>0.10</td>
<td>0.24</td>
<td>1.51</td>
<td>0.58</td>
<td>2.09</td>
<td>2.09</td>
<td>2.09</td>
<td>2.09</td>
</tr>
<tr>
<td>E - zoneSE &amp; W-zoneSW</td>
<td>17.7</td>
<td>0.10</td>
<td>0.13</td>
<td>1.77</td>
<td>0.31</td>
<td>2.08</td>
<td>2.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NE - zoneNE &amp; NW-zoneNW</td>
<td>1.5</td>
<td>0.10</td>
<td>0.69</td>
<td>0.15</td>
<td>1.67</td>
<td>1.82</td>
<td></td>
<td>1.82</td>
<td></td>
</tr>
<tr>
<td>E - zoneE &amp; W - zoneW</td>
<td>1.5</td>
<td>0.10</td>
<td>0.67</td>
<td>0.15</td>
<td>1.62</td>
<td>1.77</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total airflow path loss: 10.35 10.04 8.00
Damper [Pa]: 0.31 2.35
Table 3.5 Local loss factor values of the ducts in the main network.

<table>
<thead>
<tr>
<th>Supply Section</th>
<th>Supply ducts</th>
<th>Ci [-]</th>
<th>Floor supply ducts</th>
<th>Ci [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>s9-s8</td>
<td>0.14</td>
<td>s8-s8'</td>
<td>5.61</td>
</tr>
<tr>
<td></td>
<td>s8-s7</td>
<td>0.14</td>
<td>s7-s7'</td>
<td>6.31</td>
</tr>
<tr>
<td></td>
<td>s7-s6</td>
<td>0.14</td>
<td>s6-s6'</td>
<td>6.26</td>
</tr>
<tr>
<td></td>
<td>s6-s5</td>
<td>0.14</td>
<td>s5-s5'</td>
<td>4.01</td>
</tr>
<tr>
<td></td>
<td>s5-s4</td>
<td>0.13</td>
<td>s4-s4'</td>
<td>4.76</td>
</tr>
<tr>
<td></td>
<td>s4-s3</td>
<td>0.13</td>
<td>s3-s3'</td>
<td>4.34</td>
</tr>
<tr>
<td></td>
<td>s3-s2</td>
<td>0.14</td>
<td>s2-s2'</td>
<td>2.25</td>
</tr>
<tr>
<td></td>
<td>s2-s1</td>
<td>0.20</td>
<td>s1-s1'</td>
<td>0.12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exhaust section</th>
<th>Exhaust ducts</th>
<th>Ci [-]</th>
<th>Floor exhaust ducts</th>
<th>Ci [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>e9-e8</td>
<td>0.44</td>
<td>f9-e9</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>e8-e7</td>
<td>0.25</td>
<td>f8-e8</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>e7-e6</td>
<td>0.17</td>
<td>f7-e7</td>
<td>-1.32</td>
</tr>
<tr>
<td></td>
<td>e6-e5</td>
<td>0.08</td>
<td>f6-e6</td>
<td>-4.29</td>
</tr>
<tr>
<td></td>
<td>e5-e4</td>
<td>0.01</td>
<td>f5-e5</td>
<td>-3.59</td>
</tr>
<tr>
<td></td>
<td>e4-e3</td>
<td>-0.05</td>
<td>f4-e4</td>
<td>-6.83</td>
</tr>
<tr>
<td></td>
<td>e3-e2</td>
<td>-0.08</td>
<td>f3-e3</td>
<td>-6.93</td>
</tr>
<tr>
<td></td>
<td>e2-e1</td>
<td>-0.10</td>
<td>f2-e2</td>
<td>-6.13</td>
</tr>
</tbody>
</table>

Table 3.6 Total pressure losses and dampers losses calculation per airflow path.

<table>
<thead>
<tr>
<th>Airflow path through floor</th>
<th>Pressure losses [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Main network</td>
</tr>
<tr>
<td></td>
<td>Supply section</td>
</tr>
<tr>
<td></td>
<td>Exhaust section</td>
</tr>
<tr>
<td></td>
<td>Floor network</td>
</tr>
<tr>
<td></td>
<td>Total</td>
</tr>
<tr>
<td></td>
<td>Damper</td>
</tr>
<tr>
<td>9</td>
<td>13.53</td>
</tr>
<tr>
<td>7</td>
<td>17.87</td>
</tr>
<tr>
<td>6</td>
<td>22.24</td>
</tr>
<tr>
<td>5</td>
<td>24.74</td>
</tr>
<tr>
<td>4</td>
<td>22.00</td>
</tr>
<tr>
<td>3</td>
<td>26.30</td>
</tr>
<tr>
<td>2</td>
<td>27.82</td>
</tr>
<tr>
<td>1</td>
<td>23.91</td>
</tr>
<tr>
<td></td>
<td>15.805</td>
</tr>
<tr>
<td></td>
<td>10.186</td>
</tr>
<tr>
<td></td>
<td>0.793</td>
</tr>
<tr>
<td></td>
<td>-9.487</td>
</tr>
<tr>
<td></td>
<td>-9.516</td>
</tr>
<tr>
<td></td>
<td>-18.058</td>
</tr>
<tr>
<td></td>
<td>-18.056</td>
</tr>
<tr>
<td></td>
<td>-18.056</td>
</tr>
<tr>
<td></td>
<td>-12.193</td>
</tr>
<tr>
<td></td>
<td>10.35</td>
</tr>
<tr>
<td></td>
<td>10.35</td>
</tr>
<tr>
<td></td>
<td>10.35</td>
</tr>
<tr>
<td></td>
<td>10.35</td>
</tr>
<tr>
<td></td>
<td>10.35</td>
</tr>
<tr>
<td></td>
<td>10.35</td>
</tr>
<tr>
<td></td>
<td>10.35</td>
</tr>
<tr>
<td></td>
<td>20.35</td>
</tr>
<tr>
<td></td>
<td>20.11</td>
</tr>
<tr>
<td></td>
<td>20.30</td>
</tr>
<tr>
<td></td>
<td>22.06</td>
</tr>
<tr>
<td></td>
<td>17.62</td>
</tr>
</tbody>
</table>
3.5 Nodal airflow network in ESP-r

The above calculations result in a complex network with various duct sizes, different local loss factors for every duct and dampers of different authorities in various positions. However a simplified model of the duct network in ESP-r is not only possible, but also a prerequisite; the simplifications adopted for the representation of the main ducts and the floor ducts in the ESP-r airflow model are presented in the following. All ducts are modeled with the general flow conduit component for which the length, hydraulic diameter, cross-section area, surface roughness and local loss factor need to be defined (see also Chapter 2).

3.5.1 Model of the Main Network

In the model of the main network in ESP-r, certain simplifications and assumptions were adopted, others dictated by program restrictions and others to further simplify the model. It has to be kept in mind that this model will only be used in robustness analysis (see Chapter 6), thus simplifications that do not influence the model predicted values of the pressure inside the office zones do not introduce any error. The assumptions adopted are listed below following the order of reasoning:

(1) Friction and dynamic losses of the supply and exhaust ducts are assigned to the floor supply and floor exhaust ducts respectively;
(2) The losses (or gains) of the floor exhaust ducts are assigned to the floor supply ducts; this approach was followed because the program does not accept negative values for the $C_i$ (see Tables 3.4, 3.5) which could account for the pressure gains on the exhaust section;
(3) The dampers are assumed to be located on the supply section, i.e. at the floor supply ducts;

The above practically lead to a model where the loss of $-30\text{Pa}$ of every floor path estimated due to flow in the main network (see Table 3.6, 39.68-10.35=29.33Pa) is assumed to occur in the floor supply duct. This loss is translated into a $C_i$ for this component, since the volume flow through the network and thus the velocity in the ducts will be constant and equal to the estimated value (i.e. 2m/s for the floor supply ducts); for the same reasoning the loss imposed by the dampers would be constant (fixed position) thus this loss could also be modeled with the $C_i$ value yielding the use of dampers components unnecessary.

The pressure loss of $\Delta P=30\text{Pa}$ (same for all floor paths) is translated into an equivalent $C_i$ value of the floor supply ducts by:

$$C_i=2*\frac{\Delta P}{\rho v^2}$$  \hspace{1cm} (3.1)

It is noted that the $C_i$ values of the floor supply ducts will differ slightly among floors to compensate for the stack pressure differences between the supply ($T_{sup}=18^\circ\text{C}$) and exhaust ($T_{exh}=20^\circ\text{C}$) ducts. At every floor level (thus for every floor path) the stack pressure difference between nodes s(f) and e(f) equals:

$$\Delta P_{\text{stack}} = (\rho_{18} - \rho_{20}) \cdot g \cdot (H_{\text{total}}-H_i)$$  \hspace{1cm} (3.2)
Where $p_{18}, p_{20}$ [kg/m$^3$] the air density for air temperature of 18°C and 20°C, $g$ [m/s$^2$] the acceleration of gravity, $H_{total}$ [m] the total building height (i.e. 50m) and $H_r$ [m] the height of nodes $s(f)$ and $e(f)$

4. The final settings (roughness and $C_i$ values) of the flow components in ESP-r which will model the ducts of the main network are presented in Table 3.7.

Table 3.7 Settings of the flow components that model the ducts of the main network.

<table>
<thead>
<tr>
<th>Roughness $k$ [mm]</th>
<th>Local loss factor $C_i$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply &amp; exhaust ducts $s()$-$s()$-$e()$-$e()$</td>
<td>0</td>
</tr>
<tr>
<td>Floor supply ducts $s9$-$s9'$</td>
<td>0</td>
</tr>
<tr>
<td>$s8$-$s8'$</td>
<td>0</td>
</tr>
<tr>
<td>$s7$-$s7'$</td>
<td>0</td>
</tr>
<tr>
<td>$s6$-$s6'$</td>
<td>0</td>
</tr>
<tr>
<td>$s5$-$s5'$</td>
<td>0</td>
</tr>
<tr>
<td>$s4$-$s4'$</td>
<td>0</td>
</tr>
<tr>
<td>$s3$-$s3'$</td>
<td>0</td>
</tr>
<tr>
<td>$s2$-$s2'$</td>
<td>0</td>
</tr>
<tr>
<td>$s1$-$s1'$</td>
<td>0</td>
</tr>
<tr>
<td>Floor exhaust ducts $f()$-$e()$</td>
<td>0</td>
</tr>
</tbody>
</table>

3.5.2 Model of the Floor Network

The model of the floor network is made up of the nodes as shown in Figure 3.5. The white nodes correspond to nodes of the airflow network that are mapped to thermal zones of the ESP-r model; the airflow path to e.g. zone W passes through the nodes $s()$-NW-W-$W_{in}$-zoneW. In a similar way to the modeling of the main network, all losses of the zones’ airflow paths are assigned to the corresponding zone ducts, i.e. the 10.35 Pa (see Table 3.6) are translated into a $C_i$ value of the zone ducts. Damper components are also not used, while for all zones the $C_i$ value is the same (estimated equal to ~4.33), since no hydrostatic differences exist inside the floor network.

It is assumed that the air from the zones is exhausted in the zone of the corridor via orifice components; the cross section area of the orifice is equal to the area of the zone duct that supplies air into the zone, so that the air velocity through the orifices is also

$^4$ The nodes are assumed to have the height of the floor level’s middle height, i.e. the height of the zone nodes of the floor e.g. $H_r=3*5.5 + 5.5/2=19.25m$.

$^5$ The nodes of every thermal zone can be automatically generated in ESP-r; the name of the nodes is the name of the zones, the air volume of the node is equal to the volume of the zone as determined by its dimensions and the air temperature of this node is the one of the zone as conditioned by the HVAC control inside the zone.
2m/s. The pressure loss through the exhaust orifice is 2.40Pa (for a discharge factor of 1.0), increasing the total loss of the zones' paths to 12.75Pa (the 2.40Pa are added to the 10.35Pa which is the loss through the ducts of the floor network, see Table 3.6). This increases the total pressure drop through the floor paths to ~42.1 [Pa] (39.68+2.40, Table 3.6).

Due to the limitation in ESP-r of having in total 70 nodes in the airflow network, the above configuration could only be considered for one floor, while for the rest of the floors, the network was reduced to one node (f*(f), see Figure 3.4) and one component that connects nodes s(f)' and f*(f) and which induces a pressure drop of 12.75Pa (equal to the total loss of the floor network\(^6\)) for the floor ventilation rate of 3.63m\(^3\)/s (see Table 3.1). The equivalent component will use a user-defined equation to calculate the mass flow as a function of the pressure difference along the component. This equation is calculated to be:

\[
\text{m}_{\text{equiv}} = 1.217 \cdot \Delta P^{0.5} 
\]  

\hspace{1cm} (3.3)

### 3.5.3 Discussion

The simplifications adopted in the model of the main network will introduce some error in the predictions of the pressure inside the office zones (or the pressure of the corridor i.e. node f*(f) for the floors where an equivalent component is used); the simplifications and use of equivalent components for the floor network do not have such implications. This error is introduced by assigning the losses/gains of the exhaust section to the supply section, thus it is higher for the floors with the higher gains or losses in the exhaust section (see Table 3.6). In case the exhaust section presents losses (positive \(\Delta P\), e.g. floor 9) then the predicted pressure of f*(f) will be lower and if the exhaust section presents gains (negative \(\Delta P\), e.g. floor 4) the pressure of f*(f) will be higher than what it would actually be. It should be noted that this error could only be avoided for floors 9, 8 and 7, where losses were found (i.e. positive values for the \(C_i\) of the floor exhaust ducts could used. The lowest absolute losses/gains of the exhaust section are found for the airflow path of floor 7 (0.743Pa, see Table 3.6), thus the error introduced for this path is the lowest. It is reminded that the above are of interest only when it comes to robustness analysis (see Chapter 6), thus floor 7 will be primarily used. This also implies that floor 7 will be the one modeled in detail (as shown in Figure 3.6).

### 3.6 Thermal modeling in ESP-r

The only thermal zones considered in the building model are the floors' office zones. The ducts are modeled using only airflow nodes. Since the thermal conditions of the zones or the energy needed for heating/cooling of the zones is not a matter of interest in this study, the zones are ideally conditioned to 20°C at all times and wall construction parameters are not considered; a typical insulated construction is used for the walls, while geometry features such as windows are not modeled. It is noted that for the air conditioning a range between 20-24°C could be used, but it would have

\(^6\) The total loss of the floor network equals that of every zone's path because the zones paths are connected in parallel; between nodes s'(f) and f(f).
implications for the balance\textsuperscript{7} of the network and was thus rejected for the purpose of this study.

\textsuperscript{7} For a higher temperature difference between the supply and exhaust ducts, the $\Delta P_{\text{hydro}}$ would increase and the balance would be lost; the flow through the floors would increase from top to bottom floors.
4

Sensitivity Analysis

4.1 Introduction

Sensitivity analysis (SA) can be defined as 'the study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input' (Saltelli et al., 2008). Among the benefits of SA are that it allows the analysis of the robustness of a model (Litko, 2005), the simplification of a model via parameter screening (de Wit, 1997) and the insight of unexpected sensitivities that could jeopardize the quality of designs (Hopfe, 2009).

Sensitivity analysis is performed with respect to certain output variables of a system or model, whose sensitivity to specific input variables we want to determine; in building performance applications the output variables are also commonly referred to as performance indicators (PIs). There is a variety of methods to perform SA, among them local methods (e.g. differential sensitivity analysis), global methods (e.g. Monte Carlo, Morris analysis) and variance based methods. It is out of the scope of this report to present the various SA methods; only a short description of the methods used in this project will be given in the following sections. The reader can refer to the abundant bibliographic sources on the subject of SA for more information.

Sensitivity Analysis (SA) is performed here for the full-scale SC model, in order to establish the sensitivity to various input factors (e.g. to SC geometry, physical properties of the walls, glazing type) of the following output variables: (i) annual harvested energy and (ii) annual fan energy savings. The methodology followed here is based on Monte Carlo Analysis (MCA) which considers the total sensitivity of the output due to uncertainties in the entire input, i.e. all input factors are sampled simultaneously. Regression analysis is employed to provide quantified measures of sensitivity (standardized regression coefficients), while the simultaneous sampling of the input factors is conducted using the Latin Hypercube Sampling (LHS) method.

The SC model used for SA, some preliminary considerations, the applied methodology and SA results are presented consecutively.

4.2 The full-scale SC model used for SA

Before proceeding to the section of the applied methodology, it is considered wise to present some information regarding the full-scale SC model that will be used for the simulations.

\[ \text{Input variables are also referred to as input factors, input parameters or independent variables.} \]
4.2.1 Geometry & Construction

The full-scale SC model used in SA has a height of 50m and consists of 25 zones (of 2m height each); the other two dimensions (length and depth) are input parameters for the SA. With respect to the rest of the settings, the model is the same as the one used in calibration except for the addition of a concrete layer behind the absorbent layer of the walls. The term ‘absorbent layer’ is used here for the layer applied at the walls’ inner surface, where the absorption of the solar radiation entering the SC takes place. The thickness of the concrete layer will be an SA input variable, to represent the walls’ thermal mass. Figure 4.1 shows the construction of the SC walls as considered in the SA model. The dimensions presented in the figure are not representative.

![Concrete, Absorbent layer, Insulation, Glazing, Outer panel]

Figure 4.1 Construction of the SC walls in horizontal cross-section.

4.2.2 Airflow Network

The airflow network consists of 29 nodes, 28 connections and 4 types of components. The settings of the airflow network are presented in Table 4.3 and a schematic representation of it in Figure 4.2. Air of 20°C (assumed to come from the exhaust duct, see Chapter 3) enters the SC at its bottom, at a constant rate equal to the ventilation requirements of the prototype building (i.e. 32.66 m³/s, see Chapter 3), induced by the fan (see Figure 4.2). The settings for the SC and inlet components are based on the calibration results; wind is neglected in order to be on the safe side: in reality there are specially developed outlet components (e.g. wind directional caps) that ensure negative values for the outlet’s $C_p$ irrespective of the wind direction (i.e. underpressure which enhances the flow to the outside). Furthermore the $C_p$ databases available in ESP-r involve a high degree of uncertainty (Costola et al., 2009) and it would not be wise to use them, given the sensitivity of the airflow to this parameter.
Table 4.1 Settings of the SC model’s airflow network.

<table>
<thead>
<tr>
<th>Airflow Network Components</th>
<th>Type</th>
<th>Absolute material roughness $k$ [mm]</th>
<th>Local dynamic loss factor $C_l$ [-]</th>
<th>Length $L$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC channel</td>
<td>GFCC[a]</td>
<td>1.00</td>
<td>0.00</td>
<td>2.00</td>
</tr>
<tr>
<td>SC top/bottom</td>
<td>GFCC[a]</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Inlet opening</td>
<td>GFCC[a]</td>
<td>0.10</td>
<td>6.00</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Volume flow rate $V$ [m$^3$/s] $= 32.66$

[a] General Flow Conduit component
[b] Constant Volume Flow Rate component

<table>
<thead>
<tr>
<th>Boundary nodes</th>
<th>Type</th>
<th>Height</th>
<th>Assigned Pressure [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom</td>
<td>‘Known Pressure’</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Top</td>
<td>‘Wind induced’</td>
<td>50</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Wind Reduction Factor $= 0.00$
4.2.3 Assumptions

An assumption is made regarding the solar radiation entering the zones; all solar heat flux is absorbed by the backwall. Shading and insolation analysis could not be performed due to the fictitious surfaces considered for the bottom and top surfaces of the zones, making this an inescapable simplification of the thermal model. This simplification allowed the frame of the glass panes to be simulated by simply making a percentage of the glazing opaque, instead of creating an actual frame running along the glazing’s perimeter (i.e. two additional nodes instead of four were used).

4.3 Preliminary SA considerations

4.3.1 Input Variables Specification

The objective of the input variables specification is to include as many of the properties of the SC model as possible, considered to play a role on the system’s performance. The SA will then indicate which of them are determinant for the system’s performance, which are simply influential and which could be neglected as non important.

Relevant knowledge on the parameters influencing the performance of the SC, gained via parametric analysis studies by other researchers, allows us to be confident about the selection of the input variables in this study. Geometry features, physical properties of the materials used and construction aspects are addressed by the variables chosen for the SA.

Geometry features studied are the length and the depth. To avoid introducing a large error from neglecting the shading by the side-walls (see 4.2.3), a constraint for the SC depth to be smaller than 25% of the length is adopted. It is also noted that the area of the inlet opening, where most pressure losses occur (C_i=6, Table 4.1), assumes the same value as the cross section area of the SC. Physical properties of the walls considered are the short-wave absorptivity and the long-wave emissivity of the absorbent layer. Physical properties of the glazed wall are also considered by choosing three different types of glazing (single, double and low-e). The thickness of a concrete layer applied directly behind the absorbent layer is chosen as a variable, to account for the walls’ thermal mass. The thickness of the insulation layer, placed behind the concrete layer, is also considered. For brevity reasons, the last two variables will be referred to as ‘thermal mass’ and ‘insulation’. Short-wave absorptivity and long-wave emissivity will also be reduced to the terms ‘absorptivity’ and ‘emissivity’.

Table 4.2 presents the SA input variables chosen in this study, along with their range of values. Discrete values are chosen for all variables, thus the step sizes are also presented. Table 4.3 presents the physical properties of the three glazing types.

A special reference needs to be made for omitting the height of the SC, known to be one of the most determinant factors for the system’s performance. Not considering the
height as a variable but fixing it at the height of the prototype building is assumed a reasonable choice. It is of course implicit that it is advantageous for the SC to be as high as possible in any case.

Table 4.2 Parameters considered in SA with their range of values and step sizes.

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Range of values</th>
<th>Step change</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower</td>
<td>Upper</td>
<td>Step</td>
</tr>
<tr>
<td>Length</td>
<td>7.20</td>
<td>32.40</td>
<td>1.80</td>
</tr>
<tr>
<td>Depth</td>
<td>0.70</td>
<td>2.00</td>
<td>0.10</td>
</tr>
<tr>
<td>Thermal Mass[a]</td>
<td>0.001</td>
<td>0.10</td>
<td>0.005</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.001</td>
<td>0.12</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Absorptivity[a]</td>
<td>0.05</td>
<td>0.95</td>
<td>0.20</td>
</tr>
<tr>
<td>Emissivity[a]</td>
<td>0.05</td>
<td>0.95</td>
<td>0.20</td>
</tr>
<tr>
<td>Glazing Type</td>
<td>Single, Double, Low-e</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Glass Percentage</td>
<td>0.70</td>
<td>0.95</td>
<td>0.05</td>
</tr>
</tbody>
</table>

[a] thickness of the concrete layer behind the absorbent layer
[b] properties of the absorbent layer of the opaque SC walls (back and side walls)

<table>
<thead>
<tr>
<th>Glazing Type</th>
<th>Visible Light Transmission (at 90°)</th>
<th>U-value [W/m²]</th>
<th>Pane Absorptivity</th>
<th>Pane Emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>0.87</td>
<td>5.621</td>
<td>0.05</td>
<td>0.83</td>
</tr>
<tr>
<td>Double</td>
<td>0.76</td>
<td>2.811</td>
<td>0.05</td>
<td>0.83</td>
</tr>
<tr>
<td>Low-e[a]</td>
<td>0.79</td>
<td>1.316</td>
<td>0.06</td>
<td>0.05</td>
</tr>
</tbody>
</table>

[a] properties of the specially designed glazing used in the SC measurement test set-up

4.3.2 Output Variables Specification

The output variables are specified so that they capture the aspects of the system’s performance that are of interest for the specific problem. The performance indicators that are important in any SC application correspond to the two functionalities of the SC, i.e. as airflow inducing and heat harvesting device. In this study the SC is intended to be used in a multi-storey office building with high and constant ventilation requirements during the working hours, thus a hybrid system is considered. The hybrid system consists of a fan and the SC which complement each other so that the required ventilation rate is always ensured. The air flowing through the SC at a constant rate is also heated up, offering the possibility to harvest this heat to be used for functional needs of the building (e.g. space heating). Under the scope of the above, the output variables considered for the SA are:

- The heat harvested in the SC shaft annually
- The fan energy savings accomplished by the SC annually
It should be noted that fan energy savings are accomplished when the stack effect created by the SC compensates for part or the total of the pressure difference that the fan needs to induce to ventilate the building. There will also be some time however, when the SC fails to complement the fan but instead increases the required fan power. This additional fan energy or the fan losses, is not taken into account, i.e. the fan savings are not net savings. It is implicit that the variables which are significant to increase the fan savings will also be the ones that need to be taken into account to reduce the fan losses. For brevity reasons, the fan energy savings output variable will be referred to as ‘fan savings’.

4.3.3 Generation of the sample matrix

The Latin Hypercube Sampling (LHS) method is chosen for the generation of the sample matrix. LHS is a method commonly used to create multi-variate samples for UA and SA. The LHS technique employs a constrained sampling scheme (constrained randomization), as opposed to a Monte Carlo technique which is a random sampling technique.

In summary, the range of probable values of each input factor (variable) is divided into N intervals with N the number of samples to be generated. One observation is made in each interval using random sampling, thus for each input factor \( X_i \) (\( i=1,2, \ldots, k \) with k the number of input factors considered), N non-overlapping observations are created, of equal probability \( 1/N \). The first sample is created by randomly selecting one of the N observations for every input factor. The next sample is created by randomly selecting an observation for each \( X_i \) out of the remaining \( N-1 \) observations, and so on. Each sample is thus unique. The resulting sample matrix has \( N \) rows and \( k \) columns (\( X_{Nk} \), see A1).

LHS has the advantage of generating a set of samples that more precisely reflect the shape of a sampled distribution than pure random (Monte Carlo) samples. Also the required number of samples (and consequently of model executions) does not increase when the number of input factors increases.

The number of samples (N) and the probability distribution for each input factor (\( X_j \)) needs to be specified by the user. A number of 200 samples will be generated; this number is considered more than adequate to achieve a confidence interval of 95% (NEN 5128, 2001). Uniform distributions are considered for all input factors.

4.3.4 SA analysis method selection

To complete the SA, a method needs to be selected which will provide information on the sensitivity of the output variables (dependent) to the input variables (independent). An important method which results in quantitative measures of sensitivity is the regression analysis. The mapping between the output and the input parameters is assumed to be linear, i.e. linear regression analysis will be employed here. The result of regression analysis is the estimation of the linear regression model and thus - among others - of the regression coefficients (b\(_j\)) for each input variable (\( X_j \)). The regression coefficient of an input variable gives the size and direction (via the sign +/- ) of the change in the output if the input variable is increased by one, while all other inputs are held constant. However, because each input variable has different units, we cannot conclude on the relative importance of the parameters by comparing the regression
coefficients. Instead, the standardized regression coefficients (β or SRC) are calculated (based on bj) and used as a measure of the output’s sensitivity to the individual input variables. The β coefficients (or SRC) take values from -1 to 1 and they are interpreted as the change of the output expressed as a fraction of the standard deviation change (σXj) of the input parameter. The higher the SRC value the more influential the parameter and thus the higher the sensitivity of the model’s output to that parameter. A more analytical explanation of the linear regression analysis is presented in Appendix A1.

Except for linear regression analysis, regression in a stepwise manner is also conducted, which ranks the parameters from most to least influential by estimating the increase of the R² when the parameters are included one by one in the model. The conclusions derived by the two methods are expected to be the same, however the stepwise regression is also included here because it offers an interesting insight on the contribution of each parameter in explaining the variance of Y. Appendix A2 includes definitions of measures used in regression analysis to interpret the results which will be used in the following: R-square, t-statistic, p-value and F.

4.4 Methodology

The methodology applied for the SA is summarized in the following consecutive steps:

1. Pre-processing.
   It includes creating the input sample matrix and consecutively the necessary ESP-r input files required for the simulations. The LHS method is used to generate 200 samples.

2. Simulations in ESP-r.
   Simulations for every sample are realised automatically using user-defined batch files and the output matrix is generated. The simulation’s output variables of interest are stored in files to be used later in post-processing.

3. Post-processing.
   It includes post-processing of the output ESP-r files in order to derive the SA output variables, which are the annual harvested energy and the annual fan energy savings.

4. Linear Regression & Results Analysis
   The output variables derived for each sample from the previous step are compared to the sampled input parameters and linear regression analysis is conducted. The SRC values found for the input parameters is the measure of the model’s sensitivity to the respective parameter. At this final stage an interpretation of the

---

2 The first model includes only the parameter that gives the highest R² value, and the rest are added one by one in the regression model, with the second one being the one giving the highest further increase of the R² and so on, until the R² is not significantly increased by the addition of other parameters.

3 The term will be used to indicate the files designed by the author especially for the purposes of this project.
SA results is conducted. Conclusions drawn will determine the approach for the optimization of the SC design, presented in the next chapter.

The first three steps are presented in detail in the following subsections. Results analysis is presented in a consecutive section, followed by the conclusions.

4.4.1 Pre-processing
The sample matrix ($X_{Nk}$, see A1) is generated using the LHS method; the number of samples $N$ is chosen to be 200 (see also 4.3.3). The ESP-r input files that are modified according to the sampled parameters’ values are the construction (.con), geometry (.geo) and transparent construction (.tmc) files for each SC zone, as well as the airflow network file (.afn) of the model. The rest of the input files required for the simulation remain the same for all samples. In total 800 input files ($200\text{[samples]}*4\text{[files]}$) are created using user-defined Matlab functions.

4.4.2 Simulations in ESP-r
Annual simulations (i.e. 8760 hours) are performed for every sample using the NEN5060 climate file. The simulation step is 4min and the results are hourly integrated. The 200 simulations are realised automatically using batch files that utilise the text mode facilities of the bps and res module; the bps module performs the simulations and produces results libraries which are then explored in the results recovery module (res). For each sample the hourly values of the following quantities are stored in files to be used in post-processing:
- The air temperature of the top SC zone (zone 25, height from 48 to 50m): $T_{\text{air, out}}\,[^{\circ}\text{C}]$
- The pressure at the outlet boundary node (height:50m): $P_{\text{out}}\,[\text{Pa}]$
- The pressure at the node following the fan component: $P_{\text{fan}}\,[\text{Pa}]$

4.4.3 Post-processing
Post-processing aims at the generation of the output matrix ($Y_{N}$, see A1) for each of the two regression models, one for harvested energy ($Y_{1N}$) and one for fan savings ($Y_{2N}$). The $N$ values of harvested energy and fan savings derived from the simulations corresponding to each input sample, are contained in this column matrices ($N\times1$).

The simulation output file of each sample containing the hourly values of $T_{\text{air, out}}, P_{\text{out}}$ and $P_{\text{fan}}$ (see 4.4.2) needs to be processed further in order to get the required values of annual harvested energy and fan energy savings. The steps to derive the required values for every sample from the model’s output are given below in short:
- From the annual hourly values (8760 hrs) of $T_{\text{air, out}}, P_{\text{out}}$ and $P_{\text{fan}}$ only the values corresponding to working days (Mon-Fri) and hours (7am to 7pm) are kept for further process. The working days and hours sum up to 3132 hours.
- For every hour of the new output files (containing data for the 3132hrs) the harvested energy and fan energy savings are calculated. A detailed description of these calculations can be found in the Appendix A3.

The sum for all hours of the harvested energy and fan savings’ values is the output variable contained in the output matrix of the corresponding regression model. Post-processing is performed in Matlab, using user-defined functions (m-files).
4.5 SA Results

Linear regression analysis is performed for the two output variables (or PIs) and the standardized regression coefficients (SRC, see 4.3.4) of the input parameters that are estimated, are the measures of the PI's sensitivity to the respective inputs. In Table 4.3 the SRC value, t-statistic and p-value of each independent variable are presented, when the harvested energy is the dependent variable. The input parameters are ranked in descending order of sensitivity. The values of adjusted $R^2$ and $F$ are also indicated. Table 4.4 presents the same results for the case that fan savings is the dependent variable. Figure 4.3 presents the SA results in terms of SRC values (plot) and Table 4.5 presents the parameters' ranking for the two output variables. Tables 4.6 & 4.7 present the results of the stepwise regression for the two dependent variables; the adjusted $R^2$ for the models of the consecutive steps is presented, as well as the SRC for the final model (step 6) and the SRC of the linear regression for results' comparison. The increase of the $R^2$ resulting from the addition of the respective input parameter (predictor) in the model is presented in a separate column. The SA results for each output variable are commented on in the following two subsections.

4.5.1 SA Results for Harvested Heat

As can be seen in Table 4.3, the parameters of length and absorptivity are the most significant, followed by the glazing type and the thermal mass parameters. It is noted that the positive SRC value for the glazing type means that harvested heat is increased when moving from single to double and from double to low-e glazing. The negative value for the thermal mass means that the harvested heat is decreased when thermal mass is increased. Glass percentage and insulation are less influential while the depth and the emissivity variables can be discarded from the regression equation, because the t-statistic and p-value for these indicate that they are not statistically significant (t-statistic < 2.0 and p-value >0.05). The stepwise regression method results in the same conclusion; the parameters of depth and emissivity are not included in the final model. It is interesting to see in Table 4.6 that the dominant parameters are the length and absorptivity, explaining a 73% ($R^2=0.727$ at step 2) of the output's variance, while the rest of the four parameters together, contribute the other 14% of the explained variance ($R^2=0.87$, i.e. model explains 87% of the variance of $Y$). It can also be seen that glass percentage and insulation could also be neglected with little loss of information, since they only increase the $R^2$ from 0.835 to 0.870, i.e. by 0.035; a model without these parameters would explain only 3.5% less of the $Y$ variance compared to a model where these parameters are included. Finally, thermal mass and glazing type seem to be equally important, with almost the same values of the SRC found by both methods.

4.5.2 SA Results for Fan Savings

In the case of the fan savings performance indicator, a similar ranking of influential parameters is found for the first four places, with the difference that instead of absorptivity, depth is the second most significant parameter (Table 4.4). The glazing type and thermal mass have here as well almost equal SRC values, while insulation and emissivity are statistically insignificant and should be neglected. From the results of the stepwise method (Table 4.7) we can see that the geometry of the SC, i.e. the length and depth, are the most dominant parameters, contributing to the regression
model ~83% out of the total ~87% of the explained variance. By including in the model the first four parameters (until step 4) an R^2 of 0.853 is achieved; by including all six parameters the R^2 is increased marginally up to 0.865, i.e. only an additional 1.2% of the Y variance is explained.

Table 4.3 Linear regression results for harvested energy as the dependent variable.

<table>
<thead>
<tr>
<th>SRC</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Length</td>
<td>0.747</td>
<td>28.366</td>
</tr>
<tr>
<td>2 Absorptivity</td>
<td>0.538</td>
<td>20.575</td>
</tr>
<tr>
<td>3 Glazing Type</td>
<td>0.237</td>
<td>9.038</td>
</tr>
<tr>
<td>4 Thermal Mass</td>
<td>-0.231</td>
<td>-8.536</td>
</tr>
<tr>
<td>5 Glass Percentage</td>
<td>0.175</td>
<td>6.588</td>
</tr>
<tr>
<td>6 Insulation</td>
<td>0.066</td>
<td>2.542</td>
</tr>
<tr>
<td>7 Depth</td>
<td>0.025</td>
<td>0.960</td>
</tr>
<tr>
<td>8 Emissivity</td>
<td>0.000</td>
<td>-0.017</td>
</tr>
</tbody>
</table>

Adjusted R^2 : 0.870 / F=166.880

Table 4.4 Linear regression results for fan savings as the dependent variable.

<table>
<thead>
<tr>
<th>SRC</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Length</td>
<td>0.817</td>
<td>30.493</td>
</tr>
<tr>
<td>2 Depth</td>
<td>0.556</td>
<td>21.015</td>
</tr>
<tr>
<td>3 Glazing Type</td>
<td>0.116</td>
<td>4.353</td>
</tr>
<tr>
<td>4 Thermal Mass</td>
<td>-0.113</td>
<td>-4.113</td>
</tr>
<tr>
<td>5 Absorptivity</td>
<td>0.089</td>
<td>3.366</td>
</tr>
<tr>
<td>6 Glass Percentage</td>
<td>0.081</td>
<td>2.993</td>
</tr>
<tr>
<td>7 Insulation</td>
<td>-0.023</td>
<td>-0.855</td>
</tr>
<tr>
<td>8 Emissivity</td>
<td>0.023</td>
<td>0.840</td>
</tr>
</tbody>
</table>

Adjusted R^2 : 0.865 / F=160.548

Table 4.5 Ranking of input parameters according to sensitivity of harvested energy and fan savings.

<table>
<thead>
<tr>
<th>rank</th>
<th>Harvested Energy</th>
<th>Fan savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Length</td>
<td>Length</td>
</tr>
<tr>
<td>2</td>
<td>Absorptivity</td>
<td>Depth</td>
</tr>
<tr>
<td>3</td>
<td>Glazing Type</td>
<td>Glazing Type</td>
</tr>
<tr>
<td>4</td>
<td>Thermal Mass</td>
<td>Thermal Mass</td>
</tr>
<tr>
<td>5</td>
<td>Glass Percentage</td>
<td>Absorptivity</td>
</tr>
<tr>
<td>6</td>
<td>Insulation</td>
<td>Glass Percentage</td>
</tr>
<tr>
<td>7</td>
<td>Depth</td>
<td>Insulation</td>
</tr>
<tr>
<td>8</td>
<td>Emissivity</td>
<td>Emissivity</td>
</tr>
</tbody>
</table>
Figure 4.3 Linear regression SRC values of the input parameters for the dependent variables of harvested energy and fan savings.

Table 4.6 Stepwise regression results for harvested energy as the dependent variable.

<table>
<thead>
<tr>
<th>Step</th>
<th>Predictors</th>
<th>Adjusted $R^2$</th>
<th>Added $R^2$</th>
<th>SRC step</th>
<th>SRC linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Length</td>
<td>0.424</td>
<td>0.424</td>
<td>0.744</td>
<td>0.747</td>
</tr>
<tr>
<td>2</td>
<td>Absorptivity</td>
<td>0.727</td>
<td>0.303</td>
<td>0.537</td>
<td>0.538</td>
</tr>
<tr>
<td>3</td>
<td>Thermal Mass</td>
<td>0.773</td>
<td>0.046</td>
<td>-0.234</td>
<td>-0.231</td>
</tr>
<tr>
<td>4</td>
<td>Glazing Type</td>
<td>0.835</td>
<td>0.062</td>
<td>0.238</td>
<td>0.237</td>
</tr>
<tr>
<td>5</td>
<td>Glass Percentage</td>
<td>0.867</td>
<td>0.032</td>
<td>0.173</td>
<td>0.175</td>
</tr>
<tr>
<td>6</td>
<td>Insulation</td>
<td>0.870</td>
<td>0.003</td>
<td>0.067</td>
<td>0.066</td>
</tr>
</tbody>
</table>

*Predictors: length

*Predictors: length & absorptivity

*Predictors: length, absorptivity & thermal mass

*Predictors: length, absorptivity, thermal mass & glazing type

*Predictors: length, absorptivity, thermal mass, glazing type & glass percentage

*Predictors: length, absorptivity, thermal mass, glazing type, glass percentage & insulation
Table 4.7 Stepwise regression results for fan savings as the dependent variable.

<table>
<thead>
<tr>
<th>Step</th>
<th>Predictors</th>
<th>Adjusted $R^2$</th>
<th>Added $R^2$</th>
<th>SRC step</th>
<th>SRC linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Length</td>
<td>0.513</td>
<td>0.513</td>
<td>0.815</td>
<td>0.817</td>
</tr>
<tr>
<td>2</td>
<td>Depth</td>
<td>0.827</td>
<td>0.314</td>
<td>0.555</td>
<td>0.556</td>
</tr>
<tr>
<td>3</td>
<td>Thermal Mass</td>
<td>0.840</td>
<td>0.013</td>
<td>-0.115</td>
<td>-0.113</td>
</tr>
<tr>
<td>4</td>
<td>Glazing Type</td>
<td>0.853</td>
<td>0.013</td>
<td>0.116</td>
<td>0.116</td>
</tr>
<tr>
<td>5</td>
<td>Absorptivity</td>
<td>0.861</td>
<td>0.008</td>
<td>0.090</td>
<td>0.089</td>
</tr>
<tr>
<td>6</td>
<td>Glass Percentage</td>
<td>0.865</td>
<td>0.004</td>
<td>0.076</td>
<td>0.081</td>
</tr>
</tbody>
</table>

*Predictors: length

*Predictors: length & depth

*Predictors: length, depth & thermal mass

*Predictors: length, depth, thermal mass & glazing type

*Predictors: length, depth, thermal mass, glazing type & absorptivity

*Predictors: length, depth, thermal mass, glazing type, absorptivity & glass percentage

4.5.3 Discussion

It is important to keep in mind that the SA results are determined by the specific SC model's configuration and assumptions. The following remarks can be made with respect to that:

- For example, the insulation thickness does not prove to be important, because the SC is assumed to be integrated with the building, which means that the construction of the backwall is in contact with the walls of the internal spaces of the building. In the SC model this has been taken into account by assigning a constant temperature of 20° for the environment behind the backwall, whereas the side walls and the glazing are subject to external conditions, with the air temperature that of the climate file. It is reminded that the backwall will not only be the one with the largest dimension (length) but that the total solar radiation entering the SC is assumed to be absorbed by its surface only. Under this scope, it is not surprising that the performance indicators are not sensitive to the insulation thickness. In reality however, where the side walls participate in the thermal processes, insulation should be as high as possible.

- The limitations of the airflow network approach and the inability to capture more complex thermal and airflow phenomena, should also be regarded. It is believed that the influence of emissivity in actual conditions is higher than the SA indicates here and this influence could probably only be captured by CFD simulations.

- The fact that the depth was found to be of no influence for the harvested energy, is probably because shading by the side walls is not calculated. Since however the limitation of depth being lower than 25% of the length has been imposed, it is not to say that if shading was calculated, the depth would prove to be significantly more important. On the other hand, depth was found so influential for fan savings because it determines –for a given length– the majority of pressure losses of the flow. If the inlet opening area was assumed constant thus the pressure losses were also constant through the inlet opening.
(given the fixed value of volume flow rate and thus of velocity through the opening), SA would probably indicate the depth as statistically insignificant since the $C_i$ values in the SC components are zero.

Apart from the above, the SA came to reasonable results, with the length and wall absorptivity determining the performance indicators to a large degree. The bigger the length, the higher the solar heat flux that enters the SC and the larger the absorbent surface of the backwall; the higher the absorptivity, the more the solar radiation that is absorbed by the backwall and the more the heat that is taken up by the air flowing in the SC channel by convection. The hotter the air, the higher its energy that is harvested and the higher the SC stack effect, thus the higher the fan savings.

Finally, it is implicit by the SA findings that the two performance indicators will not constitute contradictory design objectives, i.e. the design choices appropriate for maximizing the harvested heat are also appropriate for maximizing the fan savings. This is clear by the fact that the SRC values of the parameters for both models have the same sign (positive or negative).

### 4.6 Conclusions

The SA indicated that the performance indicators considered are sensitive to four out of the eight parameters that were taken into account. The harvested energy was found to be most sensitive to the length of the SC and the absorptivity of the walls; thermal mass and glazing type are also significant factors but to a much lesser extent. The fan energy savings are dominated by the dimensions of the SC, while thermal mass and glazing type were found to have some effect, although negligible compared to that of the length and depth. The high sensitivity of fan savings to the depth of the SC is attributed to the fact that the area of the inlet opening (where most pressure losses occur) assumes the same value as the area of the SC's cross section. The linear regression and the stepwise regression came to the same results, but the latter offers more insight as to the individual contribution of each parameter in explaining the variance of the output. The two performance indicators were not found to be contradictory objectives.
5

Design Optimization

5.1 Introduction

In general, optimization is a procedure which allows us to identify the optimum solution (single-objective) or the set of optimum solutions (multi-objective) for a given optimization problem. In this case the optimization problem consists of maximising harvested energy and fan savings (two objectives). In the objective functions the variables found to be most significant in SA are included, i.e. length, depth, absorptivity and thermal mass. For the rest of the variables found to be less important, fixed values were chosen. The model used is the same as in SA. The whole procedure, including creation of input files for ESP-r, simulations, model output derivation and optimization is automatically performed with the program modeFRONTIER (ESTECO, version 4.2.1). The algorithm NSGA-II (Deb et al. 2002) is chosen to be used. A short description of the methodology, results and additional calculations for the energy savings of the optimized design are presented below; a discussion section concludes the chapter with an overview of the present limitations and suggestions for future studies.

5.2 Methodology

The applied methodology for optimization can be summarized in the following steps:

1. Define objectives;
2. Define variables;
3. Select algorithm;
4. Perform simulations for the created generations and their populations and evaluate the results;
5. Conclude optimization and make design decisions based on the Pareto front.

The objectives have already been defined in Ch.4 to be the annual harvested energy and the annual fan energy savings accomplished by the SC. The variables that are included in the optimization are the ones against which the harvested energy and fan savings are most sensitive to as identified in SA; these are the length and depth of the SC, as well as the absorptivity and thermal mass of the walls. Table 5.1 presents the fixed values of the parameters not considered in optimization. The algorithm that is selected is the non-dominated sorting genetic algorithm (NGSA-II) which has already been proven efficient in optimization of building-related problems. Steps 4 and 5 are automatically performed in the program modeFRONTIER. The creation of the ESP-r input files, simulations and derivation of the model’s output (values of harvested energy savings) are automatically performed by the program modeFRONTIER.
energy and fan savings of the simulation) are realised via user-defined batch files that are automatically initiated by modeFRONTIER.

Table 5.1 Parameters settings for optimization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>Optimization variable</td>
</tr>
<tr>
<td>Depth</td>
<td>Optimization variable</td>
</tr>
<tr>
<td>Thermal Mass</td>
<td>Optimization variable</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.12 m</td>
</tr>
<tr>
<td>Absorptivity</td>
<td>Optimization variable</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.05 [-]</td>
</tr>
<tr>
<td>Glazing Type</td>
<td>Double</td>
</tr>
<tr>
<td>Glass Percentage</td>
<td>0.90</td>
</tr>
</tbody>
</table>

5.3 Results

Optimization resulted in a single optimum solution. Figure 5.1 presents the simulation results; each square corresponds to a solution and the x and y axis correspond to the values of the harvested energy and fan savings respectively. The optimum solution is marked with a red circle; 394,370.0 KWh is the energy harvested annually for this design solution and 921.36 KWh the fan savings accomplished. For this optimum solution the variables assume the maximum possible values for length (32.4m), depth (2m) and absorptivity (0.95), and the lowest possible value for thermal mass (concrete thickness is 1mm). In the figure some other solutions have been identified to help with the results interpretation. Table 5.2 presents the values of the decision variables and of the objectives for each of these solutions; the solutions are shown in the table in ascending order of fan savings.

The influence of depth can be seen in solutions 3 and 6, which differ only in that aspect (difference in the thermal mass is negligible); for an increase in depth from 0.8 to 2.0m the fan savings are increased by ~214% while the harvested energy remains practically the same (0.7% difference is found). This is obviously attributed to the reduction of the pressure losses through the inlet opening; for a length of 32.4m the velocity through the opening drops from 1.26m/s to 0.50m/s for a depth of 0.8 and 2.0m respectively. The pressure losses are thus ~5.72Pa and ~0.9Pa in the two cases. Solutions 1 and 2 confirm that it is the cross-section area and not the individual values for length and depth that dominate the fan savings. Although different values in length, absorptivity and thermal mass influence the harvested energy (differs by ~310%) the similar value of the cross section area results in zero fan savings in both cases. The effect of thermal mass can be seen in the solutions 5 and 6; for a concrete thickness value of 12cm the fan savings and harvested energy drop by ~17% and 35% respectively, in comparison to the solution with a concrete thickness of 1mm. Solutions 4 and 6 differ only in absorptivity; for a value of 0.15 instead of 0.95 fan savings and harvested energy drop by 23% and 47%.
The above confirm what was found in SA; some additional calculations are presented in the following which explore the energy savings achieved by the SC in greater depth.

Table 5.2 Values of decision variables and objectives for certain solutions.

<table>
<thead>
<tr>
<th>No</th>
<th>Length</th>
<th>Depth</th>
<th>Absorptivity</th>
<th>Thermal Mass</th>
<th>SC section</th>
<th>Fan savings</th>
<th>Harvested energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.0</td>
<td>1.9</td>
<td>0.15</td>
<td>0.00</td>
<td>17.10</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>19.8</td>
<td>0.8</td>
<td>0.95</td>
<td>0.00</td>
<td>15.84</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>32.4</td>
<td>0.8</td>
<td>0.95</td>
<td>0.00</td>
<td>25.92</td>
<td>293.89</td>
<td>391.790.00</td>
</tr>
<tr>
<td>4</td>
<td>32.4</td>
<td>2.0</td>
<td>0.15</td>
<td>1.00</td>
<td>64.80</td>
<td>709.98</td>
<td>210.210.00</td>
</tr>
<tr>
<td>5</td>
<td>32.4</td>
<td>2.0</td>
<td>0.95</td>
<td>120.00</td>
<td>64.80</td>
<td>769.53</td>
<td>256.850.00</td>
</tr>
<tr>
<td>6</td>
<td>32.4</td>
<td>2.0</td>
<td>0.95</td>
<td>1.00</td>
<td>64.80</td>
<td>921.36</td>
<td>394.370.00</td>
</tr>
</tbody>
</table>

5.4 Optimized design energy savings

The parameters' settings of the optimized design are the ones shown in Table 5.2 for solution No.6. The fan losses are zero, i.e. during all functional hours the stack effect induced by the SC is enough to compensate for the SC pressure losses and to additionally relieve the pressure required by the fan to ventilate the building (this pressure is 40 Pa, see Ch. 3). The hours that the fan can be turned off are zero.

Some calculations follow that allow the comparison of the above energy savings to the building's energy demands.

5.4.1 Harvested Energy

The annual heating demand of the building was estimated to be:

$$E_{\text{heating, total}} = 1.115 \times 10^4 \text{ KWh} = 111.5 \text{ MWh}$$

(5.1)

This value was derived from thermal simulations of the office zones in ESP-r assuming an infiltration rate of 4ACH, a floor height of 3m, and internal gains of 30W/m² (5W/m² for people, 10 W/m² for lighting and 15 W/m² for appliances). The west and east elevation were considered fully glazed; the south elevation will be fully covered by the SC and the north is assumed to be opaque. The heating setpoint is 20°C and the hours of air-conditioning from 7am to 7pm, i.e. the office hours also considered in the SC calculations. It is noted that this value is uncertain since it is highly sensitive to the design assumptions considered here.

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3 For an occupancy ratio of 20m² per person.
4 The 'Climate Cascade' is intended to be placed on that facade (Bronsema, EWF report).
The harvested energy in the optimized SC was estimated at 394.4 MWh. A heat storage system (e.g. ground heat storage) would be necessary to fully exploit this harvested energy, since the highest enthalpic gains in the SC (during the summer) will not coincide with the building’s heating demands. In order to make reliable estimations on the energy gains that the SC offers, the efficiency of the heat storage
Figure 5.1 Optimization results: scatter plot of harvested energy and fan savings results for the solutions generated.
system (usually not higher than 0.5) must be taken into account. On the absence of a fully specified design for the building and heat storage system, the calculations that follow serve only as an example.

Depending on the efficiency of the heat storage system the harvested energy could compensate for different percentages of the building’s total heating demand. Since the value of the heating demand estimated in (5.1) is highly uncertain and equal to only 30% of the harvested energy in the SC, two more values are assumed which are double and triple the demand of (5.1). Figure 5.2 presents the absolute value of the energy harvested in the SC for efficiencies ranging from 0.1 to 0.9 and the percentage of the building’s heating demand covered if this demand is 111.5/223/334.5 MWh. It is implicit that when the heating demand doubles or triples, the percentage covered by the heat harvested in the SC becomes half and one third respectively. It should be noted that in heat storage systems efficiencies are normally not higher than 0.5.

![Figure 5.2 Heating demand of the building covered by the heat harvested in the SC for various efficiencies of the heat recovery system and three values of the demand.](image)

**5.4.2 Fan savings**

The pressure difference required to ventilate the building was estimated at 40 Pa, thus the energy that the fan (for an efficiency of 0.65) would consume annually if the SC was not integrated in the system would be:

$$E_{fan} = \Delta P \frac{V}{\eta} \cdot hrs = 40 \cdot 32.661 / 0.65 \cdot 3132 = 6295.0 \text{ KWh} \quad (5.2)$$

It is reminded that 3132 are the number of office hours within the year. From (5.2) and the fan savings of the optimized design (see Table 5.2, solution 6) it is derived that the SC offers a 15% reduction in the energy required to ventilate the building. However the SC would save more energy in a building designed with lower pressure
losses. Figure 5.2 presents the fan savings accomplished by the optimized SC as a percentage of the total fan energy required, and the hours that the fan can be shut down in case the pressure losses in the building are 5, 10, 15, 20, 25, 30 and 35 Pa respectively. It is interesting to see in the figure that there are zero hours for which the stack effect accounts for more than 20 Pa; in total for 125 hours the stack effect is between 15 and 20 Pa and another 408 hours (533-125, see figure) it is between 10 and 15 Pa.

It is reminded that the stack effect is influenced by the temperature of the supply duct (18°C, see Ch. 3); in case the temperature is lower, the stack effect will be more pronounced. Another factor which would completely alter the results presented here is wind; in case overpressure is ensured at the top of the supply duct and/or underpressure at the top of the SC, the fan savings and the percentage of time for which the fan could be shut down could increase dramatically. On the absence of estimations for the corresponding C_p values, wind was neglected here, thus these estimations are on the safe (conservative) side. It should be noted however, that the possible pressure losses imposed by the heat recovery equipment are also not taken into account; depending on the system the reduction of performance could be high, e.g. Gan and Riffat (1998) estimated a 60% overall reduction of performance when installing a pipe heat-recovery system. All these factors should be accounted for provided all relevant data are available for a specific application, since their influence is expected to be high on the system’s performance.

![Bar chart showing fan energy savings as a percentage of the total fan energy required to ventilate the building for various pressure losses and number of hours when the fan can be turned off.]

**Figure 5.3 Fan energy savings as a percentage of the total fan energy required to ventilate the building for various pressure losses and number of hours when the fan can be turned off.**

### 5.5 Discussion

The optimization of the SC design serves here as an application example and not as a means to gain more knowledge; the results could be anticipated based on the SA

5 Performance drops due to additional pressure losses (higher resistance to flow due to pipes) and reduction in air temperature after the evaporator section.
results, given certain assumptions (e.g. area of inlet opening) and the limitations of the ESP-r model to capture detailed airflow characteristics. One has to be careful in evaluating the optimization results for depth. The depth was so influential for fan savings due to the reduced pressure losses through the inlet opening for the higher value. Thus in order to optimize the SC with respect to fan savings, the pressure losses through the inlet or other areas where large losses could be introduced, should be minimised. In the specific model this is achieved by increasing the area of the inlet opening, but in reality there are other means as well that could be implemented. With respect to the influence of depth for the flow inside the SC channel, this cannot be fully captured in ESP-r. Studies based on CFD simulations have indicated that the goals of maximum enthalpic gains and maximum mass flow (i.e. lowest resistance to flow) cannot be accomplished simultaneously (Rodrigues et al, 2000) and that different optimum depths of the SC channel are found that maximise either the mass flow or the Nusselt number (thermal performance) (Zamora and Kaiser, 2009). This behaviour is attributed to changes of the flow pattern due to development of reversed flow regions, which obviously cannot be modelled in the nodal airflow network of the ESP-r program. Thus, if CFD calculations were performed, it is expected that two optimum solutions could be found which would only differ in depth; one would maximise harvested energy and the other the fan savings. It is implicit that the other parameters simultaneously maximize the two Pls.

However the range of aspect ratios (height-to-depth) considered could determine whether an optimum depth is found, even with CFD calculations; e.g. Gan (2006) argues that the optimum depth increases with height. Therefore it is not obligatory that an optimum depth exists for the range of H/d considered here (from 2 to 71).

No optimum depth has been found in another study performed with the analogous to ESP-r BPS program EnergyPlus (Ho Lee and Strand, 2009), obviously as a result of the program’s restrictions as in this case.

It is suggested that two single-objective optimizations could be performed via CFD calculations which would indicate the optimum depth to maximize each objective. With respect to multi-objective optimization, an interesting aspect to investigate would be the harvested energy versus the energy required for artificial lighting in the zones where natural light is obstructed by shading from the SC channel (i.e. the zones facing south).

5.6 Conclusions

The optimized design was found to be the one with the maximum possible values for length, depth and absorptivity and the minimum possible value for thermal mass. These results could be anticipated already from SA. The fact that the optimum depth was found to be the maximum, is because the pressure losses through the inlet are determined by the depth (for a given height). This should be translated as a requirement to minimize the losses through the inlet, which in reality could be accomplished by other means as well. The ESP-r model cannot capture the influence

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6 Analogy is in terms of the nodal network concept for thermal and airflow simulations, as opposed to CFD simulations.

7 Even though harvested energy could compensate for the increased heating demand of zones with high percentage of glazed walls that would save electrical energy for lighting.
of depth on the thermal performance and airflow patterns in the SC channel, found otherwise in CFD calculations. It was found that the main benefits of the SC will come from exploiting the harvested energy to cover functional demands of the building (e.g. space heating).
6
Robustness

6.1 Introduction

At this final stage of the study, the optimized SC (Chapter 5) and the prototype building (Chapter 3) are integrated in a common ESP-r model (Figure 6.1) so that the robustness of the system is checked with respect to operating windows. The analysis aims at making recommendations over the control of the ventilation network (e.g. dampers, fan(s)). A limited number of arbitrary scenarios were checked in order to investigate the general behaviour of the network, when flow is disturbed by windows' operation. Since the objective of the analysis is limited to a qualitative evaluation of the network, certain assumptions were adopted for the Cp values on the facades, without risking any loss of valuable information. Simulations were performed for summer days under high wind speeds and the values of the Cp for the façade walls were chosen within the range of -1.5 to 1.5. The Cp values for the inlet of the main supply duct and the outlet of the SC were assumed zero. Windows were operated on different zones of the floor modelled in detail (floor seven, Chapter 3, 3.5.3) and on different floors of the building. A short description of the investigated scenarios and indicative results for a specific timeslot are presented in the following.

Figure 6.1 Wireframe image of the integrated model.

ESP-r presents the normal minimum of the Cp values to be -1.5.
6.2 Scenarios

In order to study the disturbance of the airflow network caused by operable windows, a small number of scenarios were considered (Table 6.1); in the four out of the five scenarios windows’ operation was considered only for the floor seven. The floor seven was chosen because it was shown from the results in Chapter 3 that the smallest modelling simplifications’ error was introduced there. It can be seen in the table that scenario 1 assumes windows’ opened at one zone of floor seven while in scenario 5 windows are opened in four zones of floor seven and in four more floors in the building. The Cp values of the facades assumed values of -1.5/-0.5/0.5/1.5. For a specific façade the Cp values were considered the same for all wind directions but when two facades (here facing opposite) were considered in a scenario, different Cp values were considered for each façade (e.g. 1.5 for the west and -0.5 for the east). Since an evaluation of the performance is intended here (qualitative analysis) and the absolute measures are not the focus, the assumptions for the Cp values will not influence the findings. The phenomena (disturbance of flow patterns from over-/under-pressure) will retain their behaviour but one can imagine varying intensities for different values of the Cp. The effective area of the openings in the office zones was estimated at 15% of the area of the corresponding façade. When windows are presumably opened in floors modelled with an equivalent floor component, the opening area is 15% of the entire façade, i.e. we assume that more than one zones of the façade have open windows. Simulations were performed for 15th and 16th of July, where ambient wind speed was at high levels for the summer period. Results will be presented for 11am of the 16th where the wind speed is at its highest (6m/s). It is noted that the windows are assumed to stay open during all hours, but this will not influence the findings, similarly to the above2. The simulation results are presented below for each scenario in terms of volume flow in the office zones of floor seven and through the rest of the floors.

6.3 Results

For each of the five scenarios (Table 6.1) considered (scenario 0 corresponds to initial condition i.e. a sealed building with no operable windows) two figures are presented, one with the volume flow rates found for the zones of floor seven and one with the volume flow rates through all floors of the building. Figures 6.2-6.6 present the volume flow through all floors in the building for every scenario. For floor seven the flow indicated in the figures is the air exhausted through the floor exhaust duct. For the floors were windows are opened, the value of the volume flow rate is marked with red font.

2 Assuming a control for windows’ opening (e.g. based on the zones air temperature compared to outside) would not contribute anything more given the context of the analysis here.
It can be seen in the figures that when the windows are open only on floor seven, and for the scenarios considered here, more volume flow goes through this floor while the flow through all the rest is balanced (i.e. same amount through all floors) and lower than the required flow. This is a result of the fan's operation which induces a flow of 32.66 m³/s (see Chapter 3) at all times, thus when flow is higher through floor seven, the remaining flow is more or less evenly distributed through the rest: e.g. for scenario 1 the flow through the floors is on average equal to (32.66 - 7.34)/8 = 3.17 m³/s. The higher the difference of this flow from the design flow of 3.63 m³/s, i.e. the higher the difference of the velocity in the floor supply ducts from the design velocity of 2 m/s, the larger the differences among floors. For example in scenario 2 the flow through the floors varies from 3.52 to 3.54 m³/s, i.e. by 0.02 m³/s, while in scenario 4 it varies from 2.76 to 2.85 m³/s, i.e. by 0.09 m³/s. It is implicit that if the wind or actual Cp values were higher and over/under-pressure more extreme, the disturbances in flow would be higher. In scenario 5, where windows are open in more floors the flow is disturbed so that flow rates up to 100 m³/s are observed as well as reverse flow occurrences (see Figure 6.6). Of course these high values are irrational and are due to the model's simplifications (see Discussion below).
Figure 6.2 Volume flow through all floors for scenario 1.

Figure 6.3 Volume flow through all floors for scenario 2.

Figure 6.4 Volume flow through all floors for scenario 3.

Figure 6.5 Volume flow through all floors for scenario 4.
Figure 6.6 Volume flow through all floors for scenario 5.

Figure 6.7 the flow rate in the office zones at floor seven in the original situation, where all windows are close (scenario 0) while Figures 6.8-6.12 present the volume flow rate through these zones for scenarios 1-5. In the former figures the supply (blue colour) and exhaust (green colour) ducts are also indicated for clarity. For floor seven the flow indicated in the figures is the air exhausted through the floor exhaust duct. For the floors were windows are opened, the value of the volume flow rate is marked with red font. In the latter figures the blue arrows signify air supply into the zone and the green ones air exhaust from the zone; for the zones with closed windows one value for the flow is indicated which is both the supply and exhaust air of the zone. The $C_p$ values on the facades are also indicated, along with the pressure on the facade at the height of floor seven ($P_{win}$). Table 6.2[a,b] presents the pressure of the zones for floor seven for the different scenarios [a]; as a measure of comparison the same pressures for the situation where all windows are closed (scenario 0) are also presented. For scenarios 0 and 5 the pressures of nodes $f_1$, $f_3$, $f_5$, $f(7)$ and $f_9$ are presented [b]. It is noted that pressures of nodes $f_1$, $f_3$, $f_5$, $f_9$ are the pressures at the end of the equivalent floor component of floors 1,3,5 and 9 respectively (see Chapter 3), and pressure at node $f(7)$ is their analogy for floor seven, i.e. the pressure at the zone of the corridor. In the table the pressure of the zones where windows are opened are enclosed in squares.
Figure 6.7 Volume flow through the office zones in floor seven and scenario 0.

\[ C_p = +1.5 \]
\[ P = -388.1 \text{ Pa} \]

Figure 6.8 Volume flow through the office zones in floor seven and scenario 1.
Figure 6.9 Volume flow through the office zones in floor seven and scenario 2.

Figure 6.10 Volume flow through the office zones in floor seven and scenario 3.
Figure 6.11 Volume flow through the office zones in floor seven and scenario 4.

$C_p = +1.5$

$P_{in} = -388.1 \text{ Pa}$

$3.84 \text{ m}^3/\text{s}$

$1.21 \text{ m}^3/\text{s}$

$2.69 \text{ m}^3/\text{s}$

$0.85 \text{ m}^3/\text{s}$

Figure 6.12 Volume flow through the office zones in floor seven and scenario 5.

$C_p = -0.5$

$P_{in} = -424.2 \text{ Pa}$

$0.75 \text{ m}^3/\text{s}$

$1.26 \text{ m}^3/\text{s}$

$0.24 \text{ m}^3/\text{s}$
In Figures 6.8 – 6.12 it can be seen how the flow entering from the window is partly distributed through other zones resulting in higher flow rates in the offices for scenarios 1-4. In scenario 1 (Figure 6.8) e.g. the 1.43 m³/s that exhausts from zone W and enters the supply ducts is distributed in all other zones so that the rates are increased to 0.67 m³/s from 0.53 m³/s (scenario 0, Figure 6.7) in zones SW, SE, NW, NE and from 0.76 m³/s to 0.94 m³/s for zone E. In scenario 5 the zones where windows are closed (SW and NE) are supplied with less air than required at 0.24 m³/s, because the incoming air from zones W, NW is short-circuited and exhausted to the outside through the windows of zones E and SE (Figure 6.12). Thus depending on the differential pressures between the various office zones of the floor, disturbances of the flow can be in both directions, i.e. either to the positive or to the negative side (higher rates or lower rates than required). It can be seen in Table 6.2 that the pressure in the zones where the window is open is the same as the pressure outside, due to the large opening and thus low resistance to flow (see also $P_{\text{win}}$, Figures 6.7-6.12). Thus the outside wind pressure on the façade can have a larger or a smaller impact on the formation of the pressure inside the zones, depending on the resistance of the flow through the window; higher resistance would mean lower pressure variations and thus a more stable network.

### Table 6.2 Pressures in the office zones and corridor at floor seven for the various scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NW</th>
<th>W</th>
<th>SW</th>
<th>NE</th>
<th>E</th>
<th>SE</th>
<th>Corridor</th>
<th>Floor exhaust flow [m³/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-440.6</td>
<td>-388.1</td>
<td>-440.6</td>
<td>-440.6</td>
<td>-440.6</td>
<td>-440.6</td>
<td>-444.5</td>
<td>7.34</td>
</tr>
<tr>
<td>2</td>
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<td>-442.4</td>
<td>-449.4</td>
<td>-449.4</td>
<td>-449.4</td>
<td>-449.4</td>
<td>-452.0</td>
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</tr>
<tr>
<td>3</td>
<td>-441.2</td>
<td>-388.1</td>
<td>-441.2</td>
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<td>-442.4</td>
<td>-441.2</td>
<td>-445.1</td>
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</tr>
<tr>
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<td>-388.1</td>
<td>-433.1</td>
<td>-433.1</td>
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<td>-416.3</td>
<td>-424.2</td>
<td>-424.2</td>
<td>-416.8</td>
<td>0.75</td>
</tr>
</tbody>
</table>

### 6.4 Discussion

The purpose of the robustness analysis as defined here was to gain an impression or rather validate the disturbances expected in the airflow network when windows’ are opened. From that aspect certain observations can be made observing the results presented here, even if the simplifications adopted in the airflow network model lead to situations which would not apply in a real controlled system. For example not being able to include in the model dampers that would prevent reverse flow from happening inside the floor network but also the main network, has a major influence, with flow going from the office zones into the ducts in some cases (Figures 6.8-6.12), which is unrealistic. In scenario 5, modelling the floor network with an equivalent floor component causes irrational predictions of the volume flow values. However the following can be derived from the robustness analysis as it is, with certainty:

3 That kind of control cannot be imposed in ESP-r.

4 It is reminded that the ESP-r restriction on the maximum number of nodes dictated this approach.
It is clear that having one fan to serve the whole building would be inefficient to balance the network in case windows are operated; individual controls in every office zone should be implemented to ensure balance of the system. This control could be accomplished using many alternative approaches, e.g. by using one fan for the whole floor and dampers for every zone and window or dampers for the supply and exhaust of each zone. Fans for every office zone separately could also be another choice.

Self-regulating dampers for the supply of every zone are needed, that would limit the flow to the required value irrespective of the pressure difference and obstruct reverse flow from occurring. The windows or exhaust of the zones could also be regulated by such components to limit the flow coming from outside or the flow exiting the zone, and not allow for major pressure differences between the zones.

It is most probable that in real-time applications the control of such a system would be automated for the whole building, where windows opening are regulated depending on the situation (e.g. favourable wind pressures and outside air temperatures). The most appropriate and effective way to control this highly complex network could easily be translated into a separate subject to study, but is beyond the scope of the present one.

6.5 Conclusions
A complex network, comprising –among others- of individual self-regulating dampers for every zone and/or windows and fans for every floor and/or zone, would be required to balance the system in case windows’ opening by the users is allowed. The robustness analysis as performed here served to confirm these prerequisites, offering some basis for observations rather than realistic simulations of the network. This is attributed to the simplifications –some inescapable- adopted in the model; a detailed and more exact modelling and performance simulation of the network and its controls could be a separate subject for future study, given the resulting complexity.
Discussion & Conclusions

The present study aimed at investigating the application of a SC for natural ventilation and heat harvesting in a prototype office building in the Netherlands. The methodology applied included calibration of the ESP-r model based on measurements, SA and optimization of the design with respect to harvested energy and fan savings and robustness analysis for opening of windows by the users. Validation confirmed that the ESP-r model of the SC is able to predict the air temperature distribution in the shaft and the induced mass flow rate quite accurately. The Molina & Maestre algorithm for convective heat transfer was found the most promising for this type of problem. Sensitivity analysis concluded that the harvested energy is most sensitive to length of the SC and short-wave absorptivity of the walls, while fan savings are most sensitive to the SC’s cross section area (length x depth). The glazing type and thermal mass were also found influential but to a lesser extent. Long-wave emissivity of the walls had a negligible effect for both performance indicators. The optimized design was that with the maximum values for length, depth and absorptivity and the minimum value for the thermal mass. It has also been shown that the main contribution of the SC in the climate of the Netherlands will be the harvested energy and not so much the fan energy savings. Robustness analysis indicated the need for separate controlling mechanisms in every zone, which could be accomplished with different approaches; future research should be performed on that aspect to guide the related design choices.

The following problematic issues arose throughout the different stages of the study:

- The scalability of the calibrated model and its ability to represent a full-scale SC was not possible to be investigated with the available means. This is an issue which requires to be studied in the future.
- The choice of a specific case study – even though in reality this application is a building-specific problem – limits the generalization of results. A study in which parametric analysis is performed that takes into account aspects of the building’s design apart from those regarding the SC (e.g. ventilation requirements, pressure losses through the network, functional hours etc) would provide a wider knowledge and help with design decisions in relevant projects. This study is already planned within the EWF project and results are anticipated to be most interesting.
- Even though the selection of ESP-r as the performance simulations’ environment fitted very well the scope of the study, it also had certain implications with respect to optimization of the design. It is argued that simulations using CFD would probably indicate a different optimum depth for the SC than the one found here.
- Restrictions of the ESP-r program also dictated certain simplifications in the airflow network model which did not allow for the maximum degree of realistic representation. It is considered that a full investigation of the complex network and its controls would be an interesting research subject for a future study.
Neglecting wind effects was a choice dictated by the high uncertainty related to \(C_p\) values and it was on the safe side. However, if reliable performance estimations are to be made on SC applications (or any other natural ventilation approaches for that matter), wind effects should be included with the highest level of certainty possible (e.g. by estimating \(C_p\) values through wind-tunnel measurements, something that is scheduled for the immediate future in the case of the EWF project).

As is often the case with studies of this kind, even though the findings have value on their own, the other main contribution is that new questions are raised. Future research can thus be based on attempts to cover weaknesses and exploit in greater depth remaining interesting issues. Some possibly challenging subjects for future study are the following:

- Research on the local dynamic and friction loss factors that apply in the case of naturally ventilated ducts, with symmetrical (e.g. if photovoltaic panels instead of plane glass are used) and/or asymmetrical heating.

- Optimization of possible configurations for the inlet opening(s) to the SC channel as well as of the whole ventilation network of the integrated SC-building system for maximum performance.

- A broader study of the integrated SC-building system, which would take into account—among others—the functional energy demands of the building (e.g. for space heating), the performance of the heat storage system, or other elements of the building and their inter-dependence to the SC (e.g. the Climate Cascade in the case of the EWF project).

- A parametric analysis taking into account various building design aspects (e.g. ventilation requirements, pressure losses through the network, functional hours etc) as well as sensitivity to wind effects.

- A multi-objective optimization of the SC with respect to the harvested energy and the lighting energy required in the zones shaded by the SC.

- The performance optimization of the airflow network’s controlling mechanisms, especially given the increasing use of automated control systems.

In general the applications of the SC concept—as is the case with all other sustainable technologies—is expected to be increasingly used in future projects. In anticipation of, or concurrently with that development, research should strive to set the fundamentals so that what is innovative now, is common practice tomorrow.
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Appendix

A1 Linear regression analysis

If Y is the output variable and the k input variables X_1 to X_k, then a linear model will exist of the form:

\[ Y = \beta_0 + \sum_{j=1}^{k} \beta_j X_j \]  

(A.1.1)

Thus for each of the two output variables considered (harvested energy and fan savings) we get the following system of N \cdot (k+1) linear equations:

\[
\begin{bmatrix}
1 & x_{11} & x_{12} & \ldots & x_{1k} \\
1 & x_{21} & x_{22} & \ldots & x_{2k} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
1 & x_{N1} & x_{N2} & \ldots & x_{Nk}
\end{bmatrix}
\begin{bmatrix}
b_0 \\
b_1 \\
\vdots \\
b_k
\end{bmatrix}
= 
\begin{bmatrix}
y_1 \\
y_2 \\
\vdots \\
y_N
\end{bmatrix}
\]

(A.1.2)

Where N is the number of samples, k the number of input variables, x_{ij} with i=[1,N] and j=[1,k] the value of the j^{th} input variable for the i^{th} sample, b_0 the intercept and b_j j=[1,k] the regression coefficient of the j^{th} input variable. This system can also be written in matrix notation as:

\[ X_N B_k = Y_N \]  

(A.1.3)

Linear regression analysis solves this system of equations and determines the matrix B_k, i.e. the regression coefficients of the input variables (b_j), as well as the intercept of the model (b_0).

However, because each input variable has different units, we cannot conclude on the relative importance of the parameters by comparing the regression coefficients. Instead, the standardized regression coefficients (β or SRC) are calculated according to:

\[ \beta_j = b_j \frac{\sigma_{X_j}}{\sigma_Y} \]  

(A.1.4)

where b_j the non-standardized regression coefficient, and \sigma_{X_j}, \sigma_Y the standard deviations of the input variable X_j and the output Y.
A2. Regression Analysis measures

R-square ($R^2$): $R^2$ is the correlation coefficient squared, and it is a measure of goodness of fit of the model. It takes values from 0 to 1 and it is the portion of the variance of the output variable ($Y$), explained by the regression model, e.g. an $R^2$ of 0.90 means that 90% of the variance in $Y$ is explained by the independent variables of the regression model. However, the $R^2$ can be artificially inflated by adding more input variables to the model. Instead, adjusted $R^2$ can be used, which takes into account the number of input variables.

$t$-statistic ($t$): the t-statistic is the value of the non-standardized regression coefficient ($b$) divided by its standard error, and it indicates if the value of $b$ is statistically significant. A $t$ value higher than 2 means that the coefficient is statistically significant and that the related input variable should be kept in the regression equation (or regression model).

$p$-value ($p$): the p-value is the probability of observing the specific t-statistic in a collection of random data in which the variable has no effect (i.e. that the true coefficient is zero). With a $p$-value of 5% (or .05) there is only a 5% chance that these would have come up in a random distribution, so there is a 95% confidence that the variable is having some effect, assuming the model is specified correctly. If the p-value is higher than 0.05 or 5% (corresponding to a t<2.0) then the input variable should be discarded from the model.

$F$: Measure that tells us whether the regression model as a whole is statistically important for explaining the variance in $Y$. It is found by dividing the ‘explained variance’ by the ‘unexplained variance’, represented by the mean square of the model’s regression and the mean square of the error (residual) respectively.

A3. Harvested energy and Fan savings calculations

Calculation of harvested energy. The hourly value of harvested energy in the SC is calculated by the following formula:

$$E_{\text{harvest, hour}} = V \cdot \rho_{\text{inlet}} \cdot c_{p,\text{inlet}} \cdot (T_{\text{air, out}} - T_{\text{air, in}}) \text{ [KWh]} \quad (A3.1)$$

where,
- $V$: the volume flow rate through the SC, constant and equal to 32.66 [m$^3$/s]
- $\rho_{\text{inlet}}$: the air density of the inlet air, constant and equal to 1.2 [kg/s]
- $c_{p,\text{inlet}}$: the specific heat capacity of air at the inlet temperature, constant and equal to 1.006 [KJkg$^{-1}$°C$^{-1}$] (value for dry air at 20°C)
- $T_{\text{air, out}}$: the simulated air temperature at the top SC zone in [°C]
- $T_{\text{air, in}}$: the inlet air temperature, assumed to be constant and equal to 20 [°C]

Eqn. A3.1 is thus simplified to:

$$E_{\text{harvest, hour}} = 39.43 \cdot (T_{\text{air, out}} - 20) \text{ [KWh]} \quad (A3.2)$$

i.e. for every degree that the inlet air is heated up in the SC, approx. 40 KWh are gained hourly.
For every sample the harvested energy output variable is the sum for the 3132 hours of the hourly harvested energy, derived from Eq. (A3.2).

Calculation of fan energy savings. This calculation is more elaborate since the conditions where the SC is integrated with the prototype building need to be taken into account. For the integrated system, the pressure drops of the airflow path from supply to SC exhaust are given by:

\[ P_{\text{inlet}} + \Delta P_{\text{supply,stack}} - \Delta P_{\text{building,loss}} - \Delta P_{\text{SC,stack}} - \Delta P_{\text{SC,loss}} + \Delta P_{\text{fan}} = P_{\text{outlet}} \]  

(A3.3)

where

\[ P_{\text{inlet}} \]: the pressure of the boundary node located at the top of the supply duct (at 50m height), calculated in ESP-r based on the outdoor air temperature, in [Pa]

\[ \Delta P_{\text{supply,stack}} \]: the stack pressure of the air in the supply duct, in [Pa]

\[ \Delta P_{\text{building,loss}} \]: the total pressure losses due to airflow in the supply, exhaust and floor network ducts (i.e. sum of the frictional and local dynamic losses through building’s ducts), equal to 40[Pa] (see Chapter 3).

\[ \Delta P_{\text{fan}} \]: the pressure needed by the fan to induce the required volume flow of 32.66 [m³/s], in [Pa]

\[ \Delta P_{\text{SC,stack}} \]: the stack pressure of the air in the SC shaft, in [Pa]

\[ \Delta P_{\text{SC,loss}} \]: the sum of the frictional and local dynamic pressure losses through the SC inlet opening and the SC shaft, in [Pa]

\[ P_{\text{outlet}} \]: the pressure of the boundary node located at the top of the SC shaft (at 50m height), calculated in ESP-r based on the outdoor air temperature, in [Pa]

Since the two boundary nodes are located at the same height, then it would apply that:

\[ P_{\text{inlet}} = P_{\text{outlet}} \]  

(A3.4)

Thus it is possible to delete these terms from Eq. (A3.3). Additionally it should be noted that the stack pressures at the supply and SC ducts are calculated with the following well-known expression:

\[ \Delta P_{\text{stack}} = \rho_{\text{air}} * g * H_{\text{stack}} \]  

(A3.5)

where:

\[ \rho_{\text{air}} \]: the density of the air inside the duct, which is a function of air temperature according to the relationship \( \rho_{\text{air}} = 348.3284/(273.15+T_{\text{air}}) \), in [kg/m³]

\[ g \]: the acceleration of gravity, equal to 9.806 [m/s²]

\[ H_{\text{stack}} \]: the height of the stack column (i.e. duct length) equal to 50m in both cases
The air in the supply duct is assumed to have a constant temperature of 18 °C (accounting for preheating/cooling of the outdoor air in the climate cascade), thus $\rho_{\text{air, supply}} = 1.21 \text{[kg/m}^3\text{]}. The air temperature in the SC duct is an output of the simulation.

Based on the above, Eq. (A3.3) is simplified to:

$$\rho_{\text{supply}} \cdot g \cdot H_{\text{supply}} - (\rho_{\text{SC}} \cdot g \cdot H_{\text{SC}} + \Delta P_{\text{SC, loss}}) + \Delta P_{\text{fan}} = \Delta P_{\text{building, loss}} \rightarrow$$

$$593.26 - (\rho_{\text{SC}} \cdot g \cdot H_{\text{SC}} + \Delta P_{\text{SC, loss}}) + \Delta P_{\text{fan}} = 40 \rightarrow$$

$$\Delta P_{\text{fan}} = 40 - [593.26 - (\rho_{\text{SC}} \cdot g \cdot H_{\text{SC}} + \Delta P_{\text{SC, loss}})] \rightarrow$$

$$\Delta P_{\text{fan}} = 40 - (593.26 - \Delta P_{\text{SC, total}}) \quad \text{(A3.6)}$$

The value for $\Delta P_{\text{SC, total}}$ can be derived directly from the output quantities of $P_{\text{out}}$ and $P_{\text{fan}}$, by:

$$\Delta P_{\text{SC, total}} = |P_{\text{out}} - P_{\text{fan}}| \quad \text{(A3.7)}$$

Indeed the value of $P_{\text{fan}}$ is calculated in ESP-r so that for every simulation step:

$$P_{\text{in}} + P_{\text{fan}} + \rho_{\text{SC}} \cdot g \cdot H_{\text{SC}} + \Delta P_{\text{SC, loss}} = P_{\text{out}} \quad \text{(A3.8)}$$

Since $P_{\text{in}}$ is fixed at 0 [Pa] (see Table 1) then Eq. (8) becomes:

$$\rho_{\text{SC}} \cdot g \cdot H_{\text{SC}} + \Delta P_{\text{SC, loss}} = -\Delta P_{\text{SC, total}} = P_{\text{out}} - P_{\text{fan}} \quad \text{(A3.9)}$$

The value of the right hand-side term in Eqn. (A3.9) is negative, therefore the absolute value is used in Eq. (A3.6) since the minus is placed as an operator.

In case the quantity inside the parenthesis of Eq. (4.10) results to be negative, i.e. $\Delta P_{\text{SC, total}} > 593.26$, then the fan will need to induce a pressure difference higher than 40 [Pa] to ventilate the building and the presence of the SC does not contribute to any fan energy savings; in case the quantity results to be positive, i.e. $593.26 > \Delta P_{\text{SC, total}}$, then the SC compensates for some of the required pressure difference needed to ventilate the building, which results in fan energy savings.

According to Eqn. (A3.6) the hourly fan savings in terms of pressure difference account to the quantity inside the parenthesis, i.e.:

$$\Delta P_{\text{fan, savings}} = (593.26 - \Delta P_{\text{SC, total}}) \quad \text{[Pa]} \quad \text{(A3.10)}$$

In case $\Delta P_{\text{fan, savings}}$ results negative (no savings), the value of zero is assigned to the parameter instead. In case $\Delta P_{\text{fan, savings}}$ is positive then the fan savings are:

$$E_{\text{fan savings, hour}} = (V \cdot \Delta P_{\text{fan, savings}}) / \eta \quad \text{[Wh]} \quad \text{(A3.11)}$$

where:

$V$: the volume flow rate induced by the fan, constant and equal to 32.66 [m$^3$/s]
\( \eta \): the performance of the fan, equal to 0.65 [-]

For every sample the fan energy savings output variable is the sum for the 3132 hours of the hourly fan savings, derived from Eq. (A3.11).

Eq. (4.10) can be used to calculate the number of hours for which the fan can be shut down, which in this case would be when \( \Delta P_{\text{fan}} \) results negative, or when

\[
(593.26 - \Delta P_{\text{SC, total}}) > 40 \ [\text{Pa}]
\]  

(A3.12)