The computational optimization of heat exchange efficiency in stack chimneys
Graduation project for the
Sustainable Energy
Technology Master Program

Department of the Built
Environment
Group of Building Physics and
Services

Den Dolech 2, 5612 AZ
Eindhoven
P.O. Box 513, 5600 MB
Eindhoven
The Netherlands
www.tue.nl

Author
Ing. T.A.J. van Goch

Date
February 7th, 2011 (v1.1)

The computational
optimization of heat
exchange efficiency in
stack chimneys

Photo: Eindhoven University of Technology CERES stack chimney (2011)

Where innovation starts
Abstract

For many industrial processes, the chimney is the final step before hot fumes, with high thermal energy content, are discharged into the atmosphere. Tapping into this energy and utilizing it for heating or cooling applications, could improve sustainability, efficiency and/or reduce operational costs. Alternatively, an unused chimney, like the monumental chimney at the Eindhoven University of Technology, could serve as an “energy channeler” once more; it can enhance free cooling by exploiting the stack effect.

This study aims to identify design parameters that influence annual heat exchange in such stack chimney applications and optimize these parameters for specific scenarios to maximize the performance. Performance is defined by annual heat exchange, system efficiency and costs. The energy required for the water pump as compared to the energy exchanged, defines the system efficiency, which is expressed in an efficiency coefficient (EC). This study is an example of applying building performance simulation (BPS) tools for decision support in the early phase of the design process. In this study, BPS tools are used to provide design guidance, performance evaluation and optimization. A general method for optimization of simulation models will be studied, and applied in two case studies with different applications (heating/cooling), namely;

CERES case: “Eindhoven University of Technology monumental stack chimney equipped with a heat exchanger, rejects heat to load the cold source of the aquifer system on the campus of the university and/or provides free cooling to the CERES building.”

Industrial case: “Heat exchanger in an industrial stack chimney, which recoups heat for use in e.g. absorption cooling.”

The main research question, addressing the concerns of both cases, is expressed as follows:

“what is the optimal set of design parameters so heat exchange in stack chimneys is optimized annually for the cases in which a stack chimney heat exchanger is used for heating or cooling applications, what is the expected performance and how do the design parameters relate to this performance?”

Simulation models were developed in the BPS tool ESP-r. The most important design parameters and their relative influence on the performance indicators were analysed based on sensitivity analysis (SA). From this analysis general design guidelines were derived (“optimal set of design parameters”). A multi objective optimization of the design parameters was performed on the simulation models, using the responsive surface methods and artificial neural network capabilities of optimization environment ModECntier to speed up the iteration process. In this optimization, “heat exchange in stack chimneys is optimized annually”. The uncertainty in the optimized results has been analysed using uncertainty analysis (UA). Finally, the appropriateness of deploying a complex, high resolution simulation has been evaluated by studying current modelling resolution selection methodology found in literature.
It has been found that methodologies to support the selection of the appropriate modelling resolution are sensitive to UA parameter range selection, for which there are few guidelines. It should be noted that ‘more complex’ models/tools do not necessarily lead to ‘better’ results due to unknown bias effects, which may contain influences masked by increased modelling resolution/complexity. The value of increasing modelling resolution is therefore questionable, in particular in case of a non-calibrated/ non-validated models like the simulation models used in this study.

From the SA, the following can be concluded for the CERES case: the controlled outlet water flow temperature, and heat exchanger geometry have a large influence on the annual heat exchange. A balance exists between flow resistance posed by the heat exchanger and the heat exchanger area, there should be emphasis on reducing flow resistance rather than increasing the area. The system efficiency depends mainly on water flow temperatures while costs are only depending on heat exchanger geometry. From the optimization it can be concluded that, in order to reach an optimal design (minimizing costs, maximizing annual heat exchange), the inter-plate spacing of a flat plate heat exchanger and the controlled outlet water flow temperature should be maximized while minimizing plate width (thus minimize heat exchanger face area). Also, the heat exchanger should be positioned at the bottom of the chimney.

The system efficiency is high for the scenario in which the aquifer system is loaded, the total annual heat exchange capacity is however low in respect to the capacity required to thermally balance the aquifer system annually. It is more effective to use the monumental stack chimney heat exchanger to provide free cooling for the CERES building than to load the aquifer. Annual heat exchange is higher in the former case; it may meet the total annual cooling demand for the CERES building. At times when free cooling is not used, the aquifer can be loaded. Finally, it was found that wind is of high influence on the annual heat exchange; the addition of a roof designed to optimize the utilization of wind pressure may greatly improve heat exchange performance.

It is concluded that the monumental stack chimney on the Eindhoven University of Technology campus could be reused as sustainable cooling enhancement, in particular for providing free cooling to the CERES building. Other monumental stack chimneys may be employed for similar applications, a way to bring new life to industrial monuments.

The annual heat exchange in the industrial case chimney, from which heat is recouped, is mainly governed by the minimum mass flow required to evacuate flue gases, which is not a design parameter in this study. The main design parameters of influence are the geometrical attributes of the heat exchanger affecting the flow resistance, and heat exchanger position. Optimizing designs parameters to reach maximum annual heat exchange while minimizing costs, resulted in a large annual heat exchange capacity with a high EC. Since a (large) change in ambient temperature does not have a large impact on the heat exchange, the system not susceptible to external conditions, the high heat exchange capacity is available throughout the year. To reach optimal performance, one should choose a short length heat exchanger, with high inter-plate spacing and minimal plate width. The heat exchanger should be located high in the chimney, reducing the ‘cold column’ above the heat exchanger. Finally, the minimum allowable flue flow should be as low as possible. Using (industrial)chimneys to increase energy efficiency, may add to the sustainability of industries and/or buildings by the deploying existing structures for a new purpose.
# Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area</td>
<td>m²</td>
</tr>
<tr>
<td>Cr</td>
<td>Heat capacity rate</td>
<td>J/kg K s</td>
</tr>
<tr>
<td>C</td>
<td>(local dynamic) Loss factor</td>
<td>-</td>
</tr>
<tr>
<td>(c_p)</td>
<td>Specific thermal capacity (constant pressure)</td>
<td>J/kg K</td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
<td>M</td>
</tr>
<tr>
<td>E</td>
<td>Effectiveness (heat exchanger)</td>
<td>-</td>
</tr>
<tr>
<td>f</td>
<td>Friction coefficient</td>
<td>-</td>
</tr>
<tr>
<td>Fs</td>
<td>Statistical significance</td>
<td>-</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational acceleration</td>
<td>m/s²</td>
</tr>
<tr>
<td>h</td>
<td>Height of heat exchanger in stack chimney</td>
<td>m</td>
</tr>
<tr>
<td>h\text{conv}</td>
<td>Convective heat transfer coefficient</td>
<td>J/s m² K</td>
</tr>
<tr>
<td>k</td>
<td>Thermal conductivity</td>
<td>J/s K m</td>
</tr>
<tr>
<td>L</td>
<td>Characteristic length</td>
<td>m</td>
</tr>
<tr>
<td>(\dot{m})</td>
<td>Mass flow</td>
<td>kg/s</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>(\dot{Q})</td>
<td>(thermal) Energy /s</td>
<td>J/s (W)</td>
</tr>
<tr>
<td>Q</td>
<td>(thermal) Energy</td>
<td>J (Wh)</td>
</tr>
<tr>
<td>R</td>
<td>Heat resistance</td>
<td>m² K s / J</td>
</tr>
<tr>
<td>R²</td>
<td>Coefficient of determination</td>
<td>-</td>
</tr>
<tr>
<td>(r_{pec})</td>
<td>Pearson correlation coefficient</td>
<td>-</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
<td>-</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>K - °C</td>
</tr>
<tr>
<td>U</td>
<td>Heat transfer coefficient</td>
<td>J/s m² K</td>
</tr>
<tr>
<td>V</td>
<td>Volume flow</td>
<td>m³/s</td>
</tr>
<tr>
<td>v</td>
<td>Velocity</td>
<td>-</td>
</tr>
<tr>
<td>Yi</td>
<td>Simplified model resulting indicator</td>
<td>-</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Thermal diffusivity</td>
<td>m²/s</td>
</tr>
<tr>
<td>(\beta)</td>
<td>Linear regression coefficient</td>
<td>-</td>
</tr>
<tr>
<td>(\epsilon)</td>
<td>Absolute error</td>
<td>-</td>
</tr>
<tr>
<td>(\Delta)</td>
<td>Discretization</td>
<td>-</td>
</tr>
<tr>
<td>(\eta)</td>
<td>Efficiency</td>
<td>-</td>
</tr>
<tr>
<td>(\rho)</td>
<td>Density</td>
<td>kg/m³</td>
</tr>
<tr>
<td>(\rho_{src})</td>
<td>Spearman coefficient</td>
<td>-</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>Standard deviation</td>
<td>-</td>
</tr>
<tr>
<td>(\bar{\mu})</td>
<td>Mean of (result) set</td>
<td>-</td>
</tr>
</tbody>
</table>
General subscripts

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ex</td>
<td>Exchanged</td>
</tr>
<tr>
<td>h</td>
<td>Hydraulic-</td>
</tr>
<tr>
<td>he</td>
<td>Heat exchanger</td>
</tr>
<tr>
<td>i</td>
<td>i-th case</td>
</tr>
<tr>
<td>in</td>
<td>Inlet-</td>
</tr>
<tr>
<td>min</td>
<td>Minimum</td>
</tr>
<tr>
<td>max</td>
<td>Maximum</td>
</tr>
<tr>
<td>out</td>
<td>Outlet-</td>
</tr>
<tr>
<td>rs</td>
<td>Result Set</td>
</tr>
<tr>
<td>sc</td>
<td>Stack Chimney</td>
</tr>
<tr>
<td>var</td>
<td>Variation(s)</td>
</tr>
</tbody>
</table>
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFN</td>
<td>Airflow Network</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
</tr>
<tr>
<td>BES</td>
<td>Building Energy Simulation</td>
</tr>
<tr>
<td>BPS</td>
<td>Building Performance Simulation</td>
</tr>
<tr>
<td>CERES</td>
<td>Centraal Energie en Regelstrrating (Central energy and control station)</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>EC</td>
<td>Efficiency Coefficient</td>
</tr>
<tr>
<td>EER</td>
<td>Energy Efficiency Ratio</td>
</tr>
<tr>
<td>LHC</td>
<td>Latin Hyper Cube</td>
</tr>
<tr>
<td>MOO</td>
<td>Multi Objective Optimization</td>
</tr>
<tr>
<td>(F)MOGA</td>
<td>(Fast) Multi Objective Genetic Algorithm</td>
</tr>
<tr>
<td>NTU</td>
<td>Number of Transfer Units</td>
</tr>
<tr>
<td>PASW</td>
<td>Predictive Analytics Software</td>
</tr>
<tr>
<td>PLN</td>
<td>Plant Network</td>
</tr>
<tr>
<td>PPP</td>
<td>People, Planet, Profit</td>
</tr>
<tr>
<td>RSM</td>
<td>Responsive Surface Method(s)</td>
</tr>
<tr>
<td>SA</td>
<td>Sensitivity Analysis</td>
</tr>
<tr>
<td>TU/e</td>
<td>Eindhoven University of Technology (abbreviated in the style of the university)</td>
</tr>
<tr>
<td>UA</td>
<td>Uncertainty Analysis</td>
</tr>
</tbody>
</table>
Glossary

Some of the terms used in this thesis are introduced here.

Design case  
A set of input parameters which describe the stack chimney heat exchanger system and is used as simulation input. Every consecutive simulation run is based on a different design case.

Design guidance  
Architects, engineers, and project managers can improve the performance and quality of their buildings by following the recommendations provided concluded from the analysis of the relative importance of parameters for the performance indicators, trend found in optimizations, performance evaluation and uncertainty analysis.

Effectiveness  
The effectiveness indicated ‘how well’ a resource (e.g. energy) is employed / contributes to reach to a specified goal. A process can be highly efficient, but not very effective.

Efficiency  
In this study, efficiency is the ratio between required water pump energy versus the heat exchanged in the heat exchanger (from water to air). In general efficiency means maximizing result while minimizing expense.

Input (design) parameter(s)  
Parameter which serves as input for ESP-r simulations. The input parameters specify modelling parameters such as wind pressure coefficients and chimney geometry. A design parameter specifies designable system aspects such as heat exchanger geometries.

Modelling complexity  
Refers to tool complexity, influencing required user level/experience, the required (physical) detail in input parameters and physics details in the results (result interpretation).

Modelling resolution  
Refers to the level of detail in calculation, domain discretization and input/output parameters (detail and number of effects accounted for)

Spearman coefficient  
In statistics, the Pearson product-moment correlation coefficient is a measure of the correlation (linear dependence) between two variables $X$ and $Y$, giving a value between $+1$ and $-1$. The Spearman coefficient ($\rho_{SPE}$) basically the same but computed on the ranked matrices.
Acknowledgments

This thesis is the result of a year of work for the graduation project of the master Sustainable Energy Technology with the specialization “Energy in the built Environment” at the faculty of the Built Environment (unit: Building- Physics and Services) at the Eindhoven University of Technology and in collaboration with consulting engineering company Deerns.

During the project I realized at several stages that the world of (building) simulation is like playing Pac-Man: eat one bite-size chuck at a time, do not miss a chuck, avoid the ghosts and accept that there is a confusing tunnel which brings you back to the start. While simulation capabilities grow, reality isn’t easily caught in matrices, and simulating reality remains a game of understanding reality, simplification and requirements. The exploration of different methods and models was time consuming, but very educative. This is also true for the time I spend on getting a grip on ESP-r, which tends to be an unforgiving environment. The combination of ESP-r modelling problems, and the exploration different strategies and tools, together with my other work for the university slowed the graduation process. Eventually, this thesis only embodies a part of the struggles and work performed. However, looking back, I can conclude that this was one of the most valuable periods in my study in which I learned from mistakes and had the opportunity to work with a many inspiring people.

First of all, I want to thank Prof. dr. Ir. J. Hensen (1st supervisor) for providing inspiration and his support not only in my graduation project, but also in my current and future work for the university. I also want to express my gratitude for dr. Dipl.-Ing. Marija Trcka, my 2nd supervisor for her support during difficult phases in the graduation process, I learned a lot from your questions and guidance. I also like to thank Bruno Lee, MSc, my daily supervisor for his guidance, chats and discussions.

I like to thank Deerns, and my colleagues there, for the opportunity to work in collaboration. In particular Ir. Ivo van Kessel who was my supervisor, for providing guidance, comments and support. Also a word of thanks for Paul Stoelinga, supporting me from Deerns Rijswijk.

Special words of thanks for Dr. Daniel Costola, with whom I’ve been working on the ‘earth wind and fire’ project for the university, for all his guidance, inspiring words and support throughout my graduation.

Finally I’d like to thank everyone at the unit BPS, and all my fellow students with who I attended classes and projects in the last years. In particular Jeroen van Hellenberg-Huber, my roommates and close friends for their support during graduation and study as a whole. Finally, this thesis was not possible without the support and love of my girlfriend Moniek van Erp.

ing. T.A.J. van Goch
Eindhoven, 20-01-2012
# Contents

Abstract i  
Nomenclature iii  
Abbreviations v  
Glossary vi  
Acknowledgments vii  

1. Introduction ................................................................. 1  
   1.1 Main research question 1  
   1.2 Background 2  
   1.3 Sustainability and literature 3  
   1.4 Use of BPS tools 4  
   1.5 SECe of research 5  
   1.6 This thesis 5  

2. Research methodology .................................................................. 6  
   2.1 Literature research 6  
   2.2 Modelling resolution 6  
   2.3 Simulation model development 8  
   2.4 Sensitivity analysis 8  
   2.4.1 Pre-Processing 9  
   2.4.2 Simulation 10  
   2.4.3 Post-Processing 10  
   2.5 Optimization 10  
   2.5.1 Optimizer / Solver 11  
   2.5.2 Initiation and pre-processing 11  
   2.5.3 Processing 12  
   2.5.4 Post-Processing 12  
   2.6 Uncertainty analysis and generic uncertainty analysis 12  
   2.6.1 Uncertainty of optimized results 13  
   2.6.2 Generic model analysis 13  
   2.7 Reduced order models 13  

3. General modelling annotations ...................................................... 15  
   3.1 Stack effect 15  
   3.2 ESP-r modelling 15  
   3.3 Heat exchangers 16
3.3.1 Heat exchangers in ESP-r .................................................. 16
3.3.2 Calculation of heat exchanger properties ......................... 17
3.4 General model ........................................................................ 19

4. CERES case analysis .................................................................. 20
4.1 Eindhoven University of Technology aquifer System ............ 20
4.2 CERES case: background details .......................................... 20
  4.2.1 CERES case: stack chimney geometry and condition ........ 21
4.3 Ceres case: model ................................................................... 22
  4.3.1 CERES case: modelling assumptions ............................ 22
  4.3.2 CERES case: performance indicators ............................ 22
  4.3.3 CERES case: control .................................................... 23
4.4 CERES case: sensitivity analysis parameters ....................... 23
4.5 CERES case: sensitivity analysis results ............................... 24
4.6 CERES case: optimization ..................................................... 26
4.7 CERES case: integration of system in build environment ....... 28
4.8 CERES case: uncertainty analysis ......................................... 29
4.9 CERES case: generic model analysis ..................................... 31
4.10 CERES case: reduced order models ...................................... 32

5. Industrial case analysis ............................................................... 34
5.1 Industrial case: background details ........................................ 34
5.2 Industrial case: model ............................................................. 35
  5.2.1 Industrial case: modelling assumptions ......................... 35
  5.2.2 Industrial case: performance indicators ......................... 35
  5.2.3 Industrial case: control .................................................. 35
5.3 Industrial case: sensitivity analysis ......................................... 36
5.4 Industrial case: optimization ................................................ 38
5.5 Industrial case: Integration of system in build environment ...... 39
5.6 Industrial case: uncertainty analysis ....................................... 40
5.7 Industrial case: generic model analysis ................................. 41
5.8 Reduced order models .......................................................... 42

6. Discussion ................................................................................. 43
7. Conclusions ............................................................................... 45
8. Recommendations ...................................................................... 48
9. Future work ............................................................................... 49

References ................................................................................... 50
Appendices contents

Appendix A: ESP-r modelling 53
Appendix B: Excel model 59
Appendix C: Heat exchangers 64
Appendix D: modelling resolution 73
1. Introduction

For many industrial processes, the chimney is the final step before hot fumes, with high thermal energy content, are discharged into the atmosphere. Tapping into this energy and utilizing it for heating or cooling applications, could improve sustainability, efficiency and/or reduce operational costs. Alternatively, an unused chimney, like the monumental chimney at the Eindhoven University of Technology (TU/e), could serve as an “energy channeler” once more; it can enhance free cooling by exploiting the stack effect. This can be used for the cooling of buildings or for rejecting energy from the university’s ground heating system, which currently is unbalanced [2, 3] (referred to as “CERES case”).

The two applications described above are governed by the same principles describing the energy exchanges between chimney structure, the heat exchanger and air flow through the chimney. The stack effect and the heat exchange mechanisms are interlinked. By modelling heat transfer and airflow in the stack chimney which includes a heat exchanger, and by optimizing the design parameters, the annual heat exchange can be maximized/optimized for various applications such as heat extraction for use in plant heating/cooling, or as cooling enhancement. In this study, the effect of the system’s (design)parameters on the annual performance of a “stack chimney enhanced heat exchanger” will be identified through sensitivity analysis (SA) performed on a simulation model. Further, this study focuses on the optimization of the stack chimney heat exchanger design parameters for two cases described above (detailed case analysis, see sections 1.2, 4.2 and 5.1).

Ultimately, the results of these analyses will provide design guidance and performance evaluation. This study, may contribute to the sustainability of industries and/or (industrial) buildings energy efficiency by the employment of existing structures in a new context. Besides, the existing monumental stack chimney on the TU/e campus, other monumental stack chimneys may be employed for similar applications, saving monumental industrial buildings. Finally, this study provides an example of the use of building performance simulation (BPS) tools in early phases the design process for design support and performance evaluation.

1.1 Main research question

This study aims to identify the design parameters that influence annual heat transfer in stack chimneys and optimize those design parameters in two case studies with different applications. A general method for optimization of simulation models will be investigated, and applied to the two cases, namely:

**CERES case:** “Eindhoven University of Technology monumental stack chimney equipped with a heat exchanger, rejects heat, providing free cooling to load the cold source of the aquifer system on the campus of the university and/or the CERES building.”

**Industrial case:** “Heat exchanger in an industrial stack chimney, which recoups heat for use in e.g. absorption cooling.”
The main research question, addressing the concerns of both cases, is expressed as follows:

“what is the optimal set of design parameters so heat exchange in stack chimneys is optimized annually for the cases in which a stack chimney heat exchanger is used for heating or cooling applications, what is the expected performance and how do the design parameters relate to this performance?”

Performance is defined by annual heat exchange, system efficiency and costs (see section 4.3.2 for detailed definitions). The analyses of the relative importance of parameters (relations between parameters and performance indicators) and the optimization will lead to performance evaluation, design guidance and the evaluation of the value of applying stack chimney heat exchanger systems in the specific cases. Finally, the results of the analyses may allow for the creation of reduced order performance estimation tools which can be used to optimize design parameters and provide performance estimations for similar chimneys.

1.2 Background

Earlier this millennium, the TU/e was centrally heated by means of gas fired boilers. The building in which the heating installation was located is called CERES (“Central Energy and Regulation Station”). From 2005 onward, heating and cooling were decentralized (with support of a large aquifer system); the CERES building and the monumental stack chimney, lost their former function. However, the building will be retrofitted as part of the TU/e’s “Campus 2020” plan. The consulting engineering company Deerns designs the installations. The TU/e aims for high sustainability value (see section 1.3) and is interested in exploring a new purpose for the monumental stack chimney.

Currently the university aquifer system (estimated potential of 20 GWh) is unbalanced and additional exergy is loaded with cooling towers which consume electricity. As part of the renovation project of the CERES building, Deerns suggested to use the CERES stack chimney to enhance heat exchanger performance [2], the goal would be to provide cooling to the CERES building, prevent additional (annual) unbalance of the TU/e aquifer system and possibly load the aquifer system3. The stack chimney may contribute to the TU/e wide challenge to avoid unbalance in the aquifer caused by various buildings and facilities which require more cooling than heating, while providing a new innovative purpose for this monument. Finally, the aquifer system efficiency benefits from efficient aquifer loading techniques.

The industrial case provides a case in which heat is extracted from a stack chimney. The industrial case fits within the contours of the PhD project titled “sustainable energy producing steel frame industrial hall – advanced design support and assessment” of MSc. B. Lee, at the TU/e. The current project is partly derived from this research. The use of industrial waste heat, e.g. heat exiting an industrial stack chimney could improve the overall industrial building efficiency. The heat could be used as absorption cooling heat source, cooling the hall.

1 Translated from Dutch “Centraal energie en regelstation”
2 Term used for the potential energy of a system, mostly for the description of the potential for absorbing energy from the environment / cool the environment.
3 TU/e stated it is unacceptable to extract more cold energy than warm energy by the (new) CERES building.
1.3 Sustainability and literature

Buildings (utility, residential, and offices) are responsible for about 40% of the total energy consumption in first world countries [4]. Every newly constructed building is part of the environment for 70 years, or even more [5]. So, design decisions made now, have a long impact. Appropriate design strategies and using effective techniques are therefore of key importance for building (more) sustainable buildings.

Much literature is available on the topic “sustainable buildings”. Many of these articles focus on energy use (e.g. [6]), rating systems (e.g. [7]) or specific technologies (component level). Most research into sustainable constructions focuses on offices and residential buildings. It seems that relative little research effort is put in the field of sustainable industrial halls/constructions. Also, many papers addressing industrial zones (area-level), aim for inter-building integration, and “eco industry” (e.g.[8]). However, little research on the energy performance of individual (industrial) buildings has been identified (also see e.g. [9]).

Heat recovery is possible in many processes. Literature on the use of existing stack chimneys as cooling enhancement is limited, although new developments like solar chimneys, which is the topic of many studies, also utilize the stack effect for ventilation and/or the harvesting of thermal energy. Most research addressing heat exchanger performance is on component level, not on building level. Research in the field of industrial stack chimneys mainly focuses on structural and mechanical elements (e.g. oscillations in the structure provoked by wind). Stack chimneys are usually designed using trial and error methods and rules of thumb [10]. Negrão et. al. [10] concluded that simulation tools may contribute in optimizing natural draft in stack chimneys for industrial uses. In general, the following was concluded from literature analysis:

- limited literature is available on heat exchange in stack chimneys
- literature on heat recovery from stack chimneys is limited, in particular literature focussing on whole year performance simulations
- few studies have been found that focus on sustainability in industrial halls

The industrial case considered in this study concerns the optimization of heat exchange in an industrial stack chimney from which it may be possible to extract heat (recuperation). Generally, recuperation of heat is often used in industrial processes. In this study the specific application concerns an open, relative low pressure system. The recouping of heat could be used for improving either indoor climate in the industrial hall and/or upgrading process (resource) efficiency. The effect on sustainability can be related to the trial energetic concept which suggest to minimise energy use, use sustainable sources, and optimise the use of fossil fuels when the use is unavoidable [11].

Considering the CERES case, there are about 600 old (monumental) stack chimneys in the Netherlands [12] similar to the TU/e monumental stack chimney. The sustainability value of saving those chimneys by providing a new purpose are threefold and can be placed in the PPP concept (people, planet, profit)

---

More studies have been found, only examples are given in this section; other studies provide analysis and/or comparison based on management or economic backgrounds, focus on specific countries, or buildings.
framework [13]: saving of industrial/ cultural heritage and landmarks (people), a possibly energy efficient/ sustainable way to balance aquifer systems or to provide free cooling (planet), and a more cost effective solution opposed to demolishing chimneys and investing in additional heat pumps (profit). The optimizing aspect will ensure proper sizing and efficiency. A comparable value analysis could be performed for the use of stack chimneys (e.g. non-monumental, newly constructed) heat exchangers in general.

Summarizing the sustainability value of this study:

- Increasing the efficiency of current systems like the aquifer (increase efficiency by decreasing energetic costs of loading the aquifer), and/or providing free cooling for buildings.
- Reuse of monumental stack chimneys e.g. as sustainable cooling enhancements
- Improving industrial/domestic energy efficiency by heat recuperation.

1.4 Use of BPS tools

Usually, in the building industry, no prototypes are made to evaluate performance. Still, many decision need to be made in the early phase of the design process, in which building simulation plays an increasingly important role. In BPS, computer-based models that cover building performance aspects such as energy consumption and thermal comfort are used. Although BPS tools are becoming more powerful and capable, the use of BPS tools in the building design process remains limited [14, 15]. Practical applications of BPS tools (in building industry) are limited to thermal load calculations for sizing applications [15] and applications in which mould growth, thermal comfort, energy consumption and condensation issues are analysed [16] (mostly in post-design phases). BPS tools could however, be used for design support and analysis rather than mainly sizing and performance ‘prediction’ applications, BPS tools could provide relevant design information by indicating directions for design solutions or uncertainty [15] (design guidance).

Current problems for the use of BPS tools in the design process, as identified by e.g. de Wit [17] Hopfe [15], and Mirsadeghi [16] are the ability to deal with the tool requirements throughout the design process (modelling resolution / tool selection) and the interpretation of uncertainty in performance analysis. The uncertainty associated with performance simulations is usually high, as building behaviour is complex and user interactions are often unpredictable. Inaccurate simulation results, and lack of information about the uncertainty can lead to a poor design.

SA and uncertainty analysis (UA) methods can applied to investigate the uncertainty and inter-parameter relationships and relative importance of those parameters, which is particularly of interest in the early phase of the design process where design decision are made. The study of Hopfe [15] shows that BPS tools can successfully be used to get a better understanding of results, provide guidance throughout the design process and support the decision (e.g. by implementing SA, UA and multi-objective optimization techniques).

In this study BPS tools are used to evaluate the applicability and performance of a stack chimney heat exchanger in an early phase of the design process. The methods of optimising annual heat exchange in
stack chimneys are investigated and applied in two case studies. The current research is therefore also a case specific exercise in using BPS tools in the early phase of the design phases as decision support tools. Since this concerns non-validated, non-calibrated models, there is a focus on comparative research using SA and UA to explore the relative importance of design parameters and the methods in which this can be optimized.

1.5 Cost of research
This study focuses on buoyancy driven flows (stack effect). The study is limited to the two cases as described at the beginning of this chapter. Validation of the model through experiments is not pursuit. Furthermore, the research concentrated on the chimney heat exchanger system, coupled systems (like aquifers and building HVAC systems) will not be modelled. The existing models for heat exchangers available in the open-source simulation environment ESP-r (ESP-r, 11.11-6935, 2011) will be used in simulation. This BPS tool is selected in advance for its capability to handle (complex) airflow networks (AFN), building energy simulations (BES) and plant networks (PLT), providing whole year dynamic simulations of those systems (see section 3.2). Also, ESP-r was chosen for its open source nature (although the appropriateness of deploying a complex, high resolution simulation has been evaluated by studying current modelling resolution selection methodology found in literature exercise, see section 2.2). No additions to the native databases of ESP-r will be made however, the creation of new components (such as heat exchangers) is not a goal, rather; the research tools that are currently available are used.

Besides a general method for optimization of complex models used in the early phase of the design process, this study will provide a performance evaluation to explore the feasibility of incorporating heat exchangers in the evaluated cases/chimneys.

1.6 This thesis
The report is supported by appendices, including all calculation methods and background information. Appendices can be read independently of the report. After the introduction the general research methods and analyses used in this study are introduced in chapter 2. Necessary annotations about on the modelling process are included in chapter 3 in order to provide the required background details. The general methodology is applied to two distinct case studies which are presented in chapter 4 chapter 5. A discussion is included in chapter 6. Finally, conclusions and recommendations are presented in chapters 7 and 8 respectively, and future work annotations are included in chapter 9.

Abbreviations will be (re-)introduced every chapter for readability. A glossary including several important terms is also included.
2. Research methodology

The general research approach of this study is introduced in this chapter. The methodology used to study the optimization of heat exchange in stack chimneys, focussed on the two specific cases analysed in the current research will be introduced. The methodology is applicable for other stack chimney heat exchanger optimizations and the optimization of (complex) models in general. Design guidance is based on the results sensitivity analysis (SA), optimization and uncertainty analysis (UA).

The research methodology is included in figure 1 (below). In figure 1 the total research approach is included which will be explained further in this chapter.

![Figure 1: Research methodology (workflow) of this study, left to right.](image)

2.1 Literature research

Literature study is conducted to get insight in the different cases. Furthermore, previous research on the current topic (stack chimney heat exchange) and topics related to stack chimney heat exchange (e.g. solar chimney) is studied. General studies on the use of sensitivity analysis (SA), uncertainty analysis (UA) and optimization are used to provide the foundation for the current analysis. Furthermore, an analysis of heat exchangers is conducted, providing relations used in the current analysis (see section 3.3 and appendix C).

2.2 Modelling resolution

Many different building performance simulation (BPS) tools exist, using different approaches to model similar physical phenomena [16]. The accuracy required for the predations of different performance indicators depends on economic, technological and social constraints. The trade-off between modelling resolution, complexity and required performance is the subject of many studies (e.g. [1, 18-21]). The levels of resolution and complexity are directly related to the accuracy of the simulation and to the total cost of the simulation process [1]. In general, a more complex modelling tool provides a higher resolution although it requires more experience, time and input data. A more simple model may have higher
uncertainty, but is much faster to develop, requires less input variables and knowledge on physics. In current model resolution selection methodology, the hypothesis seems to be that higher resolution models provide ‘better’ results (decreased uncertainty, relevant parameters etc.) [1].

In this study, a resolution analysis is conducted only as an exercise to provide information on the value of selecting more complex modelling tools for non-validated, design support simulation, and provide insight into current resolution/tool selection methodology. Here, resolution refers to the level of detail in calculation, domain discretization and input/output parameters (detail and number of effects accounted for). Complexity refers to tool complexity (level of user required), the required (physical) detail in input parameters and physics details in the results (influences result interpretation).

For the exercise, a relative simple model (non-dynamic) is created, using analytical relations for the heat exchanger and stack effect found in literature [18-22] (see appendix B). The models performance is compared to a more complex/higher resolution simulation tool’s performance (BPS tool ESP-r). The models are compared using UA analysis (see section 2.6), to provide the range and uncertainty of each method for different sets of UA input data (also see [15]). Here, scenario and specification uncertainties are used to get information about the modelling- and numerical uncertainties [23]. The difference in relative importance of design parameters (in the different modelling approaches) is analysed using SA analysis (see section 2.4). Using this approach, the applicability of modelling selection methodology is explored.

The potential influences of e.g. numerical methods, uncertainty in input parameters, result analysis and modelling complexity, on the uncertainty are included in the modelling ‘bias’. Current methods do not include such bias effects in model performance judgements. In general, the effect of the modelling bias on uncertainty is partly unknown since it is difficult to estimate the effect of the bias. Many methods for selecting appropriate resolution (and complexity) are focused on evaluation of design goals, and the use of BPS tools are decision tools / design support tools, under the assumption that higher resolution models provide improved results [1, 18-21]. Given the (unknown) modelling bias however, this assumption is debatable. Modelling selection methods seem to be aimed at performance simulation only and not on the use of BPS tools for SA, UA and optimizations with ‘design guidance’ as result.

From the exercise (see appendix D), it was found that a more complex model does not necessarily provide ‘better results’, as various uncertainties may be part of the modelling bias and, as such, do not influence the UA results (e.g. convective heat transfer coefficients). The methods for evaluating the performance of different tools are sensitive to UA parameter selection and selected ranges (this is also noticed by de Wit [17]), for which there are few guidelines. In this study, in which a non-validated model is used, the value selecting a more complex/higher resolution tool is questionable.

ESP-r is however, still selected as main simulation tool in the current research. The lower order model would require additional development and testing and ESP-r was selected prior to this exercise (also see appendices A, B and D). ESP-r has superior handling of ambient conditions, and provides dynamic analysis. Results should however, be taken into account in future work.
2.3 Simulation model development

A general simulation model is developed capable of simulating both cases as described in the introduction (chapter 1), depending on the system boundary conditions and controls specified by the user. The building energy simulation (energy through building envelope and zones), (air)flow network (modelling of fluid energy transfer) and plant network (for heat exchanger modelling) capabilities of ESP-r (ESP-r, 11.11-6935, 2011, also see section 3.2) are combined to create a simulation model capable of simulating the system for a whole year. The simulation model will however not be calibrated/validated, as there is no experimental set up nor is there an existing system available. The use of the nodal approach (see section 3.2) provided by ESP-r is required to provide a relative short simulation time required to analyse many design options in optimization, SA or UA. Details about the heat exchanger included in the simulation model are included in chapter 1.

Performance indicator selection

The performance indicators are used to provide quantitative data from which to draw conclusions about the performance of the specific design. The performance indicators should therefore provide information on all aspects that specify the design, and they should be relate to the investigated parameters. The chosen performance indicators may depend on the simulation program capabilities (model resolution/complexity).

2.4 Sensitivity analysis

In the early phase of the design process, there are a lot of unknowns in the design. SA is performed to identify the, often complex, interaction between model input and the resulting output (in the form of performance indicators). Different stack chimney heat exchanger system designs cases will be simulated to relate input parameters to performance indicators. In general; the sensitivity of output parameters to input is studied to gain confidence in the model, improve the model and/or study the main parameters of influence on the performance indicators. In particular when considering airflow networks which are not calibrated and the when the simulation model is not validated, there will be a focus on the relative importance of design parameters rather than (only) absolute simulation results (which will have high uncertainties).

In this study, global SA methods are used (relative importance compared to other parameters). Procedures are based on Monte-Carlo like analysis [15] in which all parameters are changed simultaneously to analyse the global sensitivity. Important work in the field of SA has been performed by e.g. Hensen [24], de Wit [17], Hopfe [15] and MacDonald [25]. The full process for the SA in the current research is illustrated in figure 2, the following paragraphs will emphasise on the details of the SA method.

Opposed to global methods, local methods could be used in which one parameter is changed at a time, this can however only be done when the relation between parameter and output is known to be linear [2]. Other global analysis include the Morris analysis [10] and variance based methods [2].
2.4.1 Pre-Processing

In pre-processing, designs to be evaluated are sampled based on combination of design parameters.

Selecting design parameters

The main design parameters will be selected based on design specifications and research questions. Design parameters are parameters that are non-determined prior to the current research. The parameters may address the heat exchanger, boundary conditions (like water temperatures) and (other) designable conditions. The design parameters should be independent of each other (although this is not always possible).

Sampling

In order to reduce the required computing time and the amount of simulations required, statistical methods are applied to create samples in such a way that a good cross-section of the input sample variation is provided while minimizing the amount of simulations needed. Using Latin Hypercube Sampling (LHS), a good cover of multidimensional degrees of freedom can be provided [26], with a limited number of simulations. McKay et al. [27] state that LHS is better compared to traditional random sampling methods that just produce an ensemble of random numbers, which does not provide a guarantee that all parts of the input space were covered. The parameters are divided into intervals (over the sample range) of a probability depending on the selected distribution. Next, samples are selected randomly within the interval. In literature, it can be found that results change only marginally after 60 to 80 runs [15, 25]. In the current research, 80 runs are used.

Input file creation

Using Matlab, ESP-r input files (models) are created for every set of input parameters forming a design case and a script is created so ESP-r can simulate every design case automatically. The properties of the heat exchanger, such as flow resistance (governed by the local dynamic loss factor, \( C_w \)) and heat exchanger area, depend on the design parameters (e.g. heat exchanger length, plate width and inter-plate spacing). The heat exchanger properties are calculated before writing the Matlab files by a separate Matlab function prior to the file creation step (see figure 2).
2.4.2 Simulation
Simulation is performed in ESP-r. To avoid convergence problems, a short time step is required: time steps are 6 minutes and 1.5 minutes for the building/airflow (BES/AFN) simulations and plant simulations (PLN) respectively. The plant system uses shorter time steps to solve the flow equations in the whole flow network (5 components) before the next building/airflow step is taken.

2.4.3 Post-Processing
After simulation, hourly results for zone temperatures, air node temperatures, flow conditions and heat exchanger conditions are written in text files. Matlab is then used to calculate the performance indicators for each individual simulation. Results are analysed using Predictive Analytics Software (PASW, 2009) in which sensitivity analysis based on spearman coefficients is performed. Spearman coefficients ($\rho_{s}$) are used opposed to Pearson coefficients ($r_{pe}$) or linear regression coefficients ($\beta$) for their better handling of possible non-linearity [28]. Results are presented in diagrams indicating the relative importance of parameters (effect on the performance indicators) based on the spearman coefficient ($\rho_{s}$).

2.5 Optimization
Optimization is performed to get insight in the relation between different performance indicators, to optimize the design parameters, and to provide an optimized performance evaluation. An overview of optimization methods is presented by Hopfe [15] and Marler et. al. [29]. In the current case, multi objective optimization (MOO) is used to find the optimal trade-off between various performance indicators (e.g. costs and heat exchange). In MOO there is no single optimal solution, but a range of optima. These optimal results, named Pareto samples, form a Pareto front when plotted in a graph, the Pareto front indicates the collection of optimal solutions (also see [29]). Opposed to MOO, single objective optimization can be used to maximize a single performance indicator such as heat exchange. A design leading to such a maximum would however, also be included at the lower/higher boundaries of the Pareto front.

The optimization is performed for the parameters of influence on the performance indicators as is concluded from the SA. The optimization process is performed in ModEContier (ModEContier, 2011). ModEContier is an MOO optimization environment incorporating various optimizers and many post-processing options. ModEContier is however also used to control the whole process and to initialize ESP-r and Matlab automatically when required.

The optimization flow chart is included in figure 3. Several techniques are used to increase optimizer efficiency and speed namely: the use of artificial neural networks (ANN) and responsive surface methods (RSM), both included in ModEContier (see section 2.5.2 and 2.5.4 for details).
2.5.1 Optimizer / Solver

The selected optimizer is FMOGA-II (Fast- Multi- Objective Generic Algorithm). This optimizer is capable of performing efficient MOO on discrete or continuous input data see e.g. [30, 31]). The optimizer implements RSM (see e.g. [29, 30], and section 2.5.4) and ANN techniques (see section 2.5.2) to ensure the process is both efficient and fast. The number of required simulations depends on the optimiser, the amount of optimization parameters and their possible discretisation. RSM reduces the amount of required simulations and ANN reduces simulation time. Without these methods, optimization would take up to 3 weeks, including ANN and RSM, optimization takes about 48 hours (1600 samples, about 0.05% of the full result space). Recently, the applicability of meta models (e.g. ANN and RSM) in BPS, is demonstrated by Eisenhouwer et al. [32].

2.5.2 Initiation and pre-processing

The optimization process requires an initiation in form of an initial ‘seed’ and the training of the ANN.

Training of the artificial neural networks (ANN)

An ANN is a non-linear ‘black box’ method for calculation of results based on a combination of neural responses calculated from transfer functions and threshold functions weighted by training the ANN (see e.g. [33] for a good overview of ANN techniques). Before running the optimization, the ANN’s need to be trained. This is done by using previously obtained simulation results (e.g. from SA), or based on the first few iterations of the optimizer. For most parameters (in the current study), a training set of 100- 200 samples is sufficient to provide a good fit of ANN output to the training data (coefficient of determination, $R^2 < 10^{-5}$). After this training phase, the user may select the balance between ‘normal simulation’ (using ESP-r) and the use of ANN. Here, 50% is chosen. Although ANN’s are quite accurate (see section 4.10), the results are only valid within the range of the training set. If input to the ANN is outside the training data range, results get less accurate and may even be unfeasible (negative costs ed.). The ANN samples are therefore named ‘virtual’ samples which provide the optimizer with more information on the response to certain designs so iteration is more efficient (also see section 2.5.4). Analysis of the results is however, only be based on real samples (simulated cases).
Pre-Processing of heat exchanger properties
The pre-processing is similar to the pre-processing in the SA (see section 2.4.1) An initial input database will be used to provide a ‘seed’ (consisting of LHS sampled design cases) for optimization. The ‘seed’ is loaded as input database.

2.5.3 Processing
In optimizing, processing is seen as the simulation of a specific stack chimney heat exchanger system design (the whole phase after the initiation is basically ‘optimization processing’). Depending on the settings of the solver, a sample will either be simulated using ESP-r, or the results will be calculated using the ANN.

2.5.4 Post–Processing
Post processing of the samples is in three stages; the calculation of the performance indicators, the analysis of results in the result database (RSM), and the interpretation of results.

Post – Processing of simulation results
Simulation results are processed using Matlab to calculate the performance indicators (similar to post-processing in SA, see section 2.4.3).

Responsive surface method (RSM)
In order to provide efficient optimization (fast convergence towards the Pareto front), the FMOGA-II optimizer incorporates RSM (see e.g. [29-31, 34] for details). Results from the result database will be analysed to provide information about the response to input parameters. Fitting models are created automatically using different fitting techniques (e.g. ANN, Generic logarithms, Linear fitting etc.) based on all available results (at that moment) and the best method is selected (minimising $R^2$). Next, new design cases are being suggested and analysed using the fitting functions based on the gradients of the input parameter/result relations. Designs which are likely to lead to Pareto improvement are selected and provided as input for a new optimization round using ESP-r or the ANN’s. In the current optimization case, 20 samples are included per RSM iteration during which new design cases are being suggested.

Optimization results interpretation
After 1600 runs (800 real, 800 virtual), the Pareto front is analysed. Only ‘real’ simulated samples are considered for Pareto analysis. Samples on this line are seen as optimized designs. The design data can be analysed and optimal sets can be extracted. One could, for example, consider an analogy with electric engineering in which e.g. filters are usually ‘cut off’ at -3/6db of the original signal strength, to point out a single optimal result if desired. The optimal design is however depending on the wishes of the client and design constrains. Besides optimal sets of design data, also trends in design parameter are analysed.

2.6 Uncertainty analysis and generic uncertainty analysis
UA is used to determine the uncertainty of the result. Important work in this field is conducted by e.g. de Wit [17, 23] and Hopfe [15]. De Wit [17] identified four main types of uncertainties: numerical (calculation method), scenario (control, climate), specification (design parameters) and modelling (assumptions).
De Wit points out UA should be used building performance simulation since it aids the design process. The sensitivity of the results to simulation parameters other than the design parameters is analysed, here the main focus will be on modelling and scenario uncertainties (in the resolution analysis, numerical and modelling assumptions are investigated, see appendix D). In the current study Monte-Carlo like analyses is used for analysis which delivers a good view of the UA with limited runs compared to e.g. the crude UA analysis posed by Morris, 1991 [35]. The UA incorporates much of the same techniques as in SA (see section 2.4), only keeping the design parameters constant while varying the non-design parameters (e.g. wind pressure coefficient).

2.6.1 Uncertainty of optimized results

Uncertainty analysis is used to compare the performance of different models (also see section 2.5), and to provide inside in the uncertainty of the optimized results. Uncertainty parameters are selected based on modelling uncertainties, physical uncertainties and literature (e.g. de Wit [17], which states that airflow network parameters and thermal stratification are the important sources of uncertainty). In the case studies, geometries etc. are fixed, since the case studies concern existing buildings, the geometrical aspects are thus not included in the uncertainty analysis. UA results will be presented diagrams indicating the spearman coefficient ($\rho_{sp}$), so the input parameters range can be related to relative importance. More important however, the average ($\mu_{th}$) and standard deviation ($\sigma_{th}$) of the run will be presented to evaluate uncertainty in the results.

2.6.2 Generic model analysis

Here, an exercise designed to find if the conclusions of the current SA analysis, which provide design guidance, are also applicable to other stack chimneys with different dimensions is referred to as generic uncertainty analysis (response and relative importance of parameters for other geometries). Here, the design parameters and parameters describing the stack chimney geometry are varied. The effect of this variation on the conclusions about the relative importance of design parameters is analysed to find if current conclusions may apply to other chimneys. When the relative influence of design parameters changes for instance, it may be concluded that additional research in the relative importance of design parameters for different chimney geometries is required to be able to provide design guidance for all stack chimney heat exchanger system design processes (independent of geometry).

2.7 Reduced order models

Reduced order models can be created using the SA data. These models can be used to calculate the expected heat exchange (or other performance indicator) for specific input of design parameters without use of the simulation tool. Such tools can be used by design engineers, architects and constructors to estimate performance, based on scientific research performed by engineers. Reduced order models will be based on linear regression and ANN networks (for the sake of comparison and validation of ANN performance, as a comparable techniques is used in optimization).

For the purpose of creating a reduced order, linear model, linear regression is applied to the results to create a model which evaluates the performance (indicator) based on a linear combination of the input
parameters. The regression model thus assumes that there is a linear relationship between the dependent variable and each predictor. This relationship is described in the following linear equation (equation 1) [28]:

$$Y_i = \beta_0 + \sum_{j=1}^{p} \beta_j X_{i,j} + \varepsilon_i$$  

(1)

In equation 1, $Y_i$ is the resulting performance indicator value of the $i$th case of the dependent scale variable, $p$ is the number of predictors, $\beta_j$ is the value of the $j$th coefficient (linear regression coefficient), $X_{i,j}$ is the value of the $i$th case of the $j$th predictor and $\varepsilon_i$ is the error in the observed value for the $i$th case. The coefficient of determination ($R^2$) of the linear regression, quantifies how well the linear model fits the simulation results and is thus a measure of how well future outcomes are likely to be predicted by the linear regression model. In addition, the error observed in each prediction ($\varepsilon_i$) is evaluated, considering the mean error ($\bar{\varepsilon}$) and the standard deviation of the errors ($\sigma_{\varepsilon}$). Based on $\bar{\varepsilon}$ and $\sigma_{\varepsilon}$, confidence intervals for the linear regression results were derived. Only significant statistical measures ($F > 0.01$) are included in the regression model.

PSAW software can be used to generate ANN’s, the used can select functions and number of ANN layers, however, here PSAW will automatically generate the models. The performance of ANN’s will be compared with the performance of the linear models in order to evaluate ANN performance and the potential of using ANN in optimization and SA in combination with BPS tools by a limited exercise designed for proving the applicability of ANN in the current research.
3. General modelling annotations

In the general research methodology (chapter 2), the modelling process is described in a conceptual manner. General modelling annotations are introduced in this chapter, as clarification of various modelling choices/assumptions.

3.1 Stack effect

The ‘stack effect’ describes the movement of air in buildings, chimneys, flue gas stacks, driven by buoyancy. Buoyancy occurs due to differences in air density resulting from temperature differences. Only the part above the heat exchanger contributes to the stack effect. Larger temperature differences lead to higher air velocities (increased stack pressure) and to increased heat exchange in the heat exchanger. When a heat exchanger is introduced however, air experiences a flow resistance described in the local dynamic loss factors $C_{de}$ (the extend is e.g. depending on the heat exchanger geometry). Increased air velocities, lead to increased flow resistance which affects air volume flow.

Several parameters that may affect stack chimney performance are noted in other researches (mainly addressing solar chimneys). There are several cases in which the effect of wind (pressure) on chimney performance is studied, all studies indicate that performance is very much dependant on the wind [36, 37]. Studies suggest that wind force should be used to overcome flow resistances [38]. Kazansky et. al. [39] conclude that chimney height affects airflow while Bassiouny et. al. [40] conclude that the inlet size and shape have a large influence (affecting flow resistance). For solar chimneys, the convective heat transfer coefficient ($h_{conv}$ in W/m²K) can have a large influence depending on the chosen performance indicators. In recent studies at the Eindhoven University of Technology (TU/e) [41, 42] the influence of the $h_{conv}$ value on the performance indicators (and modelling resolution) is low, while a large influence on performance is also reported (e.g. [43]). This indicates that the relative importance of input parameters depends on the definition of performance (indicators). In general also heat storage in the structure, pressure losses related to friction along the walls of the chimney and in the heat exchanger could affect chimney heat exchange. The importance of the flow resistances and convective regime is also noticed in resolution selection methodologies (see e.g. [16] and appendix D). Most of these parameters are included in the sensitivity analysis (SA) or uncertainty analysis (UA), see sections 4.8 and 5.6 (and appendix C).

3.2 ESP-r modelling

A model is created which describes the chimney and the heat exchanger. Airflow and heat exchange analysis can be based on computational fluid dynamics (CFD) techniques in which the conservation equations for mass, momentum and thermal energy are solved for all nodes of a two- or three dimensional grids. CFD provides high resolution analysis, however, it requires vast computational resources, and the inclusion of dynamic boundary conditions is not very advanced [44]. In nodal network flow methods (alternatively), buildings and fluid flow systems are treated of networks of zones, and system components. The assumption is made that for each type of connection there exists an unambiguous relationship between
flow through the component and pressure difference [37]. In the latter method, large(r) domains, under influence of dynamic boundary conditions, can be considered for long periods (e.g. a year).

A simulation environment in which annual performance simulation can be performed (using the nodal approach) is ESP-r. ESP-r is an open source simulation tool under constant development since the 1970s. In ESP-r the airflow and thermal models are simulated in a nodal network which iterates towards a balanced pressure/temperature distribution for every time step. Mass and energy conservation equations are established for each finite volume and solved simultaneously⁶. In this method the conductive, convective, fluid flow (pressures), radiation and heat storage processes are explicitly modelled as the system responds to climate boundary conditions. The model is build up from and building energy simulation (BES) component, airflow network (AFN) component and a plant network (PLT) describing energy transfer in zones and trough the building envelope, inter-zone air flow and energy flow though building system components respectively.

3.3 Heat exchangers

There are as many different heat exchangers as there are studies analysing their interaction with fluids. The heat exchanger temperature and airflow domain are interlinked, and governed by heat transfer and flow resistance. Analytical descriptions for the heat transfer and flow dynamics have been derived for many types of heat exchangers often based on experiments and (or) CFD analysis.

Various types of heat exchangers are available. There are only a few types of heat exchangers which are suitable for use in the stack chimney. An air/water heat exchanger will be used. It is hypothesized that the main design considerations for the heat exchanger are:

- Low flow resistance (low head loss)
- High heat exchange at relatively low temperature differences

In the current research a counter flow plate heat exchanger is chosen as heat exchanger model. Not only is this a typical air/water heat exchanger which can account for low flow resistance at relative high $h_{conv}$ values, a model of this type of heat exchanger is also available in ESP-r.

3.3.1 Heat exchangers in ESP-r

The current ESP-r plant (-component) database includes heat exchanger plant components. In this study, the air heating coil (type 50/110)⁷ will be used as heat exchanger, it resembles a plate heat exchanger and may also represent some similar designs depending on the design parameters (see appendix C and sections 4.4 and 5.3). ESP-r uses the ‘number of transfer units’ (NTU) method together with a linear $h_{conv}$ relation

---

⁶ More information on ESP-r calculation methods can be found [14]
⁷ The type 50/110 heat exchanger is used which is a 3 node model (1 air node, 1 water node and 1 construction node). Water/air heat exchanger models are scares in ESP-r, and the only other heat exchanger plant component was less stable.
(depending on velocity) \[45\] to calculate the heat exchange between heat exchanger and air, the relation is included in equation 2.

\[ h_{\text{conv}} = 38 \cdot \bar{V}_{\text{local}} \]  

In equation 2, \( \bar{V}_{\text{local}} \) is the average local velocity in the heat exchanger (m/s), which depends on the ‘free flow area’. The “38” value is a linear constant (J/m³ K). In reality, the convective heat transfer coefficient is a complex variable, depending on (local) flow domain. The linear model of the convective heat transfer, as used in ESP-r, might not perform well in for the whole velocity range (see appendix C), but the equation cannot be edited, for the evaluation of different heat exchanger designs (without changing the source code), which would have been more convenient.

### 3.3.2 Calculation of heat exchanger properties

The design parameters for the heat exchanger are provided by the user (e.g. heat exchange surface area, flow resistance etc.). The \( h_{\text{conv}} \) calculation method is hardcoded, and can therefore not be altered without re-compiling the code. Properties like the heat exchanger flow resistance and heat exchanger area \( (A_{\text{he}}) \) be adjusted\(^8\). In order to relate the heat exchanger design parameters to the flow resistance described by local loss factors\(^9\), (also see appendix C), an investigation was performed in the relation between design parameters, local dynamic loss factors in the heat exchangers \( (C_{\text{he}}) \) and \( A_{\text{he}} \) for flat plate heat exchangers (see appendix C and figure 5). This analysis is performed to provide realistic heat exchanger properties depending on design parameters.

\( C_{\text{he}} \) values are based on the analysis of local flow regimes and depend on the face area of the heat exchanger (see figure 4), which is the heat exchanger area perpendicular to the flow. The plate width and inter-plate spacing determine the number of available plates (it is assumed that the maximum number of plates is applied), providing the heat exchange face area and the flow area’s hydraulic diameter \( (D_h) \). The inter-plate spacing, plate width and heat exchanger length influence the \( C_{\text{he}} \) values, mainly by their influence on the local velocity and face area (which provides the balance between ‘free flow area’ and ‘heat exchanger’ flow area’s). \( A_{\text{he}} \) is determined by the number of plates (heat exchanger face area), and the heat exchanger length. The equations for the calculation of \( C_{\text{he}} \) and \( A_{\text{he}} \) are presented in equations 3 and 4.

In equation 3, \( \frac{A_1}{A_2} \) is the ratio between ‘free flow area’ and ‘heat exchanger flow area’ and \( f(\text{Re}) \) is the friction coefficient, which depends on the Reynolds number, the length of the heat exchanger \( L \) (m) and the hydraulic diameter \( D_h \) (m).

\[ C_{\text{he}} = \left(1 - \frac{A_1}{A_2}\right)^2 + \left(1 - \frac{A_2}{A_4}\right)^2 + \frac{[f(\text{Re}) \frac{D_h}{A_2} \text{low } v + f(\text{Re}) \frac{D_h}{A_4} \text{high } v]}{2} \]  

---

\(^8\) When an airflow network is included (coupled), the airflow network is used for calculation of flow resistance which implies that a local dynamic loss should be included at the heat exchanger location, the assigned value can be chosen freely.

\(^9\) Flow resistance, leading to head losses, is governed by \( \Delta P = C_f \rho v^2 \)
\[ Area_{he} = \frac{D_{sc}}{(Width+Space)} \cdot (\frac{\pi}{4} \cdot D_{sc}) \cdot 2L \] (4)

In equation 4, \( D_{sc} \) is the stack chimney diameter (m), width is the heat exchanger plate width (m) and space is the inter-plate spacing (free flow slits) of the heat exchanger (m) and \( L \) is the heat exchanger length (m). As an example, the relation between \( A_{he} \) and \( C_{he} \) is shown in figure 5.

In order to take into account for possible variations in heat exchanger designs and their behaviour, the influence of the expected variations in \( A_{he} \) and \( C_{he} \) are included in the uncertainty analysis (UA) by investigating these properties for various heat exchanger types (see sections 2.6, 4.8 and 5.6). The variations are based on the analysis of the behaviour of hole type-, cross-flow-, straight plate- and circular plate heat exchangers and literature. The full analysis of flow regimes and resulting \( C_{he} \) values and \( A_{he} \) values, is included in appendix C, and presented in table 1. Notice that equation 4 only applies for flat plate heat exchangers, other calculations methods have been used for the various investigated heat exchanger types, this leads to possible variations \( (\sigma_{var}) \) from the properties for flat plate heat exchangers calculated here (see figure 5).

**Table 1: Standard deviations of heat exchanger properties due to possible variations in heat exchanger design. These deviations are taken into account in uncertainty analysis.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>One standard deviation ( (\sigma_{var}) ) due to possible variation for different heat exchanger designs.</th>
<th>Governed by design parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local dynamic loss factor ( (C_{he}) )</td>
<td>10.3</td>
<td>Inter-plate spacing, plate width, heat exchanger length</td>
</tr>
<tr>
<td>Area ( (A_{he}) )</td>
<td>178 m²</td>
<td></td>
</tr>
</tbody>
</table>

![Diagram of heat exchanger design parameters](image)

![Graph showing variations in area and heat exchange efficiency](image)
3.4 General model

The general model consists of PLN, AFN and BES components. A schematic representation of the models is provided in figure 6. In figure 6, the PLN system is included on the left side, including all components. The AFN is included, together with the BES network, on the right side, illustrating the nodes being connected with flow components. Notice that the (air/water) flow through the plant system is also calculated with the AFN network using the ‘w’ nodes and water pump used to feed water to the heat exchanger, this is illustrated on the right side. Boundary nodes are unfilled, while nodes connected to the BES simulation are black. (air)Flow nodes are connected by components (blocks).

![Diagram](image)

Figure 6: Schematic representation of ESP-r simulation model. The plant system (components) are included on the left side, while the (air)flow network is presented, together with the chimney zones, on the right side. In the simulation, the plant system, airflow network and building energy simulation (zones) are coupled.
4. CERES case analysis

This chapter presents the case study for the CERES case, in which a monumental stack chimney is used as free cooling enhancement for aquifer loading and/or free cooling applications. The case background (details) are presented as well as case specific modelling annotations (performance indicators, assumptions, design parameters etc.). The (optimization) research methodologies are applied (see chapter 2) leading to insight in the main design parameters, optimized results and uncertainty. Finally, the conclusions about the potential and integration of the stack chimney heat exchanger in the build environment are presented.

4.1 Eindhoven University of Technology aquifer System

From 2005 onward, the Eindhoven University of Technology (TU/e) has access to a large aquifer system. The total (potential) capacity is estimated to be about 20GWh, which makes it one of the largest aquifer systems in the Netherlands [3]. The aquifer system consists of warm and cold sources, which store thermal energy in the ground. The warm sources are approximately 13-15 °C, the cold sources are approximately 8-12 °C. Water can be extracted from e.g. the cold source, ran through a heat exchanger (absorbing heat from the building) and be injected in the warm sources where the heat is stored for use in winter.

Aquifer systems have to be thermally balanced annually, which means that heat removed in the winter has to be re-injected during the summer and vice versa. However, the TU/e requires more cooling than heating, which lead to unbalances in the system. The aquifer system needs to be ‘loaded’, which essentially means cooling down the cold sources. Currently, the system is balanced by three cooling towers, which load the cold source during winter. Still, the unbalance is about 8.2% (2005-2009) [3]. About 4 GWh of extra heat needs to be rejected from the aquifer system annually. The water input temperature for the cold source is designed to be 6.5 °C but is allowed to be 8°C at maximum (this means that there is a requirement for outlet water temperatures for the stack chimney heat exchanger as well; outlet water temperatures should be <8°C).

The total system has a coefficient of performance (COP) of about 15 (delivered heating + delivered cooling – cooling tower injection compared to required energy for the cooling tower and pumps), or: 1 Joule of energy is invested for every 15 Joules of heat/coolness extracted. This COP includes the electricity consumption of the sources pumps and cooling towers (which is about 600-800MWh a year)\(^\text{10}\). The cooling towers have a COP between 5 and 22 based on an energy consumption of 200-800MWh/yr (detailed energy consumption specifications were unavailable).

4.2 CERES case: background details

One of the design questions in the CERES case is whether the TU/e aquifer system could be loaded using a monumental stack chimney, and if the stack chimney can be used to supply the new CERES building with

\(^{10}\) More information on the TU/e aquifer system is publicly available via energy reports [2].
free cooling. Using the stack chimney, energy costs of the current system could be reduced (cooling towers). The aquifer can only be loaded at outdoor temperatures below 8°C, since this is the maximum water temperature that is allowed to be injected in the cold sources. In other temperature ‘slots’ the chimney can be used for free cooling or other heat rejection purposes.

The new design for the retrofitted CERES building features large glazed areas allowing a large amount of daylight into the building (also see section 1.2). The drawback of the large glazed surfaces, which are mainly orientated south, is that overheating may occur even when ambient temperatures are relatively low. Initial estimations, indicate that the building may overheat at ambient temperatures of 14-16 °C when direct solar irradiation is high. It is estimated that about 45-50 MWh of cooling energy is required annually at times when the outdoor temperature is between 12-16 °C [46]. Furthermore, the new CERES building will feature a (limited) lab facility, which requires cooling throughout the year. Annually, the total required cooling is estimated to be about 300 MWh. For ‘free cooling’ purposes, it is assumed that warm water from the building, needs to be cooled to 19 °C. At temperatures above 19 °C, there is no potential for free cooling. However, there is still potential to use the chimney for cooling higher heat qualities (e.g. from 55 to 45 °C) such as a heat pump, enhancing heat pump EC. Proposed operating modes for the ‘stack chimney heat exchanger’ for various temperature scenarios are included in table 2.

### Table 2: CERES case scenario’s

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Ambient ‘slot’ °C</th>
<th>Heat exchanger water in- and output temperatures °C</th>
<th>Description of anticipated use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquifer loading</td>
<td>&lt; 8</td>
<td>Water in: 10-15 Water out: 2-8</td>
<td>Loading of the TU/e aquifer system Water from aquifer (cold source) is directly pumped through heat exchanger</td>
</tr>
<tr>
<td>Free Cooling</td>
<td>8-19</td>
<td>Water in: 20-25 Water out: max. 12 -19*</td>
<td>Providing free cooling for CERES building When required, free cooling can be delivered directly to the CERES building</td>
</tr>
<tr>
<td>Heat Rejection</td>
<td>19 +</td>
<td>Water in: 50-60 Water out: 40-45</td>
<td>Enhancing heat pump performance by rejecting condenser heat The condenser side of the heat exchanger can be cooled, adding to EC.</td>
</tr>
</tbody>
</table>

* depending on particular application (e.g. climate ceilings, floor cooling, fan coils etc.)

4.2.1 CERES case: stack chimney geometry and condition

Geometrical characteristics of the CERES monumental stack chimney are included in table 3. Values are approximate since drawings of the monumental stack chimney were unavailable, instead, drawings of a comparable (age and size) chimney were used [52].
The chimney is in good condition (concluded from annual inspection), and is ventilated to reduce the moisture levels. Moisture is interacting with the sulphur, residue from burning processes, which affects the wall. An estimated 1100kg/year has to be removed [47]. It is expected that moisture will not be a problem in the proposed new task as the air (which is heated and can thus contain more moisture compared to ambient air) will remove the moisture. However, currently the chimney is protected from rain, liquid water has a negative influence on the structure and possibly on flow, this is something that should be considered in heat exchange design since any ‘covering solution’ has influence on the (air) flow.

### 4.3 CERES case: model

Case specific modelling annotations are presented in this section as a compliment to general annotations presented in chapter 3).

#### 4.3.1 CERES case: modelling assumptions

Apart from the temperature requirements, there are some further assumptions made in the CERES case analysis. It is assumed that the aquifer is very large, to such extend that heat exchanger inlet water flow temperatures are constant throughout the year. To further support this assumption; one may imagine water begin pumped from one side of the aquifer and injected 2 km away (in a different cold source). Given the system size, this is seen as a reasonable assumption.

#### 4.3.2 CERES case: performance indicators

The performance indicators chosen for this case reflect performance in terms of system efficiency, absolute exchangeable heat and relative economic value. This implicates that the annual exchanger heat (\(Q_{\text{ex}}\)), efficiency coefficient (EC), and costs are investigated. The performance indicators are calculated in post-processing using equations 5, 6 and 7. In equation 5, \(\dot{Q}_{\text{ex}}\) is the exchanged energy per hour (W), \(C_{\text{p,water}}\) is the water heat capacity (J/kg), \(\dot{m}\) the water mass flow (kg/s), \(T_{\text{water in}}\) and \(T_{\text{water out}}\) are the in- and outlet water flow temperatures (K). In equation 6, \(\Delta P_{\text{new}}\) is the pressure difference over the water side of the heat exchanger (Pa), \(\dot{m}\) is the water mass flow (kg/s), \(\eta\) is the pumping efficiency (assumed to be 0.65), \(\rho\) is water density (kg/m³), \(g\) is the gravitational acceleration (m/s²) and \(\dot{Q}_{\text{ex}}\) is the heat exchanged (per evaluated time step). \(Q_{\text{ex}}\) relates to the energy required for the water pump.

<table>
<thead>
<tr>
<th>Geometric attribute</th>
<th>Value (approximate, based on CERES monumental stack chimney) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>± 67</td>
</tr>
<tr>
<td>Diameter of shaft (bottom)</td>
<td>± 2.8</td>
</tr>
<tr>
<td>Diameter of shaft (top)</td>
<td>± 2.3</td>
</tr>
<tr>
<td>Outside diameter (bottom)</td>
<td>± 5.50</td>
</tr>
<tr>
<td>Outside diameter (top)</td>
<td>± 2.70</td>
</tr>
<tr>
<td>Average wall thickness</td>
<td>± 0.54</td>
</tr>
</tbody>
</table>
\[ Q_{he} = \sum Q_{ex} = C_{p,\text{water}} \cdot m \cdot (T_{\text{water in}} - T_{\text{water out}}) \]  

(5)

Efficiency coefficient \( = \frac{Q_{he}}{(\frac{\Delta P_{\text{he, W}}}{\eta P} + \rho gh \cdot m)} \) = \( \frac{q_{\text{out}}}{q_{\text{in}}} \) 

(6)

Costs = \( (A_{he} \cdot \text{Plate Width} \cdot \rho_{\text{steel}} \cdot \epsilon_{\text{steel/kg}}) + 100 \cdot h \) 

(7)

Notice that the costs (equation 7) is an indicative / conceptual parameter designed to provide a measure (for comparing designs), not to represent real system costs since this is difficult to estimate (this would include fabrication and installation costs, on top of material cost). The heat exchanger position is included in the measure, since higher position may require a larger pumping system. However, since it has been found that most industrial pumps deliver a head of 35m easily, provided that the flow is 3.6 m³/hr, the relative influence of the position is quite low. In equation 7, \( A_{he} \) is the heat exchanger area (m²), plate width (m) is the width of plates in a flat plate heat exchanger, \( \rho_{\text{steel}} \) is the density of steel (kg/m³), \( h \) is the height of the heat exchangers in the stack chimney (m). \( \epsilon_{\text{steel/kg}} \) is the price of steel per kilogram.

In the evaluation of cooling tower, the energy efficiency ratio (EER) is often used instead of EC. Here, the specifically defined EC is used instead to relate the system to heating, ventilation and air conditioning (HVAC) systems, since this relates to performance indicators often used in BPS tools.

4.3.3 CERES case: control

The control is based on a specified water temperature at the exit of the heat exchanger (see section 4.2). This control strategy is chosen based on the scenarios (see table 2) since this is a requirement (particularly in scenario A). The temperature is controlled by actuating the water mass flow through the heat exchanger. If the temperature requirement is met, flow is increased (more heat can be exchanged\(^{11}\)).

4.4 CERES case: sensitivity analysis parameters

The design parameters for the sensitivity analysis (SA) focus on system boundaries (in-outlet water flow temperatures) and heat exchanger geometric aspects. An overview of design parameters and ranges is included in table 4. The values are sampled uniformly, but not continuously (this decreases optimization time), the steps are included in table 4 as discretisation steps (\( \Delta \)).

The heat exchanger position is the position of the heat exchanger in the chimney (h). Since zones are 5 m high, the discretization depends on the zone in which the heat exchanger is placed. Inlet water flow temperature is the temperature of the water which is to be cooled (from aquifer source, or building). Taking water from the hot source implies an input temperature of about 13-16 degrees °C, water from the

\(^{11}\) In ESP-r modelling: water outlet temperature is measured in the air flow network (AFN), the water pump in the is actuated.
Cold source implies input temperatures of about 10 °C while cooling water from a building implies higher inlet water flow temperatures. Since a flat plate heat exchanger is chosen as heat exchanger model, heat exchanger inter-plate spacing, plate width and length have been chosen as design parameters instead of general attributes (e.g. face area, flow resistance etc.), these provide realistic and feasible design cases (also see the discussion, chapter 6). The heat exchanger length is based on a realistic heat exchanger set up, as are inter-plate spacing and plate width. From these parameters, the \( C_{he} \), \( A_{he} \) and face area can be derived (see equations 3 and 4). The relative importance of the design parameters and derived parameters on the performance indicators is investigated leading to design guidance.

Table 4: Design parameters included in the CERES case sensitivity analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range (for specific scenario)</th>
<th>Distribution</th>
<th>Discretisation (( \Delta ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat exchanger position</td>
<td>0 – 35 m</td>
<td>Uniform</td>
<td>5 m</td>
</tr>
<tr>
<td>Inlet water flow temperature</td>
<td>10 – 20 °C, 20-25 °C, 60-80 °C</td>
<td>Uniform</td>
<td>0.1</td>
</tr>
<tr>
<td>Outlet water flow temperature</td>
<td>2 – 9 °C, 10-15 °C, 40-60 °C</td>
<td>Uniform</td>
<td>0.1 °C</td>
</tr>
<tr>
<td>Heat exchanger length</td>
<td>0.5 – 7 m</td>
<td>Uniform</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Heat exchanger plate width</td>
<td>0.01 – 0.15 m</td>
<td>Uniform</td>
<td>0.0045 m</td>
</tr>
<tr>
<td>Heat exchanger inter-plate spacing</td>
<td>0.01 – 0.15 m</td>
<td>Uniform</td>
<td>0.0045 m</td>
</tr>
</tbody>
</table>

Al values are discretised to reduce the number of possible combinations, which supports the LHC sampling method (see section 2.4.1) and later on, and in optimizing making it possible to find trends and relative importance, while intermediate values are insignificant. Uniform distributions are chosen for all design parameters, as every possibility is of equal probability.

4.5 CERES case: sensitivity analysis results

The results of the SA are presented in this section, concerning the relative importance of design parameters. The sensitivity analysis is performed separately for each scenario (see table 2). An overview of spearman coefficients (\( \rho_{src} \)) is included in figure 7.

The main parameter of influence is the water outlet flow temperature. The positive spearman coefficient indicates a positive relation with the heat exchange. At higher allowed outflow temperatures, the heat exchanger can be used during more hours of the year. Generally, degreasing flow resistance improved annual heat exchange (increase heat exchanger inter-plate spacing, decrease width). Increasing heat...
exchanger area ($A_{he}$) is only positive for the annual heat exchange for the aquifer loading case. A balance between $A_{he}$ and flow resistance ($C_{he}$) exists. Since also the flow resistance is influenced by increasing area the inverse relation in higher temperature scenarios might be the result of the increased velocity in the higher temperature scenarios, leading to increased dependence on the $C_{he}$ value. In the case of heat rejection, an increase in inter-plate spacing does lead to decreased annual heat exchange, indicating that at those stack pressures, the area may increase leading to increased flow resistance, but the effect of increased heat exchange is larger. The lengths has a positive influence on the heat exchange, however, the relative influence is low, an increase in width leads to an increase in flow resistance, but the impact on $A_{he}$ is limited compared to an increase or decrease in either plate width or inter-plate spacing (also see table 5).

![Heat exchange results](image)

Figure 7: Spearman coefficients ($\rho_{arc}$) for CERES case heat exchange, providing insight in the relative importance of parameters for all scenario’s (see table 2).

Finally, the heat exchanger should be placed at the bottom of the chimney, leading to maximum stack effect (only part above the heat exchanger contribute to the stack effect). It was hypothesized that heat loss through the construction might influence the heat exchange, leading to reduced volume flow (and $Q_{he}$) when locating the heat exchanger at the bottom. The results contradict this hypothesis, the average temperature of the air column above the heat exchanger is higher than the ambient temperature, and heat loss though the construction is of relative low importance.

Results for the EC are included in figure 9. Increased temperature differences clearly lead to a higher EC. The other parameters seem not very significant. Although the pressure difference over the water side of the heat exchanger would decrease for increasing width, heat exchange would also decrease, leaving the EC unaffected (also see section 4.3.2 for calculation methods). One parameter shows an unexplained reaction however, increasing the heat exchanger position, should lead to decreased EC, which does not show in the results, the statistical significance of this result is however low ($F >> .01$), indicating the result might be the result of random chance.
The results for the system costs are included in figure 8. The length has the largest influence on the system costs. The plate width, which partly determines the amount of steel in the heat exchanger shows a negative influence (increased in width leads to decrease in costs), an increasing width leads to reduced area (see table 5). Overall, it is clear that increased area leads to increased system costs. This is trivial, since this performance indicator is calculated using input (design) parameters only. This parameter is however of greater importance for the optimization.

Table 5: Resulting heat exchanger surface area for different plate widths (for constant inter-plate spacing and heat exchanger length)

<table>
<thead>
<tr>
<th>Inter-plate spacing fixed at 0.055m, length = 1m</th>
<th>0.01</th>
<th>0.05</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate width (m):</td>
<td>0.01</td>
<td>0.05</td>
<td>0.1</td>
</tr>
<tr>
<td>$A_{\text{ex}}$ (m$^2$):</td>
<td>150</td>
<td>92.9</td>
<td>62.9</td>
</tr>
</tbody>
</table>

4.6 CERES case: optimization

The design parameters are optimized for aquifer loading (maximize) and costs (minimize), for the case in which the stack chimney heat exchanger is used to load the aquifer (as main application). The ranges presented in table 4 are used to produce the seed sample (see section 2.4.1). The inlet water flow temperature is fixed at 14 °C, since this is not a design choice in the current case. Results are presented in figure 10.

The Pareto front (see figure 10) indicates all the optimized results, the Pareto front is based on simulated cases only (‘real’ samples). A potential ‘single optimum’ could be specified based on the balance between cost and heat exchange, which could be about 72 MWh/yr in this case (-6db, considering an electrical analogy, see section 2.5.4). A true ‘optimum’ (or strong Pareto) result depends on the client choices. Table 6 includes the optimized design and performance indicators for each scenario (see table 2), for the 72MWh/yr
optimum based on the optimization of heat and costs in for the case in which the main use of the stack chimney heat exchanger is the loading of the aquifer. When one considers that the stack chimney heat exchanger cannot both load the aquifer system and provide free cooling for the CERES building simultaneously, the heat exchange potential for the stack chimney heat exchanger when used in a combination of scenarios emerges. This is also included in table 6.

![CERES optimizing result](image)

Figure 10: CERES optimization results for aquifer loading (including all samples, the Pareto front is marked).

<table>
<thead>
<tr>
<th>Scenario and results</th>
<th>Heat exchange (MWh/yr)</th>
<th>EC</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 8</td>
<td>72</td>
<td>103</td>
<td>Aquifer loading</td>
</tr>
<tr>
<td>8 – 19</td>
<td>143</td>
<td>151</td>
<td>Free cooling</td>
</tr>
<tr>
<td>&gt;19</td>
<td>79</td>
<td>233</td>
<td>Rejection</td>
</tr>
<tr>
<td>&lt; 19</td>
<td>541</td>
<td>166</td>
<td>Free cooling (only)</td>
</tr>
<tr>
<td>All</td>
<td>2275</td>
<td>350</td>
<td>Rejection (only)</td>
</tr>
</tbody>
</table>

Table 6: Optimized design for CERES case (single sample of Pareto front at 72 MWh/yr of aquifer loading).
The maximum heat exchange (ignoring the cost) can also be obtained using a simple optimizer where only heat exchange is maximized (single objective optimization). Results of this optimization underline the results presented in figure 10, the maximum heat exchange is about 80 MWh/yr, while design parameters were minimized/maximised according to SA results (see section 4.5).

4.7 CERES case: integration of system in build environment

The optimal capacity available for aquifer loading is about 72MWh/yr, and is included in table 6. This is about 5.4% of the capacity of a single cooling tower in the current system (about 1.8% of total capacity of the cooling tower). Using the system only (mainly) to load the aquifer thus seems to be ineffective. EC’s are however high compared to the cooling towers. Stack chimney heat exchanger EC is above 100 and ranging up to 400 in winter (compared to 5.25 – 22 for the cooling towers).

As can be seen in figure 11, heat exchange capacity decreases linearly with an increase in ambient air temperature for all scenarios: The airflow (kg/s), air temperature (°C), and water mass flow (kg/s) balance each other out to create this linear behaviour. The variance in heat exchange at a single ambient temperature are likely to be caused by wind effects.

![Heat exchange capacity graph](image)

*Figure 11: CERES case heat exchange capacity (power) as a function of the ambient temperature*

The potential for free cooling is 143MWh – 541 MWh/yr depending on the choice of use (aquifer loading and/or free cooling). This can be sufficient to provide the net CERES building with free cooling (see section 4.8 and chapter 6 for a discussion on this result). Cooling is available when temperature is below 19 °C. The stack chimney heat exchanger performance is illustrated in figures 12 and 13. As can be seen from figure 12 and figure 13, free cooling is not always available. In particular in summer, free cooling is only available during the night; buffering could be used. Cooling is required from an outside temperature of about 12 °C (sunny day), so for those moments free cooling is available (autumn and spring).
4.8 CERES case: uncertainty analysis

The uncertainty analysis (UA) is performed to get insight in the effect of modelling and scenario uncertainties. The parameters used in the UA are included in table 7. To account for various possible heat exchanger designs, standard deviation ($\sigma_{\text{vari}}$) from the calculated values for $A_{\text{hr}}$ and $C_{\text{hr}}$ are taken into account (see section 3.3.2 and appendix C)\(^2\), the deviation ($\sigma_{\text{var}}$) is sampled. The negative range is small compared to the positive range to prevent to many negative area and $C_{\text{hr}}$ values in the input sample (which would be unfeasable), the same holds for $A_{\text{hr}}$. The ‘control’ curve determines the water mass flow control setting used to maintain the outlet water flow temperature, increasing the control curve value leads to a more critical control.

The stack chimney height and diameter are uncertainties in the design, since the original drawings are unavailable, a drawing of a comparable monumental chimney is used and small deviation is size was used for the creation of the model. The uncertainties in height and diameter are distributed normal with a ($\sigma_{\text{var}}$) of 0.1 so the range is small. Other uncertainties are based on literature values (wall roughness, wind pressure, inlet resistance etc.).

The results for the uncertainty analysis are included in figure 14. Although the value of information on the relative importance of UA parameters is limited, the relation between input range and effect on the heat exchange can be analysed. For the heat exchanger loading, this shows that an increased wind pressure coefficient, leads to lower heat exchange while the input range is short compared to e.g. the area variation (also indicated by de Wit, 2001 [17]). When wind coefficient increases, the discharge from the chimney decreases, reducing airflow and annual heat exchange.

\(^2\) Properties are based on a flat plate heat exchanger, variations based on a study of various heat exchanger designs, included in Appendix C.
Table 7: CERES case uncertainty analysis parameters and ranges

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Distribution</th>
<th>Discretisation Δ / Standard deviation (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind pressure coefficient (Cₚₗ)</td>
<td>-2 – 2</td>
<td>Uniform</td>
<td>0.2</td>
</tr>
<tr>
<td>Inlet dynamic loss factor (Cₗₚₙ)</td>
<td>6 – 10</td>
<td>Uniform</td>
<td>0.5</td>
</tr>
<tr>
<td>Roughness</td>
<td>0.0001 m – 0.01m</td>
<td>Uniform</td>
<td>0.0001</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>0.1 – 1 m</td>
<td>Normal</td>
<td>0.05</td>
</tr>
<tr>
<td>Area variation (dAₘₙ)</td>
<td>-0.5 – 2</td>
<td>Normal</td>
<td>Continuous</td>
</tr>
<tr>
<td>Flow dynamic loss factor variation (dCₗₚₙ)</td>
<td>-0.5 – 2</td>
<td>Normal</td>
<td>Continuous</td>
</tr>
<tr>
<td>Height</td>
<td>66-68 m</td>
<td>Normal</td>
<td>0.1</td>
</tr>
<tr>
<td>Diameter</td>
<td>2.5 – 2.8 m</td>
<td>Normal</td>
<td>0.1</td>
</tr>
<tr>
<td>Maximum water flow rate</td>
<td>1.5 – 3 kg/s</td>
<td>Uniform</td>
<td>0.25</td>
</tr>
<tr>
<td>Control curve</td>
<td>0.5 – 2</td>
<td>Uniform</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The costs are not included in figure 14 since they only depend on SA parameters. The uncertainty can also be expressed as absolute value, indicating the uncertainty range. In figure 15, the uncertainty for 3 samples of the optimized results (see figure 10) is indicated for the case in which the stack chimney heat exchanger is used for aquifer loading. The standard deviation $\sigma$ and average value of the run ($\mu$) are presented. Uncertainty is quite large, one should however consider the non-calibrated, non-validated nature of this model, and wide range of uncertainty parameters that were chosen for this reason. The standard deviation of the uncertainty is also indicated and leads to the conclusion that one may say for example: ‘it is 67% certain that the result is within +-50% of 72MWh/yr’. Given the large influence of the wind, the stack effect may be enhanced by applying a rain cover in the form of a roof which will decrease wind coefficient possibly to about -1.3 for all angles [48, 49]. Such a wind pressure coefficient optimizing roof could have a large positive influence on the annual heat exchange, since wind has a large influence on results (also concluded by previous studies [37, 39, 50]). Furthermore, the chimney is protected from rain. Given the high dependence of the result on the wind coefficient, the total uncertainty is also mainly influenced by this parameter. Reducing the range of this parameter in UA analysis will greatly reduce the uncertainty.
The computational optimization of heat exchange efficiency in stack chimneys – MSc. Thesis

T.A.J. van Gocht, Eindhoven University of Technologies, unit Building Physics & Services

Version 1.1 07-02-2012

The computational optimization of heat exchange efficiency in stack chimneys – MSc. Thesis

T.A.J. van Gocht, Eindhoven University of Technologies, unit Building Physics & Services

Version 1.1 07-02-2012

4.9 CERES case: generic model analysis

Whether or not the conclusions about the main design parameters of importance are valid for all chimneys remains uncertain. An exercise in which various chimneys are investigated can give an indication if the conclusions about the relative influence of design parameters are also valid for other chimneys (referred to as ‘generic model analysis’), also see section 2.6.2. This analysis is only performed for the design parameter annual heat exchange, since costs only depend on design parameters and EC results depend on annual heat exchange (see section 4.3 for calculation methods). The parameters selected for generic uncertainty analysis are included in table 8. All parameters and ranges from table 7 are used, however, general geometrical parameter ranges differ so a large range of stack chimney heights and diameters is included. Ranges are based on a study of the monumental industrial stack chimneys stock in the Netherlands, as performed by STIF (foundation for the preservation of monumental chimneys) [12].

Figure 14: Uncertainty analysis results for CERES case (heat exchange and EC), spearman coefficients ($\rho_{arc}$)

Figure 15: Uncertainty analysis spread in results (ranges). The boxes indicate 1 standard deviation ($\sigma_{p2}$), the marked values are the optimized values ($\bar{p}$), see figure 10.
Results are included in figure 16; the relative influence of parameters may change for different chimneys. Heat exchanger inter-plate spacing and heat exchanger position have a higher rank compared to the SA analysis, indicating that for other chimney designs, these parameters might be more important. For chimneys smaller than the CERES stack chimney, the influence of \( C_{h} \) might be larger than the influence of the inlet water flow temperature, indicating that the relative importance of the flow resistance grows. Notice that the height and diameter themselves are much less important than the design parameters (which does not mean that the influence on the result is low, only relative to the design parameters). This exercise provides information about the importance of design parameters for other chimney designs, since the ‘rank of relative importance changes’, the conclusions about the influence of design parameters, and the trends in optimization are necessarily valid for all stack chimneys.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range (m)</th>
<th>Distribution</th>
<th>Discretisation (( \Delta ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>30-70</td>
<td>Uniform</td>
<td>1</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.5 - 3</td>
<td>Uniform</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Figure 16: Generic uncertainty analysis results (spearman coefficients \( \rho_{syr} \)).

4.10 CERES case: reduced order models

The reduced order (or ‘simplified’) models, based on linear regression coefficients (\( \beta_j \)), are capable of estimating the annual heat exchange (\( Q_{h} \)) of the stack chimney for the specific scenarios (see section 2.7), here the reduced order models for calculating aquifer loading performance are presented. The \( R^2 \) for the linear regression is provided with the reduced order models which express the relation between design parameters and performance indicators in a single equation (see equations 8, 9 and 10).
The computational optimization of heat exchange efficiency in stack chimneys – MSc. Thesis
T.A.J. van Goc, Eindhoven University of Technologies, unit Building Physics & Services

\[ Q_{he} = -27.3 - (0.236 \cdot He \ location) + (200 \cdot spacing) + (1.517 \cdot Win) + \\
(7 \cdot T_{outer\ water}) - (134 \cdot Plate \ width) \]

\[ R^2 = 0.67 \quad (8) \]

\[ EC = 452 - (3637.7 \cdot spacing) + (30.1 \cdot Win) - (87.5 \cdot Wout) \]

\[ R^2 = 0.45 \quad (9) \]

\[ Cost = 2.05 \cdot 10^4 + (506 \cdot He \ position) + (4 \cdot 10^3 \cdot Length) - (1.8 \cdot 10^5 \cdot \\
 spacing) - (1.75 \cdot 10^3 \cdot width) \]

\[ R^2 = 0.9 \quad (10) \]

The \( R^2 \) values are not very good (<0.9), an analysis of the mean absolute error (\( \varepsilon \)) shows an average absolute error for the heat exchange is 22.4 MWh/yr. These reduced order models only apply on the CERES stack chimney for two reasons: 1) height and diameter are not included as parameters in the simplified models and 2) since the generic UA analysis indicates that SA results may vary for other chimneys, further analysis is required before reduced order models can be derived for all stack chimneys.

For optimization, artificial neural networks (ANN) are used. An ANN is also a type of simplified model in the sense that output is directly calculated from design parameters instead of performing simulations (also see sections 2.5.2 and 2.7). Here the ANN for calculation of aquifer loading is compared to the linear model for aquifer loading (of the same set of 80 design cases). For the ANN, the variance in the result and the relative error is decreased, as is illustrated in figure 17. Although the ANN cannot be expressed as single analytical equation\(^\dagger\), the use of ANN in building design tools and as optimization tool, can be valuable (e.g. in optimization). The results illustrated in figure 17, provide support for the use of ANN as simplified modelling tool and in optimization. This result is also obtained in a recent (detailed) study focussing on this aspect, performed by Eisenhouwer, 2011 [32].

\[ \begin{array}{c}
\text{error Lin. Reg.} \\
\text{error ANN}
\end{array} \]

\[ \text{Relative error (%)} \]

\[ \text{No. of simulations} \]

\[ Q_{he} \]

\[ EC \]

\[ Cost \]

\[ R^2 \]

\[ (8) \]

\[ (9) \]

\[ (10) \]

\[ \dagger \quad \text{The analysis of ANN performance, structure and the provision of a trained ANN model is not part of this research.} \]

Figure 17: Comparison relative errors in the prediction of heat exchange using linear regression based simplified models and the use of an ANN.

CERES case analysis – page 33
5. **Industrial case analysis**

The industrial case provides an example of the optimization of heat recuperation from industrial stack chimneys. The case is applicable for processes where (non-destructive) flue gasses from high energy open systems (e.g. a melt), led directly to the chimney. The industrial case represents a situation in which heat is extracted from the chimney. In this chapter the industrial case will be introduced and analysed, applying method presented in chapter 2.

5.1 **Industrial case: background details**

Heat recovery is possible in practically every process. The most well-known examples are economisers in (steam cycle) power stations and combined heat and power (CHP) installations widely used in (for instance) the greenhouse industry. Mostly, the goal is to recuperate as much heat as possible before “used gasses” leave the chimney. In many processes, this is done before the flue is in the chimney, where it is easier to extract the energy (higher pressures, less heat loss and/or easier reinjection of the recouped heat in the process). However, in some cases this might not be possible as there is no “contact area” (in the form of piping etc.) between the process and the chimney.

Figure 18 presents such an open system schematically to give an impression of the situation which is subject of the current study. Several geometrical parameters are included in Table 9. In the industrial case, heat is rejected at high temperature from a ‘melt’ (open high temperature fluid) directly into a stack chimney. Besides the flue gas from the melt, ambient air is taken in at the chimney inlet. Gasses are evacuated with a 6,5 meter chimney through the roof.

![Diagram of industrial case](image)

*Figure 18: illustration of industrial case*
Table 9: geometric and flow conditions of industrial case

<table>
<thead>
<tr>
<th>Geometric attribute</th>
<th>Value (based on realistic case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of stack chimney</td>
<td>+ 6.5 m (about 0.5 m above roof)</td>
</tr>
<tr>
<td>Flue volume flow (from ‘melt’)</td>
<td>+ 2300 m³/hr</td>
</tr>
<tr>
<td>Diameter</td>
<td>+ 0.7 m</td>
</tr>
<tr>
<td>Inlet temperature (after mixing of flue from melt and ambient air at inlet)</td>
<td>+ 325 °C</td>
</tr>
</tbody>
</table>

In order to extract heat from this system, a heat exchanger needs to be installed in the existing chimney. If the required flow is reduced by (for example) reducing the amount of externally added air, temperatures (at the inlet) are higher while the required stack pressure is lower. Since heat is extracted from the system, air above the heat exchanger is cooler and therefore heavier opposed to the air at the inlet. This means a part of the stack effect / buoyancy is needed to ‘push’ out the relative cold air column, while a part of this force is required to overcome the flow resistance posed by the heat exchanger. This provides that there is a balance between minimum flow requirement, heat exchanger size and temperature above the heat exchanger. The current system is designed to evacuate the indicated flue flow volume, introducing a heat exchange will decrease the evaluated flue volume. It is hypostasised that the heat exchanger should have the lowest possible flow resistance with the highest possible heat exchange.

5.2 Industrial case: model

Modelling detail, specifics for the industrial case are presented in this section, as a compliment to general annotations presented in chapter 2.

5.2.1 Industrial case: modelling assumptions

For the industrial case, it is assumed that a minimum flow volume needs to be maintained. This minimum flow may be a design condition, however for the current study a minimum flow of 0.5 m³/s is assumed, this is a design requirement rather than a design parameter. Inlet flue gasses are at a constant temperature (see table 9). This is a simplification as inlet temperature could be depending on the amount of low temperature air taken in. The chimney is for 80% inside a building, the boundary condition is ‘constant temperature’ at 20 degrees °C. The upper part is exposed to outside conditions. The outlet water flow temperature is not controlled in this case.

5.2.2 Industrial case: performance indicators

The main performance indicators for the heat exchange in the industrial stack chimney are the same as for the CERES case. The performance indicators are expressed in equations 8, 9 and 10 (see section 4.3.2).

5.2.3 Industrial case: control

The model is controlled based on the minimum required flow. The minimum flow might not be reached because of two factors: a) heat exchanger geometric properties are such that the flow resistance is too high,
and/or b) so much heat is removed that the required volume flow cannot be maintained. In case of b), the water flow is decreased in order to remove less heat. The outlet temperature of the water is not controlled so the heat exchange is governed by airflow volume and water flow volume (also see chapter 6; discussion). The minimum flow is thus a restrain which has potentially a major influence on heat exchange. In post processing; when chimney flow is below the requirement, heat exchange ($Q_{ex}$) is set to 0 in post-processing.

5.3 Industrial case: sensitivity analysis

In the sensitivity analysis (SA), the relative influence of design parameters on the performance indicators is studied. An overview of design parameters and ranges is included in Table 10. The minimum flow is a modelling constrain rather than a design parameter. The maximum inlet water mass flow rate is included as this depends on the size of the water pump of the heat exchanger, and affects the maximum heat exchange while influencing the required energy to do so. The values are samples uniformly, but not continuously (decreases optimization time), the steps are included in table 10 as discretisation steps ($\Delta$).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Distribution</th>
<th>Discretisation ($\Delta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat exchanger position</td>
<td>0 – 9 m</td>
<td>Uniform</td>
<td>1 m</td>
</tr>
<tr>
<td>Water inlet temperature</td>
<td>18 - 25 °C</td>
<td>Uniform</td>
<td>0.1 °C</td>
</tr>
<tr>
<td>Maximum water flow</td>
<td>5 – 20 kg/s</td>
<td>Uniform</td>
<td>0.5 kg/s</td>
</tr>
<tr>
<td>Heat exchanger length</td>
<td>0.5 – 7 m</td>
<td>Uniform</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Heat exchanger plate width</td>
<td>0.01 – 0.1 m</td>
<td>Uniform</td>
<td>0.0045 m</td>
</tr>
<tr>
<td>Heat exchanger inter- plate spacing</td>
<td>0.01 – 0.1 m</td>
<td>Uniform</td>
<td>0.0045 m</td>
</tr>
</tbody>
</table>

In figure 19 the relative importance, expressed by spearman coefficients (see section 2.4), of the design parameters on the performance indicator annual exchanged heat ($Q_{ex}$) is presented.
The annual heat exchange mainly depends on the minimum required mass flow, a higher required mass flow limits the potential size of the heat exchanger (not included in figure 19, since this is not a design parameter). Higher flow resistances ($C_w$) lead to zero water mass flow and iteration problems in ESP-$\tau$, these results are discarded. The heat exchanger inter-plate spacing and plate width have the largest influence on the result for the; increasing space decreases flow resistance, while increasing width leads to the opposite effect. When the heat exchanger is located higher in the chimney, heat exchange increases, the influence of the cold column of air above the heat exchanger (which needs to be ‘pushed out’) decreases. The industrial case’s high velocity lead to a large dependence on the $C_w$ value, which also leads to the indication that increased area leads to decreased heat exchange, there exists a optimum between resistance and area in which area is minimized and annual heat exchange ($Q_{he}$) is maximized.

Figure 19: Spearman coefficients ($\rho_{sre}$) for industrial case heat exchange

Figure 20: Spearman coefficients ($\rho_{sre}$) for industrial case EC
In figure 21, the influence of design parameters on the efficiency coefficient (EC) is presented. Given the large dependence of this performance indicator on the annual exchanged heat, the main conclusions are similar to the influence of the design parameters on the annual heat exchange. For the costs (figure 20), the results are quite trivial: increased heat exchanger lengths and plate width lead to increased material costs while increased inter-plate spacing leads to a decrease in heat exchanger area ($A_{ax}$) and material costs which only depends on the design parameters. Again the same negative relation between heat exchanger plate width and total area is seen in the results (see section 4.5), but result do depend largely on $A_{ax}$.

5.4 Industrial case: optimization

Multi objective optimization (MOO) was performed on the industrial case, maximizing annual heat exchange would require to design the system based on the SA indications (maximizing positive parameters, minimizing negative parameter). Here, heat exchange should be maximized while minimizing cost. The resulting collection of optimized results (Pareto front) is included in figure 22. In figure 22, the heat removed from the stack chimney air is presented (negative values). As may be expected, an increase in heat exchange, requires an increased cost.

The maximum potential is about 4 GWh of annual heat exchange, while 3 GWh could be considered an optimum, as it is an approximate balance between heat exchange and costs (although all marks for the Pareto front are optimal). The 3 GWh/yr result can be translated to an average power of 342 kW. The absolute results for 3 locations on the Pareto front are included in table 11. In table 11, heat removed from the chimney is presented as negative value. The trends in design parameters is as may be expected from the SA: inter-plate spacing is maximized, while plate width is minimized. Heat exchanger length is relatively short (influences $C_{no}$), and heat exchanger position is average (both influence costs).

![Optimization of industrial case](image)

Figure 22: Optimization result for industrial case, including Pareto-front (based on real results only), negative heat exchange indicates heat recouping (heat removed from chimney)
Table 11: Optimized designs industrial case

<table>
<thead>
<tr>
<th>Position (m)</th>
<th>Length (m)</th>
<th>Inter-Plate spacing (m)</th>
<th>Water inlet temperature (°C)</th>
<th>Plate width (m)</th>
<th>Maximum water flow (kg/s)</th>
<th>Area (m²)</th>
<th>Derived Parameters</th>
<th>Heat exchange (Qₑ) in MWh/yr</th>
<th>EC</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.15</td>
<td>22.9</td>
<td>0.121</td>
<td>15</td>
<td>35</td>
<td>1</td>
<td>-1951.8</td>
<td>72</td>
<td>1289</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.15</td>
<td>18.7</td>
<td>0.07</td>
<td>11.5</td>
<td>43</td>
<td>0.5</td>
<td>-2993.8</td>
<td>126</td>
<td>1621</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0.15</td>
<td>22.9</td>
<td>0.02</td>
<td>11</td>
<td>59</td>
<td>0.5</td>
<td>-3931.8</td>
<td>154</td>
<td>1971</td>
</tr>
</tbody>
</table>

5.5 Industrial case: Integration of system in build environment

The system can provide heat constantly, which can then be used for heating/cooling of the industrial complex, or in the industrial process itself. The annual heat exchange capacity is illustrated in figure 23, for the optimized case of 3GWh annually. More heat can be exchanged in winter, however, in summer, heat exchange is still about 300 kW. In general, a large change in ambient temperature only has a small influence on the heat exchange capacity, the heat exchange (Qₑ) is therefore considered quite stable. The 300-400kW is available throughout the year. The heat can be used in the industrial process, the heating of nearby buildings and for the heating or cooling for the industrial building itself.

![Heat exchange capacity](image)

Figure 23: Annual heat exchange performance of industrial case (3GWh/yr design).
5.6 Industrial case: uncertainty analysis

The uncertainty in the result is analysed in an uncertainty analysis (UA). The parameters are included in table 12. Potential variations in heat exchanger designs are taken into account (see section 3.3.2 and appendix C) in the form of area variation and flow resistance variation ($\sigma_{\text{var}}$). The geometric attributes of the industrial case are not known in detail (only approximate values) so also height and diameter are included in the UA. The ‘control’ curve determines the water mass flow control setting used to maintain the outlet water flow temperature, increasing the control curve value leads to a more critical control.

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Range</th>
<th>Distribution</th>
<th>Discretisation $\Delta$ / Standard deviation ($\sigma_{\text{var}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet water flow temperature</td>
<td>250-350 °C</td>
<td>Uniform</td>
<td>1</td>
</tr>
<tr>
<td>Inlet local dynamic loss factor (Cw)</td>
<td>6-10</td>
<td>Uniform</td>
<td>1</td>
</tr>
<tr>
<td>Chimney wall thickness</td>
<td>0.4-0.7 m</td>
<td>Normal</td>
<td>0.05</td>
</tr>
<tr>
<td>Heat exchanger local dynamic loss factor (dCw)</td>
<td>-0.5-1.5</td>
<td>Normal</td>
<td>Continuous</td>
</tr>
<tr>
<td>Height</td>
<td>12-14.5 m</td>
<td>Uniform</td>
<td>0.5</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.5-1 m</td>
<td>Normal</td>
<td>0.1</td>
</tr>
<tr>
<td>Control curve</td>
<td>0.4-0.7</td>
<td>Uniform</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Figure 24: Spearman coefficients ($p_{\text{corr}}$) for industrial case uncertainty analysis
The relative influence of the UA parameters contains information about the relation between range of parameters and influence on the result and provides information about the system performance / relations (see figure 24). The small variation in diameter can have a large effect on the performance, as can the height (higher, wider chimneys means less influence of flow resistance for the same heat exchanger area). The resulting uncertainty in heat exchange is included in figure 25, where the UA range, standard deviation ($\sigma_{ua}$) and the average value of the run ($\mu$) are included. The standard deviation is about 25% of the simulated value. An optimized sample, e.g., the 3GWh case (green) is ‘67% certain to be within ± 500MWh, or 16% (1 standard deviation $\sigma_{ua}$) of -3000 MWh’. Uncertainty is large, this is as expected from a non-calibrated and non-validated model.

![Uncertainty optimized result](image)

Figure 25: industrial case uncertainty range, uncertainty of optimized results (see table 11) The boxes indicate 1 standard deviation ($\sigma_{ua}$), the marked values are the optimized values ($\mu$) (see figure 22).

### 5.7 Industrial case: generic model analysis

A generic UA is performed to check the applicability of the model on other systems/chimneys. An exercise in which various chimneys are investigated can give an indication if the conclusions about the relative influence of design parameters are also valid for other chimneys (referred to as ‘generic model analysis’). The input is the same as presented in table 10. However, diameter and height variations are increased to 0.5-3m and 7-20m respectively to include a broad spectrum of industrial stack chimneys. The relative influence of the different parameters is included in figure 26.

From the results, it is concluded that diameter and height have a high influence. Also, variation in area and heat exchanger resistance ($dC_a$ and $dA_h$) are important. As can concluded from figure 26, the relative importance has changed in comparison with the SA. For larger chimneys (height/diameter), the flow restrictions are met easier, and other parameters are more important in that case. This indicated that the current analysis is not valid for all chimneys, increased length (and) area have a larger (positive) effect on heat exchange.
5.8 Reduced order models

Reduced order models (simplified models) are related to the SA analysis (see 5.3). Linear regression models for calculation of the various performance parameters are presented in equations 14, 15 and 16. The $R^2$ values are below 0.9 for EC and costs. Here, an ANN might improve the result (see section 4.10). These reduced order models only apply on the industrial stack chimney for two reasons: 1) height, diameter and minimum flow resistance are not included as parameters in the reduced order models and 2) since the generic UA analysis indicates that SA results may vary for other chimneys, further analysis is required before simplified models can be derived for all stack chimneys.

\[
Q = -2363 - (190.7 \cdot \text{He position}) + (116.4 \cdot \text{Length}) - (57923.2 \cdot \text{Space}) + (67.293 \cdot \text{Win}) + (39018.5 \cdot \text{Width}) \quad \text{R}^2 = 0.68 \quad (11)
\]

\[
EC = -240.4 + (1741.5 \cdot \text{Space}) + (15.93 \cdot \text{Win}) - (2238.2 \cdot \text{Width}) \quad \text{R}^2 = 0.23 \quad (12)
\]

\[
\text{Cost} = -621.5 - (147833.54 \cdot \text{Space}) + (1028.8 \cdot \text{Length}) - (145495.9 \cdot \text{Width}) \quad \text{R}^2 = 0.94 \quad (13)
\]
6. Discussion

Several of the used research methods and results are discussed in this chapter, which include annotations about the results, performance indicators, modelling resolution and ESP-r. The full conclusions are presented in chapter 7.

### CERES case results
Results for the CERES case clearly show design trends from the sensitivity analyses (SA) and multi objective optimization (MOO), providing design guidance. In general there is a balance between flow resistance ($C_{he}$) and heat exchanger area ($A_{he}$), low influence of heat loss through the wall (optimal position heat exchanger is at the bottom) and a maximum temperature difference between inlet water flow temperature and controlled outlet water flow temperature. The CERES case results indicate that use of the stack chimney heat exchanger system for aquifer loading is possible, but effectiveness is low since the expected capacity is only 2% of the current loading capacity. The capacity for providing free cooling to the CERES building is higher. The high uncertainties imply however, that it remains uncertain whether the system can meet the building’s annual cooling demand. The high uncertainties are influenced by the range in the uncertainty analysis (UA), a smaller wind coefficient range in particular would decrease uncertainty. The value of selecting a higher resolution model (e.g. coupled CFD and ESP-r) for performance evaluation is questionable since the model is not calibrated/validated, also the effect of bias effects is unknown (see section 2.2).

### Industrial case results
Industrial case results show high annual heat exchange potential for the stack chimney heat exchanger. The case analyses lead to clear design guidance: the heat exchanger can be placed in the top of the chimney and the performance depends mainly on the balance between flow resistance ($C_{he}$) and $A_{he}$. The minimum required flow is of high importance. Although this is not a design parameter, it has a large influence on the maximum heat exchanger size. Compared to the CERES case the relative uncertainties are lower ($\sigma_{\theta} = 16\%$, compared to 50% in CERES case), however the absolute uncertainty is 500 MWh/yr.

### Performance indicators
Performance indicators are chosen based on design questions and relate to design parameters. The efficiency, which is defined as exchanged heat in relation to the required pumping energy, is expressed in the efficiency coefficient (EC). It might have been better to include the energy consumption of the pump as performance indicator (energy efficiency ratio, EER). EC is influenced by required pumping energy and heat exchange (which is a factor 100 times as larger). Using the EER (energy efficiency ratio) might lead to improved results.

For optimal SA result, parameters should be independent of each other, with the geometrical attributes of the heat exchanger, this is not the case. Therefore, area and flow resistance are included in the results (water temperatures, area, flow resistance and heat exchanger position are independent). Including a heat exchanger in SA poses challenges
in selecting design parameters, simply area and flow resistance and face area could have been sufficient for this resolution. However, the current design parameters provide a realistic relation between face area (heat exchanger plate width and inter-plate spacing), flow resistance, and area. This assures that there are no unfeasible designs in the results. Including fully independent parameters would require filtering in post-processing, requiring the same kind of analysis of the relation between heat exchanger properties (checking feasibility).

**Optimization and analysis**

Optimization is performed based on costs and annual heat exchange. Since the EC is high in all cases (starting ranging from 100-300), this performance indicator was considered less important since the system efficiency was high for each case. In respect to the title of this thesis, the maximization of heat exchange efficiency is thought of as optimizing the amount of annual heat exchanged rather than total system efficiency. Since the EC depends mainly on the annual exchanged heat and always above 100, and given the fact that costs only depend on the design parameters, only the annual heat exchange performance parameters was used in parts of the analysis (like generic UA).

**Modelling resolution**

A modelling resolution exercise was performed inspired by modelling difficulties encountered in ESP-r modelling of the complex coupling of the airflow network, plant modal and building energy components, the exercise is included in appendix C. Although the lower resolution/complexity model includes a less complex airflow and building energy network, the plant part (heat exchanger model) could be more accurate for some cases, as heat transfer calculations can be controlled. The absolute (real) accuracy of the models can however not be studied. Resolution selection (and conclusions in general) are mainly based on comparisons. The range of the UA used for model performance evaluation does however influence SA, UA results and thus conclusions.

**ESP-r**

ESP-r posed several difficulties in coupling of the airflow network, plant network and building energy calculations. The plant module is for instance not able to calculate flow resistances (these are thus calculated based on analytical method based on literature). This also applies on the heat exchanger area, as the plant component offers ‘area’ as input, which is not based on ‘coil packing’ (amount of plates etc.), which is thus calculated as well. Heat exchange calculations are based on the water side of the airflow network (AFN).

ESP-r documentation is fragmented to say the least. And the plant-network is not widely used and under constant development. Documentation on specific components is difficult if not impossible to find. The heat exchanger component used here is based on component type 50 (110) [33], but might have been changed.
The main research question is repeated below:

“what is the optimal set of design parameters so heat exchange in stack chimneys is optimized annually for the cases in which a stack chimney heat exchanger is used for heating or cooling applications, what is the expected performance and how do the design parameters relate to this performance?”

7. Conclusions

The current study is an example of the application of building simulation tools in the early phase of the design process, in which building performance simulation (BPS) tools are used to provide design guidance and performance evaluation. To find “the optimal set of design parameters so that heat exchange in stack chimneys can be maximized”, general methods for the optimization of heat exchange in stack chimneys, modelled in an ESP-r simulation model, have been studied. The most important design parameters and their relative influence on the performance indicators were analysed based on sensitivity analysis (SA). From this analysis, general design guidelines and simplified models were derived. Multi objective optimization (MOO) of the most important design parameters is performed on the simulation models using responsive surface (RSM) methods and artificial neural network (ANN) capabilities of ModEContier to speed up the process leading to the “optimal set of design parameters”. Uncertainty of the optimized results has been analysed using uncertainty analysis (UA). An overview of the evaluation process is presented in figure 27.

![Figure 27: overview of method for evaluating design parameters, (optimized)performance and providing design guidance.](image)

It has been found that the optimization methodology can be applied to find the optimal set of design parameters. The use of ANN techniques proves valuable for reducing the optimization time, their capability to handle complex (non-linear) input/output relations has been demonstrated in a comparison
with multi-variable linear regression based reduced order models. The application of RSM methods for finding the Pareto front more efficiently further reduces the required optimization time. Optimization was performed with 800 simulations (real) and 800 ANN simulations, optimized results should be analysed based on the real simulations only. The optimization methodology can be used for all optimization cases and is particularly valuable for complex models which require extensive simulation times. The SA, UA and optimization methods have been applied to a “heating application” (industrial case), and a “cooling application” (CERES case), to evaluate the optimized “performance of such systems in terms of annual heat exchange”, and relation between design parameters and performance (providing design guidance).

CERES case

The main design parameters which govern heat exchange in the monumental stack Chimney on the Eindhoven University of Technology are identified as the outlet water flow temperature and flow resistance (geometric attributes of heat exchanger). Increasing heat exchanger length has a large negative influence on the costs, while little influence on the annual heat exchange since the heat exchanger area \(A_{he}\) is mainly influenced by heat exchanger face area. To reach optimal performance in which annual heat exchange is maximized and costs are minimized, the heat exchanger should be placed in the bottom of the chimney, and a balance between flow resistance and heat exchanger area should be reached in which flow resistance should be minimized. Also, outlet water flow temperature should be maximized, so the heat exchanger can be used at higher ambient temperatures.

From the optimization in which costs are minimized, and annual heat exchange is maximized, follows that the heat exchange potential which can be used for aquifer loading is about 72 MWh/yr (maximization leads to 80 MWh/yr). When the chimney is used for aquifer loading an additional 145 MWh/yr is available for free cooling of the CERES building \(T_{ambient} < 19 \, ^{\circ}C\) and 80 MWh at ambient temperatures above 19 \, ^{\circ}C. The efficiency coefficient (EC) of such a system, the ratio between exchanged heat and water pump energy requirement is about 150-180. Since the model is not calibrated or validated, the uncertainties are large: 1 standard deviation is +-50%.

Although the EC is much higher compared to the cooling tower system, which are currently used to balance the aquifer system on the campus of the Eindhoven University of Technology, the aquifer loading potential is about 2% of the total installed capacity and about 5.4% of the a single cooling tower. Although the stack chimney heat exchanger is very efficient for loading the aquifer system (high EC), it is not very effective (low capacity). The heat exchange potential for free cooling is much higher, up to 500 MWh/yr is available when no aquifer loading is applied, in spring and autumn, the CERES building can be cooled with an EC>100.

It is concluded that the CERES industrial stack chimney can be used in combination with a heat exchanger to provide free cooling to the CERES building, and provide (limited) loading of the aquifer system. The sustainability values are high as the stack chimney provides highly efficient cooling while saving a monumental industrial building.
The optimal annual heat exchange found by maximizing the heat exchange and minimizing the costs is about 3 GWh/yr with a EC of about 150. In general, a large change in ambient temperature only has a small influence on the heat exchange capacity, the heat exchange \( Q_{ex} \) is therefore considered quite stable. The heat exchange can be translated a capacity of about 343KW which is available throughout the year. The maximum heat exchange, by maximizing / minimizing the design parameters according to SA analysis results, leads to a potential of 4 GWh/yr. Since the model is not calibrated or validated, the uncertainties are large: 1 standard deviation is +-16%.

It is concluded that installing a heat exchanger in an industrial stack chimney can be a valuable asset for increasing the efficiency of an industrial hall. The heat exchange may benefit from increased chimney height and reduced volume flow requirements.

Reduced order models derived from the SA analysis can be used for calculating stack chimney heat exchanger performance in a linear model relating input parameters to the performance indicators. Model accuracy is however quite low, \( R^2 \) values are <0.9. Here, the ANN’s perform better.

Conclusions about design parameters may change for other chimneys, since the flow resistance of the heat exchanger is less of a problem in higher chimneys. The current models and conclusions about the design parameters, and simplified models do therefore not per se applicable to other chimneys.

Finally, it has been found that methodologies to support the selection of the appropriate modelling resolution are very sensitive to UA parameter range selection, for which there are few guidelines. The increased model bias, which is difficult to estimate using UA as model performance evaluation, may influence the accuracy of more complex models. Therefore, it should be noted that ‘more complex’ models/tools do not necessarily lead to ‘improved’ results, and the value of increasing modelling resolution in the current study (concerning non-validated, non-calibrated simulation model) is still questionable.
8. Recommendations

The analysis of the case studies has led to recommendations concerning the application of stack chimney heat exchangers in those specific cases. These recommendations are presented in this section.

1) The monumental stack chimney at the Eindhoven University of Technology can be used for free cooling of the retrofitted CERES building. The annual heat exchange (capacity) potential for free cooling is higher compared to the potential for aquifer loading; building efficiency will benefit from this (cooling EC>100). Also, it indirectly influences the aquifer, since less building heat will need to be rejected to the aquifer. At times when free cooling is not used (e.g. night), the aquifer can be loaded. For this purpose, the heat exchange in the stack chimney can be optimized for free cooling specifically (currently; the system is optimized for aquifer loading), although the main conclusions are likely to remain the same. The use of a monumental stack chimney for a sustainable application can also be a good public relation asset/example.

2) Heat exchangers should be located at the bottom of the chimney. Heat exchanger selection should be focussed on minimizing flow resistance by minimizing face area. Thin fins should be used (minimal plate width), this does influence water flow, but since water mass flow is relatively low, the influence on pump energy is low. Outlet temperatures should be as high as possible.

3) Using a wind optimizer at the top of the chimney may have a large, positive, effect on the annual heat exchange.

4) The potential for the industrial application is high, so it can be implemented in the current system, it should be noticed that the minimum required has a major influence on system performance.

5) Heat exchanger should be located high in the stack chimney, and heat exchanger flow resistance should be minimized.
9. Future work

Uncertainty can be reduced by calibration/validation of the model, which requires physical experiments. This may lead to increased understanding of parameter relations, and an reduction in uncertainty. Uncertainty depends strongly on the uncertainty analysis (UA) input ranges, a slight reduction in the ranges for the wind pressure coefficient, area variation, flow resistance and inlet flow resistance may greatly decrease uncertainty while still providing a realistic UA. A detailed analysis of convective heat transfer relations, may also decrease uncertainty, a coupled CFD and nodal approach (ESP-r + CFD) can be performed. The value of such an increased modelling resolution is however questionable. There should be emphasis on the UA range guidelines in relation to resolution / tool selection support methods. The influence of the modelling resolution on sensitivity analysis (SA), optimization conclusions, the modelling bias and the ‘improvement in results’ provided by a ‘more complex’ model should all be addressed.

Currently, simplified models are capable of calculation or stack chimney heat exchanger system performance for the specific chimneys in this study (annual heat exchange, system efficiency in the form of the efficiency coefficient and system costs). Further study is required to implement the for all stack chimneys (requires additional simulations). Also, simplified models capable of calculating optimized design parameters could be developed by running optimization for a broad scale of stack chimney designs.

Although the stack chimney heat exchanger is very efficient for loading the aquifer system, it is not very effective (low capacity). The current cooling tower system is therefore still needed. A full system analysis of the TU/e stack chimney and bordering systems e.g. building installations and the aquifer system would lead to a better insight in the potential of the total system, and the selection of operation modes (aquifer loading at one time, loading of buffers, free cooling etc.). This analysis can be performed using BPS tools such as TRNSYS. Also, the system can be optimized in combination with bordering systems, e.g. in combination with the current cooling towers. A full analysis of the decentralized energy supply, in combination with potential additional installations (replacement of systems, adding short period buffers) and the development of an improved (smart) control systems for the campus as a whole, might be more effective in terms of costs reduction, aquifer balancing potential and reduction of the total energy consumption compared to the use of the CERES stack chimney for aquifer loading.

Finally, the addition of new water/air heat exchanger plant component in ESP-r with different convective heat exchanger calculation methods (preferably selectable), the inclusion of automatic calculation of flow resistance from geometric parameters and calculation of heat exchanger surface area from geometrical attributes would be helpful for future research into HVAC/building interaction, solar chimney research etc. Possibly improving results, the capabilities of ESP-r and aiding in the research process. Also, ESP-r documentation should be updated.
References


11. VROM, Dossier Duurzaam Bouwen en Verbouwen, overzicht strategieën voor duurzaam bouwen, R.V.D. government), Editor. 2010: Den Haag (the Hague)


References – page 50
23. de Wit, S., influence of modeling uncertainties on the simulation of building thermal comfort performance. Delft University of Technology Delft.
25. MacDonald, I., Quantifying the effects of uncertainty in building simulation. 2002, University of Strathclyde.
30. ESTECO, MedEContier ModEContier documentation, 2010. 4.3.0(b).
37. Goodarzi, M., A proposed stack configuration for dry cooling tower to improve cooling efficiency under cross wind, in Faculty of Engineering. 2010, Bu-Ali Sina University (Iran): Hamedan.


Software

CASAnova CASAnova, An educational software for heating and cooling energy demand as well as temperature behaviour in buildings, version 3.3.08, Division of Building Physics & Solar Energy, University of Siegen, Germany, 2007

ContamW ContamW, version 3.0, National Institute of Standards and Technology, Building and Fire Research Laboratory, US, 2011

CygWin CygWin, Unix emulation, 4.1.10(4), 2009

ESP-r ESP-r, integrated energy modelling tool, version 11.11 trunk 6935, www.esry.strath.ac.uk , University of Strathclyde, Glasgow, 2011

Matlab Matlab 2008b, version 7.7.0.471 (R2008b), MathWorks Inc. 2008

ModeFrontier ModeFrontier, multidisciplinary and multi-objective optimization and design environmentversion 4.3.0 b20101110, www.esteco.com, ESTEMCO, 2011

PASW PASW Predictive Analytics software, version SPSS 18 (18.0.0), IBM Corporation, 2009
Appendix A: ESP-r modelling

Esp-r is used for simulation environment for modelling the stack chimney heat exchanger system. The CERES case is a low temperature heat exchange application, where heat is injected in a stack chimney, in the industrial case, heat is extracted from a high temperature stack chimney flow. The existing models for heat exchangers available in ESP-r will be used, this building performance simulation (BPS) tool is selected in advance for (apart from its open source nature) its capability to handle (complex) (air)flow networks (AFN), building energy simulations (BES) and plant systems (PLT) and provide whole year dynamic simulations of those systems using a nodal approach.

In network flow methods, buildings and fluid flow systems are treated of networks of rooms, and system components. The assumption is made that for each type of connection there exists an unambiguous relationship between flow through the component and pressure difference [37]. In this method, large(r) domains can be considered for long periods compared to e.g. CFD. In ESP-r the (air)flow and thermal models are simulated in a nodal network which iterates towards a balanced pressure/temperature distribution for every time step (details e.g. [33]). Mass and energy conservation equations are established for each finite volume and solved simultaneously. In this way the conductive, convective, fluid flow (pressures), radiation and heat storage processes are explicitly modelled as the system responds to climate boundary conditions.

General model description

The model approach combines the BES, AFN and PLN components of ESP-r. Energy exchange between the zones, chimney thermal envelope, and the external environment are calculated with the building energy component. Air exchanges between zones are based pressure network ((air)flow network), which calculated the buoyancy flow. The plant system contains the heat exchanger and calculates the (thermal) interaction between water and air. The components are coupled and temperatures, pressures and energy flows are calculated for each time-step (also see [51]).

Model design

A 13 zone model is created in ESP-r for the CERES case, incorporating the geometry in high detail 14, each zone is 5m high (except for the last zone, which is 7m). For the industrial case, 7 zones are used (1.5 meter per zone). Other researches with similar velocities and temperatures (or higher), indicate that this resolution is sufficient [44]. The ESP-r model is schematically represented in figure A.1.

---

14 Based on drawings of the Stack Chimney
Building energy simulation (BES)

In figure A1, the building energy (BES) system is illustrated on the right side, holding the general geometry, building structure and zones. The BES component is connected to the (air)flow nodes, for which the temperature is calculated every time step.

![Figure A.1: Schematic representation of ESP-r model](image)

(air)Flow network (AFN)

The nodal (air)flow network consists of components over which the pressure drop and mass balance is calculated. The (air)flow components used in the flow network (connecting nodes) are characterized by loss coefficients ($C_{lw}$) and friction losses (major and minor losses). Mass flow can be related to pressure loss using the Bernoulli theory (also see [33]). The (air)flow network is illustrated within the zones (of figure A.1), and is represented by the nodes and inter-nodal components, which are connected to the zones. Boundary nodes are coloured blue. A description of the various components and their $C_{lw}$ values is provided in table A.1

<table>
<thead>
<tr>
<th>Component</th>
<th>$C_{lw}$</th>
<th>Friction factor</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet damper</td>
<td>4-10</td>
<td></td>
<td>Entrance</td>
</tr>
<tr>
<td>General flow conduct</td>
<td>~ 0</td>
<td>0.001 – 0.01</td>
<td>Inter-zone connections of (air)flow nodes</td>
</tr>
<tr>
<td>Heat exchanger air side</td>
<td>0.5 – 100 (calculated)</td>
<td></td>
<td>Heat exchanger component in (air)flow network to include heat exchanger flow restriction</td>
</tr>
<tr>
<td>Outlet</td>
<td>-2 – 2 ($C_{lw}$)</td>
<td></td>
<td>Output (wind induced)</td>
</tr>
<tr>
<td>Water pipe</td>
<td>0</td>
<td>0</td>
<td>Water side of plant system</td>
</tr>
<tr>
<td>Heat exchanger water side</td>
<td>5-10 (calculated)</td>
<td>0.01</td>
<td>Water side heat exchanger in plant system</td>
</tr>
<tr>
<td>Water pump</td>
<td>5</td>
<td>0</td>
<td>Water pump</td>
</tr>
</tbody>
</table>
Plant network (PLN)

ESP-r has the capability to include flow elements and HVAC systems, in a ‘plant system’. A plant system consists of various components linked in a nodal network (comparable to the (air)flow network). The heat exchangers heat transfer will be modelled using this module. The PLN is illustrated on the left side (figure A.1). Flow through the plant network is governed by the (air)flow network, which includes a pump and water nodes (w-nodes in figure A.1). In ESP-r heat exchanger component type 50 (110) is used [33]. Water originates from a water source component in which also the water inlet temperature is provided.

Control system

For the CERES case the water outflow temperature (sensed) is controlled by actuating the water pump. When the required outflow temperature is reached, water mass flow (and heat exchange) may increase. When outflow temperature increases above the specified temperature, flow is decreased. In order to keep control system simple (also for stability reasons), a single control is applied, this means that ESP-r can be used for 1 temperature scenario at a time, and a full evaluation of a single design requires 3 simulations with different control settings.

Model functioning and automation

The model is tested to investigate response. A climatic input file was created without wind and solar influences, the temperature rises stepwise from -10 to 24 degrees °C. The results are plotted in figure A.2 and A.3. For this case, the water flow is controlled to be 8 degrees °C, providing 100% flow beneath 6 °C, and 0% above 8 °C. Flow is at maximum (1.5 kg/s) for ambient temperatures of -10 °C, and is decreased as ambient temperature and water outflow temperature increase. At 8 °C water output temperature, flow becomes 0%, or 0kg/s. Meanwhile, chimney mass flow decreases from 6 kg/s to 0, becoming negative for ambient temperatures > 8 °C. When the water flow is turned off, water temperature in the heat exchanger increases towards the water input temperature. Mass flow in the stack chimney becomes negative when ambient temperatures are above the water inlet temperature.

![Massflow response](image)

*Figure A.2: Mass flow response ESP-r model (CERES case)*
For stability reasons the minimum mass flow of the water is 1% at minimum in the simulations. In post processing, heat exchange is 0 when water flow is 1% (or water outflow temperature is above the specified amount.

ESP-r modelling difficulties and bugs

The coupling of PLT, BES and AFN is considered a application for nodal networks and ESP-r. ESP-r is under constant development since 1979. There are however, still bugs/ inconsistencies, in particular in the relatively new plant network. The PLT is unable to handle negative mass flows (also see figure A.2). This leads to convergence problems when mass flow does become $< 0$. Also, since the plant system used (air)flow component information, the plant system seems to use the temperatures of the previous time-step, as calculated with the (air)flow network and building energy. Thus, when temperature changes, plant temperature lags 1 time step, leading to inconsistencies for one time step. This is illustrated in figure A.4. A difference in temperature automatically results in a difference in heat exchange observed by the plant and airflow networks. To reduce the inaccuracy caused by this, a high number of simulation steps is required, the time steps are included in table A2.

Other bugs include bugs in the automatic ESP file creation (e.g. .htc files and .afn files), in the control system (e.g. mass divergence) and treatment of input data (e.g. user interface problems). Also, the translation from user input to networks, and the consistency in user interface feedback, provides difficulties in modelling and model evaluation. The plant system is e.g. sensitive for the order in which the used provides the network description, and when one node is deleted, the whole network has to be re-entered. The limited documentation on the (particularly in the plant system), further adds to modelling difficulties.

Effects like ‘inconsistency in plant/flow network for negative mass flows’ are filtered out in the post-processing.
Differences CERES and industrial model

Apart from the geometries and materials, the industrial model is comparable to the ESP-r model, the only difference being the heat exchanger component, which is a cooling coil in the industrial application. The control strategy is based on the acquisition of the pump, the measured quantity is however the flow (which needs to be at a certain minimum specified flow).

Model overview

The general model approach is included in figure A5. Input design parameters are translated to heat exchanger properties using Matlab (see appendix C). Next, ESP-r files are created based on the design parameters. After simulation, post-processing is required to calculate the performance indicators (based on (design)input parameters and results). After one run, the next design to be evaluated may be selected automatically (controlled by Cygwin scripts) for evaluation.
Figure A5: Esp-r simulation flow chart (method)
Appendix B: Excel model

The Excel model is created as a simplified model to compare the ESP-r modelling tool to an approach based on analytics in a non-dynamic model (lower resolution / less complex). For the Excel model, the potential heat exchange can be calculated for ambient temperatures depending on design parameters. The Excel model is used to calculate heat exchange in the CERES case only.

Model design

The excel model is based on a single airflow node (calculated from average stack temperature), 10 nodes for the thermal network (calculating stratification, average stack temperature and losses), and a single plant node (NTU method for heat exchange calculation). The three components require iteration to reach convergence.

Building energy simulation (BES)

The energy losses through the construction is calculated per zone, for this purpose, 10 zones are considered. The temperature in the zone and the ambient temperatures are used to calculate heat loss through the construction. The temperature of the next zone is the temperature of the current zone minus the heat losses in the zone (governed by equation b1, also see figure b1). This nodal system needs to be iterated to balance the system since the temperature of the first zone depends on the heat exchanger temperature (see PLT), which in turn depends on the mass flow and average stack temperature. Although the wall temperature itself is calculated, heat storage is not taken into account in a dynamic way.

\[ \dot{Q} = h_c(T_{in} - T_{wall}) \]  \hspace{1cm} (b1)

![Figure b1: calculation of losses in Excel model](image)

(a)Flow network (AFN)

The airflow volume is calculated using the resulting average stack temperature for the analytical stack chimney formula (equation b3). The airflow depends on the total flow resistance \( \sum C \), average stack temperature and ambient conditions. The mass flow is calculated from equations b2 and b3, which are
derived from general pressure / flow relations as used in ESP-r e.g. described by Hensen, 1991 [51], and also used in the research of e.g. Bahavand, 2010 [42].

\[
C_d = \frac{1}{\sum \frac{\Delta L}{D} + \sum C_i} \tag{b2}
\]

\[
\tau_h = C_d \cdot A_{\text{flow}} \cdot \beta_{\text{average}} \cdot \sqrt{2 \cdot g \cdot h_{\text{above}} \cdot \frac{T_{\text{in average}} - T_{\text{out}}}{T_{\text{in average}}}} \tag{b3}
\]

In equation b2, \( f \) is the friction coefficient, \( L \) is the characteristic length (m), \( D \) the hydraulic diameter (m). \( C_d \) is the discharge coefficient. In equation b3, the massflow (m) is valuated depending on temperature \( T \), the height of the chimney above the heat exchanger (h), \( \beta_{\text{average}} \) is the average air density (kg/m\(^3\)) above the heat exchanger and \( A_{\text{flow}} \) is the free flow area. The mass flow thus depends on the average stack temperature resulting from the heat loss calculation (BES). The process is illustrated in figure b2.

![Diagram](image)

**Figure b2: calculation method for Excel model**

### Plant network (PLT)

The heat exchanger is located in one of the thermal zones. The heat exchange \( Q_{\text{ex}} \) is calculated using the NTU formula which is similar to the NTU-function used in ESP-r heat exchanger component [51], see appendix C.

The heat exchanger inlet and outlet water flow temperatures are specified by the user. The inlet air temperature is the ambient temperature. The heat exchange \( Q_{\text{ex}} \) depends on the heat exchange efficiency.
value of the heat exchanger, which in turn depends on the air outflow temperature (see appendix C). This system thus requires iteration to reach a balance between average stack temperature, mass flow and maximum heat exchange for the resulting temperatures.

The U value (total heat transfer coefficient m²K/W) is governed by the convective heat exchange value of the air (and metal thermal resistance and water-metal convective heat transfer coefficient), which is fixed and calculated in an analytical approach (see appendix C)

**Control system**

The water outflow temperature is specified by the user, and the heat exchange depends on this setting. So, the system makes sure that the specified outflow temperature is reached by adjusting the water mass flow and balancing the heat exchange, airflow and temperature.

**Model response and automation**

The model response is included in figure b3 (mass flow, temperature above the heat exchanger and heat exchange).

![Figure b3: Excel model response](image)

Since this simulation only takes into account the thermal mass in the calculation of the wall temperature, it is important to know whether or not the stack chimney system will operate when it is turned on at very cold ambient conditions in which the inside wall temperatures are e.g. at -10 °C, since heat loss though the system will be high for those moments. This is illustrated in figure b4. Even when walls are at -10 °C degrees, the average stack temperature is above the ambient temperature. This could also be concluded from figure b4, in which a positive mass flow is calculated at -10 °C.
Figure b4: average stack temperature for wall temperature = ambient temperature = 10°C.

The convective heat transfer coefficient ($h_{conv}$) is based on the local flow domain analysis (Reynolds number, Nusselt relations, Raleigh number etc.), based on the expected free flow velocities of 0.2 – 3.2 m/s. Also flow resistance analysis is based on this velocity estimation. The estimation is based on equations b3 and b2. From the distributions of velocity found in the optimized results from the ESP-r models and the excel model included in figure b5, it can be concluded that the assumption might be on based on a high velocity. However, this means that the convective heat transfer value is slightly over estimated (see table b1). From appendix C, it can be concluded that the value is still in a realistic range, and that the overrated values are below ESP-r values (see appendix A and C).

Figure b5: velocity distribution throughout the year for low temperature, medium temperature and high temperature case.

<table>
<thead>
<tr>
<th>Method</th>
<th>Optimized result (aquifer loading)</th>
<th>High temperature (heat rejection) case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Convective heat transfer coefficient value ($h_{conv}$)</td>
<td></td>
</tr>
<tr>
<td>ESP-r h calculating</td>
<td>Mean in year</td>
<td>26.6</td>
</tr>
<tr>
<td></td>
<td>Standard deviation $\sigma_{var}$ from mean</td>
<td>9.9</td>
</tr>
<tr>
<td>Excel analysed h</td>
<td>Constant</td>
<td>10.13</td>
</tr>
</tbody>
</table>

Table b1: convective heat transfer coefficient values in Excel and ESP-r

Appendix B: Excel – page 62
General model description

For each ambient temperature, the heat exchange capacity is calculated. Next, the annual heat exchange is calculated by combining the amount of hours a year a single temperature is measured. The total simulation flow scheme is included in figure b6.

Figure b6: Complete overview of Excel model calculation methods
Appendix C: Heat exchangers

The heat exchanger in ESP-r is implemented using the plant network (PLT). Type 50/110 (hensen, 1991) is used. When a plant network is coupled with an airflow network, the airflow network calculations override the plant flow calculations (heat transfer is governed by the plant system). Heat exchanger flow resistance depending on (geometrical) design parameters, need to be calculated and provided to the airflow network, while properties like heat exchanger area and plate width need to be provided to the plant network. In order to provide the correct heat exchanger properties, values are calculated based on analytical approaches based on heat exchanger literature. Various types of heat exchangers are available. There are only a few types of heat exchanger which are suitable for use in the stack chimney. And air/water heat exchanger will be used. The design consideration is: low head loss. The calculation methods are discussed in this appendix.

Heat exchanger modelling

For the heat exchanger modelling, a counter flow plate heat exchanger is assumed as standard model. The heating coil component in ESP-r approximately matches this heat exchanger type. Given the extensive literature on heat exchangers and analytical approaches, together with the vast amount of available designs, the heat exchanger properties will be based on a survey of several heat exchanger types in order to account for variations in designs and properties found in real systems.

The properties will be based on a flat plate counter flow heat exchanger, however, in uncertainty analysis, potential design variations and their implications on heat exchanger properties will be taken into account. The main idea is illustrated in figure c1. In the following paragraphs the calculation method is discussed. This will be applied to calculate heat exchanger properties based on design parameters for a flat plate heat exchanger. The analysis of the other heat exchangers is used to obtain uncertainty in the form of a standard deviation $\sigma$ (deviation from average area and flow resistances found in the analysis of the various types of heat exchangers), see figure c1.

ESP-r uses the ‘number of transfer units’ (NTU) method together with a linear $h_{conv}$ relation (depending on velocity) [45] to calculate the heat exchange between heat exchanger and air, the relation is included in equation c1. In the NTU –method (number of transfer units the heat exchanger is described by heat exchanger effectiveness (E). E is ratio between maximum theoretical- and actual heat transfer [18]. Using the hypothetical maximum temperature difference and NTU, the effectiveness can be calculated. Or, when E is known (as one of the heat exchanger properties) the other parameters can be calculated. The NTU is defined in equation c2. In equation c2, $U$ is the heat transfer coefficient ($\frac{W}{K\cdot m^2}$) and $A$ the area ($m^2$). The heat exchange $\dot{q}$ ($\dot{\Omega}$) is calculated based on the heat exchanger effectiveness derived for a heating coil (ESP-r component type 50/110) defined by the NTU, see equation c3.
The computational optimization of heat exchange efficiency in stack chimneys – MSc. Thesis
T.A.J. van Goethem, Eindhoven University of Technologies, unit Building Physics & Services

\[
NTU = \frac{U A}{C_{\text{min}}} \tag{c1}
\]

\[
E = \frac{1-e^{-(NTU(1-C_{\text{min}}/C_{\text{max}}))}}{1-C_{\text{min}}/C_{\text{max}}}
\tag{c2}
\]

In equation c3, the heat exchanger effectiveness is calculated depending on \( C_{\text{min}} \) and \( C_{\text{max}} \), the heat capacity rates of the air and water respectively \( \left( \frac{\text{kg}}{\text{K}} \right) \) and NTU, which is defined in equation 2.

\[
\dot{q} = E \cdot C_{\text{min}} \cdot (T_{\text{he}} - T_a) \tag{c4}
\]

\[
h_{\text{conv}} = 38 \cdot \overline{\nu}_{\text{local}} \tag{c5}
\]

The exchanged energy \( \dot{q} \) can then be calculated from equation c4 in which \( T_{\text{he}} \) is the heat exchanger temperature (K) and \( T_a \) the air temperature (K). The U value from equation c5, depends on the convective heat transfer coefficient, \( h_{\text{conv}} \) (W/m² K). This coefficient is linearly approached by ESP-r from equation c5 where, \( \overline{\nu}_{\text{local}} \) is the average local velocity (m/s) and “38” is a linear constant (J/m³ K). In reality, the convective heat transfer coefficient is a complex variable, depending on (local) flow domain. The linear model of the convective heat exchange, as used in ESP-r, might not perform well in for the whole velocity range (see appendix C), but the equation cannot be edited for the evaluation of different heat exchanger designs, which would have been more convenient.

**Investigated heat exchangers and methods**

Besides the flat plate counter flow heat exchanger, also a cross-flow tube bundle heat exchanger will be investigated, along with a counter flow ‘hole’ model and a circular plate heat exchanger.

![Calculated NTU value, based on design parameters](image_url)

*Figure c1: Calculating heat exchanger properties uncertainty*
Area calculation

The area is calculated based on the (heat exchanger) design parameters: plate-width, inter-plate spacing and length. The width and length determine the number of plates which can be implemented in a given diameter $D$ (maximum packing is assumed). For a flat plate heat exchanger, the area is described by equation (c6). The $\pi/4$ value provides the average plate size: The plate size depends on the position in the chimney, in the centre, the plate size is $D$. at a distance $D$ from the centre line, the size decreases to about 0. The average is however $\approx 0.78$. the method of calculation changes for different designs. The bottom and top of the plates facing the flow, are assumed to have a negligible heat exchange and are thus not included in the area calculation.

$$\text{Area}_{\text{he}} = \frac{D_{\text{chimney}}}{(\text{Width+Space})} \cdot \left(\frac{\pi}{4} \cdot D_{\text{chimney}}\right) \cdot \text{Length} \cdot 2 \quad (c6)$$

For the circular heat exchanger, the area is defined by formula (c7). The size of the plates is determined by the average radius of the circular plates.

$$\text{Area}_{\text{he}} = \frac{D_{\text{chimney}}}{(\text{Width+Space})} \cdot \left(\frac{D_{\text{chimney}}}{2} \cdot \pi\right) \cdot \text{Length} \cdot 2 \quad (c7)$$

For the cross flow tubes, the area is dependent on the amount of tubes per layer, and the amount of layers per meter (thus; the packing). The amount of tubes per layer is determined by the spacing and width. The amount of layers per meter is governed by the tube width ($2 \times$ horizontal width = vertical spacing), see equation (c8).

$$\text{Area}_{\text{he}} = \frac{D_{\text{chimney}}}{(\text{Width+Space})} \cdot \left(\frac{\pi}{2} \cdot D_{\text{chimney}} \cdot \text{Width}\right) \cdot \frac{\text{Length}}{2 \cdot \text{Width}} \quad (c8)$$

For the ‘hole’ type heat exchanger, the heat exchanger area is determined by the inner tube width. Here, the area is dependent on packing density (closest circular packing in a larger 2d circle is 0.9*surface of the larger circle), tube width and length (equation (c9)).

$$\text{Area}_{\text{he}} = \left(\frac{\pi D_{\text{chimney}}}{2} \right)^2 \cdot \left(2 \times \frac{\text{Width}}{2}\right) \cdot \text{Length} \quad (c9)$$

Resulting areas are included in figure c2 as a function of the free flow area (chimney face area – heat exchanger surface) for a heat exchanger with 1 meter length. For a single free flow area, multiple area’s a possible given the dependency on both inter-plate spacing and plate width.

The standard deviation in the total variation of area’s is calculated based on the average standard deviation of the standard deviations for various face areas. The average standard deviation is $178 \text{ m}^2$ ($\sigma = 178$). In uncertainty analysis, this variation will be taken into account.
Flow resistance (local loss factor)

The calculation of flow resistance ($C_L$) is based on the flow area reduction and heat exchanger length, and is also depending on velocity. The resulting pressure drop relation is stated in equation c10. Dynamic loss factors ($C_{Lw}$) are standardized for various elements (in literature, often $f$ or $k$ are used), but can also be calculated based on pressure losses.

$$\Delta P = C_{x} \frac{1}{2} \rho v^2 \quad \text{(c10)}$$

The $C_{x}$'s themselves are also depending on the velocity, since this determines the encountered resistance of the flow along the length of the plates. Here, the $C_{x}$ is analysed for low and high velocities, which are then averaged. The $C_i$ value is calculated using equation c11. For tube bundles a different relation is used, see [18].

$$C_{i_{\text{he}}} = (1 - \frac{A_2}{A_1})^2 + (1 - \frac{A_2^2}{A_1^2}) + \left(\frac{f(Re)}{D'}\right)_{\text{low}} + \left(\frac{f(Re)}{D'}\right)_{\text{high}} \quad \text{(c11)}$$

In equation 11, the flow resistance due to friction loss along the plate length is given by the D'Arcy-Weisbach friction coefficient $f(Re) \cdot \frac{1}{D'}$ in which $f$ (the friction factor) is given by the ColeBrook formula (equation c12). In equation c12, $D'$ is the hydraulic diameter, $Re$ is the Reynolds number and $k$ the roughness. In the current study, $C_i$ is evaluated for high and low $k$ values of 0.09 and 0.015 to account for possible different materials used in the heat exchangers.

$$\frac{1}{D'^2} = -2 \cdot \log \left(\frac{2.51}{(Re)^{0.5}} + \frac{k}{3.72} \right) \quad \text{(c12)}$$

The flow is analysed on free flow velocities of 0.2 and 3.2 m/s (also see appendix B) since these are the expected velocities based on dimensionless analysis of the flow domain ($Re$, $Ra$, $Ar$, $Nu$ etc.). The analysis
is based on the local velocities in the heat exchanger, and are thus depending on inter- plate spacing and width.

The resulting Ci values for the various heat exchangers is presented in figures c3, including literature values [52]. The average deviation is calculated to be 10.31 (σ = 10.31), which will be taken into account in uncertainty analysis. In figure c4, the flow resistance as function of plate width and inter- plate spacing is presented while in figure c5 an example of the relation between area and flow resistance is included.

Figure c3: Flow resistance versus free flow area for various heat exchanger types

Figure c4: Relation between heat exchanger spacing, width and flow resistance
Comparison to literature

In literature, C_i values can be found in tables. Literature values for damper systems at various flow reductions are included in figure c3. The values show good comparison to the values found in the current analysis [18, 52].

Convective heat transfer coefficient analysis

In ESP-r the convective heat exchange coefficient, which governs the heat exchange from heat exchanger surface to the air, in ESP-r, this is calculated with equation 5 (see section 3.3.1 of main report). This method cannot be adapted (without changing the source code). For the Excel model (see appendix B), the relation can be defined. In the method used in excel, an average convective heat transfer coefficient value is used based on the analysis of this parameters on low and high velocities (0,1 – 3,2 m/s in free flow area), see appendix B for a discussion on the applicability of this assumption.

From an analysis of the flow domain, it is concluded that flow is mainly turbulent (in the heat exchanger), and heat exchange is governed by forced convection (based on Archimedes number analysis Gr/Re^t). The convective heat transfer coefficient value is based on the Nusselt relation (for forced convection) which differ depending on the type of heat exchanger. Equation c13 is used for flat plate and circular plate configurations and equation c14 is used for cross flow designs [7] (in which Re is the Reynolds number and Pr is the Prandtl number). For cases in which Re < 2300, free convection Nusselt relation is used (equation c15).

\[
Nu = \frac{(1.58 + \ln(Re) - 3.28)^2}{2.7^{1.26}} \left(\frac{Re-1000}{Pr^{(5/3)}}\right) \quad (equation \ c13, \ valid \ for \ 2300<Re<10^7)
\]

\[
Nu = 0.27 \cdot Re^{0.63} \cdot Pr^{0.36} \quad (c14)
\]
\[ \text{Nu} = \frac{44}{\sqrt{\text{Re}}} \]  

\( (c15) \)

From the Nusselt number, the h value can be calculated using relation c16, in which h is the convective heat transfer coefficient (W/m²K), L is characteristic length (m) and \( k \) is the thermal conductivity (W/m K).

\[ N_u = \frac{h L}{k_f} \]  

\( (c16) \)

Resulting \( h_{conv} \) values are included in figure c6, in relation to the free flow area. Here, also the ESP-r method is included (minimum and maximum depending on analysed velocity). The values from the current analyses compare to the results for the lower velocity results of ESP-r. However, the values found are already averaged for high and low analysis, and maximum ESP-r values are higher (based on equation c5).

Comparing to literature

The current analysis can be compared to other heat exchanger literature [20] presented heat exchanger relations for small cavities of high length compared to width for various Reynolds numbers. When comparing the results of the current analysis (at comparable Reynolds numbers and spacing), it may be concluded that results match to experimental results for low velocities for a 3m tall cavity (0.1m wide) with 100W/m² heat injection [19]. For high velocities, values found in the current analysis are higher compared to the values found in literature. However, ESP-r values are even higher than this (also see equation c5), the relation is based on ‘when \( h_{conv} \) is unknown’. Nu relations used in the current research are based on multiple sources: [18, 20, 52, 53] and valid for the analysed Re/Ra regimes. Experimental results confirm that these findings are plausible, the comparison is included in figure c7. ESP-r values are possibly only valid for low velocities.

![Convective heat exchange coefficients a function of free flow](image)

*Figure c6: convective heat transfer coefficients for various heat exchangers and ESP-r*
Figure c7: convective heat transfer regime from current analysis compared to literature [19]

The convective heat transfer coefficients found in this study are only used in the Excel model. The average standard deviation in h value found in the analysis of the various heat exchanger types is ($\sigma = 16.25$). This value will be used in uncertainty analysis to account for various heat exchanger designs.

**Calculations in automated modelling**

In the simulations, the $C_w$ and area’s (and for Excel: h), are calculated using Matlab. The flow scheme is presented in figure c8.
Figure c8: analysis of flow resistance, heat exchanger area and convective heat transfer coefficients based on design parameters.
Appendix D: modelling resolution

An analysis of the modelling resolution required for a specific simulation/study should be performed before a modelling tool is selected to verify that the modelling tool meets the required accuracy and detail while not being ‘too complex’. Many different building performance simulation (BPS) tools exist, using different approaches to model similar physical phenomena’s [16]. The accuracy required for the predictions of different performance indicators is different and depends on economic, technological and social constraints. The trade-off between modelling resolution, complexity and required performance is the subject of many studies. In the current research, this analysis was conducted as an exercise investigating the value of selecting more complex modelling tools for non-validated, design support simulation, as is performed in the current study (sensitivity analysis, uncertainty and optimization)15. In this paragraph, the analysis and general conclusions of this exercise are introduced.

Many different BPS tools exist, using different approaches to model similar physical phenomena’s (Cwaley et al 2008, via mirsaeghi). The accuracy required for the predictions of different performance indicators is different and may depend on economic, technological and social constraints. Different approaches should be used in different design stages [14].

Several methodologies have been developed in recent years guiding the modeller in selecting the appropriate modelling resolution. In general, a more complex modelling tool provides a higher resolution although it requires more experience, time and input data. The levels of resolution and complexity are directly related to the accuracy of the simulation and to the total cost of the simulation process [1]. A more simple model may have higher uncertainty, but is much faster to develop, and requires less input variables and knowledge on physics. An example of high resolution modelling is coupled nodal approaches and CFD, or full CFD. A low resolution model could be BES only. In general, a more complex and higher resolution model is hypothesized to provide ‘better results’ (more accurate). The aim of increasing the modelling resolution is to decrease modelling uncertainty, increase the level of detail and get more accurate results. Higher resolution models include more domain detail, numerical detail/complexity, parametrical detail etc. However, while modelling uncertainty might be reduced in this way, other uncertainties (e.g. in physical properties etc.) may increase. Important work in the field of modelling resolution and tool selection has been performed by e.g.: Djunaedy et. al. [1, 54], Hensen et. al. 1996 [51], Mirsadeghi, [16] Slater and Cermell and Tracka [55].

For model performance evaluation, UA analysis is used (as suggested by Djunaedy et. al., 2003 [1])16, although no guidelines for UA analysis use in model selection (for UA ranges and parameters). Hensen...
and Beausoleil-Morrison, [44] identify airflow parameter assumptions and convection coefficients as the most important characterizing parameters. High uncertainty of model results based on variation of those parameters would require increasing the resolutions. Djuanedy, [1] suggests “coupling procedure decision method” (CPDM) procedure for selecting the modelling resolution in which the sensitivity for two parameters in particular is analysed: airflow parameters assumptions and convection coefficients. Methodologies for selecting appropriate modelling resolutions also include “coupling necessary procedure” [16] which suggests coupling CFD and BES simulation when results are sensitive to the convective heat transfer coefficient. More generally, approaches suggest to increase modelling complexity when the uncertainty (concluded in UA) makes that the result could be either under, or above a certain design goal, so that conclusions about the design are margin of the uncertainty which may lead to erroneous decisions (poor performing designs). This is illustrated in figure D.1.

However, while modelling uncertainty is reduced in this way, other uncertainties (e.g. in physical parameters) may increase. In more complex, higher resolution tools (1) it is difficult to assess the quality of numerical methods used in a specific simulation, also calculation methods might not be accessible by the user. For example: one of the parameters, which is important for modelling resolution (the convective heat transfer coefficient) selection cannot be investigated in ESP-r (directly) without changing the source code. Furthermore interpreting the result requires more experience and insight into the physics (2). Total uncertainty may increase due to a larger number of relatively small uncertainties in the input parameters (3). Finally, increased modelling complexity may lead to difficulties in the modelling, simulation initiation processes and result handling (4). These potential influences on the uncertainty are included in the ‘modelling bias’. Current methods do not include such ‘bias’ effects in model performance judgements. This may lead to to the false assumption that modelling resolution is sufficient or false assumptions about the uncertainty of a high resolution model. In general the effect of the ‘modelling bias’ on uncertainty is unknown since it is difficult to estimate this ‘bias’. The bias may differ per specific BPS tool, and the full effect of the bias can never be estimated. Even so, the bias has a potential large effect on the resolution/complexity selection and value of increasing modelling resolution. The effect is illustrated in Figure . All methods are focused on evaluation of design goals, and the use of BPS tools are decision tools / design support tools, under the assumption that higher resolution models provide improved results. Given the (unknown) modelling bias however, this assumption is debatable. Furthermore, there is little emphasis in literature on the effect of increased complexity on sensitivity analysis, the way uncertainty analysis should be conducted and the effect on optimizations.
Method of research

The current exercise offers a case study in which two models will be compared. Both models (see appendix A and appendix B) are non-validated, non-calibrated models for the performance evaluation of a stack chimney heat exchanger. Here, the models/ tools are handles from a user point of view, so only user adjustable values are taken into account. Uncertainty analysis will be conducted on both models, investigating sensitivity of results on modelling uncertainties (also see[15]). Analysis method based on global sensitivity analysis (LHC/spearman). The sensitivity of the models on design parameters will be investigated to get insight into the influence of modelling resolution on the analysis of the relative importance of design parameters. Also, the optimization trend (optimized sets of design parameters) of the Excel model is compared ESP-r results to investigate if the modelling resolution affects optimization results.

Model comparison

With calibration, one could calibrate the airflow components to match measurement results. This calibration could be performed on both models. Both models include airflow, (building)energy and plant calculations. The level of coupling and detail differs however, also the influence of boundary effects differ (also see appendix A and B). In the following table (table D1), the differences are presented. The ESP-r model is assumed to be the more advanced simulation tool, considering that it includes full transient (dynamic) modelling of building energy simulation, airflow network and plant systems, and its capability is proven for many applications and case studies17.

---

17 Notice that the validations mainly consist of BES, and BES+AFN simulations, and plant simulations. The full coupling between AFN, BES and PLT networks is not often used and under constant development.
Table d1: Comparison of model complexity/resolution

<table>
<thead>
<tr>
<th></th>
<th>Excel</th>
<th>ESP-r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convective heat</td>
<td>[ \tilde{h} = f(\tilde{Re}, \tilde{Nu}) ]</td>
<td>[ h = 38 \cdot v_{local} ]</td>
</tr>
<tr>
<td>transfer coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control strategy</td>
<td>No control / outlet temperature always reached,</td>
<td>Water outflow temperature controlled by actuating water pump by</td>
</tr>
<tr>
<td></td>
<td>water flow calculated from required ( m = \frac{Q}{c_p}dT ) and</td>
<td>sensing absolute temperature difference of water</td>
</tr>
<tr>
<td></td>
<td>possible heat exchange (NTU)</td>
<td></td>
</tr>
<tr>
<td>Heat exchange</td>
<td>NTU: * can be altered</td>
<td>NTU: * fixed</td>
</tr>
<tr>
<td>calculations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulation</td>
<td>Static (steady state)</td>
<td>Dynamic (transient)</td>
</tr>
<tr>
<td>Heat exchanger</td>
<td>Ci ( f(\tilde{Re}, \tilde{\nu} \ldots) ) and ( A f(L, w, s) )</td>
<td>Ci ( f(\tilde{Re}, \tilde{\nu} \ldots) ) and ( A f(L, w, s) )</td>
</tr>
<tr>
<td>properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nodes AFN</td>
<td>1 node, generalised analytical approach</td>
<td>10 nodes, nodal-network</td>
</tr>
<tr>
<td>Nodes BES</td>
<td>10 nodes, steady state heat balance calculation</td>
<td>10 nodes, transient heat transfer calculation</td>
</tr>
<tr>
<td>Nodes Plant</td>
<td>1 nodes, potential heat transfer analysis NTU-based for each</td>
<td>2 +1, potential heat transfer analysis NTU-based for each time step</td>
</tr>
<tr>
<td></td>
<td>temperature</td>
<td></td>
</tr>
<tr>
<td>Coupling</td>
<td>Lose</td>
<td>Fully coupled</td>
</tr>
<tr>
<td>Boundary effects</td>
<td>Wind (static), Heat transfer coefficients</td>
<td>Wind, External heat exchange coefficient, including heat storage etc.</td>
</tr>
<tr>
<td></td>
<td>internal/external surface (fixed), no heat storage</td>
<td></td>
</tr>
</tbody>
</table>

Simulated temperatures and mass flows are presented in figure d3 to show the difference in model performance. Since this concerns non-calibrated/validated models however, no conclusions can be drawn on which one performs ‘better’. As can be concluded from figure d3, excel mass flow is significantly below the esp-r mass flow, temperature is however above the esp-r result.

Figure d3 (a, b and c): Mass flow, temperature, heat exchange comparison of ESP-r and Excel.
Uncertainty analysis

For comparing the performance of models, uncertainty analysis (UA) is often used [15, 17]. Here, uncertainty analysis is performed on both models, for two separate input sets, see table d2. Both of the result sets are viewed as ‘realistic inputs sets’ which an engineer could choose to use as comparison range. The design parameters are fixed in both cases. It is hypothesized that the UA ranges influence model performance analysis and thus affect conclusions about the required modelling resolution.

<table>
<thead>
<tr>
<th>Table d2: Uncertainty input sets</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Set 1</strong></td>
</tr>
<tr>
<td><strong>Min</strong></td>
</tr>
<tr>
<td>Cp air *</td>
</tr>
<tr>
<td>Cp water *</td>
</tr>
<tr>
<td>Cp wind</td>
</tr>
<tr>
<td>Diameter</td>
</tr>
<tr>
<td>Height</td>
</tr>
<tr>
<td>Inlet Ci</td>
</tr>
<tr>
<td>Roughness (Ci)</td>
</tr>
<tr>
<td>h_in *</td>
</tr>
<tr>
<td>h_out *</td>
</tr>
<tr>
<td>Wall thickness</td>
</tr>
<tr>
<td>dA</td>
</tr>
<tr>
<td>dCi</td>
</tr>
<tr>
<td>dh</td>
</tr>
</tbody>
</table>

* small variation in Cp values is used to take into account heat transfer variations and fouling effects in the heat exchanger, these are only included in Excel analysis. This also applied for the h_in and h_out, which are the inside and outside convective heat transfer coefficients for the chimney walls.

These input values lead to very different results, as can be concluded from figures d4 and d5. Using UA set 1, it might be concluded that ESP-r performs worse compared to Excel, which shows a smaller spread in the results. Using UA set 2 however, this result is reversed. Here, the role of the variation in convective heat transfer coefficient, and large sensitivity to inlet Ci value in the first set, are of importance (see appendix C).

The effect of the inlet flow resistance is very large, reducing the range has a large influence on the heat exchange, this is also true for the diameter. Also, variations in the heat exchanger properties influence the total range in the results (dA, dC_v and dh_c_v).
In the 2nd set, the uncertainty in ESP-r results has dropped significantly, the effects of inlet resistance is large, which is also true for the diameter variation and height. Meanwhile, the influences of the convective heat coefficient variation are large for the Excel model, but cannot be changed in ESP-r, so they are not taken into account. Also, the influence of the wind is very limited in Excel, but very influential in ESP-r, also see figure d6. Not included in figure d6 graphs is the h itself (without variance), which has a spearman coefficient of 0.9.
Using the first set, the user might falsely assume the simulation performs to an extent at which design goals are met/rejected, while this might not be the case as the UA range was chosen unrealistically. Using the 2nd set, one may assume that the more complex method performs better, and performance is thus sufficient (see figure d1), while parts of the uncertain effects are not included (in 'bias'). Using the first set, one may falsely assume modelling resolution is sufficient because increasing modelling resolution does not improve results.

SA analysis
To analyse the influence on the use of the different models on SA analysis conclusions, a sensitivity study is performed on both models. The input sets (ranges) are the same as in the main sensitivity analysis presented in chapter 4 of the main report. Sensitivity analysis is only performed for the aquifer loading case (see section 4.5 of the report). From figure d7, it can be concluded the order of relative influences changes. When the Excel model was to be used, a designer may focus on length and width in particular, and not on inter-plate spacing (increasing spacing reduces area). While in Excel the effects of flow resistance may be under-estimated. The influence of the total area is comparable. The differences are likely to originate from calculation differences (numerical uncertainties and bias effects). Finally, it remains uncertain whether the ESP-r results are ‘better’ compared to Excel, and if conclusions about the design parameters would change when using a higher model resolution (e.g., coupled CFD and ESP-r methods) for non-validated, non-calibrated models. Finally, the relative influence of parameters in Excel and ESP-r differs, however the signs do not change, indicating that Excel simulation uses correct methods in calculation (assuming that the ESP-r model is working properly, also see appendix A).

![Sensitivity analysis comparing ESP-r and Excel models](image)

Figure d7: Sensitivity analysis comparing the ESP-r and Excel models

Excel optimization results
The excel model has also been optimized (MOO), cost was minimised, heat exchange for aquifer loading was maximized (see section 2 for methods). Total optimization results are higher compared to annual heat
exchange found in ESP-r optimization, this is due the a higher allowed inlet temperature (the results for the ESP-r optimization are presented in section 4.8). The main value of the analysis is to find if the modelling resolution has an effect on the optimization trends found in the ESP analysis. The optimization result is included in figure d8, for the heat exchange for aquifer loading. In figure d9, the trends of both optimizations are included for the samples as included.

![Heat exchange versus costs](image)

*Figure d8: Excel optimization*

![Design trends comparison](image)

*Figure d9: Design trends comparison, including design parameters for low, medium and high optimized heat exchange (along the Pareto front).*

Optimization trends are comparable, length is increased to an average value (reducing costs), while inter-plate spacing is increased. Width is minimized for both applications. Both modelling methods thus lead to comparable optimization trends, while the SA ranks differs. Heat exchange is simulated, while costs are based on design parameters (and are thus the same), this is likely the cause of the comparable results. The absolute results in terms of annual heat exchange are however different.
Conclusions

It was hypothesised that more complex modelling tools / methods not always lead to improved results, and that modelling bias is under-values in current complexity selection methods.

A more complex model does not necessarily provide ‘better results’, as various uncertainties may not show in UA analysis (e.g. convective heat transfer coefficients). This conclusion is very sensitive to the range of variance of design parameters and uncertainty parameters. The methods for evaluating the performance of different tools are sensitive to UA parameter selection and selected ranges (this is also noticed by de Wit [17]), for which there are few guidelines. It was found that results are sensitive to convective heat transfer values and airflow network settings. In such cases, it is advised to use CFD or CFD coupling methods. For the current research, in which a non-validated model is used, the additional value of the more complex/higher resolution tool is questionable. The value of using a complex model is debatable given the uncertainties in modelling, including of heat exchangers (complex system/flow interaction), model performance and unknown modelling bias influence. Modelling selection methods seem to be aimed at performance simulation only and not on the use of BPS tools for SA, UA and optimizations with ‘design guidance’ as result. In current methods.

Uncertainty remains large and it is not certain that Excel results are ‘less good’ since the heat exchanger models in Excel are based on analytical methods widely used in industry, in Excel different heat exchanger designs can be implemented more easy (different NTU calculation methods, and different CHTC models, for which the results are very sensitive although this cannot be concluded from ESP-r results), leading to more careful and potentially improved analysis. For both models the absolute accuracy of the result cannot be validated. The ‘simple’ analytical approaches should not be rejected based on available complex models, or UA conclusions, but also on an analysis of calculation methods and capabilities of ‘advanced’ models.

ESP-r is however, still selected as main simulation tool in the current research. The Excel model would require additional development and testing and ESP-r was selected prior to Excel. ESP-r has superior handling of ambient conditions, and provides full dynamic analysis. Results should however, be taken into account in future research into this subject.

In the pursuit of creating building simulation codes, including general methods of selecting appropriate modelling resolutions and tool(complexity) selection, emphasis on the on resolution analysis and the influence of the modelling bias in particular is required.
Graduation project for the Sustainable Energy Technology Master Program

Department of the Built Environment
Group of Building Physics and Services

Den Dolech 2, 5612 AZ
Eindhoven
P.O. Box 513, 5600 MB
Eindhoven
The Netherlands
www.tue.nl

Illustration: wordle of main report text (http://www.wordle.net/ - 2012)

*Where innovation starts*