

MASTER

**Learning from real buildings
building performance evaluation and improvement : a case study**

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MASTER THESIS | EINDHOVEN UNIVERSITY OF TECHNOLOGY

LEARNING FROM REAL BUILDINGS

Building Performance Evaluation and Improvement: a Case Study

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SUMMARY

Though both methodological and practical references are available, current building performance evaluation still requires further discussion in terms of coverage of stakeholders and identification of proper building performance indicators. Consequently, the following research question is put forward: How to systematically evaluate and improve a building's performance with the assistance of standardized building assessment methods and building simulation tools?

The basic concept of the project is to perform a case study of a real building so that the process of a complete building evaluation can be demonstrated and the sensitivity of different parameters and design scenarios can be tested.

The building evaluation indicates that the building is performing well in energy consumption, since it fulfills the expectations of the building operators and is better than average Dutch office buildings and most buildings in the *HOPE* database. However, in terms of design quality and indoor environment, some design deficiencies have been pointed out in open space offices and some performance indicators fail to meet the requirements of the building management or occupants.

In the second part of the project, sensitivity studies are made to evaluate how the differences between design and as-built situation may influence the accuracy of building performance predictions in the design phase. Vabi 114, the simulation tool used during design, is employed for the assessment. Based on the original design model, two models are developed for further analysis: the modified design model which corrects the irrational settings and the as-built model which can reflect the actual indoor environment. As the results indicate, improper weather data, wrongly estimated internal gain, incorrect heating and cooling capacity may influence the accuracy of the prediction on indoor environment and productivity. However, when it comes to other aspects like circulating flow in air-handling units and heat pumps, minor influence is found.

In addition, design scenarios of four indoor environment aspects are evaluated in terms of energy use and productivity. Compared with the increased energy use, an improved environment can bring more profit, which proves that productivity should be considered as an important performance indicator.

Key words: *Building Performance, Post-occupancy Evaluation, Indoor Comfort, Energy, Productivity*

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1

INTRODUCTION

1.1 Background

There is a growing awareness on the importance of building performance, since buildings consumes over 40% of national energy uses in most developed countries (ASHRAE, 2010) and the indoor environment is closely related to occupants' physical well-being and productivity (REHVA, 2006). However, though nowadays many buildings are described as 'low energy' or 'high performance', it is not always clear on what evidence these judgments are based, which leads to limited value of such claims.

To facilitate objective evaluation and comparison of buildings' performance, several scientific efforts have been made to establish standardized building performance evaluation methods. For instance, ASHRAE emphasized the necessity of standardized protocols that can coherently assess the building's performance and in 2010, together with USGBC and CIBSE, they proposed a set of building performance measurement protocols which were developed at three levels (basic, intermediate and advanced) for each of six building performance categories (energy, water, thermal comfort, indoor air quality, lighting and acoustics). These protocols aim at more secure energy supplies as well as reduction of energy costs, energy demand and carbon emissions (ASHRAE, 2010).

Furthermore, a number of practical projects have been executed to investigate the real buildings' performance. On European level, the *HOPE (Health Optimization Protocol for Energy-efficient Buildings)* project was conducted from 2002 to 2005. With checklists addressing the building characteristics and questionnaires enquiring the occupants' perceived health and comfort inside the buildings, in total 164 buildings of 9 countries were investigated (Bluyssen *et al.*, 2011). The outcome showed that perceived comfort can be influenced by personal, social and building factors and their inter-relationship is complex. On UK level, a research project named *Probe (Post-occupancy Review Of Buildings and their Engineering)* undertook surveys in 16 British buildings with normative questionnaires and reporting method. This study concluded that chronic problems that may lower occupants' perceived comfort and performance were still prevalent in the buildings investigated. Lessons learned through this project were summarized and factors that may contribute to a successful building design were listed (Leaman, 1999).

In summary, both methodological and practical references are available for building performance evaluation. However, with regard to existing references, the methodology may require further discussion in terms of coverage of stakeholders and indication of building performance. This will be further explained in *Chapter 1.2*.

1.2 Problem Definition

A literature research has been performed as part of this project, which summarizes the background information on building performance evaluation, available evaluation methods and demonstrates several case studies. This gives insights to this practical project.

The Federal Facilities Council (2001) put forward the concept of ‘stakeholders in buildings’, which refers to people who have specific concern and objectives on a building. For a commercial building, stakeholders include investors, operators, designers, contractors, maintenance personnel and occupants. *Figure 1* lists ‘stakeholders’ of a building and indicates their concerns towards the building.

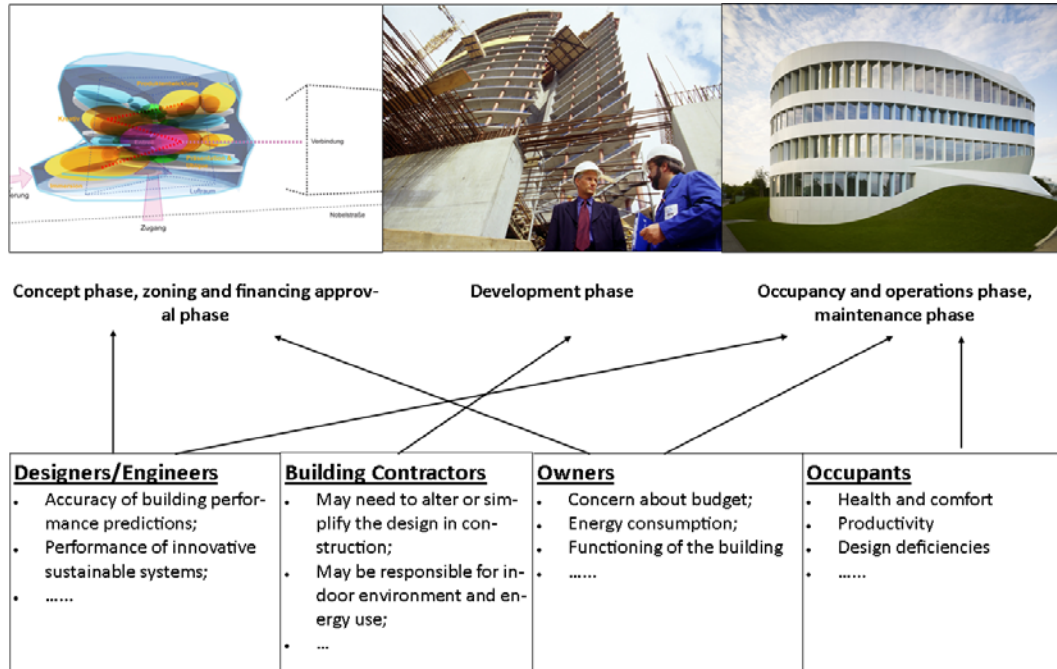


Figure 1. Different stakeholders of a building and their concerns (picture source: UNStudio.com and Tommypoconstruction.com)

To make an all-around evaluation, it is requisite to take different stakeholders related to the building into consideration. For projects like *HOPE* and *Probe*, the methodology was to employ the same evaluation methods in different buildings and get feedback. As such investigations were mostly conducted on the building site, the information and data source was limited to occupants and building operators. Hence, the link between design and as-built situation might be ignored. For instance, building simulation tools are usually used in design phase to predict the building’s performance on indoor climate and energy use. However, as designers have limited feedback with respect to real building’s performance, disparity may exist between predicted and as-built performance (Menezes *et al.*, 2012). There have been researches that try to develop calibrated models whose outputs closely match the measured data, which can provide benefits to both designers and managers (Pan *et al.*, 2007). For designers, various design scenarios can be compared; for facility managers, actual building performance can be better evaluated and potential measures which can be employed to improve the building performance can be tested.

In addition, with respect to data processing, the performance of a building is mostly indicated by indices for health, comfort and energy consumption. However, another important indicator, productivity, is often ignored or treated simply. For instance, in the *HOPE* project productivity is assessed by one subjective question and only rough qualitative evaluation is made. Recent researches have revealed that

the economic cost of a deteriorated indoor environment on productivity is high. For instance, a research conducted by Hassen (2000) showed that 80% of the life cycle cost of an office building is salary costs while the HVAC installation and running costs are less than 6% (see *Figure 2*). Moreover, In *Figure 3*, a comparison is made between the staff costs and energy costs in the building for the case study (denoted as 'Building X'). For the comparison, an assumption is made that the annual staff cost for each occupant is 30,000 €. The results show that the staff cost is around 100 times the energy cost in the operating year 2011. This further proves the importance of an improved indoor environment, since the increase of the investment for improving indoor climate can be paid back by a relative small increase in productivity.

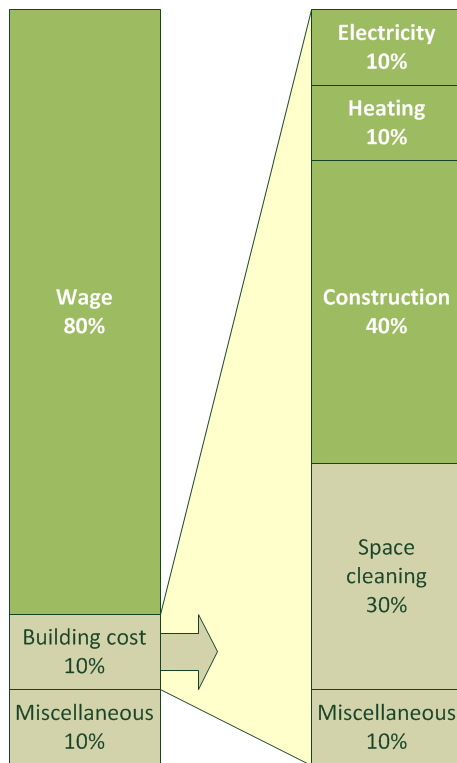


Figure 2. Relative significance of wage costs in relation to annual cost for an office building (Hanssen, 2000)

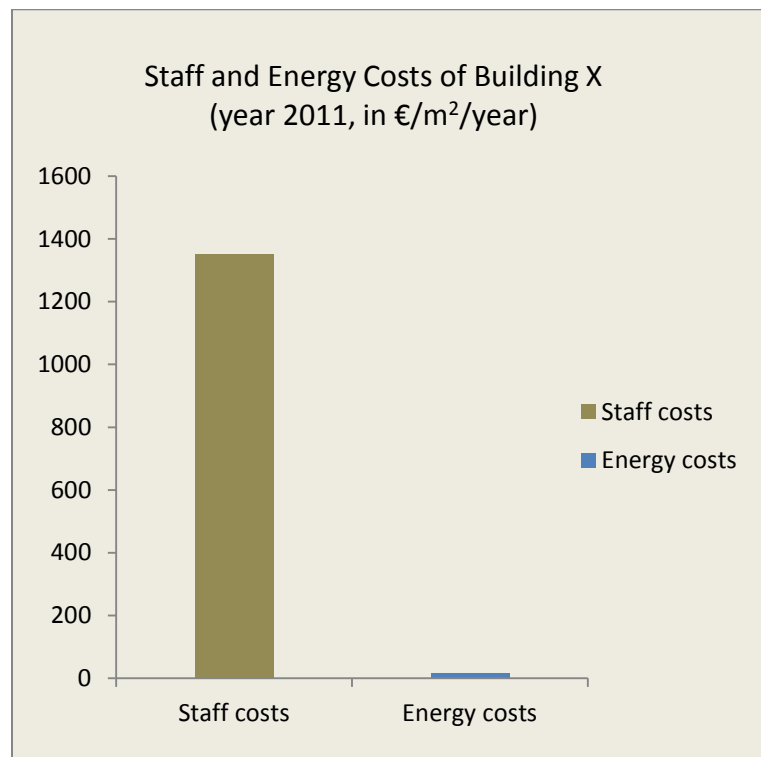


Figure 3. Comparison of staff and energy costs in Building X

Consequently, for a building performance evaluation, it is of practical value to probe into the following issues:

- **Design vs. As-built:** How to identify the differences between design and as-built situation; how these differences may influence the accuracy of predictions on the indoor environment, energy consumption and productivity in design phase;
- **Productivity studies:** Evaluate the cost effectiveness of different design scenarios while taking indoor environment, energy consumption and productivity into consideration. Here the design scenarios refer to possible settings which may influence the building indoor environment and energy consumption, e.g. set-temperature (REHVA, 2006) and illuminance level (Jin *et al.*, 2012).

For this project, these topics will be integrated into a real building’s performance evaluation and analysis by means of case study.

1.3 Research Question

Based on the discussion hereinbefore, the following research question is put forward:

How to systematically evaluate and improve a building’s performance with the assistance of standardized building assessment methods and building simulation tools?

To answer the research question, the project is divided into two parts: building performance evaluation and sensitivity studies.

The building evaluation covers three aspects of the building performance, namely design quality, indoor environmental quality (IEQ) and energy performance. Description of these aspects is given in *Table 1*.

Table 1. Description and involved stakeholders of the evaluation

Topic	Involved Stakeholders
Design quality: Whether there are designs that may cause inconvenience and interference to the occupants?	Designers (e.g. layout) Occupants
IEQ: How is the quality of the indoor environment? Whether the IEQ has negative effects on occupants’ perceived health and productivity?	Occupants Building managers
Energy Performance: Whether the energy consumption is acceptable and how is the building performing compared with other similar buildings?	Building managers Designers (e.g. sustainability)

The sensitivity studies deal with the proposition of incorporating design and productivity into building performance evaluation. With the assistance of building simulation tools, it is feasible to evaluate the influences of the differences between design and as-built situation as well as testing various design scenarios.

1.4 Structure of the Report

After this introduction, the methodology applied to the project is explained in *Chapter 2*. This part deals with how the building performance will be evaluated and how sensitivity studies will be performed. In addition, information about the building for the case study is given. Then results and discussion will be made for building evaluation and sensitivity studies respectively in *Chapter 3* and *Chapter 4*. Conclusions are drawn in *Chapter 5*.

Several appendices are attached to the end of the report, which covers information on:

- Analysis of the design model and development of the calibrated model;
- Theory on productivity;
- Some additional information with respect to this project.

Structure of the report is shown in *Figure 4*.

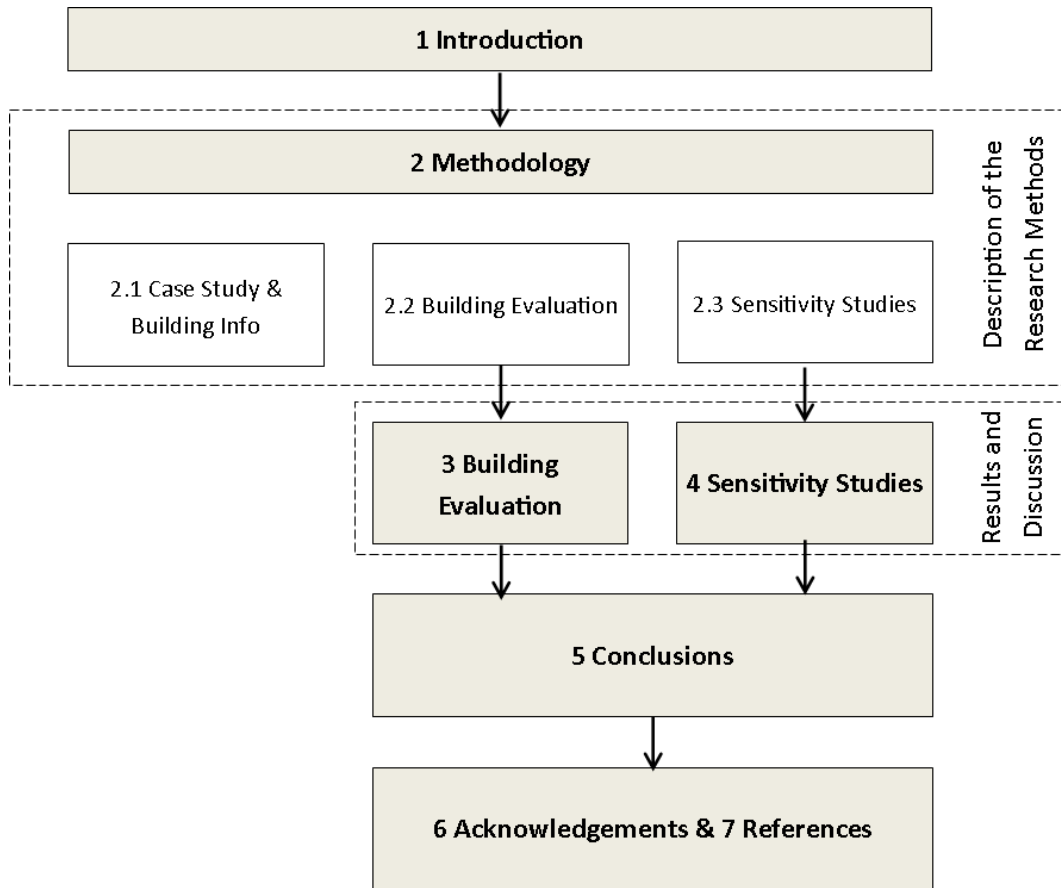


Figure 4. Structure of the report

2

METHODOLOGY

The basic concept of the project is to perform a case study in a real building so that the process of a complete building evaluation can be demonstrated and the sensitivity of different parameters and design scenarios can be tested. Expected outcomes include a complete building performance evaluation and suggestions aiming at improving the design quality as well as the building's performance.

Accordingly, the methodology is divided into three parts: information about the building for case study, introduction to the building evaluation process and the scope of sensitivity studies. Essential background information is provided as well for each part.

2.1 Case Study and Building Information

An available real building is the prerequisite of building evaluation and data analysis. For this project, a case study will be performed in a real building (denoted as '*Building X*' in following) in the Netherlands.

In this section, firstly practical information about the building itself, which is categorized into building, floor and room levels, will be given. Then there is an introduction to the design and management of the building.

2.1.1 Building Information

Building X is an 85-meter-high building with a floor area of about 45,000 m² which accommodates around 2,500 workstations. There are both cell offices and open space offices. The cell offices are located along the west and east façade of the building while two open space offices are situated at the north and south end of each floor respectively. Functionally, there is recreation space, meeting rooms, kitchens and data centers besides offices.

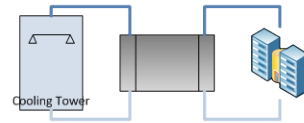
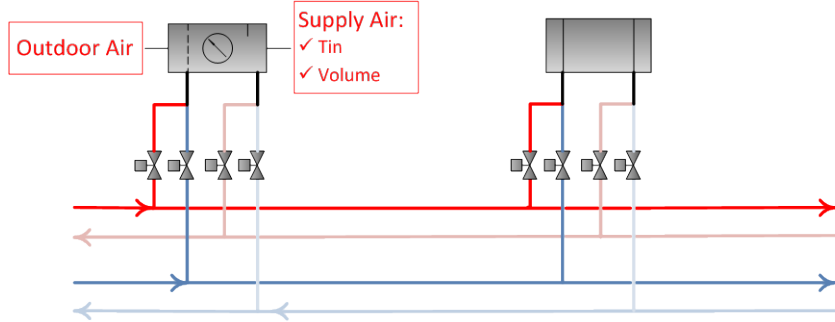
In respect of energy issues, the building uses an aquifer system for long term thermal energy storage, which provides a majority of the heat and cold required by the air handling units and heat pumps. Besides, a boiler using natural gas is incorporated as complementary heating source and dry coolers are used to provide free cooling to data centers when possible. The HVAC system is summarized in *Figure 5* and *Figure 6*.

4 Air Handling Units
 AHU 1-3 (for high-rise)
 AHU 4 (for low-rise)

3 Heat Pumps
 Heat pump 1 and 2 (for concrete core activation)
 Heat pump 3 (for convectors)

Cooling machine (with dry coolers)

Provides cooling to data center/server rooms



Boiler (using natural gas)

As a supplement heating equipment to heat pumps

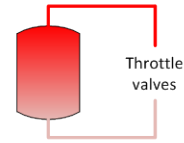


Figure 5. HVAC system for the building



Figure 6. HVAC terminals and control systems in Building X

- (a) Overview
- (b) Raised floor ventilation
- (c) Convectors
- (d) Thermostat
- (e) Operable windows and solar blinds

	b	c
a	d	e

At room level, concrete core activation is the primary terminal system for heating and cooling while convectors are responsible for the required additional heating. Raised floor ventilation is applied for the sake of flexibility and high comfort level. On personal level, various control strategies like operable windows, solar blinds and thermostats offer occupants the possibility to influence the indoor temperature and air quality.

2.1.2 Design and Management

In this section, information on design and management of the building will be introduced. This covers the requirements designers aimed at during the design phase and the targets building operators should fulfill for management, which provides input for the case study as well.

2.1.2.1 Building Design

According to the research question, models that were used to predict indoor environment and energy consumption in design phase are reviewed.

Vabi 114 (Vabi) is the simulation tool employed to predict the indoor environment during design phase. In total four models were developed and they cover four orientations and both types of offices (cell offices at west and east façade, open space offices at north and south façade). Quality of the indoor environment is indicated by the number and degree of severity of overheating and undercooling hours according to the Adaptive Temperature Limits in Dutch thermal comfort guidelines (van der Lindena *et al.*, 2006).

In light of the guideline, two types of building are defined: Alpha buildings in which occupants have sufficient adaptive opportunities to influence the indoor climate and Beta buildings in which limited adaptive opportunities are presented (van der Lindena *et al.*, 2006), see *Figure 7*. For *Building X*, the cell offices can be treated as Alpha type while open space offices are defined as Beta type. This judgment is made based on the occupants' access to control strategies, e.g. operable windows and thermostats. In cell offices occupants have the opportunity and freedom to adjust the individual environment while in open space offices where several occupants work in a limited space, the access is limited due to different people's preferences.

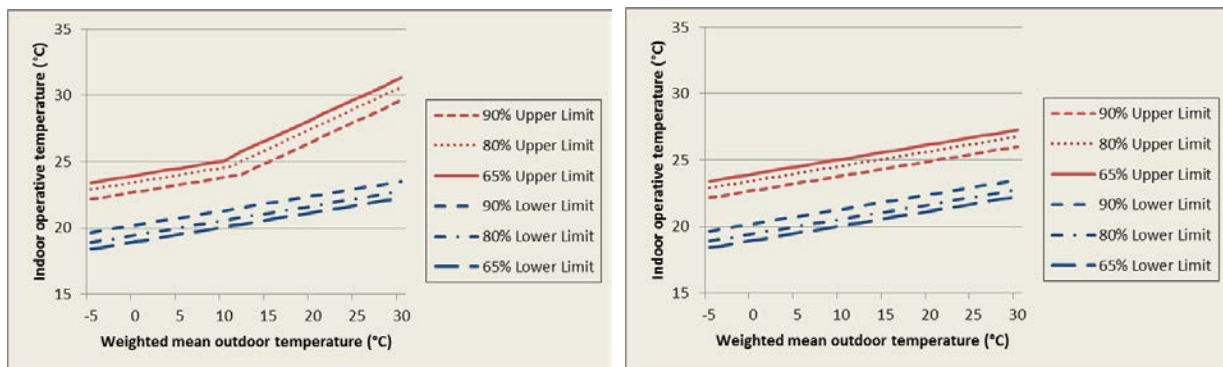


Figure 7. Adaptive temperature limits for Alpha (left) and Beta buildings (right). Revised according to van der Lindena *et al.* (2006)

Figure 7 illustrates the adaptive temperature limits for both Alpha and Beta buildings. According to *Output Specifications*¹, the indoor temperature should stay within the boundary of 80% acceptability, which indicates the indoor climate is 'good'.

Energy consumption was estimated with empirical formulas for building management. The calculation process was conducted in Excel and is in line with the methods proposed by ASHRAE (2009). The energy consumption was estimated on yearly basis and it is used to monitor the building's energy performance.

2.1.2.2 Building Management

During actual management, several means are employed to ensure *Building X* is performing under acceptable conditions. For instance, to ensure the performance targets are fulfilled and occupants are satisfied with the indoor environment, several indoor environment parameters are measured and monitored while complaints from the occupants are registered. In respect of energy use, running statuses of building services systems are monitored and monthly energy consumption on electricity, natural gas and water are recorded. Details of these approaches are extended in this section.

For indoor environment quality, during the building management, in total 21 aspects should fulfil corresponding requirements according to the *Output Specifications*. Their performance is evaluated by means of inspection, measurements, etc. A list of these aspects is shown in Figure 8. In general, these aspects can be divided into four areas: indoor air quality, visual comfort, thermal comfort and acoustic comfort.

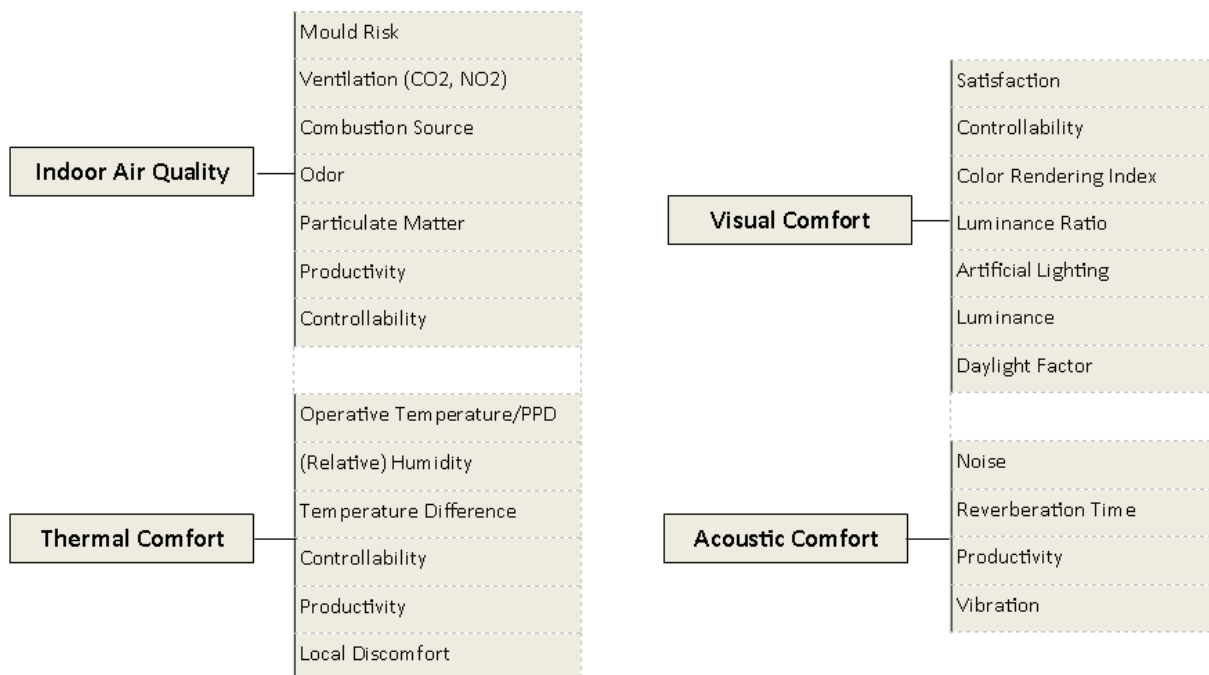


Figure 8. Aspects that should be covered in the management

¹ Output Specifications: This is a series of documents that indicate what building performance the managers should achieve during building management.

In addition, complaints from the occupants are recorded through the building management system. These complaints are also the reference for the building managers to regulate the indoor environment. Five types of complaints are recorded: thermal, acoustic, visual, hygric discomfort and dissatisfaction over air quality. *Table 2* gives an example of what information is included in the registration.

Table 2. Example of the complaints registration

Item	Log	Remark
Date and time reported	10:45, 16/January/2012	Three categories of complaints are differentiated according to the degree of severity: A: Immediately resolvable B: Limited research needed C: Specialist research needed
Deadline	10:45, 17/January /2012	
Date and time solved	16:50, 16/January /2012	
Concerns / Description	N0.55 is cold there	
Location	N0.55	
Standardized notification	interference thermal conditions	
Category	A	

For the energy consumption, besides the monthly recorded energy consumption, in *Building X*, the building services systems (e.g. flow rate and running statuses) and some indoor environment parameters (e.g. indoor temperature) are monitored by the Building Management System. The monitored data can also provide input for the analysis of the building performance. For the building services systems, parameters like flow rate and flow temperature are monitored for fault detection, but few data have been recorded; for indoor environment parameters, e.g. temperature and CO₂ level, they are monitored at each floor but only some historic data have been stored.

In summary, information is available in terms of building design, operation and management, which provides sufficient input to probe into the research question. However, the information should be structured in a way that based on which clear and convincing evaluation and analysis can be performed. This will be explained in *Chapter 2.2* and *2.3*.

2.2 Building Evaluation

As first part of the case study, the building's performance was evaluated and its merits and deficiencies were indicated. Methods and process of the evaluation are described in this section.

2.2.1 Evaluation Methods

A literature research has been performed beforehand in order to select appropriate building evaluation methods. In this section, a brief introduction will be given to methods that have been employed in this case study. To give a clear presentation of the information, the methods are divided into two categories, i.e. post-occupancy evaluation and building assessment.

2.2.1.1 Post-occupancy Evaluation

Post-occupancy evaluation (POE) is the process of evaluating an occupied building's performance by systematically assessing human response to the indoor environment (Federal Facilities Council, 2001). In this project, POE refers to evaluations that assess occupants' subjective perception towards the building performance. Two methods, namely questionnaires and complaints registration, are used.

Questionnaires: For *Building X*, a revised *HOPE* questionnaire was used for a questionnaire survey, in which two types of questions are included.

- Questions related to perceived comfort. 7-point-scale questions are used to numerically indicate occupants' degree of satisfaction (Bluyssen *et al.*, 2011). As this questionnaire employed the same rating method with the *HOPE* questionnaire, it is possible to compare the attained results with buildings in the *HOPE* database. *Figure 9* shows how this type of question looks like.

The image shows a 7-point scale for perceived comfort. The title is "Temperature in winter". Below the title, there are seven numbered boxes (1 to 7) representing the scale. The word "Comfortable" is written to the left of box 1, and "Uncomfortable" is written to the right of box 7.

Figure 9. Example of questions on perceived comfort (HOPE, 2005)

- Questions related to personal, building and social aspects. Open questions were used to identify whether design deficiencies exist in the building.

For the survey, in total 30 questionnaires were answered by respondents. Most of the questionnaires were distributed in or near the open space offices of various floors. Every respondent gave feedback on the evaluation of the perceived comfort. For the open questions, around 60% of the respondents provided their comments (Boerstra, 2012).

Complaints registration: As described in *Chapter 2.1.2.2*, the complaints are recorded. For the case study, they are helpful in digging out more information about occupants' perception towards indoor environment. For instance, it can be linked with the outcomes of questionnaires and measured building performance data. This coupling of information facilitates further analysis of the building performance.

2.2.1.2 Building Assessment

For the case study, building assessment was done by employing three methods that can objectively record the building's characteristics and performance. These methods include building inspection, commissioning and measurements.

Building inspection: the *HOPE* checklist is used to record *Building X*'s characteristics. It provides an all-round and standardized overview on the building design, installations and energy use. In addition, suggestions are given for building management (e.g. recommendation on the maintenance of the HVAC installations) and options are listed for problem identification (e.g. sources of noise, see *Figure 10*).

Principal relevant performance criterion	Checklist item (with TOBUS reference link where available)	Options / Scales
Acoustics	Are there any nearby noise sources outside the building that might influence the indoor environment?	<input type="checkbox"/> None <input checked="" type="checkbox"/> Car parking close to the building <input type="checkbox"/> Busy road <input checked="" type="checkbox"/> Railway or station <input type="checkbox"/> Air traffic <input type="checkbox"/> Sea, river or canal traffic <input checked="" type="checkbox"/> Building, construction etc. (Demolishment) <input type="checkbox"/> Sports events <input type="checkbox"/> Other entertainment or leisure <input type="checkbox"/> Factories or works <input type="checkbox"/> Other commercial premises <input type="checkbox"/> Forestry, farming etc. <input type="checkbox"/> Community buildings (halls, churches, etc.) <input type="checkbox"/> Other (specify)

Figure 10. Possible source of noise in HOPE checklist

Commissioning: Commissioning is a process for achieving, verifying, and documenting the performance of facilities, systems and assemblies to see whether they meet defined objectives and criteria (ASHRAE, 2007). As mentioned in *Chapter 2.1.2.2*, the Building Management System is used to detect fault in operation and can provide data for analysis on the building performance.

Measurements: For *Building X*, measurements have been done by environmental consultants according to the requirement of the *Output Specification*. In addition, building management system monitors or records key data of the building system and indoor environment. Consequently, for the case study, besides site-measurements, data collected by consultants and building management system will be reviewed and employed. Hence data validation is required to test and verify whether the data can indicate the indoor environment accurately. This has been done by comparing the used measurement tools, methods and data processing with standardized protocols.

With respect to the energy consumption, monthly energy consumption (electricity, water and natural gas) is available and will be used for analysis.

2.2.2 Evaluation Process

Design quality, indoor environment quality and energy consumption are evaluated in the project. For each topic, a general evaluation process is developed and followed: Firstly, both post-occupancy evaluation and building assessment are conducted to evaluate the performance. Then the results are compared with corresponding performance targets (for building assessment) or benchmarked with similar buildings (for POE). If some aspects fail to meet the performance targets or have caused notable dissatisfaction among the occupants, then the reasons are analyzed and proper follow-up actions will be taken to improve the building performance. This process is illustrated in *Figure 11*.

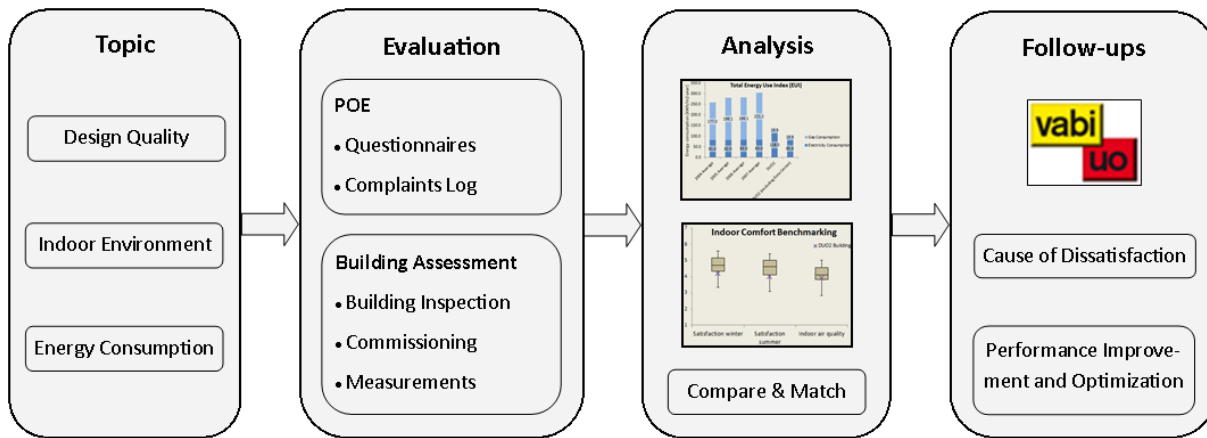


Figure 11. The evaluation process

However, with respect to each topic, details may differ in application. In this section, specific evaluation process for each topic is explained respectively.

2.2.2.1 Design Quality

The process of design quality evaluation is shown in *Figure 12*, the evaluation deals with the following research topics:

- What suggestions have been pointed out by the occupants with respect to design?
- Are these suggestions general or specific cases?

Evaluation	Analysis	Follow-ups
Questionnaires (Open questions)	Feedback	Suggest possible changes

Figure 12. Evaluation process for design quality

There is no specific question enquiring occupants' attitude towards the design; however, open questions (e.g. 'List 3 things you want to change in this building') are used to receive the occupants' feedback. In total 40 suggestions were received,

According to the occupants' feedback, suggestions that aim at improving the design quality will be evaluated. Aspects that have caused prevalent dissatisfaction among the occupants are filtered by the number of corresponding feedback. Later suggestions can be made.

2.2.2.2 Indoor Environment Quality

The evaluation process of indoor environment quality is shown in *Figure 13*.

Evaluation	Analysis	Follow-ups
Questionnaires; Complaints Registration; Building Inspection; Measurements.	Listen to the feedback from occupants; Compare the building performance with expectations/requirements.	Suggest possible changes; If necessary, try to improve or optimize the performance (e.g. with building simulation tools).

Figure 13. Evaluation process for IEQ

In this project, each aspect of indoor environment, as defined in *Figure 8*, has been evaluated by both post-occupancy evaluation and building assessment respectively. *Figure 14* shows an example of the scheme for IEQ evaluation, in which the following information is included:

- Category the aspect belongs to;
- Performance targets or requirements during the building management;
- The employed evaluation methods and corresponding results.

Category	Indicator	Requirements	Results	
			Measurements/observations	Occupants' perception
Indoor air quality	Mould growth risk	Evaluation on the surface of building components; Microbiological values: Minimum class 'good'. <i>(Reference: Microbiologische waarden CAG)</i>	Simple: Review <input checked="" type="checkbox"/> A: Excellent, no mould or wet surfaces, no moisture sources. B: Good, no mould or wet surfaces, present moisture sources not problematic. C: Adequate, no mould or wet surfaces, present moisture sources are acknowledged. D: Acceptable, surface wetness observed, but risk for mould growth just acceptable. E: Poor, surface wetness and/or complaints indicating mould growth related health problems observed.	

Figure 14. Example of the evaluation scheme for IEQ

By this means, comprehensive evaluation can be performed and it is convenient to identify whether discrepancy exists between subjective evaluation (POE) and objective evaluation (building assessment). According to the results, these aspects can be classified into four categories:

1. Fulfill the performance target and few dissatisfaction is expressed by occupants;
2. Fulfill the performance target but slight dissatisfaction has been expressed by occupants;
3. Aspects fail to meet the performance target and improvements are required;
4. Fulfill the performance target but obvious dissatisfaction is reported by occupants.

More detailed information and analysis about indoor environment quality is given in *Chapter 3.2*.

2.2.2.3 Energy Performance

The evaluation of energy consumption follows the Performance Measurement Protocols proposed by ASHRAE (2010), in which three levels of assessment are differentiated (see *Table 3*). The following two questions are to be addressed:

- Does this building fulfill the expectations in energy use?
- How is the building performance compared with similar buildings?

Table 3. Three levels of energy performance assessment according to ASHRAE (2010)

	Basic	Intermediate	Advanced
Description	Basic energy-related building/system characteristics	Specific energy-related building/system characteristics	Detailed energy-related building/system characteristics
Period of data	Monthly and annual	Monthly, weekly and possibly daily	Daily and hourly
Level	Whole-Building	System and end-uses	System and end-uses
Objectives	Benchmarking with rating tools	Performance improvement	Comprehensive performance evaluation

Due to limited information, only the basic protocol is applied for the evaluation of *Building X*'s energy performance. Two indices, namely annual energy use index and energy cost index, are required for the benchmarking. These indices are defined as follows:

$$\text{Total Energy Use Index (EUI)} = \frac{\text{Total Annual Energy Use}}{\text{Gross Floor Area}} \left(\frac{\text{kWh}}{\text{m}^2 \cdot \text{yr}} \right)$$

$$\text{Energy Cost Index (ECI)} = \frac{\text{Net Annual Energy Cost}}{\text{Gross Floor Area}} \left(\frac{\text{€}}{\text{m}^2 \cdot \text{yr}} \right)$$

For the benchmarking process, energy information of Dutch office buildings (Agentschap NL, 2012) and HOPE database (HOPE, 2005) are used. This database is chosen since:

- 75% Buildings in the database are low-energy buildings;
- The buildings are of the same type;
- Building information is reported, which facilitates further analysis and comparison.

2.3 Sensitivity Studies

For this project, sensitivity studies deal with the proposition of incorporating design and additional performance indicators into building performance evaluation. That is, design models will be employed in the studies and productivity is introduced as a supplement indicator to indoor temperature and energy consumption. The following issues are covered:

- How the differences between design and as-built situation may influence the accuracy of building performance prediction;

- Evaluation of design scenarios on the basis of indoor environment, energy use and productivity.

It is notable that for this case study, simplified approaches are applied for the sensitivity studies. When evaluating the differences between design and as-built situation, only the values in design phase and actual situation are used and compared.

Productivity is a relatively uncommon indicator compared with temperature and energy use, so firstly there will be an introduction to theories of productivity calculation. Then simulations and calculations that are to be performed in this case study will be explained.

2.3.1 Theory on Productivity

2.3.1.1 Background

For this project, productivity is introduced as an economic indicator of the indoor environment. As shown before, wage costs significantly outweigh the HVAC installation and running costs in the life cycle analysis of an office building, which indicates that large economic benefits can be achieved by improving the indoor environment quality (Fisk, 2000).

The occupant productivity in working can be affected by various factors, e.g. working environment, the ability to perform a job and personal motivation (Brothers, 1997). The working environment comprises indoor climate (e.g. temperature, ventilation, noise and lighting level) and facility services (e.g. cafeteria, mail services, workstation layout, landscaping). Specifically, influence of indoor climate will be the focus for this case study.

2.3.1.2 Theory

Productivity can be measured by different means: physiologically, objectively, or subjectively (Ilgen & Schneider, 1991). To facilitate further analysis, calculations or measurements that can objectively evaluate the productivity are mainly referred to. There have been researches that aim at establishing the quantitative relationships between indoor environment and occupant productivity. Two of them, conducted by REHVA (2006) and Jin *et al.* (2012) respectively, are explained in detail in *Appendix 2*. Here a summary is given.

REHVA (Federation of European Heating and Air-conditioning Associations) summarized the state-of-the-art researches that describe the effects of indoor environment on productivity. In their Guidebook (2006), research on how productivity can be influenced by indoor temperature and air quality is summarized. In respect of temperature, 22 °C is deemed as the reference temperature at which maximum productivity can be achieved; it also suggests that the performance drops about 1% for every 1 °C change of temperature. On the other hand, ventilation rate is linked with sick leave and productivity during work. A quantitative relationship between ventilation rate and short-term sick leave was estimated combining published field data and a theoretical model in which sick leave or short-term illness were outcomes (Fisk *et al.*, 2003). The relationship indicates that higher ventilation rate leads to lower relative prevalence of sick leave. Furthermore, Seppanen *et al.* (2006) developed the relationship between ventilation rate and task performance based on seven studies. According to the model, the increase of ventilation rate can lead to higher productivity.

On the other hand, Jin *et al.* (2012) linked two independent studies undertaken by Wong *et al.* (2008) and Kawamura *et al.* (2007) and put forward a model that can evaluate the occupant productivity based on overall IEQ. The methodology applied was to establish quantitative relationship among three concepts related to indoor environment and productivity, namely acceptance of indoor environmental quality (IEA), satisfaction with indoor environment (IES) and self-assessed productivity (SP).

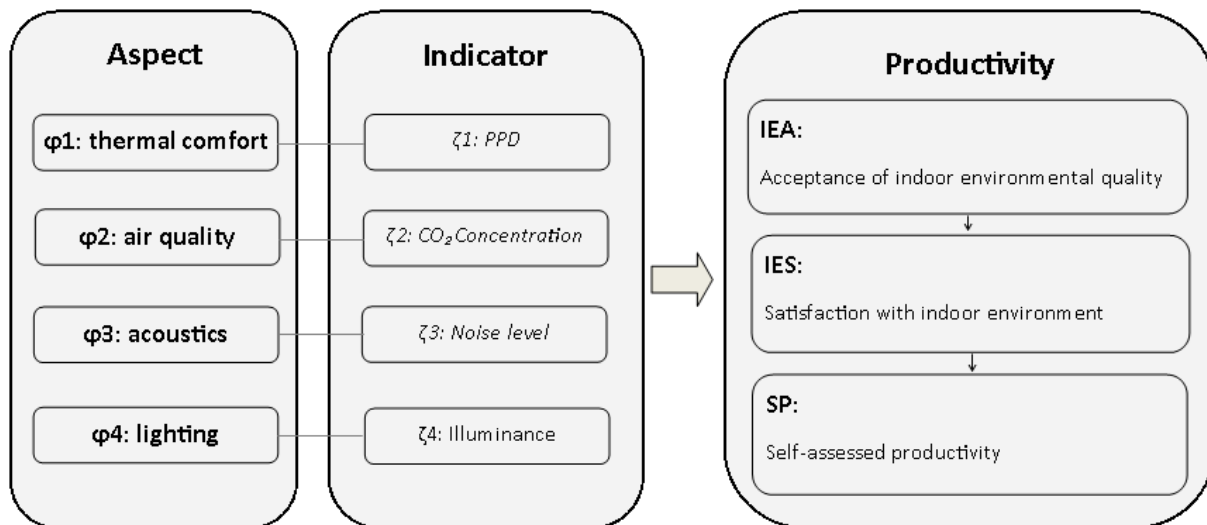


Figure 15. Calculation of productivity on the basis of indoor environment indicators

As Figure 15 illustrates, with four indicators representing the indoor environment, it is possible to calculate the occupants' acceptance of indoor environmental quality (IEA), then based on mathematical transitions, satisfaction with indoor environment (IES) and subsequently occupants' self-assessed productivity (SP) can be obtained.

However, though a quantitative relationship has been established between indoor environment indicators and productivity, it is not directly applicable to calculate productivity with this approach for this case study, since:

- The validity of the link between IEA and IES is not fully tested (Jin *et al.*, 2012);
- According to the calculation of IEA, for each indicator, the acceptance must be lower than 0.95 (95%). However, this is not applicable since some researches have indicated that acceptance higher than 95% can be achieved in real buildings, e.g. when the CO₂ concentration is limited to 500 ppm, occupants' acceptance towards indoor air quality can be as high as 97.6% (Wong *et al.*, 2008)

Consequently, for this case study, when Jin *et al.*'s approach is applied, only the IEA is used to evaluate occupants' perception towards the indoor environment. This can be regarded as an indirect indication of the occupants' productivity.

2.3.1.3 Selection of Methods

Table 4 lists the indicators that are required to predict the productivity inside offices. It is notable that different indicators are employed in the two methods so that it is requisite to analyze the applicability of the indicators for the project.

According to the building management, temperature data are stored and ventilation rate is already known, which makes it possible to use the REHVA methods for thermal comfort and air quality analysis. On the other hand, PPD and CO₂ concentration are used by Jin *et al.* but the information is not available for *Building X*. For acoustic and visual comfort, REHVA guidebook doesn't provide further information on the calculation but Jin *et al.* have put forward relationships that are applicable for the case study.

Table 4. Indicators of two evaluation methods

	Thermal comfort	Air quality	Acoustics	Lighting
REHVA	Temperature	Ventilation rate	Not available	Not available
Jin <i>et al.</i>	PPD	CO ₂ concentration	Noise level	Illuminance

Consequently, for the productivity studies, the REHVA methods will be used to discuss the influence of thermal comfort and air quality. Jin *et al.*'s method will be used for acoustics and lighting, but only acceptance will be calculated and analyzed.

2.3.2 Case Studies

The sensitivity studies comprise two parts:

Case Study 1: How the differences between design and as-built situation can influence the accuracy of predictions on indoor environment, energy consumption and productivity.

With respect to this case study, differences between design and as-built situation need to be identified firstly. As the building performance is predicted by Vabi 114, the identification process is accomplished by comparing the input with site measurements and data collected during building management. These differences may lie in building management (e.g. set-temperature), unknown parameters in design phase (e.g. heating and cooling capacities of HVAC components) and the use of empirical values (e.g. weather data).

In *Appendix 4*, input of the original design model is summarized. Further analysis reveals that the model has limited reliability when predicting the performance (see *Appendix 1*). Irrational settings of the design model are pointed out and two models, namely modified design model and as-built model, were developed for further analysis.

Modified design model: for this model, irrational settings are corrected and it can be used to predict the building performance. However, the model still cannot reflect the real building performance, since some parameters are unknown in the design phase and the used value may be different from as-built situation. Development process of this model is demonstrated in *Appendix 1*;

As-built model: based on parameters and data collected from actual building management, an as-built model is developed. Reliability of the model is tested by comparing the outcomes with measured data. Since a high similarity in temperature is shown, it is concluded that the modified model can be applied to test the influence of the differences in terms of indoor environment. Development process of the model is shown in *Appendix 1*.

The models used for this case study is listed and summarized in *Table 5*.

Table 5. Description of different models

Model	Abbreviation	Description
Original Design Model	ODM	Design model created by the design company
Modified Design Model	MDM	Original design model with set-point and irrational settings corrected
As-built Model	ABM	Modified model with values in as-built situation

To test the sensitivity of each parameter, four models will be used, namely:

- Modified design model (MDM);
- Modified design model with the tested parameters in as-built situation (MDM + Change);
- As-built model with the tested parameter in design value (ABM – Change);
- As-built model (ABM).

In this sense, the sensitivity of individual parameter on both modified design and as-built model can be reckoned. The reviewed outputs include indoor environment (overheating and undercooling hours), energy consumption (annual heating and cooling load) and productivity. This sensitivity study is performed for the open space offices near south façade. With respect to data analysis, the indicators for indoor environment and energy consumption can be read from the software directly and the productivity is calculated solely based on temperature.

In addition, for the overheating and undercooling hours of different levels, weighting factors are applied. Severity of the temperature is weighted proportional to the PPD. That is, when the PPD equals to 10%, the weighting factor is 1. Accordingly, the weighting factor is 2 and 3.5 respectively for overheating or undercooling hours that are between 65% and 80% satisfaction range and below 65%. The used models and performance indicators are summarized in *Figure 16*.

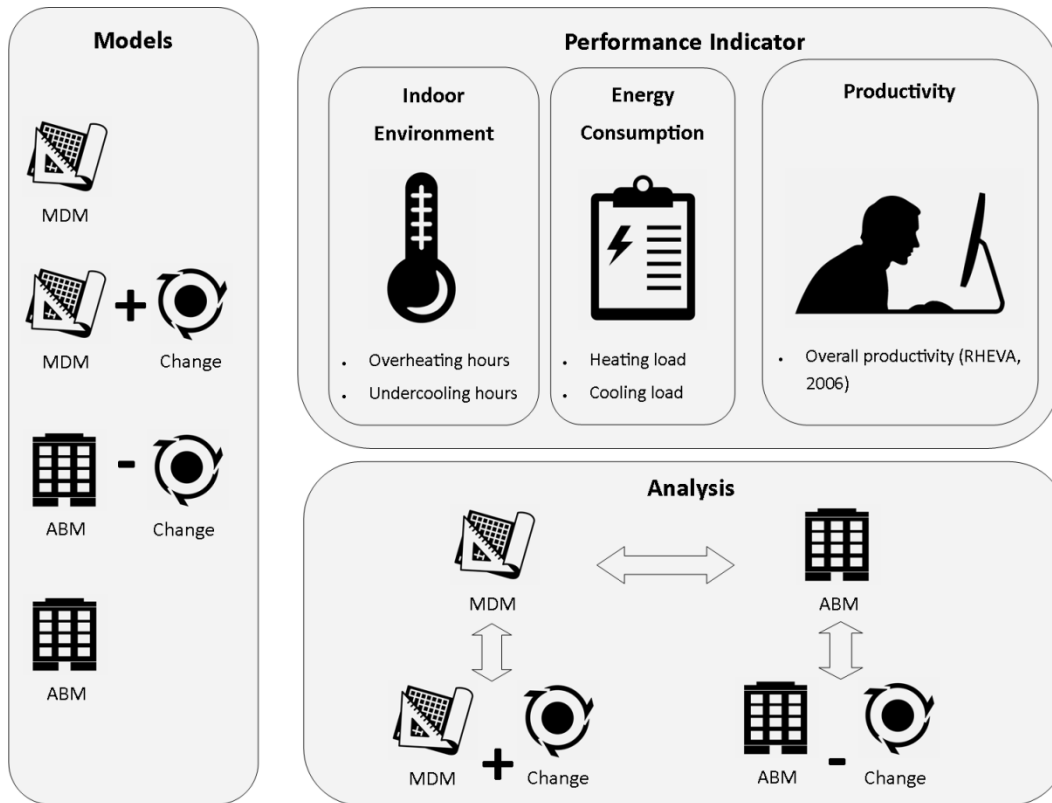


Figure 16. Applied models and performance indicators

2 Evaluate the cost effectiveness of different design scenarios while taking indoor environment, energy consumption and productivity into consideration.

Another issue to be addressed is to test how different design scenarios may influence the indoor environment, energy use and productivity. Aim of this study is to gain a deeper understanding of the economic relationship between traditional performance indicators (IEQ and energy) and productivity.

The sensitivity of four building indoor environment aspects will be tested:

- Thermal comfort
- Air quality
- Noise level
- Visual comfort

According to *Chapter 2.3.1*, the choice of certain indicators may influence the indoor environment and thus affecting the productivity in offices. *Figure 17* summarizes possible scenarios or the applicable range of these indicators for this case study, based on which simulations and calculations can be performed.

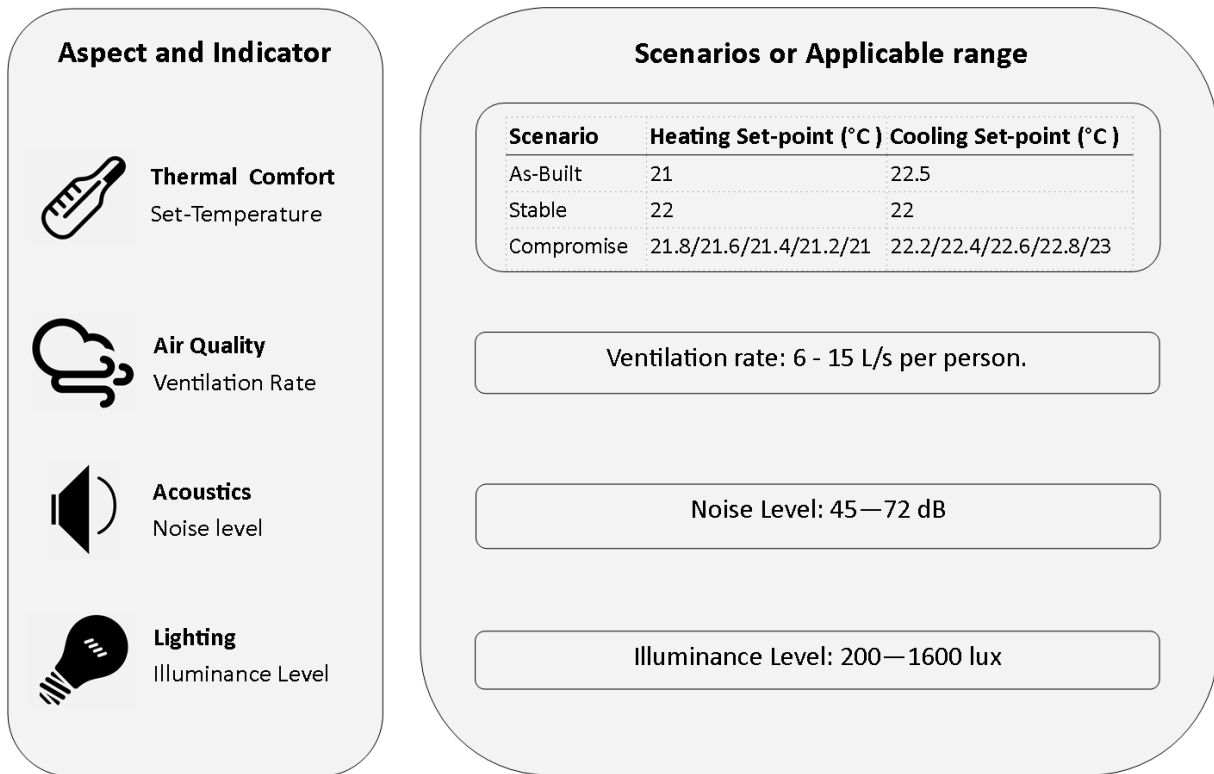


Figure 17. Scenarios for Sensitivity Study 2

For thermal comfort and air quality, the REHVA methods will be employed. By adjusting parameters (set-temperature and ventilation rate), different scenarios' influence can be compared.

With respect to acoustic and visual comfort, Jin *et al.*'s methods are applied. To test the sensitivity of one specific parameter, assumptions are made for other indoor environment indicators. Three concepts are defined: Optimal, Requirements and Actual Performance, see *Table 6*.

For the concepts of Requirements and Actual Performance, occupants' acceptance to each indoor environment aspect is calculated according to the requirements of *Output Specifications* and the measured data by the environmental consultants respectively. For the Optimal situation, the data from Jin *et al.* (2012) are used.

When testing the sensitivity of one parameter, the other parameters will remain the same. In this way, the specific parameter's sensitivity under different indoor conditions can be tested.

Table 6. Three Pre-defined Indoor Scenarios

	Thermal comfort		Air quality		Acoustic comfort		Visual comfort	
	PPD	φ_1	CO ₂ concentration	φ_2	Noise level	φ_3	Illuminance	φ_4
Optimal	5%	0.95	500 ppm	0.976	45 dB	0.971	1600 lx	1.00
Requirements	20%	0.8	660 ppm	0.962	55 dB	0.897	500 lx	0.854
Actual	20%	0.8	500 ppm	0.976	60 dB	0.817	750 lx	0.973

3

BUILDING PERFORMANCE EVALUATION

Building performance evaluation has been performed with approaches indicated by *Chapter 2.2.2* and *Figure 11*. In this chapter, results will be illustrated and discussion will be made for *Building X'*. The evaluation covers three aspects: design quality, indoor environment and energy consumption.

3.1 Design Quality

3.1.1 Results

The open question 'List 3 things you want to change in this building' is used to receive feedback on the design quality. In total 40 suggestions were received, see *Table 7*.

Table 7. List of suggestions

Category	Number of suggestions	Examples
Layout	14	More private space; Fixed workplace; Place for exercise; More colors on the wall; More plants
Thermal comfort	7	Better temperature regulation; Fast response of control; Higher temperature; Draught caused by diffusers
Indoor air quality	2	More fresh air
Acoustics	7	Less noise; Sound insulation
Lighting	1	Self-regulating lighting
Other	9	Radio, lockers, drawers etc.

According to the results, most suggestions are related to the office layout, which includes lack of privacy, monotonous design and dissatisfaction with the workplace. At the same time, feedbacks due to thermal comfort, acoustics and other (mainly due to insufficiency of necessities, e.g. lockers) have been received.

In respect of indoor air quality and lighting, few negative feedbacks are drawn.

3.1.2 Discussion

During the post-occupancy evaluation, most questionnaires were distributed in the open space offices, thus the results can reflect how occupants feel about the design in such areas. An overview of a typical work station is given in *Figure 18*.



Figure 18. Overview of the work station

Due to the fact that there is a relative higher occupant density in open space offices, it is reported that occupants' have limited controllability over the indoor temperature and air quality. According to the feedback, this can be caused by different occupants' preference. In addition, the large floor area of open space offices also leads to problems of slow response time of HVAC system, noise and lack of privacy.

Other research has also indicated that special care should be given to the design open offices. For instance, Roulet *et al.* (2006) concluded that open offices are perceived as less healthy, noisier and lack of privacy compared with cell offices.

During the questionnaire survey, design quality is not assessed directly. However, as the results show, the applied questionnaire can be used as a supplement to the building management. Firstly, more information can be derived from questionnaires compared with complaints registration; this is because complaints registration only covers certain areas of the indoor environment and the dissatisfaction towards other aspects, e.g. design quality, is not included. Secondly, even if some indoor environment indicators have been included in the complaints registration, questionnaires can provide information that the occupants are not likely to report to building managers, e.g. noise caused by other occupants' telephone calls in open space offices.

3.2 Indoor Environment

The evaluation on indoor environment deals with the following topic: how are the 21 aspects required by *Output Specifications* performing? According to the results of POE and building assessment, the aspects can be divided into four categories:

1. Fulfill the performance target and few dissatisfaction is expressed by occupants;
2. Fulfill the performance target but slight dissatisfaction has been expressed by occupants;
3. Aspects fail to meet the performance target and improvements are required;
4. Fulfill the performance target but obvious dissatisfaction is reported by occupants.

In this section, results are shown and will be discussed. A complete evaluation scheme is attached in *Appendix 7*.

3.2.1 Results

Category 1: Aspects that meet performance targets while little dissatisfaction is expressed by occupants. This category includes 12 out of 21 aspects. A list of these aspects is shown in *Figure 19*.

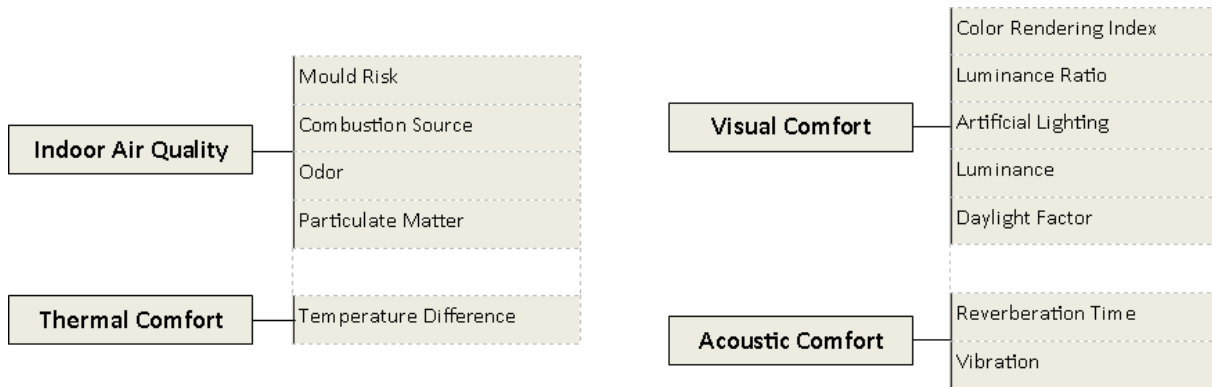


Figure 19. List of aspects in Category 1

Category 2: Aspects fulfill the performance target but some dissatisfaction has been expressed by occupants. This category covers four aspects:

- Humidity (e.g. dry eyes);
- Local discomfort (e.g. draught);
- Satisfaction of lighting (e.g. frequent lighting malfunctioning);
- Controllability of lighting (e.g. sometimes the lighting switches are difficult to find).

Category 3: Aspects fail to meet the performance target and improvements are required. Only one aspect is included in this category, which is noise. Measurements performed by environmental consultants have shown that for some internal walls, the sound insulation doesn't meet the performance target (some of these walls are indicated red in *Figure 20*) while occupants have expressed their dissatisfaction towards the noise in complaints registration and questionnaire (see *Table 8*).

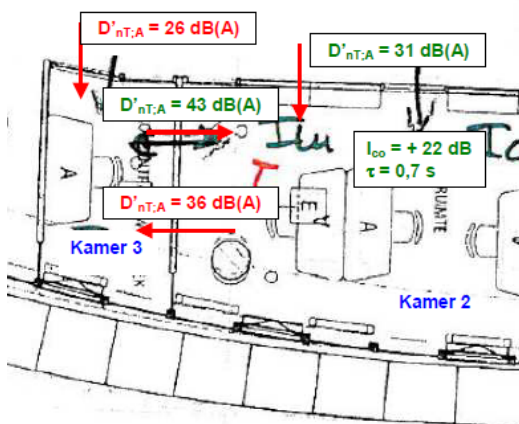


Figure 20. Measurement results on sound insulation, extracted from the building management files

Table 8. Reported dissatisfaction about noise

Complaints registration	
-	Noise from the road
-	Noise caused by wind
Questionnaire	
-	Less privacy in open spaces
-	Noise from colleagues (e.g. calls)

Category 4: These aspects meet the performance target but dissatisfaction is reported by occupants, which means discrepancy exists between building assessment and occupants' perception. There are four out of 21 aspects in this category:

- Controllability over indoor air quality;
- Controllability over thermal comfort;
- Indoor air quality (Ventilation);
- Indoor temperature.

For controllability, both control over thermal comfort ('able to influence the indoor temperature by ± 2 K') and indoor air quality ('able to influence the indoor air quality') meet the requirements of *Output Specifications*. However, according to the average score of the questionnaire (see *Figure 21*), limited controllability is reported.

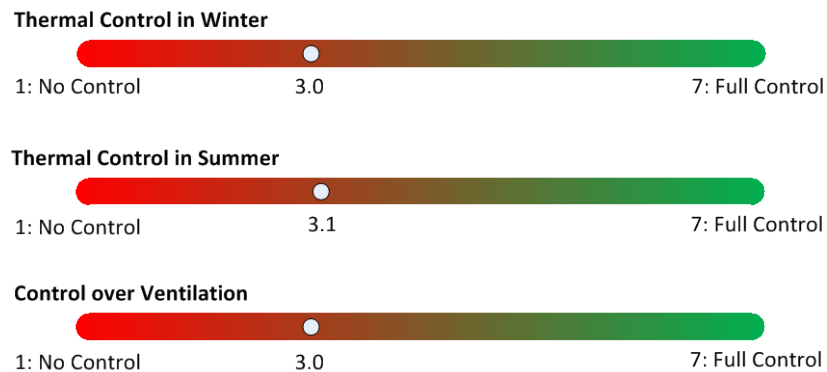


Figure 21. Results of POE on controllability

With respect to ventilation and temperature, both targets are met according to site measurements and the management system. For ventilation, measurements have been conducted and the upper limit of CO₂ concentration (660 ppm above outdoor concentration) was not exceeded. For indoor temperature, mostly the temperature stays within the 80% satisfaction boundary of ATG (as illustrated in *Figure 22*, the red line and blue line illustrates the upper limit and lower limit of the 80% satisfaction boundary respectively).

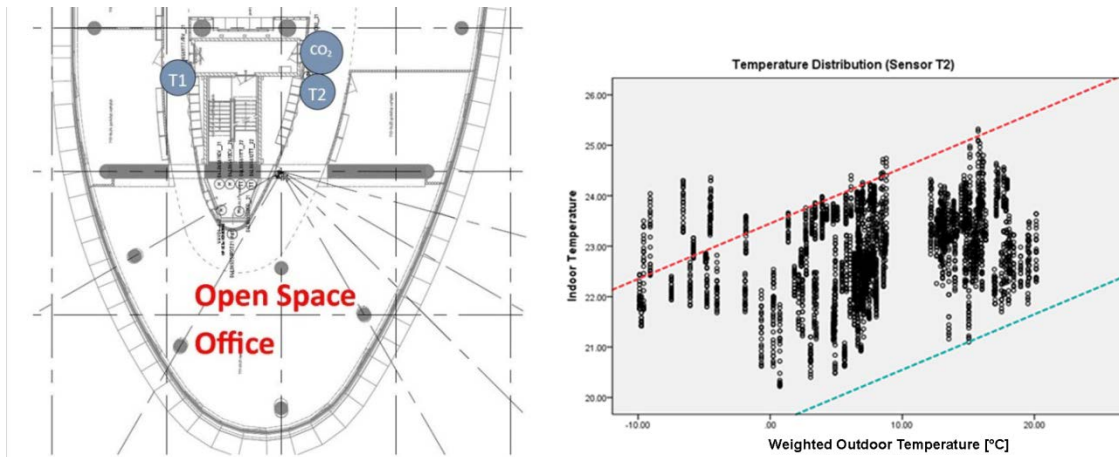


Figure 22. (Left) Location of sensors; (Right) Temperature distribution according to T2

However, according to the average score from POE, the results are not satisfying.

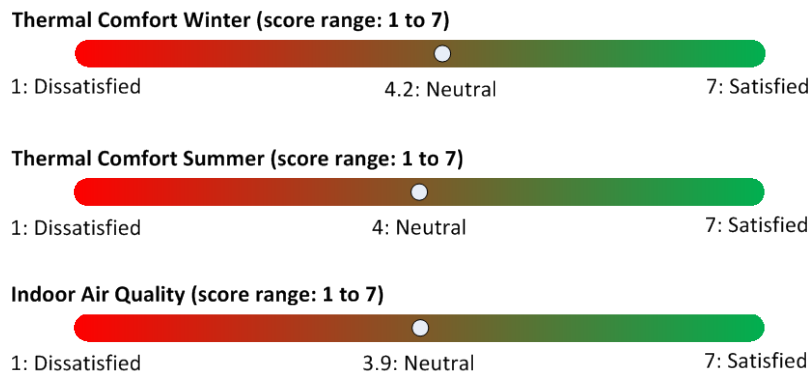


Figure 23. Results of POE on indoor temperature and air quality

Results show that occupants have neutral attitude towards indoor thermal comfort and air quality. To better illustrate the performance, the results are compared with buildings in the HOPE database, see Figure 24. In the figure, the average score of the HOPE database is marked as well. For indoor comfort, a higher value means that more satisfaction is expressed by the occupants, but for *Building X*, the score is below average. For the BSI (Building Symptom Index), a lower value means there are less building symptoms, which indicates a healthier environment. Consequently, it can be concluded that the building is conditionally healthy but is underachieving in indoor comfort.

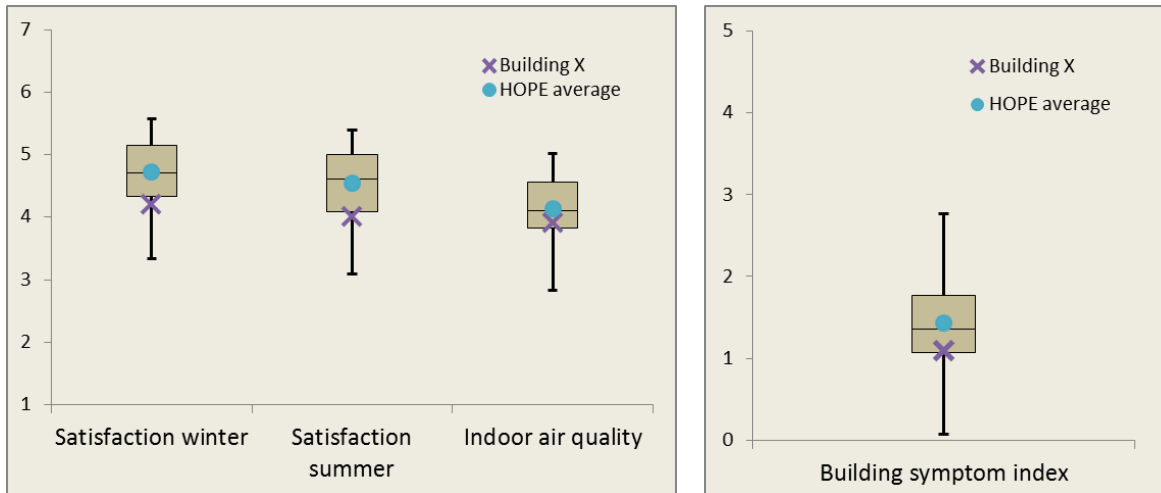


Figure 24. Benchmarking with building HOPE database, (Left) on Indoor environment; (Right) on Building symptom index

3.2.2 Discussion

For aspects in *Category 1*, since they fulfill the requirements of both building managers and occupants, no further discussion will be taken.

For these aspects in *Category 2*, complaints and suggestions have been expressed by occupants. However, as the information is still limited, it is not possible to identify whether they are local cases or common problems in the building. As a result, another survey is suggested. For this survey, questions related to these topics should be included.

For noise, the only aspect in *Category 3*, improvements are suggested. Besides deficient sound insulation that has been identified by measurements, according to the occupants, traffic noise and deficient sealing of the windows also lead to dissatisfaction and should be avoided. The importance of an improved acoustic environment can be shown by the sensitivity study in *Chapter 4.2.3*.

Category 4 covers four aspects; in general, they can be divided into two categories: controllability over temperature and air quality, occupants' perception towards indoor temperature and air quality.

With respect to controllability, several factors may lead to the mismatch between measurements and real building performance. Firstly, the requirements are not strict enough. For instance, in the *Output Specifications*, there are no requirements on response time when evaluating the controllability over temperature. A report by Creemers *et al.* (2012) has shown that only when proper quantitative goals have been described and reached (e.g. on response time and step response range) can the occupants get a more comfortable environment. Secondly, according to the outcome of questionnaires, users' behavior and preference may limit each other's controllability in large offices. For instance, different occupants may have different preference over indoor temperature and this will restrict others' controllability. What's more, outside environment also limits the controllability. Though it is possible to adjust the temperature, air quality and humidity by opening windows, occupants have indicated that factors like noise outside may reduce the feasibility of such control strategies through questionnaires.

On the other hand, several reasons may contribute to the differences between measurements and occupants' perception towards the indoor temperature and air quality. Firstly, due to the location of the sensors, the monitored data may not reflect the actual temperature and CO₂ concentration near occupants' workplaces, thus disparity may occur. As shown in *Figure 22*, the sensors are located in the hallway instead of the workplaces; in addition, accuracy of the monitoring data is questionable. As shown in *Figure 25*, a comparison has been made between a handheld temperature sensor (model number: *TESTO 625*) and the temperature sensor of the building. The results are shown in *Table 9*, due to location and accuracy of the sensors, disparity exists between the readings of the two models. Thirdly, according to the requirements, the temperature should stay within 80% satisfaction boundary of ATG. However, there is difference between the monitored temperature and the temperature that the occupants' actually perceived. In *Building X*, air temperature is measured and this may not reflect the actually perceived temperature by the occupants.

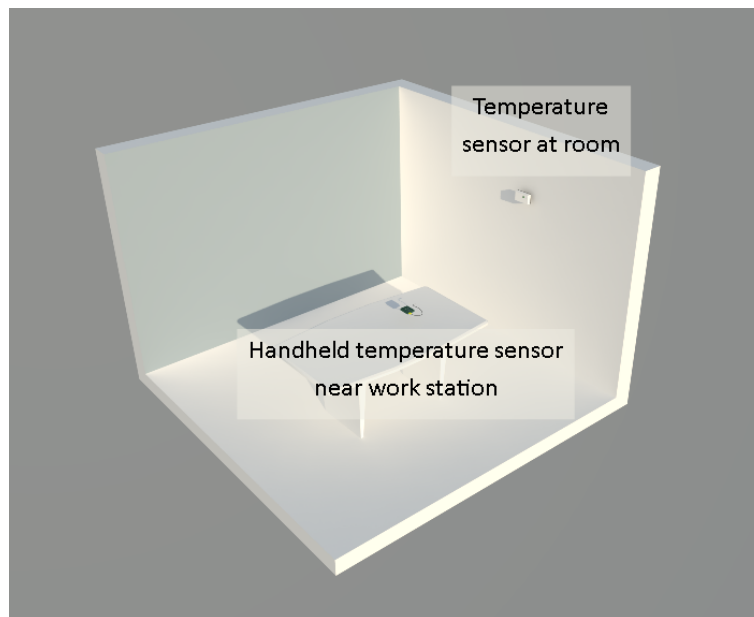


Figure 25. Location of the sensors

Table 9. Comparison of the readings from two sensors

Time	Handheld sensor [°C]	Wall sensor [°C]
13.55	23.1	23.7
14.05	23.6	22.8
14.20	22.3	21.2
14.25	22.1	20.9
14.30	23.5	22.9

Finally, the methods of how the data are collected in the building may not be standard. *Table 10* compares the methods employed by ASHRAE protocols, environmental consultants and actual building management in terms of thermal comfort evaluation. As shown by the table, during actual

management, the monitored data is so limited that it may not reflect the actual performance (e.g. no information is available for humidity and air speed). In addition, there is no strict guideline on what types of instrumentation should be used and how the data should be collected (e.g. the temperature should be monitored at the work station at different heights according to ASHRAE protocols and consultants, but no information is available for the management). As a result, it may be not sufficient to evaluate the building performance based on the building management data solely.

Table 10. Comparison of ASHRAE protocols, consultants measurements and actual building management in terms of thermal comfort

	ASHRAE protocols	Consultants	Actual management
Reference	ASHRAE, USGBC, CIBSE, 2010	-	Output Specifications
Performance indicators	Air Temperature Humidity Radiation Air speed	Air Temperature Humidity Radiation	Air Temperature
Measurement instrumentations	Listed	No information	No information
Measurement methods	Yes	Yes	No

3.3 Energy Consumption

3.3.1 Results

The evaluation of *Building X*'s energy performance covers two parts:

- How is the actual energy use compared with design intent;
- How is the building performing compared with other buildings in terms of energy use.

Energy consumption has been estimated several times during the design and management of the building. For building managers, empirical functions from ASHRAE were used to estimate the energy consumption and the value is used to ensure the building's actual building consumption is under acceptable conditions (ASHRAE, 2009). For the energy estimation, energy use breakdown is available; however, this is not possible for actual energy use. *Figure 26* compares the predicted and actual energy use. In the figure, relative energy consumption is illustrated, in which predicted energy consumption for basic services is defined as '1'. The figure shows that the actual energy use is satisfactory since the energy consumption of each sub-category (basic services, server room and other) is below design intent.

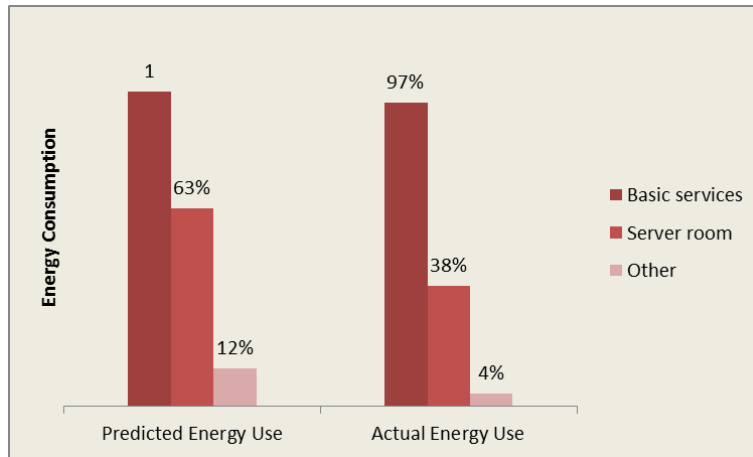


Figure 26. Comparison of predicted and actual energy consumption

The second part of the energy performance evaluation is to compare the building performance with other buildings. In this way, a clear vision of how the building is performing in terms of energy use can be obtained. Firstly, the energy use and energy cost is compared with average Dutch offices. Results indicate that *Building X* is low in both indicators, especially when the energy use of Data Center is excluded (see *Figure 27*). However, as indicated by NVM Business (2011), 62% of the Dutch offices are 18 years and older, which means the comparison may not reflect the state-of-the-art situation of building energy use.

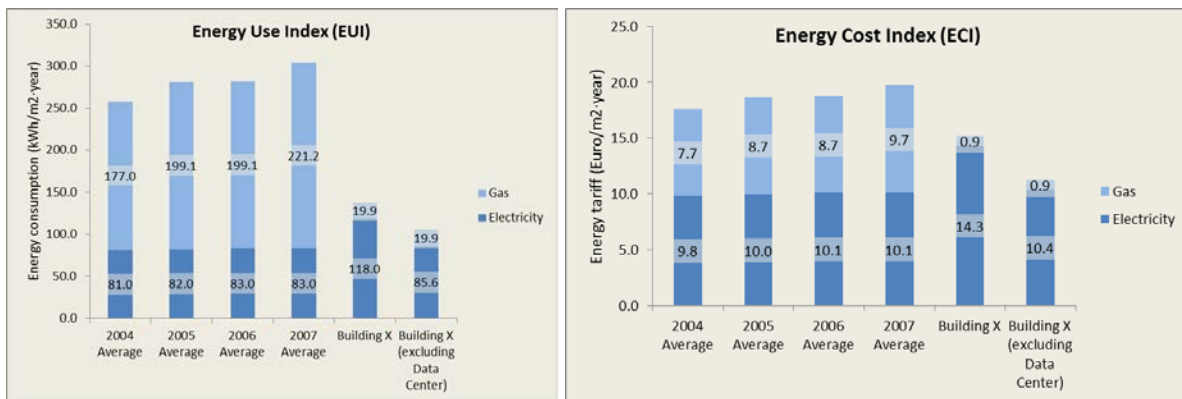


Figure 27. Comparison with Dutch offices average

Accordingly, energy performance of *Building X* is compared with the energy use of buildings in *HOPE* database.

Building X's performance is benchmarked and the results are visualized by box plot, see *Figure 28*. In the plot, *Building X*'s predicted energy use and energy consumption of the average Dutch offices are listed as well. *Building X* outweighs about 75% buildings of the *HOPE* database in all four scenarios:

- All offices in *HOPE* database;
- All offices in *HOPE* database with energy use adjusted by heating degree days;
- Offices larger than 10,000 m² in *HOPE* database;

- Offices larger than 10,000 m² in *HOPE* database with energy use adjusted by heating degree days.

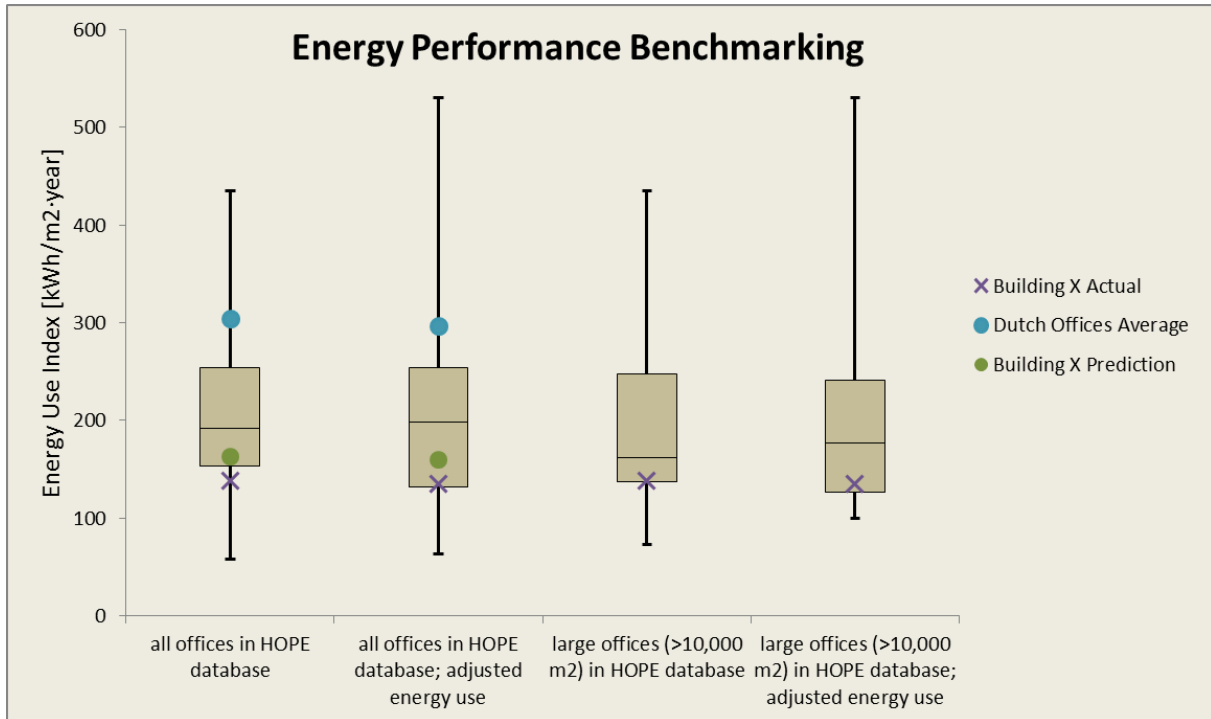


Figure 28. Benchmarking with HOPE database

The results show that the building is relatively low in energy consumption compared with both average Dutch offices and buildings in *HOPE* database.

3.3.2 Discussion

Since *Building X*'s energy performance fulfills the expectations of building managers and is satisfactorily compared with other buildings, no further analysis will be taken in the report. However, suggestions can still be made to further fulfill the potential of the building's performance:

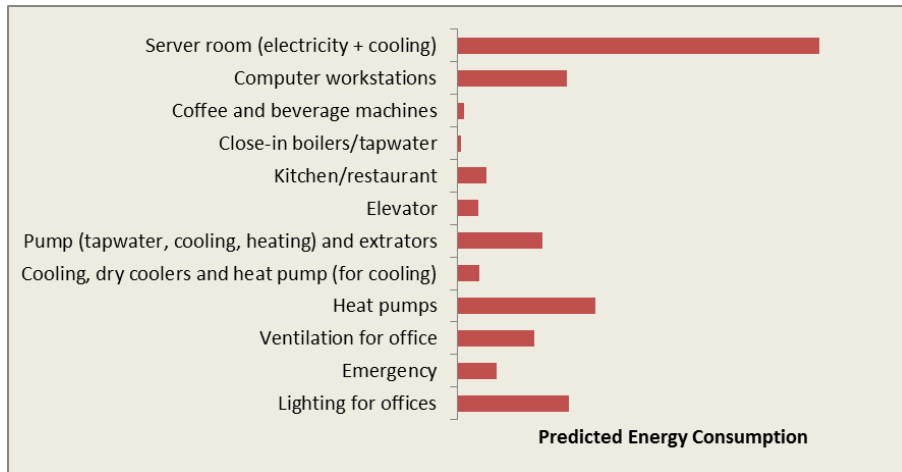


Figure 29. Breakdown of energy consumption predictions

As shown in *Figure 29*, energy use prediction breakdown is available. However, when it comes to the actual energy consumption, only general end-uses are recorded. As a result, though the overall building performance is acceptable, it is not clear whether all end-uses are within acceptable range.

In addition, due to limited information, the energy consumption is evaluated according to the basic protocols proposed by ASHRAE (2010). Though the building management system monitors the running statues of the building services system and some indoor environment parameters, limited information is recorded, which restricts further analysis. As indicated by ASHRAE (2010), more specific data and more frequent data collection are required for intermediate and advanced level, which aim at diagnosing and improving the building’s energy performance.

Besides, attention should be paid to the reliability of the collected data.

4

SENSITIVITY STUDIES

In this chapter, sensitivity will be tested for the differences between design and as-built situation and different design scenarios in terms of indoor environment, energy consumption and productivity. To compare a certain parameter's influence, both design model and as-built model, which reflects the actual building indoor environment, are employed. The sensitivity is tested by replacing the tested parameter with the actual value in the design model and the design value in the as-built model.

For different design scenarios, four indoor environment aspects will be tested. That is, the relationship between productivity and indoor temperature, air quality, acoustic comfort and visual comfort will be analyzed.

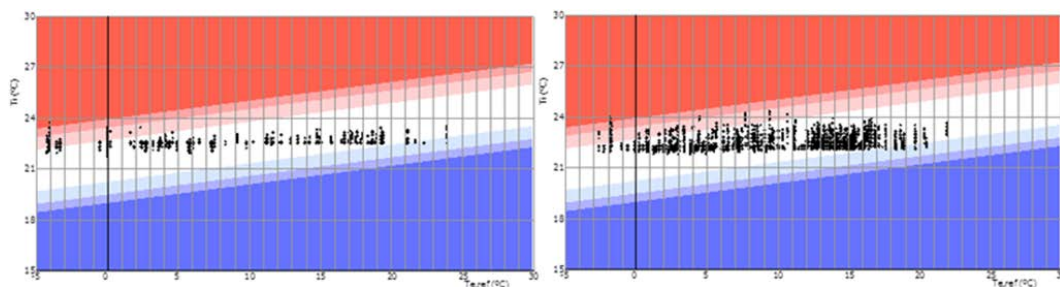
4.1 Design vs. As-built

During the design phase, predictions are made about the building's indoor environment and energy use. However, as some parameters were unknown at design phase and actual management plan may differ from the design, creditability of the design model is worthy discussion. In this section, the following two issues are to be addressed:

- Evaluation of the design model and development of the as-built model;
- Furthermore, how the differences between design and as-built situation may influence the accuracy of predictions on indoor environment, energy consumption and productivity.

4.1.1 Models for Analysis

Evaluation of the design model and development of the as-built model is shown in *Appendix 1*.



Modified Design Model (MDM)

Overheating Hours:

- 41 (90%); 3 (80%); 1 (65%)

Undercooling Hours:

- 36 (90%); 0 (80%); 0(65%)

As-Built Model (ABM)

Overheating Hours:

- 98 (90%); 12 (80%); 2 (65%)

Undercooling Hours:

- 32 (90%); 0 (80%); 0(65%)

Figure 30. Number of overheating and undercooling hours in two models

In *Figure 30*, ATG graph and the number of overheating and undercooling hours are shown for both models. Compared with the as-built model which reflects the actual building performance, the modified design model underestimates the overheating hours and slightly overestimates the undercooling hours. The differences are caused by the input of some parameters. In next section, sensitivity of these parameters will be tested.

For the analysis, weighted overheating and undercooling hours are used to indicate the comfort level of indoor environment while productivity is calculated to show the economic influence of these changes. As other indoor indicators remain the same, the productivity is calculated based on temperature.

When it comes to energy consumption, in Vabi 114, only heating and cooling energy are calculated. As the energy use breakdown is not available for *Building X* and necessary information about the estimation of actual heating and cooling consumption is missing (e.g. energy use at floor or room level, COP of the heat pumps and efficiency of the boiler), the estimated energy consumption according to Vabi 114 results in a wide gap with actual energy use (see *Table 11*). As a result, only qualitative analysis will be made for energy use. That is, for each tested scenario, only the relative change in energy consumption compared with the base models will be given.

Table 11. Predicted and measured energy consumption

	Area (m ²)	Heating local (kWh)	Heating central (kWh)	Cooling local (kWh)	Cooling central (kWh)	Total Energy Use (kWh/m ²)
Modified Design Model	169	1093	8349	12844	1189	34.1
As-built Model	169	4364	10828	11315	688	39.2
Measured Data	169					68.1

4.1.2 Evaluation of the Differences between Design and As-built Situation

To evaluate the sensitivity of these differences, the differences between design and as-built situation should firstly be identified. The differences may lie in building management (e.g. set-temperature), unknown parameters in design phase (e.g. heating and cooling capacities of HVAC components) and the use of empirical values (e.g. weather data). By comparing the input in design phase and the information collected in actual building management, the differences can be identified, see *Table 12*.

Table 12. Summary of the differences between modified design model and as-built model

Item	Design value	Actual value
Weather data	RA2008T5 ('t Hooft, 2009)	Actual weather data
Operation schedule of AHU²	7 a.m. -8 p.m., working days	5 a.m. - 8 p.m., working days
Circulating flow temperature of AHU	45 - 35 °C (heating) 8 - 14 °C (cooling)	30 - 20 °C (heating) 12 - 18 °C (cooling)
Circulating flow temperature of heat pumps	45 - 43 °C (heating) 16 - 18 °C (cooling)	45 - 25 °C (heating) 12 - 18 °C (cooling)
Power of convectors	250 W	100 W
Power of CCA³	99999 W/m ²	40 W/m ²
Circulating flow temperature of CCA	27 -25 °C (heating) 18 - 20 °C (cooling)	29 - 25 °C (heating) 17 - 21 °C (cooling)
Internal gain (people)	130 W, 15 occupants 100% during occupancy hours	85 W, 21 occupants Variable (80%) during occupied hours
Internal gain (Apparatus)	150 W per person 100% during occupancy hours	100 W per person Variable (80%) during occupied hours
Night cooling	Applied	Only for data center
Heating/Cooling capacity of AHU	99999 kW	10 kW

Then the sensitivity can be tested and each parameter's influence on indoor environment, energy use and productivity can be evaluated. The data showed and analyzed are from the model of the open space office at south façade.

4.1.2.1 Indoor Environment and Energy Use

Figure 31 to Figure 33 summarizes the models' sensitivity to the differences respectively. Firstly a summary is given, and then analysis will be made for each of the differences.

² AHU refers to air-handling unit

³ CCA refers to concrete core activation

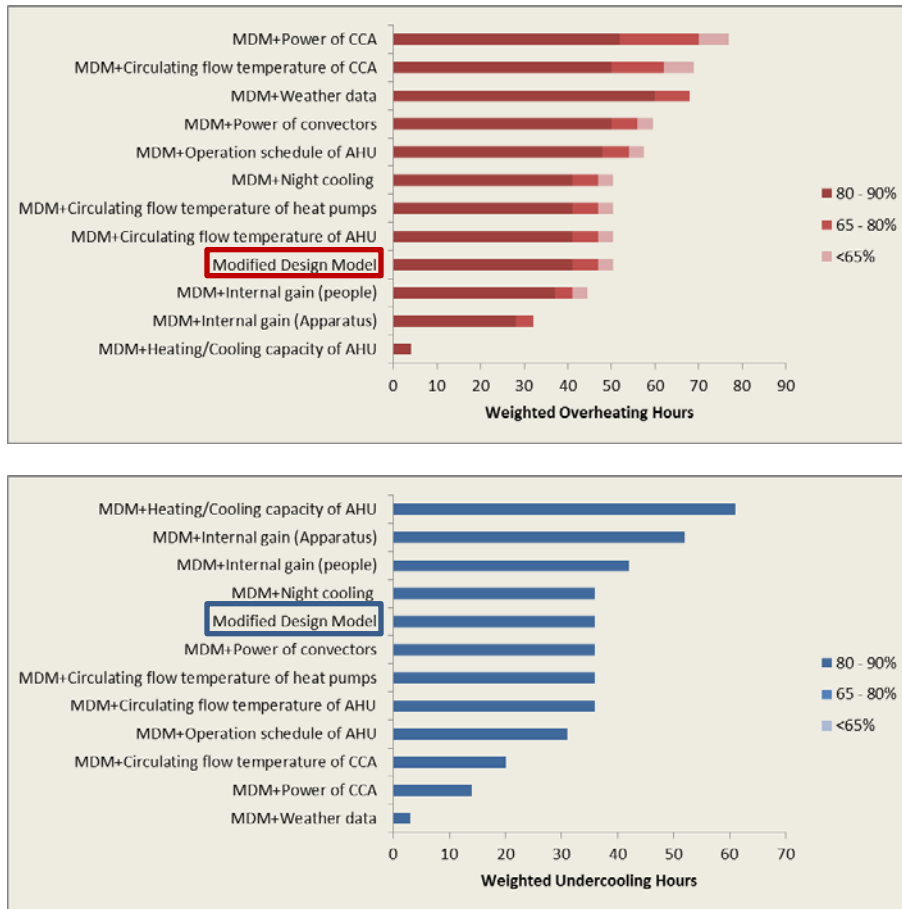


Figure 31. Modified Design Model's sensitivity towards the differences

For Figure 31 and Figure 32, different scenarios' weighted overheating undercooling hours are illustrated. Similarly, different scenarios' energy consumption is shown in Figure 33. For each figure, the base model is marked with rectangle of corresponding color. By comparing the length of the bar, it is possible to see when a certain change is applied, how the results will be influenced.

Figure 31 compares the modified design model's sensitivity towards different changes. For the modified design model, as a higher power of CCA is applied, it underestimates the overheating hours and overestimates the undercooling hours. The same trend is shown for the weather file and schedule of air-handling units. For the convectors, a higher power is applied but this only leads to underestimation of overheating hours.

On the other hand, due to overestimation of the internal load in the design model, the overheating hours are overestimated and the undercooling hours are underestimated.

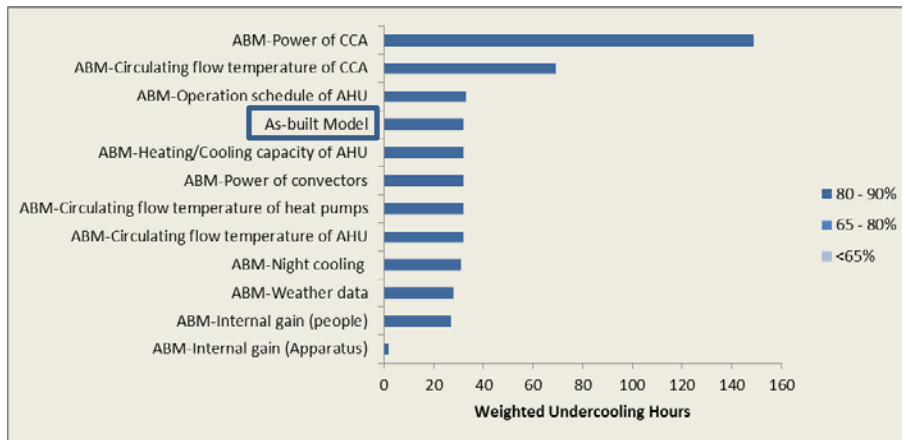
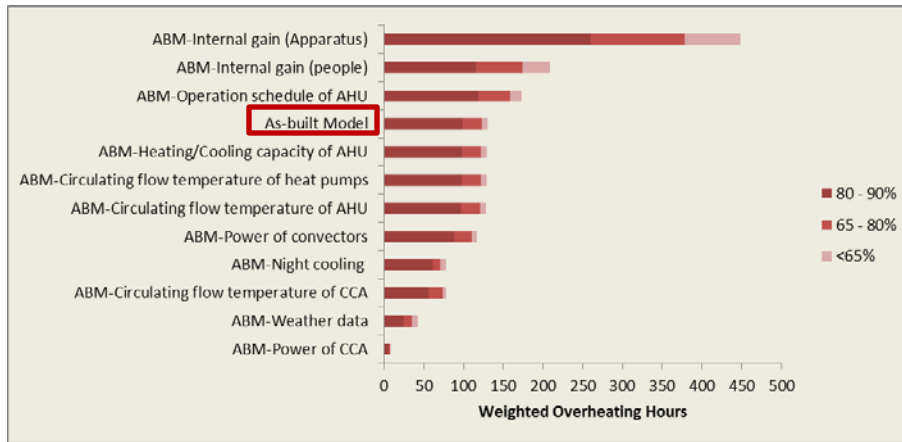
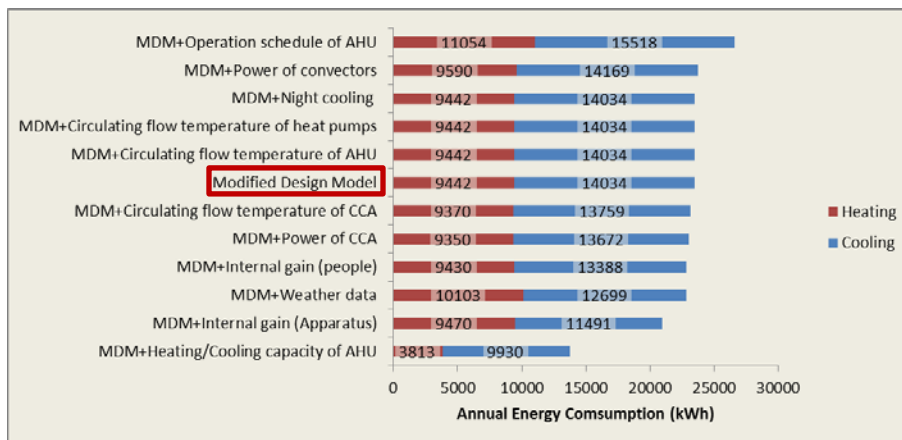


Figure 32. As-built Model's sensitivity towards the differences

The results of sensitivity study for the as-built model is shown in *Figure 32*, which shows similar trend to *Figure 31*. Factors like internal gains and power of CCA have most influence on the accuracy of the predictions.



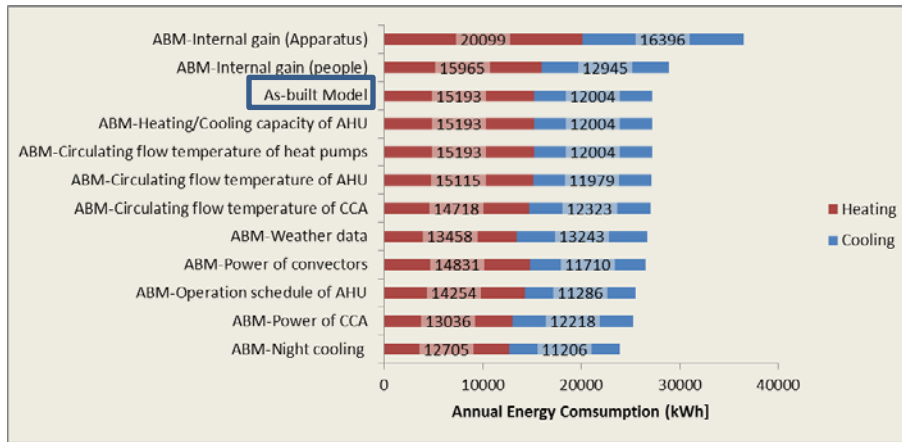


Figure 33. Different scenarios' energy consumption

According to *Figure 33*, for energy consumption, the schedule of AHU, internal gains and capacity of AHU have influence on both modified design model and as-built model. For night cooling and power of CCA, however, effects are only shown on the modified design model.

In the following part, each difference's influence on indoor environment and energy use are analyzed. For the analysis of indoor environment, weighted overheating hours and undercooling hours those are between 7 a.m. to 8 p.m. are counted (the occupied hours are from 8 a.m. to 6 p.m.). For energy consumption, relative annual energy consumption compared with base models (the modified design model and as-built model) will be used.

Weather file

During the design phase, an empirical weather file (*RA2008T5*) was used. As the measured weather data (which is collected on the weather station *Eelde* for the year 2011) was different from the empirical data, the design model underestimates the weighted overheating hours and overestimates the weighted undercooling hours. The energy use is also influenced, when actual weather file is applied in the modified design model, the energy use will reduce by 2.8%; when the weather file for design is applied in the as-built model, the energy use will reduce by 2.4%.

Operation schedule of AHU

In the actual building management, conditioned air is supplied from 5 a.m. instead of 7 a.m., which provides pre-heating or pre-cooling to the building. Additionally, the air quality can be improved. However, when the actual schedule is applied to the modified design model, there is an increase in overheating hours. However, these surplus overheating hours are mostly located between 6 a.m. to 8 a.m. due to pre-conditioning, which means the indoor environment is still comfortable during most occupied hours. For other three scenarios, the new schedule brings better thermal condition as well as air quality. With respect to energy consumption, both more heating and cooling consumption is required since the number of the running hours rises. For the modified design model, the new schedule will bring an energy increase of about 13.1%; for the as-built model, a shorter schedule will result in 6% reduction on energy use.

Circulating flow of AHU and heat pump

These two parameters are about the water side of the HVAC system and only flow temperatures are defined. As there is no input on the flow rate, the system's heating and cooling capacity is determined by the heating/cooling terminal systems. As a result, these two parameters do not have influence on neither comfort nor energy consumption for both modified design model and as-built model.

Power of convectors

As concrete core activation can provide most of the heating and cooling required by the room, a lower power of convectors is still sufficient for the conditioning. As a result, the change of heating power only has slight influence on indoor environment. Similarly, the change on energy use is small. When the power of convectors is lower for the modified design model, the energy consumption will rise by about 1.2%; when a higher convector power is given to the as-built model, the energy consumption will reduce by 2.4%.

Power of CCA

Concrete core activation is deemed as the main terminal system for heating and cooling supply. For the as-built model, in which the heating and cooling power is reduced to actual level, the increase in cooling power can significantly reduce the overheating hours. However, when it comes to heating, the results turn out to be reversed. A higher CCA power leads to more undercooling hours, which seems illogical. According to the simulation results, this is because in winter, the room temperature may exceed the cooling set-point (which is 22.5 °C), especially in the midday hours. As a result, cooling may be still required in winter. As a higher power of CCA can lower the temperature quickly with a higher cooling energy, a higher temperature drop can be achieved. As a result, the risk of undercooling is higher due to the higher temperature drop.

For the energy use, higher energy consumption is required when the CCA power is higher. For both models, the change is within 2%.

Circulating flow of CCA

In the design model, the temperature difference between water inlet and outlet of CCA is smaller, which leads to a higher local heating and cooling capacity. This explains why there will be more overheating hours when the actual flow temperature is used. However, since the lower temperature difference also increases the power of CCA, it can also lead to more undercooling hours according to Vabi 114. Similarly, higher energy consumption is required when the CCA power is higher, but the shift of energy use caused by circulating flow of CCA is limited to 1.5% for both models.

Internal gains

In the actual building use, the internal gain from people is lower than predicted. Consequently, less heat gain leads to less overheating hours and more undercooling hours. With respect to the internal gain from apparatus, the actual value is much lower than predicted. This leads to higher diverge from the

prediction. It is especially obvious for the as-built model. As in the as-built model, the heating and cooling capacity is limited, the influence is more evident.

For energy use, a lower internal gain leads to more heating load and less cooling load. This trend is more obvious for apparatus since the difference between actual and design value is higher. For instance, for the as-built model, when the design value of internal gains caused by apparatus is applied, the energy consumption will rise by as much as 34%.

Night cooling

According to the settings, night cooling will be applied when the differences between indoor and outdoor temperature reaches certain values. Consequently, the application of night cooling has little influence on the modified design model. Due to the model's large heating and cooling capacity, the temperature difference between indoor and outdoor environment is low and the night cooling is seldom applied. However, the effect of night cooling can be seen from the as-built model. Because of the setting, the night cooling can reduce the energy use while having no negative influence on the indoor environment.

For the as-built model, night cooling can save energy up to 12%.

Heating/Cooling capacity of AHU

For the modified design model, when actual heating and cooling capacity of AHU is applied, the overheating hours is reduced and there will be more undercooling hours. This is caused by the algorithm of Vabi 114. As the CCA power is ultimate in the modified design model, when the capacity of AHU is limited, most of the required heating and cooling will be provided by CCA. As has been explained before, a higher CCA power leads to less overheating hours but will result in more undercooling hours.

This is also proved by the as-built model. As the power of CCA is limited, AHU is responsible for conditioning the building during occupied hours. As a result, for the as-built model, the capacity has little influence on the prediction on the indoor environment.

With respect to energy use, when actual heating and cooling capacity of AHU is applied, the energy use will reduce by about 40%. However, for the as-built model, the change has no influence on the energy performance.

4.1.2.2 Productivity

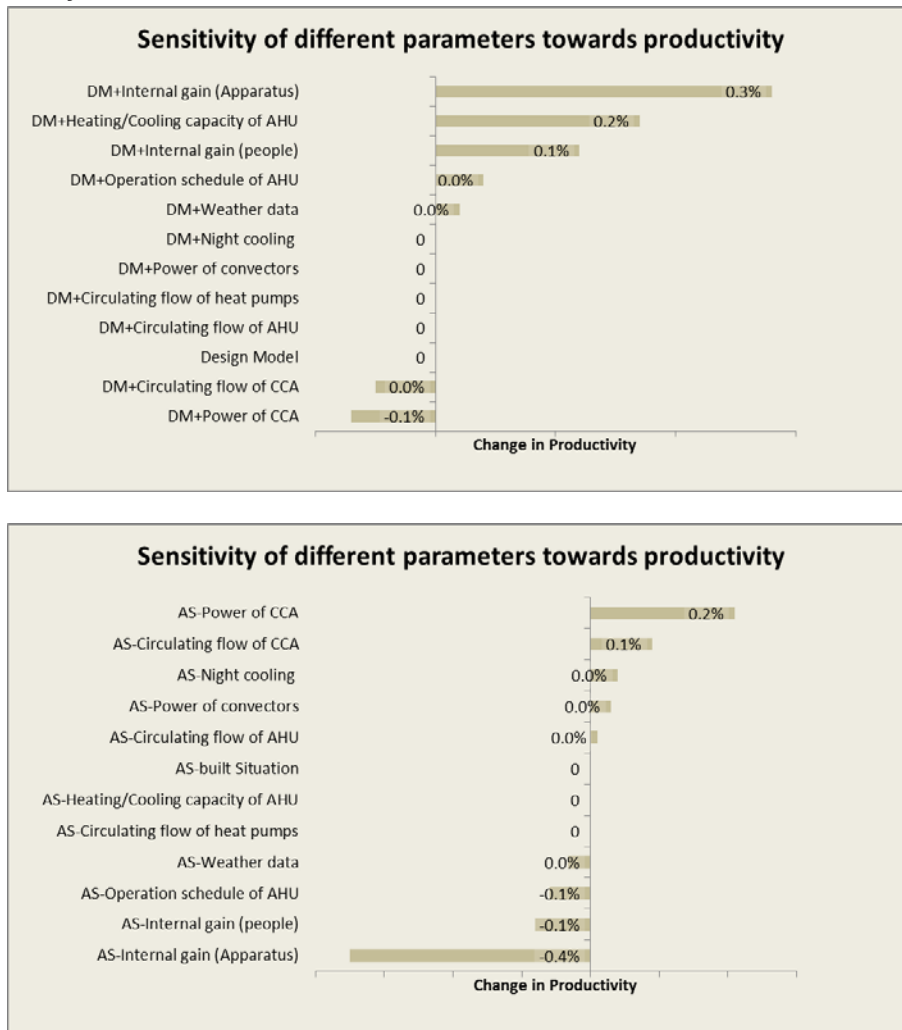


Figure 34. Sensitivity of different parameters towards productivity

Figure 34 shows these differences' influence on productivity. As the productivity is calculated solely by temperature according to the relationship proposed by REHVA (2006), parameters that have more influence on indoor environment also tend to have more impact on productivity. This means, attention should be paid to power and flow rate of CCA and internal gains when productivity is calculated in design phase.

4.1.3 Discussion

An as-built model was developed and it shows good consistency with the measured temperature data. However, discrepancy still exists, and may due to:

- Information is still limited to fully calibrate the model (e.g. running statues and energy use of the building services systems requires further calibration);
- Possible errors of the site measurements;
- The unexpected user behavior that may influence the indoor environment;

- Some indicators are dynamic in reality but can only be set as fixed value in the simulation tool (e.g. set-temperature);
- Operative temperature is used to regulate the building performance in the models but only air temperature can be measured and used for actual management.

In the design phase of a building, some parameters may be unknown and hypothetical or empirical values have to be used for prediction. In this case study, the sensitivity of these parameters is tested. The results indicate that the designers should be cautious when selecting the values for power and flow rate of CCA, internal gains and heating/cooling capacity of AHU since they may influence the accuracy of predictions on indoor environment and productivity obviously. This conclusion is supported by several works, for instance, Lehmann *et al.* (2010) indicated that the improper estimation of internal gains has led to the differences between design and actual building performance for a building in the Switzerland.

On the other hand, internal gain, operating schedule and capacity of AHU have most influence on the accuracy of predictions on energy use, thus attention should be paid to them to understand the building energy performance in design phase.

4.2 Evaluation of Design Scenarios

Another issue to be addressed is testing the influence of different design scenarios on indoor environment, energy use and productivity. Aim of this study is to gain a deeper understanding on the economic relationship between traditional performance indicators (IEQ and energy) and productivity.

The sensitivity of four building indoor environment aspects will be tested: thermal comfort, air quality, noise level and visual comfort. Background information on the evaluation process and data analysis can be found in *Chapter 2.3*.

4.2.1 Thermal comfort

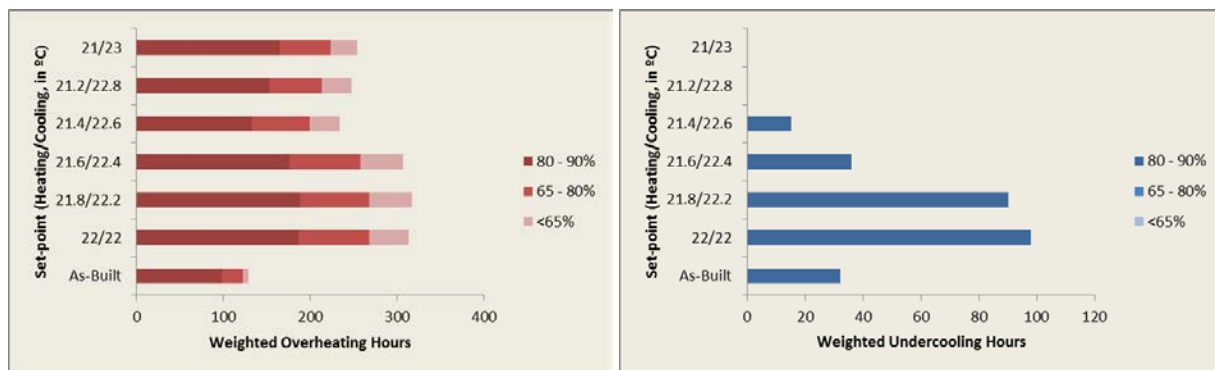


Figure 35. Weighted overheating and undercooling hours

Several design scenarios are tested for the analysis of thermal comfort. *Figure 35* lists the outcomes in terms of indoor comfort. The as-built situation has the optimal results since it has least overheating hours and relative few undercooling hours.

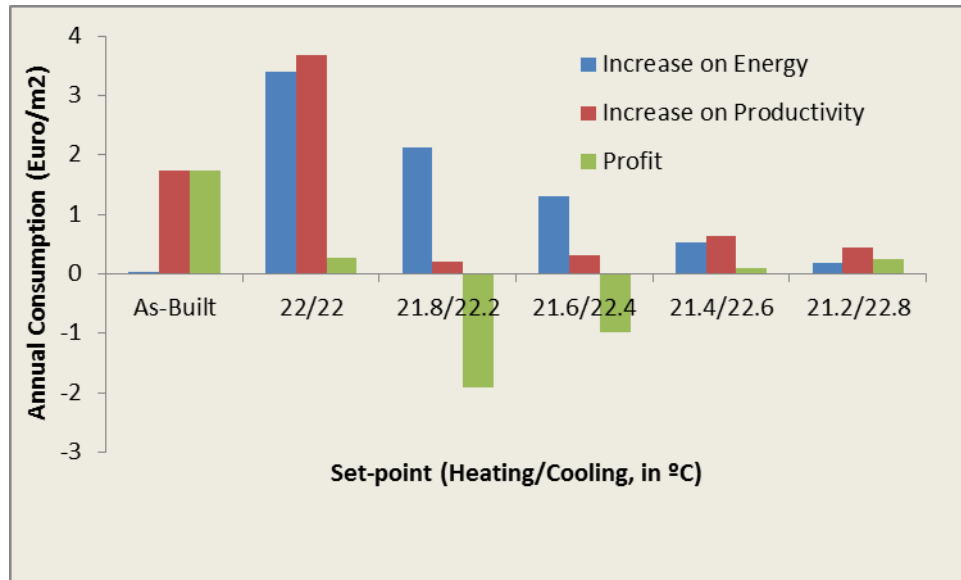


Figure 36. Change in energy use, productivity and profit for different scenarios

Figure 36 compares the change in energy use, productivity and profit of different scenarios compared with the scenario 21/23 (the heating set-point is 21 °C and the cooling set-point is 23°C). For the scenario 21/23, its profit is defined as 0, for other cases, the profit is calculated as follows:

$$\text{Profit} = \text{Increased Income on Productivity} - \text{Increase Expense on Energy Use}$$

If only productivity is considered, when the set-point is stable at 22 °C for both heating and cooling, highest productivity can be achieved. However, since this scenario also has higher energy consumption, its profit is lower than the as-built situation.

4.2.2 Air quality

Air quality can influence the productivity by three parameters:

- Sick leave;
- Productivity change due to indoor temperature;
- Productivity change due to ventilation.

In total five scenarios are tested: as-built situation and four ventilation rates ranging from 1 to 2.5 h⁻¹. Since it is not clear how to calculate the combined effects of these changes, the effects of each change are evaluated separately.

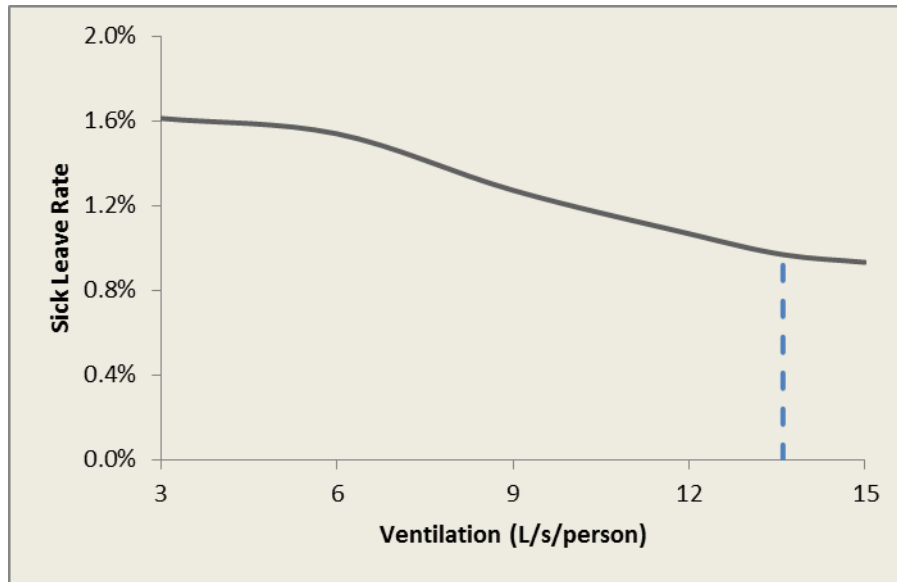


Figure 37. Relationship between ventilation and sick leave rate

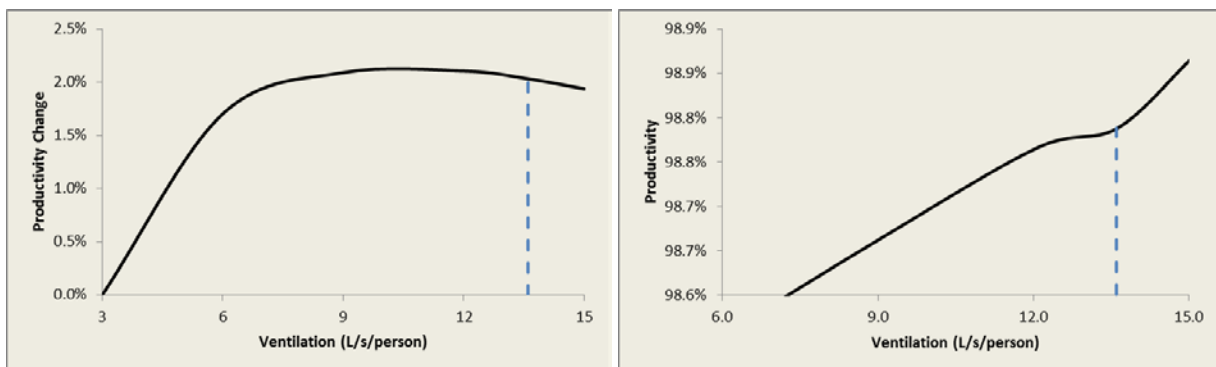


Figure 38. Productivity change due to ventilation (left) and temperature as a result of ventilation change (right)

The results are shown in *Figure 37* and *Figure 38*. In general, when the ventilation rate goes up, there will be less sick leave and higher productivity. The actual ventilation rate is marked by blue dot line.

4.2.3 Noise level and visual comfort

For noise level and visual comfort, Jin *et al.* (2012)'s method is employed. Instead of testing the productivity, occupants' acceptance towards the acoustic comfort and visual comfort are calculated. To test the sensitivity of one specific parameter, three concepts are defined: Optimal, Requirements and Actual Performance. Description of these scenarios is given in see *Table 6*.

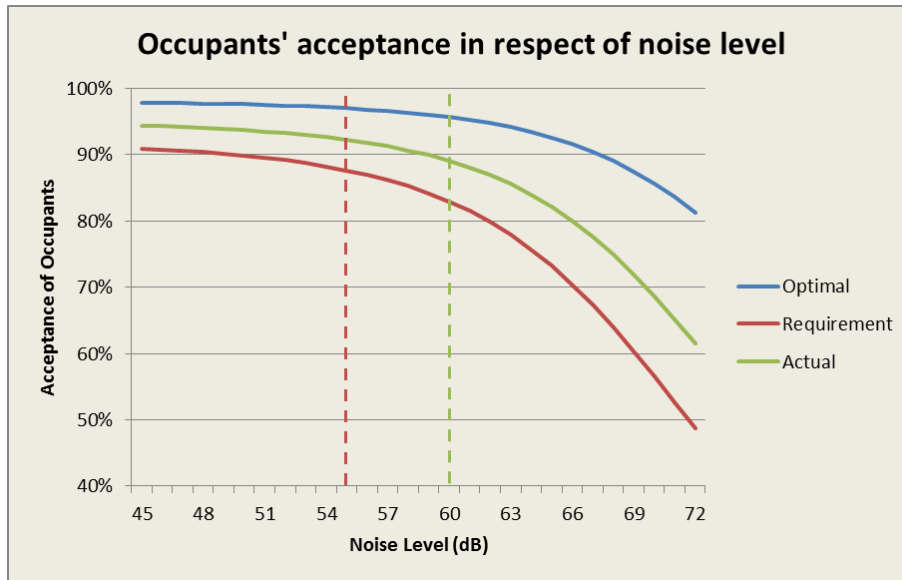


Figure 39. Occupants' Acceptance in respect of Noise Level

Figure 39 compares the influence of noise level in three pre-defined scenarios. The required noise level and actually measured noise level is marked by red and green dot line respectively. As illustrated, occupant's acceptance will decrease as the noise level goes up. When the noise level exceeds 60 dB, all three trend lines show that the occupants' acceptance will drop rapidly.

As the performance of the other three indoor environment parameters (PPD, CO₂ concentration and illuminance) exceeds the requirement but is lower than optimal situation, for a certain noise level, the actual acceptance is between the two scenarios. The actual building performance and required performance is marked by green and red triangle respectively. Though the noise level is underachieving, occupants' overall acceptance is still higher than the requirements of building management.

However, since the noise level is high in the building, it is necessary to improve the acoustic comfort. For the actual building performance, since the noise level is at the point where the slope is steep, a higher noise level can lead to significant performance drop.

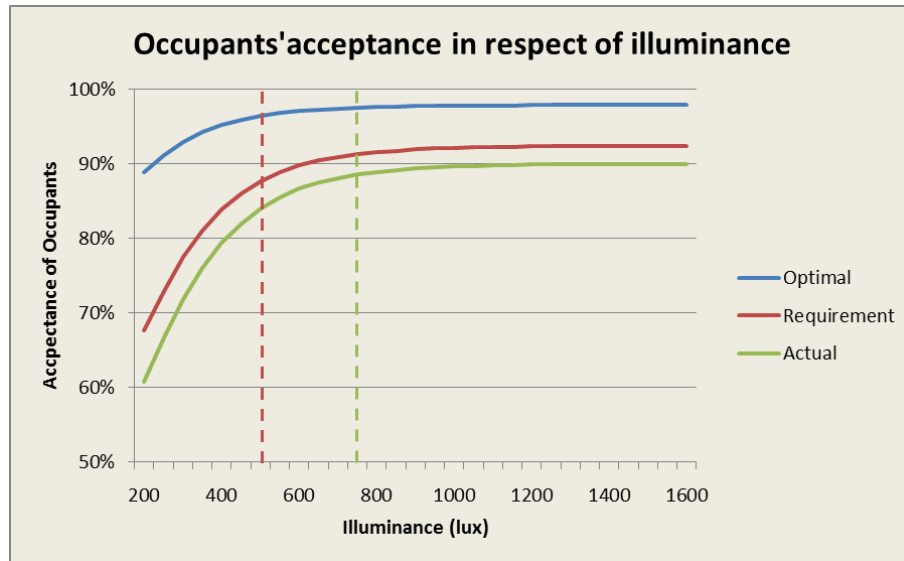


Figure 40. Occupants' Acceptance in respect of Illuminance

In *Figure 38*, the sensitivity of occupants' acceptance towards illuminance is shown. The required illuminance level and actual illuminance level is marked by red and green dot line respectively.

As the acoustic performance of *Building X* is underachieving, when the illuminance is set at certain level, the actual performance will be lower than both optimal and requirements. However, as the actual illuminance is higher than required, the overall building performance (blue triangle) still outweighs the required performance (green triangle).

As the illuminance increases, occupants' acceptance towards indoor environment will rise as well. However, the trend line turns stable after the illuminance level exceeds 900 lux.

4.2.4 Discussion

For thermal comfort, the results indicate that there is a disparity between indoor comfort (temperature) and productivity. This disparity is caused by the different calculation methods between these two indicators. The comfort is calculated dynamically which means parameters like outdoor temperature have to be taken into consideration. On the other hand, the productivity is estimated by indoor temperature solely, which means in some cold or hot days, even though the set-temperature can be considered as overheating or undercooling, high productivity can still be achieved. Consequently, if only comfort is considered during a building design, its productivity might be influenced.

On the other hand, for the influence of four indoor environment aspects, following questions still exist:

- For thermal comfort, it is not clear whether the temperature is air temperature or operative temperature. Besides, there is no information on whether the maximum productivity will be influenced by factors like outdoor temperature;
- Ventilation can influence several indoor environment parameters, e.g. temperature and air quality, however, further discussion is required on how to calculate the combined effects of different individual changes.

- For visual comfort, higher illuminance level leads to higher acceptance towards the indoor environment. However, the influence of other factors, e.g. daylight factor and possible glare caused by excessive lighting, should not be ignored.

For each of the four indoor environment aspects, occupants' acceptance or productivity is calculated with one parameter respectively. However, as shown by projects like *Perfection* (Loomans *et al.*, 2011), several parameters may contribute to the indoor environment quality. Accordingly, the relationship between other parameters and productivity or acceptance requires further discussion.

As shown in *Chapter 4.2.3*, Jin *et al.* (2012)'s methodology can be applied to evaluate a certain indicator's influence on building performance. If one parameter is underachieving, the building performance can still be compensated by other parameters' good performance.

In addition, further research is still required to establish the relationship between occupants' acceptance and productivity, so that further economic analysis can be made.

5

CONCLUSIONS

5.1 Research Question

Based on the results and analysis, the research question proposed in this report can be answered:

How to systematically evaluate and improve a building's performance with the assistance of standardized building assessment methods and building simulation tools?

It is feasible to use standardized building assessment methods to evaluate the building's performance. In fact, some methods have been adopted in the building management, e.g. complaints registration and the application of building management systems. For these methods, standardized methods should be applied. For instance, the location of sensors should be determined with care so that the readings can reflect occupants' perceived temperature.

Questionnaires and building inspection were used for the building evaluation. They can be used as a supplement to the building management. Firstly, more information can be derived from questionnaires compared with complaints registration; this is because complaints registration only covers certain areas of the indoor environment and the dissatisfaction towards other aspects. Secondly, even if some indoor environment indicators have been included in the complaints registration, questionnaires can provide information that the occupants are not likely to report to building managers, e.g. noise caused by other occupants' telephone calls in open space offices.

With respect to the application of building simulation tools, an as-built model is developed, which makes it possible to evaluate the differences between design and as-built situation as well as testing different scenarios. In this way, some parameters that require attention during design phase are identified.

However, it is notable that improvements are still possible for this project. For building assessment, new questionnaires are recommended to receive occupants' feedback on some aspects (Category 2 of the indicators, see *Chapter 3.2.1*), since it is not clear whether they are local issues or general problems. It is also possible to conduct the assessment several rounds so that it is possible to see whether the building's performance has improved.

For building simulation tools, a further calibrated model is recommended, since it can facilitate further analysis on energy use and productivity.

5.2 Conclusions

The conclusions are summarized into three categories: methodology, performance evaluation and sensitivity studies.

About the methodology:

- Post-occupancy evaluation can be used as a supplement to the building assessment, since it can offer a deeper understanding to the building performance as more information can be derived from questionnaires compared with traditional management;
- For the building management, some indoor environment parameters have been monitored or measured. To better understand the building performance and facilitate comparison with other buildings, standardized measurement protocols and list of performance indicators can be referred to, e.g. the performance measurement protocols by ASHRAE (2010) and indicators summarized by Perfection project (2011);
- Building simulation tools is employed for the case study and the output of the as-built model shows a good consistency with the measured temperature. This proves that building simulation tools can be employed for both design and as-built situation. However, further calibration is required, which can also facilitate further analysis.

According to the evaluation, the following outcomes are obtained:

- In *Building X*, the layout of open space offices causes dissatisfaction in terms of privacy and acoustics;
- Noise level of the building failed to meet the requirements and improvements are suggested. For instance, the sound insulation of internal walls can be enhanced; the windows can be better sealed so that the noise caused by wind can be reduced; and in open space offices, separate space can be created for telephone calls or chatting, in this way, the influence of noise on other occupants can be reduced;
- The building is relatively healthy (compared with buildings in HOPE database), but improvements in thermal comfort and control are suggested. For instance, in open space office, requirements should be set for response time of different control strategies;
- Energy performance (both energy use and cost) fulfills the expectations of building managers and the performance is better than average Dutch offices and most buildings in HOPE database.

About the sensitivity study:

- In the design phase of a building, some parameters may be unknown and hypothetic or empirical values have to be used for prediction. In this case study, the sensitivity of these parameters is tested. The results indicate that for the used simulation tool (Vabi 114), the designers should be cautious when selecting the values for power and flow rate of concrete core activation, internal gains and heating/cooling capacity of air-handling units since they may influence the accuracy of predictions on indoor environment and productivity obviously;
- On the other hand, internal gain, operating schedule and capacity of AHU have most influence on the accuracy of predictions on energy consumption, thus attention should be paid to them to understand the building's thermal performance in design phase;
- In general, proper set-temperature, higher ventilation rate, better sound insulation and higher illuminance level can lead to higher productivity, which results in more profit;

- If one parameter is underachieving, the building performance in terms of productivity can still be compensated by other parameters' good performance.

5.3 Future work

For aspects that fulfill the performance targets but have received dissatisfaction from the occupants, another questionnaire with related topics is suggested to see whether they are local or special cases.

For the energy use, further analysis is restricted due to limited information and data. More specific data (e.g. end-uses) and more frequent data collection are suggested to improve the building's energy performance (at intermediate and advanced level of ASHRAE Performance Measurement Protocols). In addition, the building management system monitors some parameters but does not record them. If possible, some parameters can be logged and tracked to obtain input for further analysis.

The as-built model has shown that with proper settings, it is possible to use the building simulation tools to evaluate a real building's performance. However, for this case study, only indoor temperature is calibrated due to limited information. It is suggested to further calibrate the model, which requires further information on energy use and load curve of the building services systems. With a fully calibrated model, more in-depth analysis can be made on the building performance, especially on energy use and productivity analysis.

Further research is still required to establish the relationship between occupants' acceptance and productivity, so that further economic analysis on acoustic and visual comfort can be made.

6

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APPENDIX

1

ANALYSIS OF DESIGN MODEL

In total four models were used in this project, see *Table 11*. In this appendix, information will be given on how the as-built model is developed based on the original design model. Detailed input of these models can be found in *Appendix 4*.

Table 13. Information of the employed models

Model	Abbreviation	Description
Original Design Model	ODM	Design model created by the design company
Design Model 2	DM2	Original design model with corrected set-point
Modified Design Model	MDM	Original design model with set-point and irrational settings corrected
As-built Model	ABM	Modified model with values in as-built situation

Vabi 114 was used to predict the building performance in terms of indoor environment. Results of one design model, which was based on open space offices near the south façade, are illustrated in *Figure 39*. However, the set-temperature is 20 °C for heating and 20.5°C for cooling, which is different from actual management.

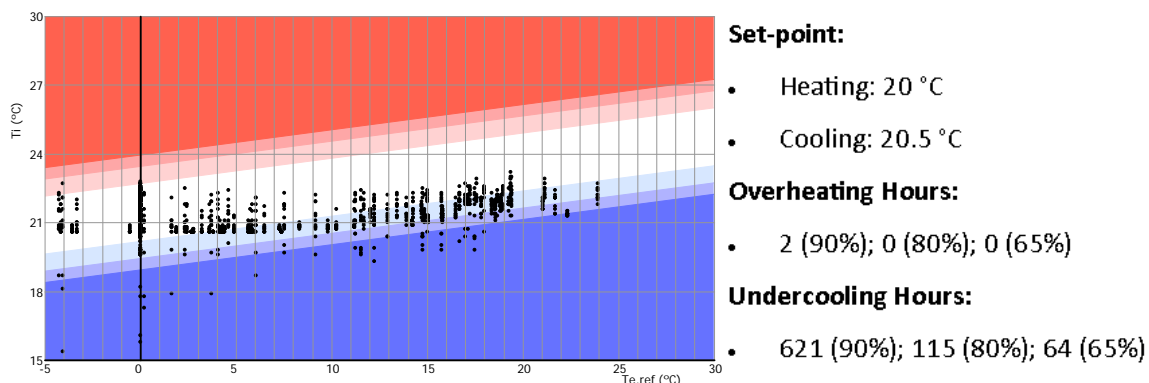


Figure 41. Distribution of Indoor Temperature According to the Original Design Model

Accordingly, a new design model was developed (denoted as “Design Model 2”, see Figure 40). In this model, the set-temperature is adjusted according to actual management (21 °C for heating and 22.5°C for cooling) while other boundary conditions remain the same.

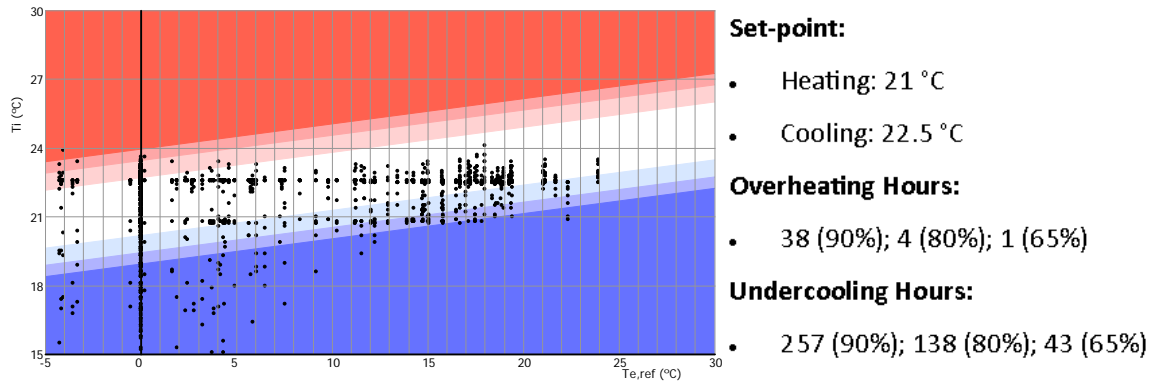


Figure 42. Distribution of Indoor Temperature According to Design Model 2

As the result shows, there is more overheating hours and less undercooling hours compared with the original model. However, the distribution of indoor temperature indicates that there are several hours that are way below the 65% boundary of undercooling hours when the outdoor temperature is low, which indicates irrational settings may exist in the design model.

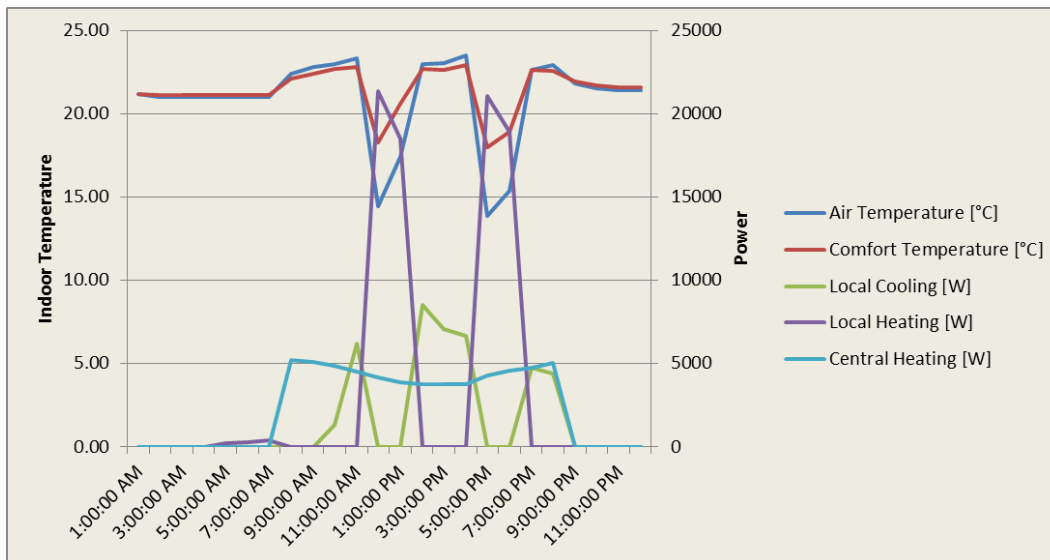


Figure 43. Temperature and Energy Use of a Typical Winter Day in Design Model 2

To further analyze the model, the temperature and energy use of a typical winter day (16th January 2003) is shown in Figure 41. It is notable that there are two sudden temperature drops right after the indoor temperature exceeds 23 °C. These temperature drops were caused by operable windows since according to the model, windows will be opened when the temperature exceeds certain values. However, this is not logical since in winter the windows are closed and the temperature adjustment can

be made by turning down the thermostat. In addition, there is local cooling in winter, which is not possible for the building.

Based on the analysis, two models have been developed, which will facilitate further analysis:

- Modified Design Model in which irrational settings of the original design models are corrected;
- As-built Model, which is based on parameters and data collected from actual building management. In *Figure 42*, predicted temperature is compared with the measured temperature for a typical summer day (1st August 2011). It is clear that the predicted air temperature is close to the measured temperature (the error bar is $\pm 2.5\%$ of the measured temperature), which shows a good accordance has been achieved. This indicates that the as-built model can be used to evaluate the building performance in terms of indoor environment. However, with respect to energy consumption and power of different systems (e.g. convectors and CCA), there is limited information so it is not possible to calibrate the model with respect to these aspects.

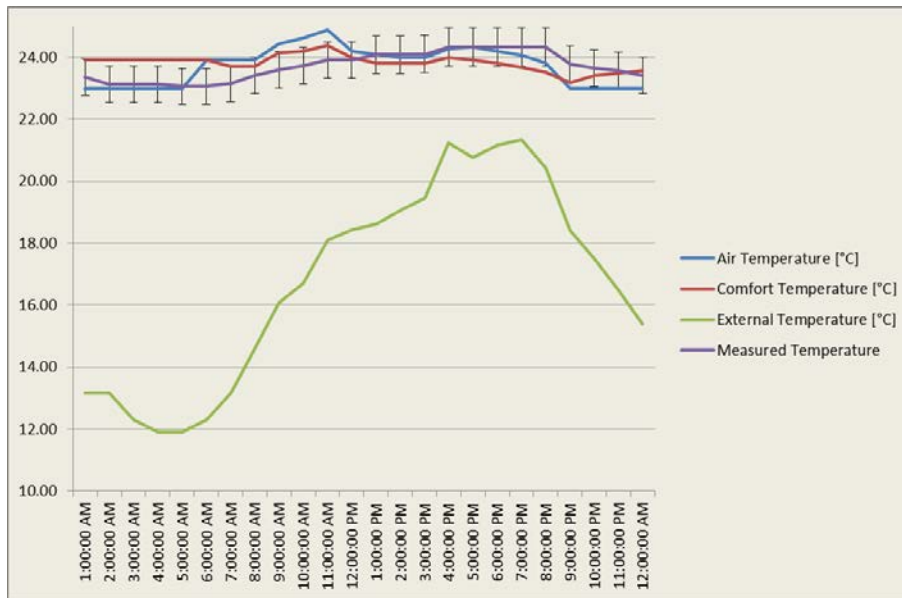


Figure 44. Comparison of Predicted and Measured Temperature in the Calibrated Model

2

THEORY ON PRODUCTIVITY

In this chapter, the calculation methods proposed by REHVA (2006) and Jin et al. (2012) are reviewed.

A2.1 REHVA

REHVA (Federation of European Heating and Air-conditioning Associations) summarized the state-of-the-art researches that describe the effects of indoor environment on productivity. In their Guidebook, research on how productivity can be influenced by indoor temperature and air quality is summarized.

Temperature and performance of office work: Seppanen *et al.* (2006) proposed the relationship between temperature and performance based on 24 studies. The results are shown in *Figure 43*. 22 °C is deemed as the reference temperature at which maximum productivity can be achieved; it also suggests that the performance drops about 1% for every 1 °C change of temperature.

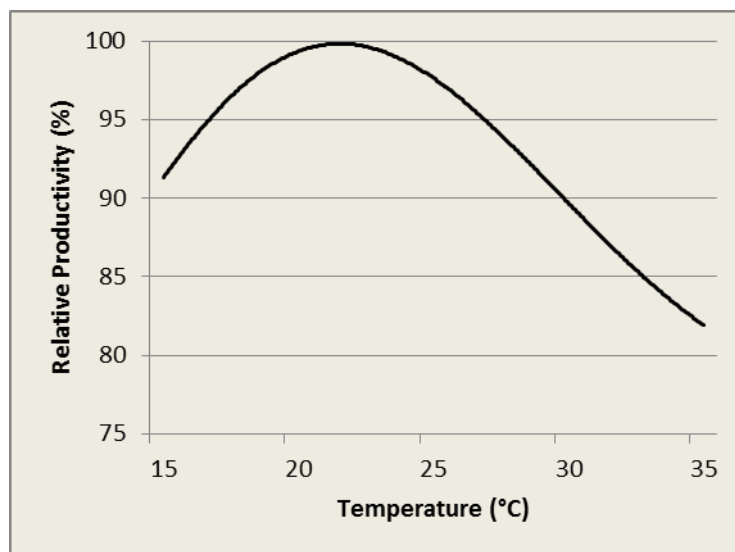


Figure 45. Relationship between temperature and performance

Ventilation rate and sick leave: A quantitative relationship between ventilation rate and short-term sick leave was estimated combining published field data and a theoretical model in which sick leave or short-term illness were outcomes (Fisk, Seppanen, Faulkner, & Huang, 2003). This relationship is applicable only in open plan offices or when the air is recirculating within the office building. As the result shows, higher ventilation rate leads to lower relative prevalence of sick leave. A study was performed by Milton *et al.* (2000) and a reference value is provided for calculation: the sick leave rate is 2 % in an office with a ventilation rate of 0.45 h⁻¹.

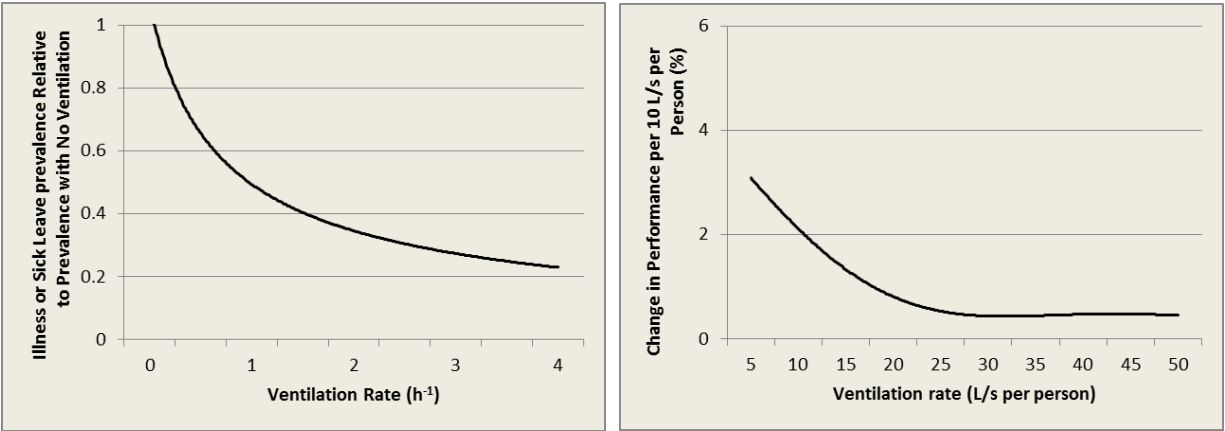


Figure 46. (Left) Relationship between ventilation rate and sick leave; (Right) Relationship between ventilation rate and performance

Ventilation rate and performance of office work: Seppanen *et al.* (2006) developed the relationship between ventilation rate and performance based on seven studies. According to the model, the increase of ventilation rate can lead to a higher productivity. This model is statistically significant up to 15 L/s per person.

Others: the RHEVA guidebook indicate that other factors, e.g. noise, lighting level and controllability could influence the productivity as well. However, no quantitative relationships are mentioned.

A2.2 Jin et al.

Jin *et al.* (2011) linked two independent studies undertaken by Wong *et al.*(2008) and Kawamura *et al.* (2007) and put forward a model that can evaluate the occupant productivity based on the overall IEQ.

The methodology employed by Jin *et al.* was to establish the quantitative relationship among three concepts related to indoor environment and productivity, namely acceptance of indoor environmental quality (IEA), satisfaction with indoor environment (IES) and self-assessed productivity (SP).

IEA was the ratio of occupants who consider the indoor environment is ‘acceptable’. With regression analysis, empirical relationship is developed so that it is possible to estimate the IEA with four indoor environmental indicators:

$$IEA = 1 - \frac{1}{1 + \exp[k_0 + \sum_{i=1}^4 k_i \varphi_i(\zeta_i)]}$$

For the formula, φ_1 to φ_4 are the acceptance variables of thermal comfort, air quality, acoustic comfort and lighting level, while k_1 to k_4 indicate the relative importance of these variables.

Aspect	Equation	ζ_i	Applicable range	k_i
φ_1 : thermal comfort	$\varphi_1 = 1 - PPD$	-	$0 \leq PPD \leq 1$	6.09
φ_2 : air quality	$\varphi_2 = 1 - \frac{1}{2} \left[\frac{1}{1 + \exp(3.118 - 0.00215\zeta_2)} - \frac{1}{1 + \exp(3.23 - 0.00117\zeta_2)} \right]$	CO ₂ Concentration (ppm)	$500 \leq \zeta_2 \leq 1800$	4.88
φ_3 : acoustics	$\varphi_3 = 1 - \frac{1}{1 + \exp(9.540 - 0.134\zeta_3)}$	Noise level (dBA)	$45 \leq \zeta_3 \leq 72$	4.74
φ_4 : lighting	$\varphi_4 = 1 - \frac{1}{1 + \exp(-1.017 + 0.00558\zeta_4)}$	Illuminance (lux)	$200 \leq \zeta_2 \leq 1600$	3.70

Table 14. Calculation of IEA

On the other hand, IES is a measure of satisfaction with which the self-assessed productivity could be calculated:

$$SP = 15.097 \times IES + 75.466 \quad (-1 \leq IES \leq 1)$$

From the formula it is notable that the productivity ranges between 60.4% and 90.6%.

Jin *et al.* (2011) suggested that it is possible to establish a quantitative relationship between IEA and IES so that indoor environment indicators can be used to predict productivity.

$$IEA = 0.95 \exp\{-0.0312 \exp[1.7568(1 - IES)]\}$$

3

ADDITIONAL INFO

- Input of the Models (Vabi 114)
- HOPE Questionnaire
- Complete Building Checklist
- Complete Building Evaluation Scheme