Building energy simulation based assessment of industrial halls for design support

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Building Energy Simulation Based Assessment of Industrial Halls for Design Support

PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Technische Universiteit Eindhoven,
op gezag van de rector magnificus prof.dr.ir. C.J. van Duijn,
voor een commissie aangewezen door het College voor Promoties,
in het openbaar te verdedigen
op maandag 6 oktober 2014 om 14:00 uur

door

Bruno Lee

geboren te Hong Kong

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BUILDING ENERGY SIMULATION BASED ASSESSMENT OF INDUSTRIAL HALLS FOR DESIGN SUPPORT

BRUNO LEE

This research was carried out under the project number M81.1.08318 in the framework of the Research Program of the Materials innovation institute M2i (http://www.m2i.nl).

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TO MY GRANDPA

an engineer with integrity, sincerity, and passion

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Appendix A

Foreword

LIFE IS A CONSTANT EXPLORATION WITH MANY PHASES, AND this four-year PhD work is one of the most memorable and unique phases in my life. The academic training has been demanding and intense, yet equally satisfying and worthwhile with the help of many exceptional people.

吾十有五而志於學
三十而立
四十而不惑
五十而知天命...

At fifteen, I aspired to learn.
At thirty, I stood firm.
At forty, I had no doubts.
At fifty, I knew my destiny ...

Unlike Confucius, I did not set my goal when I was fifteen. At that age, I was captivated by the many possibilities awaiting me. Having been trained as a computer engineer in the ‘90s and subsequently working in different industries, I became aware of energy issues and fixed my eyes on sustainable energy design since 2000. I started off casually with some energy design courses, and got accredited as an installer for ground source heat pumps by IGSHPA (International Ground Source Heat Pump Association) in the year 2002. However, practical training did not satisfy my quest for knowledge, and I formally returned to school to study Building Engineering. Between the years of “standing firm ” and “having no doubts ”, I drew closer to “knowing my destiny”. What I did settle on in my 30’s was the profession that I would like to pursue and to which I would like to contribute, no matter how little it might be that I could possibly achieve.

The exploration continues with this new discipline in Building Engineering, and it is not just in coursework or research, it is in the world around us, and in our own selves.

知止而後有定
定而後能靜
靜而後能安
安而後能慮
慮而後能得

Knowing the boundary of what is essential will allow a firm stand;
a solid ground will offer quietude;
a serene heart will nurture content;
a tranquil repose will promote deep thinking;
a holistic deliberation will lead to achievement.

The PhD project may be a prolonged cycle of repetitive brain activities, while a weekend excursion may be a shorter cycle of physical movements. In brief, life is composed of small and big cycles. We learn · we think; we challenge · we settle; we decompose the problem · we formulate a solution. We advance in each incremental step.

My unsettled mind remains unsettled. Life, to me, is always an endless journey of exploration. It has been exactly ten years since I formally went back to school, and it will be many more cycles of ten years from now on under different capacities of my life.

I should attribute my quest for solutions to my grandpa. I can still vividly remember how he made a ship model for me by curving wet wood over the stovetop. To every problem, there is a solution, and he never backed off from difficulties, when he encountered a problem. I hope I can uphold this attitude.

My father, Joseph, a mathematician and an artist, always urges me to think critically and to dig beyond the surface. He never simply gives me answers without having me know precisely what I want to ask first. Joseph never tries to pass on to me any knowledge, but always leads me to seek the knowledge myself.

學而不思則罔
思而不學則殆

To learn without thinking is confusing,
to think without learning is dangerous.

My mother, Katherine, an administrator, always gives me lessons on organization and methods. She enjoys planning, for matters big or small, long term or short term. Even the dull task of dish washing after dinner can be turned into a fun mission of improving my washing skill day by day. The point is not just about the discipline, but about the attitude towards life.

The unconditional love of my parents has never slipped through their mouths, it is felt in their acts. Without my parents, I would not be who I am now.

There is a long list of people I would like to thank. One's action will sow a seed in others somewhere somehow. I am too an outcome of the many seeds planted by others. I am lucky enough to have met many great people in my life. Without them, I would not be in a position to write these lines.

If my parents have opened my eyes to the world, Prof. Paul Fazio, has opened my eyes to the world of research. Paul exerts great passion in nurturing young researchers and goes the extra mile to make sure things work as they are intended. From him, I saw how important it is to put "heart" into our work.

Under the supervision of Prof. Bill Bahnfleth, I learned to appreciate more the role research plays in industry and vice versa. I also learned from Bill's ruthless pursuit of perfection. We could spend considerable time in fine-tuning a single term. Through this process, we would discuss not just a single term, but would dissect and examine the whole concept.

Without Prof. Jelena Srebric's encouragement, I may not have dared to take on the big task of a PhD project. Jelena knows my capabilities and limitations better than I know them myself. She is always there to shed light on my concerns and ease my doubts.

I am indeed very lucky to be able to work under the supervision of Prof. Jan Hensen. Jan has a great vision of the future, has sharp insight into the problems at hand, and gives concise and profound directions that enable the research to reach new heights. His trust allows me to explore different approaches and to formulate my own work. He is wise in work and caring in life. Jan is definitely a role model for me and many others.

Dr. Marija Trcka and Dr. John Bynum, the daily supervisors of my PhD project, have seen my project grow from zero to completion. Marjia contributed tremendously to the development of ideas. These ideas matured through vigorous discussion and fierce debate, through constructive development and bountiful rejection. John reviewed the thesis with great attention to details. He helped a lot in reorganizing the structure and fine-tuning the sentences. I must thank the other members of the doctoral committee as well, Prof. Bert Snijder, Prof. Christoph van Treeck, Prof. Angele Reinders, and Mr. Bauke Hoekstra Bonnema, for their valuable comments. In fact, Bauke, who represented my industrial partner, was heavily involved in my project and provided many useful inputs that helped make the project an industrial success.

I am privileged to work among a group of great colleagues; I must mention Pieter-Jan Hoes, Roel Loonen, and Mike van der Heijden. Pieter-Jan is my senior and always shows me the way. I can still remember the many lunch conversations, cool or heated, on anything ranging from Dutch culture to robustness of building design. Roel is very knowledgeable in topics related to our field. He never denies any request for help even though it might add on extra burden to his already heavy workload. Mike too is well versed in technologies. He always tries something new and earnestly shares ideas with his colleagues. Together with many other wonderful people in the unit, they definitely contributed to my project and enriched my life in the Netherlands. I would like to thank you all.

There are so many encounters in our lives, through work and everyday life. Some barely touch, while others make bigger dents. There are a few people whom I have not mentioned and yet I am in debt to them for their generous support throughout the years. We make the past and look into the future, we care about work and cherish about life. I treasure our friendships and I send them my best wishes.

Last but not least, my wife, Margaret, is my main source of inspiration. Despite her talents and abilities, she unselfishly dedicates her life to be with me so that I can pursue my dream. From folded clothing to insightful thoughts, from nicely decorated space to well planned trips; in any scale and in all dimensions, my life is infused with her endless loving care. There is so little I can give her in return. This lovely little book, designed by Margaret, serves as the best witness to the life that we have gone through. Next, I will join Concordia University, my alma mater, as Assistant Professor in the Department of Building, Civil and Environmental Engineering for the new academic year of 2014/15. It will be another chapter for us, filled with challenges and joy, I am sure.

Eindhoven, June 2014
Bruno Lee

Summary

INDUSTRIAL HALLS STUDIED IN THIS RESEARCH CAN BE characterized as single-storey, large floor area, rectangular shaped structures, which are commonly built in suburban industrial settings in Europe and North America. Due to their relatively high roof-to-floor area ratio as compared to other types of buildings of similar total floor area, it is more advantageous for industrial halls to incorporate energy producing components into the building design. However, because of the unique geometry and also the variety of manufacturing processes typically found inside industrial halls, modeling of industrial halls at the building level is quite different from that of other types of buildings. Energy saving and generation measures, ranging from improving the building envelope to introducing daylighting to installing building-integrated elements such as transpired solar collectors or commonly available PV systems, are included in the investigation and studied for their impact on the energy performance of the buildings in a holistic manner.

The main objectives of this research are to explore different configurations of energy-efficient industrial halls; to develop computational models for such halls using building energy simulation tools; to advance a simulation model framework that is meant to identify design solutions based on energy, environmental, and economic performance; and to propose an assessment methodology to facilitate informed design decisions regarding energy saving and generation measures.

The research includes a thorough survey of the characteristics of the current stock of industrial halls and a critical review of existing energy related standards, guidelines, design practices, and assessment practices for industrial halls. Based on the

characteristics of industrial halls, the deficiencies in current practices, and the capabilities of state of the art building energy simulation tools, a simulation model framework is developed and proposed. Based on the framework, this research develops a building energy simulation based assessment of industrial halls for design support.

The development of the assessment methodology adopts an integrated design approach that investigates parameters from the demand side to the generation side. Building energy simulation evaluates the performance in terms of energy. However, there are also environmental and financial concerns, which can also be determining factors in making informed choices among different design options. Based on energy performance, derived performance indicators are developed for objectively evaluating the environmental impact and cost-effectiveness. These indicators, together with energy, allow objective evaluation of performance in a comprehensive manner. Based on what has been developed for the evaluation, objective means to search for design solutions are proposed. Stochastic risk analysis is deployed to assess the design solutions unbiasedly. The proposed assessment methodology facilitates the design decision process by transforming the energy design of industrial halls from abstract representations (based on the simulation model framework) to objectively assessed design solutions.

The assessment methodology is useful to the users and applicable to the design of industrial halls if and only if the resulting design solutions offer significant performance advantages. This is demonstrated with a case study that compares the design solutions offered by the assessment methodology to those of current design practice, with respect to the design objectives.

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List of Acronyms

ACH	Air Changes per Hour
BREEAM	Building Research Establishment Environmental Assessment Method
CHP	Combined Heat and Power
COP	Coefficient of Performance
EIFS	Exterior Insulation and Finish Systems
EPC	Energy Performance Certificates
EUI	Energy Use Intensity
LED	Light-emitting Diodes
LEED	Leadership in Energy & Environmental Design
LHS	Latin Hypercube Sampling
LPD	Lighting Power Density
MOGA	Multi-objective Genetic Algorithm
NZEB	Net Zero Energy Building
PCC	Partial Correlation Coefficient
PRCC	Partial Rank Correlation Coefficient
PV	Photovoltaic
SRC	Standardized Regression Coefficient
SRRC	Standardized Rank Regression Coefficient
STC	Standard Test Conditions
TSC	Transpired Solar Collector

Organizations:

ARAB	Algemeen Reglement voor de arbeidsbescherming
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BSRIA	Building Services Research and Information Association
BSC	Building Science Corporation

CBSC	California Building Standards Commission
CDIAC	Carbon Dioxide Information Analysis Center
CEC	California Energy Commission
CEN	Comité Européen de Normalisation
CIBSE	Chartered Institution of Building Services Engineers
CPUC	California Public Utilities Commission
EC	European Commission
ECEEE	European Council for an Energy Efficient Economy
EERE	Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
ENER	Directorate-General for Energy, European Commission
EU	Publications Office of the European Union
ICC	International Code Council
IEA	International Energy Agency
IMT	Institute for Market Transformation
IRENA	International Renewable Energy Agency
ISSO	Instituut voor Studie en Stimulering van Onderzoek op het gebied van gebouwinstallaties
NABCEP	North American Board of Certified Energy Practitioners
NIOSH	National Institute for Occupational Safety and Health
NNI	Nederlands Normalisatie-instituut
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety & Health Administration
REN	Renewable Energy policy Network
SCI	The Steel Construction Institute
SRI	Steel Recycling Institute
UKHOC	UK House of Commons
USGBC	US Green Building Council

1

Introduction

INDUSTRIAL HALLS STUDIED IN THIS RESEARCH CAN BE characterized as single-storey, large floor area, rectangular shaped structures, which are commonly built in suburban industrial settings in Europe and North America. Most industrial halls are relatively simple building structures, both in terms of geometry and construction method, which are often built in accordance with common construction practices without considering any sustainability issues. Energy is one of the most significant contributors to sustainability but is seldom taken into account in the design decisions of industrial halls. It is not common to follow any energy codes or standards (most building standards do not apply to industrial buildings), investigate the energy saving potential, nor consider any emerging energy generation technologies (CPUC, 2012). Under this premise, this research develops an assessment methodology which is based on building energy simulation to facilitate informed design decisions in terms of energy, environmental impact and cost.

1.1 Sustainability and industrial halls

In the last 20 years, rising awareness of sustainability in buildings has sped up the development of green building rating systems, such as LEED (USGBC, 2014), BREEAM (BREEAM, 2014), and others, which provide assessment schemes to rate sustainability of buildings. Green building rating systems gained even more traction in the last few years; for example, the floor area of new constructions certified by LEED in 2013 is almost 3 times more than those certified five years ago (USGBC, 2013). The intended scope of green building rating systems (whether LEED, BREEAM, or others) covers building life-cycle phases from construction, to operation, to demolition, and aspects from site development to material choice, and from energy efficiency to water use reduction. Under the existing rating systems, most of the rating points are awarded by satisfying some prescribed values (e.g. 1 LEED point by providing bicycle racks for 5% of all building users). By contrast, LEED points for improving operational energy performance need more detailed calculations and typically involve building energy simulation.

However, it is not clear whether green building rating systems can be applied directly to industrial halls, since some of the assessment schemes are based on consensual or prescriptive values that are pertinent to office buildings but not to industrial halls. In fact, operational energy constitutes a large portion of the life-cycle energy consumption of industrial halls. Even though operational energy performance is considered under LEED, the conversion from performance results to LEED rating points and the corresponding proportion of the obtained points among the total LEED rating points might not truly reflect the significance of operational energy for industrial halls if the same approach as for office buildings would be followed. The aforementioned BREEAM green building rating system follows a similar energy performance calculation procedure but adds yet another layer of abstraction. In this case, the energy performance results are first converted to the Energy Performance Certificates (EPC) Ratings before being converted to BREEAM rating points. The added layer of abstraction does not help illustrate the issues related to assessing operational energy consumption for industrial halls. Even though the methodology developed in this research is applicable to other green building rating systems, LEED is selected as the system of choice for illustrative purposes.

According to current EU energy policy (and recommendations from other international bodies such as IEA), energy, environmental, and cost performance should be considered for the whole life-cycle of buildings. This research, therefore, investigates the energy performance together with the environmental impact and cost effectiveness of energy related measures for industrial halls. When considering energy consumption, in addition to the operational energy, the embodied energy in the building materials also contributes to the total life-cycle energy consumption. Therefore, this research does not only investigate energy related matters of industrial halls during the operation phase, but also supplements the investigation with a limited life-cycle energy analysis that also considers the embodied energy in the building materials. The focus of this research and the corresponding positioning under green building rating systems are depicted in **FIGURE 1.1**. LEED is taken as an example, where operational energy performance only accounts for 17% of all possible LEED points. Material choices affect both LEED points and the life-cycle energy consumption; therefore, the energy and material categories of LEED are studied in this research.

1.1.1 Energy — relevance to industrial halls

The industrial sector is one of the largest consumers of energy. In Europe, the sector used 26% of the total energy consumption

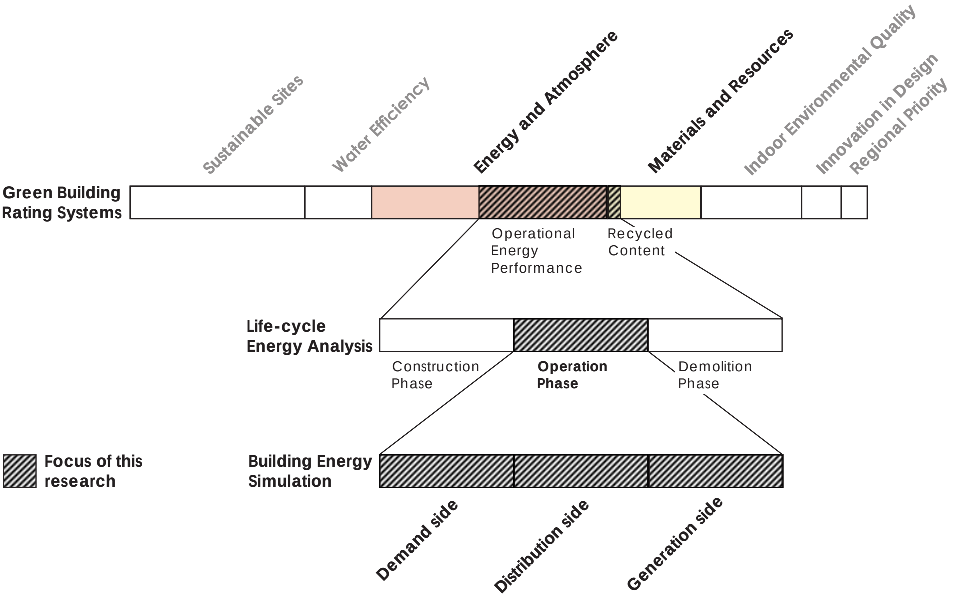


FIGURE 1.1 *The focus of this research and the corresponding positioning under green building rating systems*

in 2011 (Eurostat, 2013), while in the US, this sector consumed 31% in the same year (EIA, 2012). The energy is used for the manufacturing processes, the manufactured products themselves, and the operation of the buildings. Only 7.5% of total energy consumption in 2011 for the industrial sector in the US came from renewable sources (EIA, 2012). Consideration of on-site energy generation technologies could help reduce the dependence on fossil fuels by the sector.

Industrial halls serve different industries with a variety of manufacturing processes. Industrial halls can also be warehouses for logistics companies or big-box stores for retailers, both categorized under the service sector. In **FIGURE 1.2**, service sector is grouped under the “Others” category for Europe and under the “Commercial” category in the US. Apart from the statistics of energy

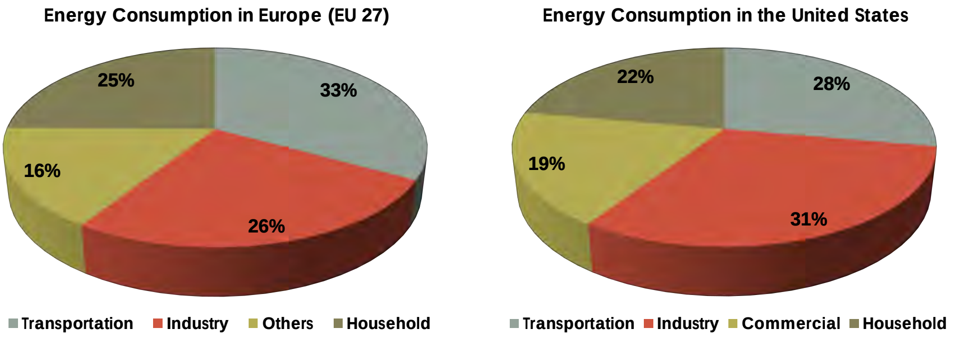


FIGURE 1.2 *Energy consumption by sectors for EU (data source, Eurostat, 2013) and for the US (data source, EIA, 2012)*

consumption under the sector “Industry”, there are no known statistics confirming the exact amount of energy being consumed inside the industrial hall type of buildings in Europe or in North America. If warehouses and big-box stores are included, industrial hall type buildings could very likely account for more than a third of total energy consumption. However, this notion requires further examination since some industrial processes are not conducted within the building enclosures.

For 15 different surveyed industries in the US (ORNL, 2012), around 15% of the energy consumed is on non-manufacturing process activities, out of which, more than 80% is spent on lighting and space conditioning. Lighting energy can be significant for halls with lower process loads. Cooling energy for halls with higher process loads can also be substantial, even though industrial halls are understandably not being conditioned to the same comfort level as required for office buildings. Because of the large floor area of most industrial halls, saving in operational energy consumption for lighting and for space conditioning is a big issue since even a modest percentage reduction in energy consumption could be translated into a large monetary sum for the building owners or utility bill payers.

1.2 Assessment of industrial halls for design support

There is indeed a demand to tap into the operational energy saving potential of industrial halls. In recent years, quite a few design guides or technical support documents on the energy saving potential of industrial halls have been published by related professional organizations and industrial trade bodies (ASHRAE, 2008; ASHRAE, 2011; NREL, 2009a; TargetZero, 2011). Those general guides mainly focus on low process load industrial halls such as warehouses and retail spaces. For industrial halls with higher process loads, the process load itself becomes a target for energy saving investigations, which are industry or process specific. However, as suggested previously, even if only 15% of the energy is spent on non-process activities, the saving potential is considerable given the scale of most manufacturing facilities. There is much to investigate at the building level with many energy saving measures to explore. Moreover, on-site energy generation can also be a cost-effective alternative to energy saving measures, particularly for industrial halls where there is available idle real estate space for the installation of generation equipment. It could be the case that energy generation might be more cost-effective than energy saving, or vice versa. There is a lack of research for industrial halls to provide an assessment methodology that integrally and objectively evaluates the different design options in order to support informed design decisions (with respect to investment in energy saving and generation measures in terms of the different design aspects: energy performance, environmental impact, and cost effectiveness).

Since there is a lack of research in how energy saving and generation measures are deployed in industrial halls and thus a lack of performance data for these measures (not to mention the impact on overall performance due to the integral effect of combinations of these measures), the assessment methodology must include an exhaustive investigation that covers many aspects of the design of industrial halls, such as different choices of material, types of constructions, and sizes of components. Computational whole building energy simulation is an effective means to evaluate many different design options. Under this presumption, it is hypothesized that building energy simulation will enable an assessment of industrial halls that are energy optimized and objectively evaluated under different aspects.

1.3 Objectives

The main objective of this research is to develop a building energy simulation based assessment methodology for industrial halls to facilitate informed design decisions on energy saving and generation measures. The focus of this thesis is the development process itself, and the outcome is the resulting simulation based assessment methodology. The main objective can be achieved with the following:

- identifying issues in the energy design and assessment of industrial halls,
- formulating the simulation based assessment that could work towards energy optimized industrial halls,
- and, demonstrating the applicability and the usefulness of the assessment methodology.

1.4 Research methodology

The research methodology can be organized into two tracks: problem decomposition and assessment methodology development. Through the problem decomposition track, the research problem is examined and the generic elements of the simulation models appropriate for industrial halls are assembled. Through the assessment methodology development track, the assessment methodology is constructed based on the assembled simulation models. **FIGURE 1.3** presents an overview of the two tracks including tasks that are explained in detail below. The corresponding chapters for the tasks are referenced in the figure, and a brief description of each chapter is presented in the next section.

To form the basis to decompose the problem, a **literature review** is performed on current energy design and assessment practices (common practice, design guidelines, building standards and norms) as they relate to the study of industrial halls. This review helps stipulate the direction of the research by thoroughly examining the pitfalls in current practices and understanding the unique characteristics of industrial halls. Based on the findings, the simulation model framework is proposed through an **analysis of requirements**. The simulation model framework illustrates the relationship between the physical building and the virtual simulation models with respect to different aspects being studied. Building energy simulation tools and approaches that seem to be suitable to objectively evaluate energy related aspects of industrial halls are also selected and assembled.

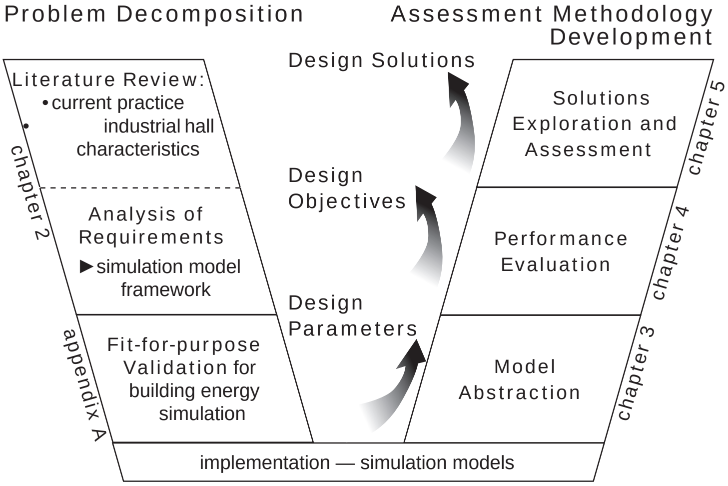


FIGURE 1.3 *Graphical representation of the research methodology and the structure of the thesis (Figure 2.3 presents the same figure with additional details of the findings of Chapter 2)*

The assembled simulation tools and approaches are appraised for their appropriateness as they are applied to industrial halls. **Fit-for-purpose validation** is performed to address concerns regarding the applicability of computational simulation tools to industrial halls. Simulation models are implemented based on the results of the fit-for-purpose validation.

The development of the assessment methodology adopts an integrated design approach that investigates parameters from the demand side to the generation side, which are location specific. Through **model abstraction**, simulation models are built using a finite set of varying design parameters. Design considerations with respect to the design parameters are discussed. Building energy simulation evaluates the performance in terms of energy. However, there are also environmental and financial concerns, which can also be the determining factors in making choices among different design options. Derived performance indicators (based on energy performance) for objectively evaluating the environmental impact and the cost effectiveness are developed. These indicators, together with energy, allow objective **performance evaluation** in a comprehensive manner. Based on what has been developed for the objective evaluation, objective means are proposed for **solutions exploration and assessment**. This is accomplished by either performing a full factorial design or an optimization over the entire design space. Stochastic risk analysis is deployed to objectively assess the involved risks of the design solutions. The assessment methodology developed facilitates informed design decisions by offering objectively assessed design solutions. The design solutions are supported by a vast amount of data, which can be analyzed to observe design trends.

As for any data driven assessment schemes, data are pertinent to the users (e.g. designers) with respect to design support in two ways: the generation of objectively assessed data that enables informed design decisions to be made, and the presentation of data that makes the design decision process convenient.

The focus of this research is on the generation of data (thus making them available), which is accomplished by an assessment methodology that can be generalized and universally applied to other situations. In other words, the suggested methodology is repeatable. The personnel involved in the generation of data are assumed to be professionals who possess the knowledge to follow the suggested methodology.

On the other hand, even though the presentation of data also affects greatly the design decision process, it is not the focus of this research. How the users are making use of and interacting with the data is very situation specific and dependent on what is available to the end users (who do not necessarily possess any building related knowledge). The data could be made available to the users as a paper-based report, a computer file, or even an application on a smart tablet. The possibilities are endless and affect the usefulness of the assessment greatly. Some of those possibilities are presented to demonstrate the potential capability and usefulness of the assessment methodology with respect to design support.

The assessment methodology is useful to the users and applicable to the design of industrial halls if and only if the proposed design solutions offer significant performance advantages. This is demonstrated with a case study that compares the best performing design solutions offered by the assessment methodology to solutions of current design practice, in terms of the design objectives. The performance of the design solutions evaluated by the assessment is also contrasted with the rating assigned by green building rating systems (for the rating categories of interest).

1.5 Thesis outline

Description of subsequent chapters is presented below.

- Chapter 2 presents the literature review and lays out a roadmap to develop the simulation based assessment methodology.

- Chapter 3 develops stage 1 of the assessment methodology. This chapter is the model abstraction stage, in which physical buildings are being transformed into simulation models and the physical components are represented by design parameters.
- Chapter 4 develops stage 2 of the assessment methodology. This chapter is the performance evaluation stage, in which the performance of a design solution is evaluated on design objectives that are to be discussed.
- Chapter 5 develops stage 3 of the assessment methodology. This chapter is the solutions exploration and assessment stage, in which optimized solutions are being identified and assessed.
- Chapter 6 demonstrates the applicability and usefulness of the assessment methodology that is developed from Chapter 3 to Chapter 5.
- Chapter 7 provides a summary of the assessment methodology, presents its limitations and applications, and identifies future research opportunities based on this newly established assessment methodology.
- Appendix A appraises the simulation tools and approaches as they are applied to industrial halls by addressing the raised concerns (mainly in Chapter 2) through fit-for-purpose validation.

2

Industrial Halls — from Current Practice to Assessment for Design Support

THIS CHAPTER PROVIDES A REVIEW OF CURRENT DESIGN AND assessment practice for industrial halls, and identifies the required qualities for assessment for design support. Unique characteristics of industrial halls are presented with respect to those qualities. The chapter concludes with a roadmap to the development of the simulation based assessment methodology.

2.1 Current design and assessment practice

Even though there is no specific regulation with respect to the design and assessment of industrial halls in terms of energy performance, practices that are applied to office buildings may offer some insights into how buildings can be designed and assessed. The following discussion focuses on current practice for office buildings and supplements them with particular references to industrial halls.

2.1.1 Common reference

Even though there is no energy performance regulation for industrial halls, there are guidelines for structural safety, fire safety for specific manufacturing process, and provision of certain building services such as sanitary facilities. The availability of these non-energy specific guidelines sometimes provides valuable insight into what constitutes a “typical” industrial hall.

However, the lack of regulation prompts the very fundamental question of how could industrial halls be potentially built under current practice. In fact, if capital investment (without considering the return on investment) is the only concern, then the function of the building enclosure for industrial halls can be and is often limited to the basic function of keeping out rain and sun. By contrast, enhancing environmental control or improving energy efficiency is not necessary to consider. In other words, under the current practice, industrial halls can perform quite poorly in terms of energy performance.

Since cost effectiveness can be a key decisive factor in the design of industrial halls. It is therefore very important for the assessment methodology to consider the associated potential cost and benefit of any energy saving or generation measures and to evaluate if such additional investment is justified. The evaluation requires a comparison between buildings with and without the additional investment in energy saving or generation measures. A natural case, where no additional investment is necessary, is the building that is built according to current design practice. Since no regulation exists in terms of energy performance for industrial halls, there is no consensus on design practices other than that of pursuing the common goal of cost reduction. Two approaches — benchmark or baseline building, are commonly used to constitute the building that can serve as a comparison.

Benchmark

EERE (2013) emphasized the importance of letting the designers visualize the benefit in measurable terms, which can be accomplished by comparing the performance of a building with the performance of similar buildings. A common benchmark could be the national median Energy Use Intensity (EUI) for a specific building type. For office buildings, the difference in EUI between buildings is mainly due to the difference in design and construction; therefore, a median EUI value nevertheless roughly reflects the norm of the building stock. However, for industrial halls, the difference in energy consumption (even just the heating and cooling) is largely depending on the operation of a building (where process load is a major contributor). In fact, as discussed in Section 2.3.8, the range of energy consumption can be wide even within a certain industrial sector. A statistical EUI value of industrial halls not only reflects the design and construction of the building stock but also reveals the variation in manufacturing techniques among the same industrial sector. A comparison with such EUI values will either over- or under-estimate the benefit by unavoidably including unrelated building design factors into the evaluation.

Baseline building

A baseline building can be defined with a set of specifications according to which the building is to be built. Even though there is no regulation for industrial halls to follow, an arbitrary set of specifications nevertheless provides an unbiased basis for comparison. Since the comparison results are relative to the baseline building and are evaluated solely based on energy performance, different design alternatives can therefore be compared objectively. As NREL (2011) aptly put, a baseline building provides the necessary common reference point.

2.1.2 Prescriptive-based design and baseline building

There are prescriptive requirements for office buildings to follow. International and national organizations as well as regulatory bodies maintain design values for many aspects of building design. ASHRAE (2004, 2007a, 2007b, 2013), ISSO (2002), NNI (2009) and others suggest values for the thermal resistance of insulation and glazing, the infiltration rate, the ventilation rate and many other parameters. Many of these values are climate specific. The values are themselves subject to change with technological advancements and higher performance requirements. Actually many of the above mentioned documents have been updated to current years. However, for the composition of the baseline building for industrial halls, older documents, more realistically represent what is readily available in the market.

2.1.3 Rating, labeling, and certificates for assessment

The evaluation of design solutions with reference to the baseline building provides designers with valuable information and a reference base for their design decisions. The information, however, only represents the direct benefit as a result of potential energy saving or generation. It has to be borne in mind that there could be indirect benefit for the building owners.

The indirect benefit can come in the form of increased rents or sale prices for energy efficient properties. That added incentive for building owners requires a mature market, where potential occupants rely on publicized and comparable information to determine the premium they are willing to pay for the added energy efficiency. In this respect, the many international and country specific rating, labeling, and certification systems provide such information. These systems vary in scope (from energy specific to those including other sustainability aspects) and in nature (how the rating is determined). One thing in common is that all these systems give their ratings in incremental steps (usually in letter grades) instead of numerical values, despite the fact that the raw evaluation is based on numbers. With a letter grade, the market can easily profile each building with a label. According to ENER (2013), both rents and sale prices increase a few percentage points for each letter grade increase in EPC rating (Energy Performance Certificates in Europe).

Energy Performance Certification is one of the many rating systems. In fact, the terms — rating, labeling, and certificates represent different stages of the assessment process. IMT (2013) presents an in-depth discussion on related terminologies and the many rating systems. The introduction of an asset rating helps formulate the necessary requirements for the objective assessment of industrial halls.

> *Operational rating versus asset rating*
>
> An operational rating, as its name implies, evaluates the energy performance solely on measured energy consumption, with no reference to how the building is designed or operated. As an extreme example, a warehouse under 1-shift operation can be rated side by side together with a warehouse under full-time operation. In fact, it is really a true account of the energy performance of a building in operation. The purpose is to facilitate identification of operational issues rather than improvement in the design of a building. This operational rating is not too useful for the assessment of industrial halls for the same reasons as discussed for benchmarking in Section 2.1.1.
>
> An asset rating, on the other hand, focuses on how the building is designed based on physical characteristics and excludes operational and behavioral factors. LEED certification (USGBC, 2009) is based on this asset rating approach. The evaluation of energy performance is based on an assumed set of operations, which may deviate much from the actual operation. As a result, a high asset rating

> only implies the “assets” (such as components of building envelope and mechanical systems) are energy efficient under the assumed operation. Nevertheless, this asset rating approach allows an objective assessment of energy saving and generation measures.

An evaluation of existing buildings based on the asset rating approach could identify poorly performing assets or help to recommend cost-effective operational improvements. This approach works particularly well for office buildings based on the assumption that there are universally accepted “good” assets and there is a “best” solution regardless of the operation. For office buildings, where operational variations are mainly occupant behavior driven, the impact is not at all comparable to that of industrial halls, where operational variations are mainly manufacturing process load and occupancy schedule driven. In such cases, under greater operational variations, the “best” design solution for a particular operational scenario may not work well for another scenario. Therefore, asset ratings must be applied exhaustively to cover representative variations of industrial halls. A further discussion is conducted in subsequent sections.

2.1.4 Simulation approach as applied in current practice

Published design guides (suggested in Section 1.2) provide recommendations for many of the energy assets (e.g. energy saving potential of installing insulation at a certain thermal resistance value), which nevertheless, provide valuable insight into possible design options. Many of these design options are unconventional and require investigation of their potential. In that respect, LEED certification (USGBC, 2009) does promote the use of computational whole building energy simulation to evaluate energy performance by following the method stated in ASHRAE (2007b). It is indeed in practice that computational simulation is being deployed to study energy performance for buildings. However, there are concerns regarding how it can be applied to industrial halls with respect to the unique characteristics that are to be discussed in Section 2.3.

A design guide from ASHRAE (2008) suggests 30% energy savings over a building design according to the already stringent ASHRAE Standard 90.1 (ASHRAE, 2007b). A design guide from TargetZero (2011) tries to achieve zero carbon emissions through aggressive energy generation. In both design guides, to achieve the stated design goal, design options are bundled into improvement packages and presented. For example, for a conditioned warehouse in the Netherlands (ASHRAE Climate Zone 5), it is recommended to have a roof insulation with a thermal resistance of 3.5 m^2K/W, a skylight coverage of 5% - 7% of gross roof area, and many other recommendations.

Though these improvement packages achieve ambitious goals, there are a few questions regarding the heuristic and deterministic approach associated with the establishment of these packages:

- *Multiple operational scenarios:* what will be the performance for operational scenarios other than the assumed one? For example, skylight coverage favors day-shift operation, but it may not offer savings for full-time operation.
- *Multiple design options:* is there any other design option package that will achieve better performance than the recommended package? That is, even though the recommended package achieves the stated design goal, is there another package offering better energy efficiency at the same cost, for example?
- *Multiple design objectives:* the previous notion also highlights the fact that there could be design objectives other than energy efficiency, such as lowering cost and reducing carbon emissions. A similar question then arises: is there another package that offers the same energy efficiency but costs less? For example, under a certain operational scenario, more insulation may be more cost effective than skylights, for the same level of energy performance.

The heuristic and deterministic approach to achieving energy design goals does not offer the design support that allows for comprehensive and informed design decisions. Here are a few more propositions that are to be elaborated in subsequent sections:

- A systematic exhaustive search approach can evaluate the many different possible combinations of design options and suggest the optimal packages.
- Energy performance is just one performance indicator. Better performance can result in higher cost, or create a trade-off in another aspect. Assessment methodology must provide designers with information comprehensive enough to weigh different options and trade-offs.
- A deterministic approach based on one set of assumptions does not present the potential risk (due to uncertainty in assumptions) associated with each recommended package.

The heuristic and deterministic approach may be deemed necessary for the investigation of other building types. However, based on the unique characteristics of industrial halls, which are presented in Section 2.3, a systematic exhaustive search and stochastic analysis approach may prove to be a better choice for industrial halls.

2.2 The principles of assessment for design support

The aforementioned current design and assessment practice simply does not offer much guidance into how the assessment methodology should be shaped. In principle, the assessment methodology for design support must serve one most important purpose, which is to facilitate informed design decisions by attending to the needs of the users (such as designers, building owners, and even building operators).

An industrial hall is usually a structure tied to a specific function, such as, certain manufacturing process or business activity. The investment in the building adds directly to the unit cost of the function in the future. By contrast, the investment cost in buildings of other building types might well be dispersed over societal, aesthetic, and psychological purposes and functions. In other words, construction of industrial halls is particularly cost sensitive. In practice, no extra budget is set aside to investigate energy saving and generation options for each individual case.

Discussions with industrial partners and practitioners with design experience in industrial halls support the above notion that it is not common in practice to investigate energy performance aspects of industrial halls on an individual basis. Based on the discussions, it is clear that the assessment methodology being developed must possess certain qualities to make it useful for and relevant to the industry. Since there are industrial halls of different sizes, process loads, occupancy patterns, and other scenario factors, the assessment must be directly and universally applicable, scalable, practical, and novel to achieve the goal of design decision facilitation. Each of these qualities is described below.

> *Direct and Universal Applicability*
>
> The assessment methodology can be directly applied to a vast array of industrial halls without adaptation or modification for each individual case. That is, halls shall be investigated according to a set of parameters, which could well define and be general enough to describe the energy performance characteristics of the halls. Similar halls in the same climatic location shall perform similarly to the halls that have already been studied.
>
> *Scalability*
>
> The studied energy performance characteristics of industrial halls can be scaled to different size halls. This principle is in line with the concept of universal applicability.
>
> *Practicality*
>
> Investigation shall consider solutions that are economically feasible and technically readily-available. The assessment shall preclude any custom-made solution or component.

Novelty

Assessment methodology must be novel in a sense that the assessment provides additional information that is not available with current practice.

Design Decision Facilitation

The information provided must facilitate informed design decisions by considering the fact that designers might not possess the knowledge to further interpret the information beyond what is being provided.

Direct and universal applicability, scalability, and practicality can be thought of as essential but not sufficient qualities that the assessment methodology must possess. While novelty and design decision facilitation add value and usefulness to the assessment methodology. The next section presents the unique characteristics of industrial halls with particular reference to these listed qualities.

2.3 Characteristics of industrial halls

Industrial halls of interest in this research are a particular form of buildings that house a variety of businesses from retailers, to logistics, to general assembly lines, to heavy industries. The concern is about the energy design of the "industrial hall" as a building form. Energy design is limited to those items related to the operation of the building itself (such as heating, cooling, and lighting) and not the activities (e.g. manufacturing processes) inside the building; however, those activities do have an impact on the operation of the buildings.

In contrast to multi-storey office buildings, industrial halls, which are mainly single-storey structures, maintain a relatively high roof-to-floor area ratio. Unlike in office buildings, thermal comfort is seldom a concern for industrial halls. Internal heat gain due to manufacturing processes has a huge impact on heating and cooling energy, especially in the case of high process loads. The occupancy pattern is another factor affecting heating and cooling, and also lighting. Industrial halls exhibit certain unique characteristics that are not relevant to many other types of buildings. The following sections illustrate these unique characteristics of industrial halls. Because of the unique characteristics, simulation can possibly be applied in certain manners. Concerns regarding how simulation is applied are presented in Appendix A corresponding to the respective characteristics.

2.3.1 Abstraction of activities and manufacturing processes

In order to develop an assessment methodology that is universally applicable, the scope of the investigation has to exclude activities that are tied to certain industries and cannot be generically applied. To limit the scope, activities and manufacturing processes can be abstracted and represented as a process load and an occupancy pattern.

Uniformly distributed process load

The simplest form of industrial hall is the logistic warehouse, which basically only involves uniformly distributed lighting and minimal process load. In other cases, industrial halls usually involve different activities or manufacturing processes, such as lifting, drilling, punching, screwing, wiring, packaging and many others. These processes generate various amounts of heat, and in most cases, are spaced quite uniformly across the floor area. Appendix A.1 investigates the possibility in modeling the industrial hall as one non-partitioned space (a single-zone model).

In the extreme end of the spectrum, some heavy industries involve highly concentrated point sources of heat (such as a furnace for a steel foundry). For the purpose of limiting the scope of the research, industries that involve point sources of high heat are excluded as the investigation requires specific modeling details that go against the generic nature of the research.

The building enclosure

For some industries (again, the example of a steel foundry), because of the extreme amount of heat generated, the building structures are generally not enclosed. The building structures act more like shelters and not like enclosed conditioned spaces. Since a significant part of the research is to investigate energy saving measures of building enclosures to reduce the amount of heating and cooling energy, shelter-like structures are outside the scope of this research. Some manufacturing processes are even conducted outside the building enclosures. These processes are also excluded from this research since they have no impact on the operational energy of the building.

In summary, this research investigates industrial halls representing a variety of industries that are for now arbitrarily represented by an aggregated and uniformly distributed process load (in units of W/m^2). In fact, to conserve the generic nature of the research, industries are arbitrarily classified in Section 2.3.8 into warehouses, light manufacturing, and heavy industry, for example.

2.3.2 Loose thermal comfort requirements

Thermal comfort is seldom a concern for industrial halls, in which space conditioning (heating and cooling) is provided to maintain the building within a reasonable or legally allowable temperature range.

Temperature range for workplace

A report filed by the UK's House of Commons aptly stated *"there is no simple answer as to what the minimum or maximum workplace temperature should be"* (UKHOC, 2010). For industrial halls, the concern is more about heat stress, which might come as a result of the hot environment associated with high heat gain manufacturing processes. The American Conference of Governmental Industrial Hygienists or the Canadian Centre for Occupational Health

& Safety, for example, refer to the 1999 Occupational Safety & Health Administration technical manual (OSHA, 1999) to recommend a high ceiling for indoor temperature.

The most explicit recommendation for the workplace temperature of industrial halls might come from a Belgian guideline (ARAB, 2006). It recommends that the temperature of the space should be maintained under 30°C to protect workers from heat stress and heating has to be provided only if the space drops below 18°C during occupied hours. This temperature range assumes the workers are performing light work.

Loose control

Not only is the temperature range quite wide (from 18°C to 30°C, for example), there is no requirement as to how to maintain the temperature. Unlike for office buildings, in which the temperature of the space cannot be allowed to fluctuate by more than 2.2°C/h (or 1.1°C per 15 mins cycle; ASHRAE, 2004); there is no such requirement for industrial halls. The principle argument for the lack of requirements lies with the fact that the industrial hall type of environment is not meant to be thermally comfortable. The fact that workers move from one place to another, and go in and out of the facility, offers another reason why such tight temperature control is not necessary.

Notable exceptions to loose temperature control are mission-critical facilities, such as data centers or cold storages. Although these facilities are also housed in industrial halls, their industry specific requirements demand special consideration that is outside the scope of this research.

With relatively loose requirements in space conditioning and comparatively high internal heat gains, the approach to industrial hall design is quite different from that of office buildings. In fact, what is potentially an energy efficient design for office buildings might not be appropriate for high internal heat gain halls. Since tight temperature control is no longer a concern, equipment that is energy efficient but coarse in temperature control can be an alternative to more conventional heating and cooling equipment found in office buildings. The loose comfort requirement on temperature fluctuation also potentially allows the simulation to be carried out with a larger time step (to reduce the execution time for each simulation). Appendix A.2 discusses the impact of loose thermal comfort requirements, and the possibility of having a larger time step.

2.3.3 Simple geometry and construction methods

Industrial halls are tied to specific functions (e.g. manufacturing, or storage), and simple rectangular shaped structures serve most purposes well. As land cost in industrial areas is not high enough to justify the higher cost of constructing multi-storey buildings, industrial halls are typically lower construction cost single-storey structures (GT, 2011). Moreover, single-storey construction also facilitates the logistics of the production line, in which semi-finished products could be readily moved within the same floor among different operations, while raw materials and finished products could be unloaded and delivered through easily accessible loading bays.

It is quite understandable that windows are not commonly installed as the benefit provided by daylighting through vertically placed windows is limited since daylight cannot penetrate deep into the floor space. CIBSE (2012a) suggests that daylight is more commonly admitted through skylights for industrial halls. CIBSE (2009) further suggests that skylights are a very effective way to provide daylight over a large area of a single-storey building. Further considerations regarding skylight design as it is applied to industrial halls are discussed in Section 3.1.

Industrial halls are built with simple construction methods. Aesthetics are usually not a consideration and construction is based on functionality and cost. The roof and wall can be either steel or concrete construction. In the case of steel construction (later shortened to STL), the sandwich panel is the most common choice for wall cladding and is gaining popularity for roof applications (SCI, 2008). Steel sandwich panels are composed of an insulation layer in between an outer and inner layer of steel sheeting. In the case of concrete construction (later shortened to CONC), a variety of construction methods are commonly deployed depending on local practice. Concrete panels (and also steel panels) shorten the construction time quite significantly for large buildings like industrial halls. Since cost is a major factor, concrete panels, either with the tilt-up or the precast type of construction, are often the choice. Insulation can be applied as Exterior Insulation and Finish Systems (EIFS) on the exterior of the concrete panel or installed on the interior of the concrete panel as spray foam.

To avoid undesirable infiltration, airtightness plays an important role. In practice, airtightness can be specified qualitatively and measured directly, but cannot be implemented quantitatively with off-the-shelf materials. Airtightness is achieved through a combination of procedures, such as the use of continuous barriers, proper workmanship at joints, and installation of weather seals. The weakest link of the enclosure is largely due to the workmanship at the joint and seal between the panels, which is a detailing issue not to be considered in this research. Both steel sandwich panels and concrete panels (the panels themselves as components of the building envelope) can be considered as continuous air and vapor barriers (BSC, 2013; Corus, 2007) that offer a reasonable level of airtightness. Typical infiltration rates for industrial halls are suggested by ISSO (2002).

A typical industrial hall can be summarized as a single-storey, large floor area rectangular shaped structure built with either steel or concrete panels with insulation. There is typically no window, but skylights are more common. FIGURE 2.1 depicts a graphical representation of a typical industrial hall with skylights. The dimensions of a typical hall are discussed in Section 2.3.8.

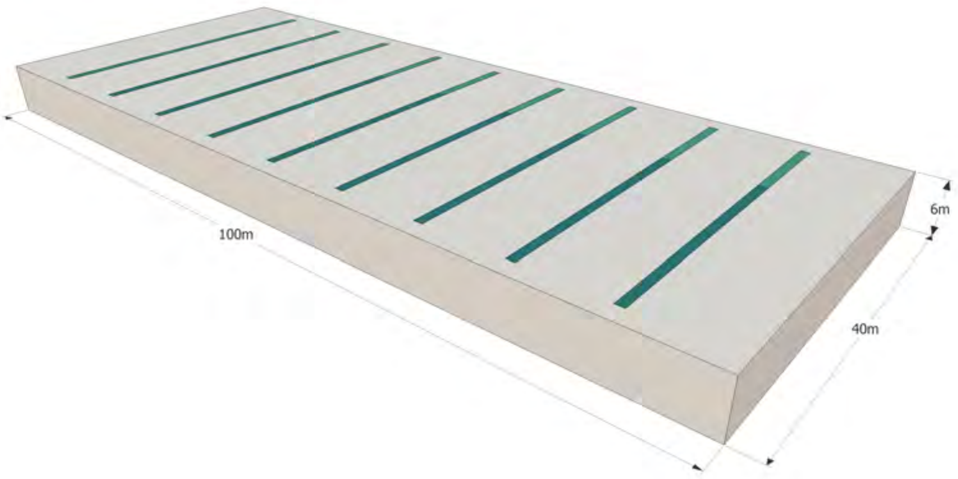


FIGURE 2.1

Graphical representation of a typical industrial hall with skylights

With simple geometry and construction methods, the design parameters related to the energy performance of industrial halls have been greatly reduced. With a limited number of parameters, it is possible to investigate each parameter quantitatively. The following explains the different approaches.

Qualitative approach

Qualitative approach studies the problem by varying the quality of the subject of interest. This kind of investigation is highly dependent on the characteristics of the subject of interest. Recent development of light-emitting diodes (LED) as lamp fixtures best demonstrates the idea. LED lamp is portrayed as an energy saving device by consuming less power for the same lighting output. There are additional benefits such as longer durability and potential drawbacks such as poorer color rendering.

The execution of a qualitative study cannot be limited to the performance indicator of interest alone, but has to consider the many benefits and drawbacks that might not have any direct relationship to the original performance indicator of interest (e.g. energy consumption) but do affect the perceived performance. In the LED lamp example, a lamp that renders poorly in color will not be perceived as providing sufficient lighting (for a certain application) even though the lighting output does satisfy the specification.

The LED lamp example suggests that qualitative analysis is situation dependent (e.g. acceptability of color rendering for a certain application) and cannot be evaluated with a single performance indicator. This qualitative approach is excluded in this research since it does not fulfill the need of the industry for a universally applicable and scalable assessment methodology.

Quantitative approach

Quantitative approach studies the problem by observing the predicted performance through adjusting the quantity of the subject of interest. An example in this research is varying the skylight coverage and observing the impact on energy consumption in lighting, heating and cooling. Section 3.1.1 suggests a lighting source with a lighting power density (LPD) of 9 W/m^2. Fluorescent tubes are a typical choice to provide artificial lighting while LED lamps also gain popularity in recent years. However, the quantitative assumption is the LPD of 9 W/m^2, which is scalable (to a smaller or larger value depending on the actual lighting installation) and universally applicable in any situations regardless of the qualitative characteristics of the lighting fixtures (e.g. fluorescent or LED) as long as the lighting requirement is fulfilled.

Quantitative approach is particularly applicable in this research with the limited number of design parameters, which are further discussed in Chapter 3.

2.3.4 High roof-to-floor area ratios

Since industrial halls are single-storey structures, the roof-to-floor area ratio is equal to one. The implications of this are two-fold.

Roof dominancy and scalability

Internal factors such as a process load are always proportional to the floor area regardless of the number of storeys, while external factors such as solar radiation apply to both the roof and the walls. For high-rise buildings, wall surfaces cover a high percentage of the building enclosure. By contrast, for a single-storey building, the roof surface increases at the same rate as the floor area, while wall surfaces increase at a disproportionate rate. Therefore, the impact of external factors through the roof becomes dominant for larger halls. Moreover, the lack of windows (as stated in last section) also renders the investigation of orientation of industrial halls superfluous (orientation corresponds to the wall surfaces). This notion further supports the dominant nature of the roof.

Because of the dominant nature of the roof and the fact that the interior is a large non-partitioned space, division of the building into multiple zones in a simulation may not be necessary. This idea has been explored in Appendix A.1.

If the hall is investigated as a single zone, performance results can be expressed per unit floor area. For halls with a roof dominant load (halls of larger size, where external impact through the wall is relatively insignificant), total energy performance of halls can be obtained by scaling this per unit area performance value with the floor area. This possibility is further studied in Appendix A.3.

Direction of investigation for generation equipment

This research also investigates renewable energy generation measures. The most suitable location for installation of renewable energy generation technologies will be the proportionally large rooftop, which in most cases does

> not serve any particular purpose. In other words, utilizing the rooftop as the installation location does not incur any opportunity cost. On the other hand, installation on the ground will displace real estate space that most likely is reserved for other purposes, such as a parking lot or future development. Technologies that can be scaled with the size of the rooftop offer clear advantages.
>
> From an environmental standpoint, it is better to consume locally generated energy on-site to prevent transmission losses through the grid. The on-site energy consumption is proportional to the floor area. For single-storey structures, the roof area is equal to the floor area, the energy generation per unit roof area can then be directly applied for energy consumption at a one-to-one ratio. If an equal amount of energy can be generated as is consumed on the same floor area, then a design goal such as zero energy building can be achieved. In other words, one of the determining design factors for energy generation is the energy generation density — that is, the amount of energy generated per unit of roof area. This notion becomes apparent in Section 4.1.3. The total amount of energy generation is scalable with this energy generation density value.

All these factors limit the way industrial halls respond to the external environment, and thus promote the scalability of their energy performance.

2.3.5 Sparsely built and monotonous sites

Industrial areas are sparsely built for many reasons including business related considerations (e.g. lower land cost and reserve for future expansion) and practical considerations (e.g. large loading area for truck maneuvering). With single-storey structures, land-to-building ratios of 2 to even 10 are not uncommon. Moreover, industrial areas are usually quite flat to accommodate the layout of manufacturing equipment and to facilitate logistics.

Unlike high-rise buildings in a city center, where one building will cast a shadow on or block the wind from the others, a single-storey industrial hall on a sparsely built site does not have an interactive relationship with its neighboring buildings in terms of energy performance. The detachment of one building from the others implies that the energy performance of each building can be independently investigated without considering surrounding structures. And as a result, the outcomes of such investigations can be readily applied to similar buildings of the same construction regardless of the very likely difference in the surroundings. This notion satisfies the universal applicability and scalability principles of the assessment methodology.

The independent nature of building sites is relevant to energy generation investigations as well. Without blockage of sun or wind, energy generation measures investigated for one building at a particular climatic location can be readily applied and scaled to another building in the same location.

2.3.6 Discrete occupancy patterns

With the exception of a few notable labor-intensive industries, industrial halls are usually not densely occupied. Occupant load factors for warehouses range from approximately 2 to 0.2 occupants/100 m^2 (given as 500 to 5000 ft^2/occupant in the original documents), in which the denser number is provided by ICC (2012) for safety purposes while the sparser number is given by CBSC (2010) for building service provisions. Regardless of the exact number of occupants, industrial halls are much less populated than office buildings (ASHRAE, 2007a, stipulates occupant densities from 5 to 60 occupants/100 m^2, depending on the function of the office space).

The higher occupancy of office buildings also comes with more uncertain and spontaneous occupancy patterns. More predictable events such as a project due date or Friday gathering, as well as more spontaneous events such as an office briefing, can both influence a team of workers, or individual workers, to stay overtime or leave earlier than their normal working schedule. An office building can host several companies, and each company is made up of many individuals. Moreover, individuals can have their own occupant related unpredictable user behavior, such as opening of windows. Investigation of energy performance of buildings at one assumed occupancy pattern and behavior may prove to be contradictory to reality. With such great uncertainty, the occupancy pattern of office buildings is by itself a large topic of investigation.

On the other hand, in most cases an industrial hall is occupied by a single company. Whether the hall is used as a logistics warehouse or for manufacturing purposes, each industrial hall follows a very discrete and regular occupancy pattern. The industrial halls are either occupied (with activities going on) or not occupied. That is, either no or all workers are at work. Workers also act quite uniformly, with little opportunity to exercise any individual preference on the building environment. In general, occupancy is scheduled in the unit of an eight-hour shift. A full-time operation can be divided into three shifts of work (NIOSH, 1997). There could be variation in the occupancy pattern throughout the year due to seasonal factors, economic cycles, product demands, and industry specific characteristics, but the variation is more predictable in nature and occurs in weeks or months, and not in hours. Such variation can be handled in a model in a rather controlled and predictable manner. Stochastic risk analysis in Section 4.4 gives a fuller account.

2.3.7 Design decision facilitation for industrial halls

The assessment methodology is meant to facilitate informed design decisions. Design decisions are made based on the availability and quality of information. However, the availability of information depends very much on what has already been decided. In many cases, the interaction between availability of information and making design decisions creates a dilemma about what shall be done to facilitate the design decision process.

Gibson (1994) and Bottom et al. (1999) emphasize the importance of provision of information for informed design decisions that affects the building performance. In fact, based on what has been discussed regarding the characteristics of industrial halls, it is indeed possible to provide useful information before making any design decisions. **FIGURE 2.2** presents the characteristics of industrial halls as they contribute to each of the qualities of the principles of assessment for design support (Section 2.2) and shows how they could lead to the ultimate goal of design decision facilitation.

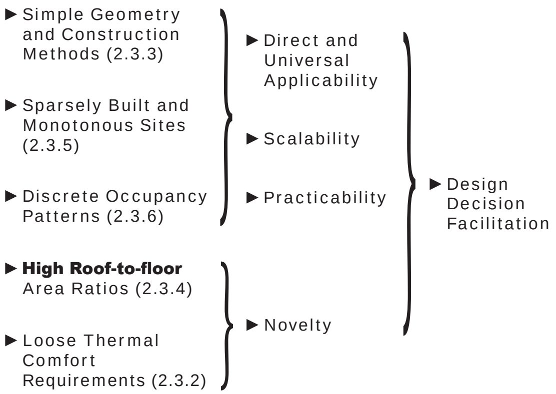


FIGURE 2.2 *Relationship between characteristics of industrial halls and principles of assessment for design support*

2.3.8 Classification according to process load, occupancy pattern, and building size

The most basic characteristic of the industrial hall, which must be identified upfront, is the intended use of the hall (i.e. the manufacturing process and the related process load of the hall). Because of the unique characteristics of industrial halls (such as high roof-to-floor area ratios and discrete occupancy patterns), typical process loads, occupancy patterns, and building sizes for representative industries can be deduced from limited information presented in building stock surveys.

CIBSE (2012b) summarizes the process energy consumption and average number of shifts for a few representative industries. Selected industries (specifically excluded are those discussed in Section 2.3.1 and 2.3.2) have process energy consumption up to 3,589 kWh/m^2-yr and operate from 1-shift to full-time. Based on the occupancy schedule and the process energy consumption, industries are assigned into five groups in **TABLE 2.1**, from low to high representative process loads in units of W/m^2 (the representative values are arbitrary).

TABLE 2.1 Five groups of industries categorized by arbitrary process loads that are derived from annual process energy consumption and occupancy schedule

Arbitrary Process Load (W/m^2)	Average shifts	Representative Industries	Process Energy Consumption Range (kWh/m^2-yr)	Occupancy Schedule (shift)
5	1.0	Distribution	–	1.0
25	1.7	Engineering, Light Manufacturing	82 – 85	1.7
50	2.3	Lab, Plastics, General Manufacturing, Textiles, Electronics, Chemical Factory	341 – 532	1.5 – 2.5
125	2.3	Food, Rubber	795 – 1247	1.8 – 2.6
300	3.0	Chemical Plant, Paper	2,636 – 3,589	3.0

Full-time operation is more typical for heavy industries, while 1-shift operation is common for warehouses. There could be variation in the occupancy schedule throughout the year, particularly for manufacturers. Based roughly on an eight-hour shift, occupancy schedule can be arbitrarily defined into three patterns.

- 1-shift operation: Mon – Sat, 08:00 – 18:00, including breaks on-site, total 2,610 hours annually
- 2-shift operation: Mon – Sat, 06:00 – 22:00, total 5,008 hours annually
- Full-time operation: total 8,760 hours annually

EIA (2010), through its Manufacturing Energy Consumption Survey, provides industry specific statistics on energy consumption and building size. Based on sector description and energy consumption similarity, selected industries described above have been identified in the survey. Identified industries, such as light manufacturing, general manufacturing, textiles, electronics, rubber, and food processing occupy average spaces from 2,343 to 5,672 square meter per building enclosure (each facility location may include a few buildings). The average across all industries occupies a floor area of 4,691 m^2. Based on correspondence with Bouwen met Staal (the Dutch steel construction organization), a width-to-depth aspect ratio of 2.5 at an increment of 20 m is common for industrial halls. A rectangular shape hall with an arbitrary dimension of 100 m (W) by 40 m (D) may represent a typical industrial hall for the purpose of developing an assessment methodology. These dimensions are further investigated in Appendix A.3 in terms of fitness for scalability.

2.4 Roadmap to simulation based assessment

Industrial halls are usually built according to industry experience. Computational whole building energy simulation, which is more commonly applied to office building design, rarely plays a role in industrial hall design. Based on the discussion of the unique characteristics of industrial halls in Section 2.3, a simulation based exhaustive search approach for design solutions is not only plausible but can also contribute to the design support.

2.4.1 Simulation model framework

In summary, the industrial halls under investigation are single-storey structures with simple geometry and construction methods. High internal heat gains may need to be removed from the space, but thermal comfort is seldom a concern. Energy saving or generation measures utilizing the rooftop can possibly be applied to the whole building area. Through fit-for-purpose validation, a simulation framework that represents the physical characteristics of industrial halls can be drawn upon. **TABLE 2.2** displays a simulation model framework with the corresponding physical characteristics and parametric representation.

TABLE 2.2 From physical characteristics to simulation model framework

Abstract Level	Operation	Building Design	Outcome
Physical Characteristics	• Manufacturing Processes • Activities	• Building Envelope • Mechanical System • Energy Generation	• Economics • Sustainability
Parametric Representation	• Process Load • Occupancy Pattern	• Thermal Resistance • Thermal Capacity • Amount of Daylighting • Amount of PV Energy Generation	• Capital Investment • Energy Consumption • Carbon Emissions
Simulation Model Framework	• User Inputs / Assumptions	• Building Energy Simulation • Lighting Simulation • PV Energy Generation Simulation	• Cost-Benefit • EUI • Embodied Energy • Carbon Footprint • Risk

2.4.2 The roadmap

This research is based on the need for an assessment methodology for design support of industrial halls. The outcome of the assessment should provide unbiased information upon which informed design decisions can be based. In this research, the much needed information is centered on the building design options. The information can come in a few forms:

> *Single design option based recommendation* — provides insight into the performance of each of the building components, but does not make available a quick and direct overview of what the design should be. This goes against the direct applicability principle.

Multiple design options cross comparison on single design objective — gives a good overview; however, design trends observed may work for one design objective, and may not work for another design objective.

Objectively assessed design solutions based on multiple design objectives — these solutions are directly applicable, and most importantly address all considered design objectives at the same time. Designers simply select from a list of design solutions based on the trade-off among design objectives and on the objectively assessed ranking (e.g. a risk indicator).

FIGURE 2.3 graphically presents the roadmap of the development of the simulation based assessment of industrial halls for design support. Through problem decomposition, the initial conceptual need of the assessment methodology is translated into conceivable simulation models (that fall within the earlier discussed simulation model framework). The simulation based assessment is what transforms the simulation models into design solutions according

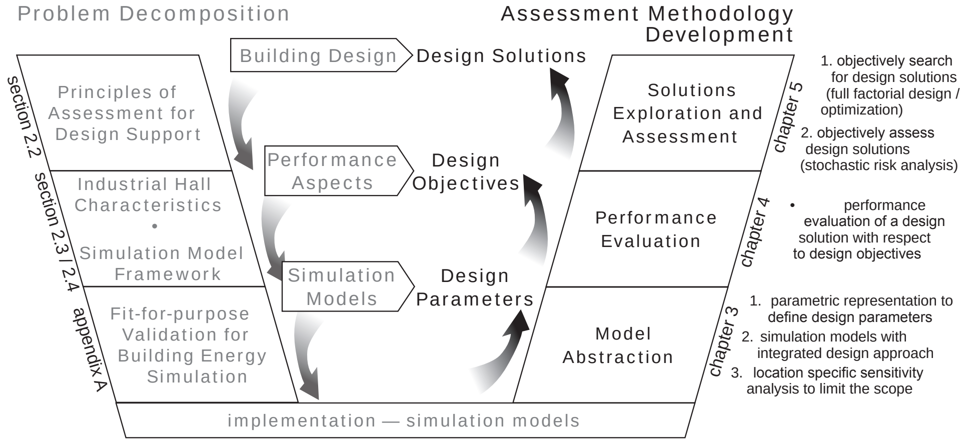


FIGURE 2.3 *Development of the simulation based assessment for design support*

to design objectives. The assessment methodology is the result of this research.

Problem decomposition

The principles of assessment (Section 2.2) are the only constraints that dictate the direction of the development of the assessment methodology. The tangible outcome of the assessment is design solutions that could fulfill the design objectives. Through investigation of the unique characteristics of industrial halls (Section 2.3), it becomes apparent what should be included, how simulation can be applied, and what will be the outcome of the simulation model framework (Section 2.4). Fit-for-purpose validation (Appendix A) bridges the gap between the simulation models and the physical characteristics of the buildings (and the associated simulation concerns). The problem decomposition ends with a set of simulation models that are appropriate to be deployed for the assessment methodology.

Assessment methodology development

The simulation based assessment for design support can be conceived in three sequential steps.

Model abstraction (Chapter 3) — defines the design parameters of a location specific problem through parametric representation according to the simulation model framework, and performs sensitivity analysis to limit the scope and to facilitate future solutions exploration. This step ensures representativeness of the simulation models to the physical problem.

Performance evaluation (Chapter 4) — portrays a design solution in terms of performance corresponding to the design objectives.

Design solutions exploration and assessment (Chapter 5) — systematically and exhaustively searches for design solutions and assesses them objectively.

Figure 2.3 also depicts the structure of the thesis by locating the sections / chapters where the problem is being decomposed and where the simulation based assessment methodology is being developed. The assessment methodology will be applied to a case study in Chapter 6 to demonstrate the applicability and usefulness of the assessment in terms of design decision facilitation.

3

Model Abstraction — Parametric Representation Based on Design Considerations

THROUGH PARAMETRIC REPRESENTATION, THE PHYSICAL presence of industrial halls is translated into simulation models. Based on the simulation model framework outlined in Chapter 2 and the knowledge on building energy simulation for industrial halls gathered in Appendix A, this chapter investigates the details of the simulation models with respect to design parameters. The investigation involves a single-zone building energy simulation model, a lighting simulation model, and a photovoltaic (PV) energy generation simulation model. The studied parameters are categorized into demand side, distribution side, and generation side. Since the PV energy generation simulation model requires no data exchange with other simulation models, the investigation can be conducted independently. Therefore, this chapter is structured in two parts: the demand and distribution side investigation with an integrated design approach followed by a sensitivity analysis, and the generation side investigation. This chapter concludes with ready to deploy energy simulation models.

Throughout this chapter, a warehouse (with a process load of 5W/m^2) under 2-shift operation in Amsterdam will be used as an example to demonstrate the development of the assessment methodology.

3.1 Demand side and distribution side considerations

The operational energy consumption of buildings consists of heating, cooling, ventilation, and lighting. Other common energy demands for buildings, such as that for the elevator, are not applicable for low-rise industrial halls, while demands such as lifting heaving items shall be considered under manufacturing operation rather than building operation. Hot water use for manufacturing process shall also be treated under manufacturing operation and is not considered here. Demand side design parameters are those related to building envelopes and distribution side design parameters are those related to the provision of heating, cooling, and ventilation.

3.1.1 A typical industrial hall and its demand side design parameters

The investigation includes a hypothetical building that represents a typical industrial hall in Amsterdam, the Netherlands, which measures 100 m (W) x 40 m (D) x 6 m (H). Some details are presented in Chapter 2. In the building energy simulation model, the insulation is represented in terms of thermal resistance value (in m^{2}K/W). Steel sheets are assumed to have no thermal resistance and no thickness. While concrete is measured by thickness (in m) with a thermal conductivity of 2.1 W/m·K, a thermal capacity of 1 kJ/kg·K, and a density of 2400 kg/m^3.

For newly built industrial halls, both steel and concrete constructions can be considered as quite airtight. Infiltration mainly comes as a result of opening doors, which is more of an operation and case specific issue. A constant infiltration rate of 0.2 ACH is assumed (ISSO, 2002).

As depicted in Figure 2.1, skylights can be installed on the rooftop to introduce daylight and are measured in terms of a percentage of the rooftop area in this research. CIBSE (1999) provides extensive guidance in the design of daylighting. Fluorescent lighting with a lighting power density (LPD) of 9 W/m^2 is assumed, and will be dimmed according to the lighting level by following the dimmable lighting characteristics suggested by Rubinstein et al. (2010). Lighting fixtures of higher or lower LPD can be deployed and their performance can be scaled linearly on the performance of this assumed 9 W/m^2 fixture. Since skylights are introduced, the U-value of the glazing as well as the reflectance of the interior surfaces (modeled as absorptance) can affect energy performance.

Daylighting brings significant energy savings by covering the rooftop with skylights up to a certain limit. Extra skylights bring in excessive amount of light beyond the required 500 lx (CEN, 2002) during the day and only prolong the hours of daylighting at either early morning or late evening hours when the sun is dim. However, the lighting energy savings will be somewhat offset by the additional cooling required due to solar heat gain during the day and heating required due to heat loss during the night particularly in the winter (even a double-glazed skylight has a much lower thermal resistance value than most of the studied values of roof insulation, which is being replaced by the skylights). **FIGURE 3.1** illustrates the interdependency of heating, cooling and lighting energy consumption due to daylighting. As the skylight coverage increases beyond 15% of the roof area, increase in energy consumption due to heating and cooling more or less cancel out the reduction in lighting energy consumption.

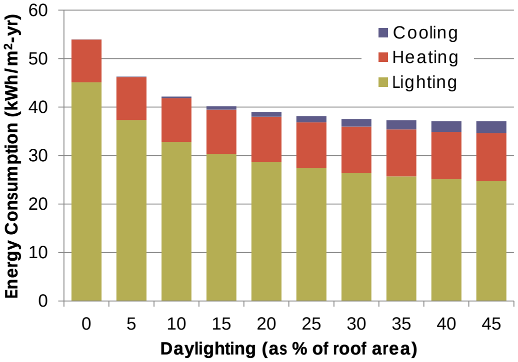


FIGURE 3.1 *Effect of daylighting on heating, cooling, and lighting energy consumption.*

Since cost is the main concern, the implications on the design of daylighting are two-fold. First, only the most basic translucent single-glazed or double-glazed skylights with no shading control will be installed. Excessive lighting levels can be an issue, and the amount of daylighting must be limited to a certain level. However, the lighting concern and thus the maximum possible amount of daylighting are beyond the scope of this research. Second, the incremental benefit of daylighting beyond that of 15% does not seem to be economically sound. Not to mention, the extra amount of daylighting implies limiting the amount of PV energy generation, which both share the same rooftop space. Therefore, in the subsequent investigations, skylight coverage is explored up to 15% of the roof area.

3.1.2 Distribution side parameters

Efficient distribution side equipment / systems are desirable to fulfil the heating, cooling, and ventilation demand. As suggested in Section 2.3.2, the air conditioning requirements of an industrial hall are quite different from an office building in mainly two ways — the wider acceptable temperature setpoint range and the higher allowable temperature fluctuation rate.

Since the requirement (to maintain thermal comfort) for distribution side equipment is loose, the choice of distribution side equipment may follow other priorities, which are industry-specific. In fact, in many cases, distribution side equipment does not only serve the function of provision of heating and cooling, but also is designed as part of the manufacturing process. A noted example is the utilization of “low-temperature” water for many manufacturing processes. Depending on the usable temperature range, heat rejection from equipment such as a chiller or combined heat and power (CHP) plant, can be recouped for the manufacturing processes. Because of the economic value of the by-product (e.g. low temperature water) of the heating and cooling equipment for the manufacturing processes, in most cases, the design of the equipment gives priority to the design of the manufacturing processes. These industry-specific cases are outside the scope of this research.

For most industrial hall settings, the heating and cooling system is quite simple. A wider comfort range and an acceptable frequent temperature fluctuation allow industrial halls to adopt distribution side equipment that provides substantial energy savings but falls short of tight thermal comfort control. The default equipment and system selection for this research is, therefore, based on current best practice instead of an in-depth parametric study as proposed for the demand side investigation and is also independent of any industry-specific manufacturing process.

Cooling

For cooling, forced ventilation with heat recovery is a common system, particularly for industrial halls in a moderate climate, in which the halls can be efficiently cooled by drawing in ambient air at a lower temperature. In addition to fans that fulfill the minimum outdoor air ventilation requirements (ASHRAE, 2007a), multiple fans are installed to draw in ambient air for cooling purposes. The fans are controlled by a feedback controller, which moderates the fan output to maintain the space at the desired temperature setpoint. The fans are rated at 2kW per 10,000 L/s of air flow. The fan selection is in the mid-range with more efficient fans rated at 1 kW to fans rated at 7 kW, per 10,000 L/s of flow (TWF, 2010).

There are times that forced ventilation cannot effectively cool down the building due to high outdoor air temperature. In such a case, supplemental cooling is provided by precooling the outdoor air with a mechanical system that includes an air-cooled chiller. The COP of the system is temperature and humidity dependent, the exact relationship between COP and temperature / humidity is provided by the industrial partner with actual measured data (Bekaert, 2013).

Heating

A transpired solar collector (TSC) is a potentially effective means (Gunnewiek et al., 1996; Leon and Kumar, 2007) of heating, where outdoor air is heated up as it is drawn through the perforated metal wall cavity of the collector installed on the south facing wall (for the northern hemisphere) to take advantage of the free solar energy. TSC is investigated with coverage on the south wall from 0% to 100%. The only energy consumption for the system is that of the fans, which draw in and distribute the heated air.

During early morning or late evening hours, or whenever solar irradiance is not strong enough to heat the air through TSC, local heating using suspended infrared gas radiators will ensure the space is kept at the required temperature. Radiators are the only elements that consume gas rather than electricity; which will be significant in subsequent work, where carbon emission reduction is the goal instead of just energy saving and generation.

With the exception of TSC, which will be investigated quantitatively by varying the area of coverage on the south wall; other distribution side equipment are set up and operated at their fixed design values (e.g. chiller at a fixed size, instead of investigating over a range of sizes). The study of distribution side equipment is to provide realistic estimates of heating and cooling energy consumption, rather than to search for distribution side design solutions.

3.1.3 Integrated design approach

This project adopts an integrated design approach for two main reasons:

- to facilitate informed design decisions, and
- to consider the interdependent nature of some parameters.

Design decision facilitation

In an integrated design approach, different energy saving and generation measures will be weighed against each other to lower the total energy consumption if not to increase the energy generation. As opposed to an integrated design approach; a single parameter / design option consideration will, in many cases, arrive at a definitive conclusion whether a particular measure shall be adopted or not. However, in reality, it is always difficult to decide if one energy saving or generation measure should be adopted when compared to other measures. For example, for a warehouse of low internal heat gain, an extra amount of insulation always exhibits some benefit by lowering the heating energy in a mild climate. If the amount of insulation is the only parameter then the conclusion will be to increase the amount of insulation for a warehouse. However, if the skylight coverage is also studied, then it might be the case that for the same cost, skylights can reduce the total energy consumption more by reducing the artificial lighting reliance. That is, skylights might be more cost effective than insulation installation.

The idea is partially demonstrated in FIGURE 3.2, in which changes in the skylight coverage will have a more significant impact on energy consumption than changes in the amount of insulation. Whether skylights are more cost effective will be further explored in Section 6.2.3 when cost is considered. However, Figure 3.2 does demonstrate that if insulation is the single parameter of interest (for example, with no skylight), extra insulation will reduce energy consumption and thus will be interpreted as the definitive solution. An integrated design approach yields comparably performing but largely different solutions.

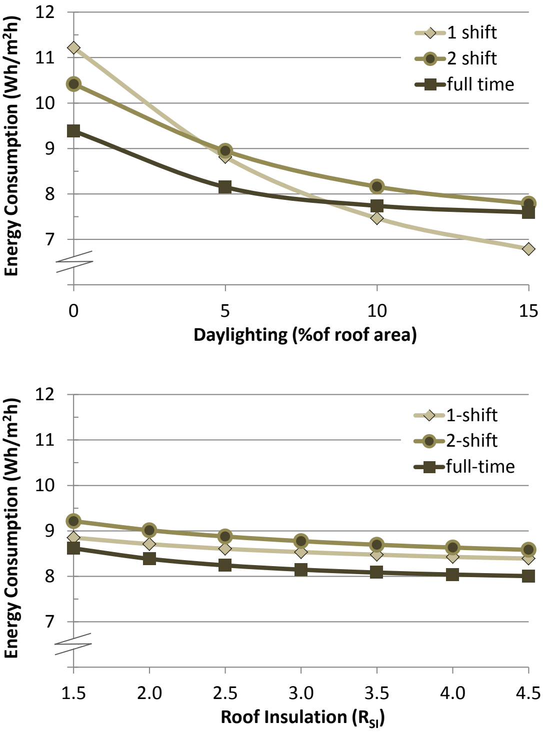


FIGURE 3.2 *Changes in hourly total energy consumption with respect to changes in the daylighting level (top) and roof insulation level (bottom)*

Interdependency among parameters

Some of the many parameters investigated are independent of each other. For instance, the design of PV systems is totally independent to the design of building envelopes. Increasing the amount of insulation will not affect the energy generation of the PV systems regardless of the setup of PV systems' parameters.

On the other hand, some parameters must be investigated at the same time due to their interdependent nature (the concern is interdependency and not dependency). From the previous example, it is suggested that increased insulation reduces the total energy consumption (by reducing heating energy consumption) for a warehouse. This may be true if there is no skylight. By introducing skylights, the amount of heat gain through the skylights might create a situation, where it is preferable to dissipate heat rather than retain heat. In such case, an increase in insulation might only increase the total energy consumption.

Based on these two concerns (design decision facilitation and interdependent nature of the design parameters), an integrated design approach is deemed necessary, and will be adopted in the subsequent investigations.

Based on the description of a typical industrial hall, **TABLE 3.1** presents the demand and distribution side parameters under investigation with their respective ranges and resolutions (in terms of the number of discrete values or "levels") of investigation. The ranges and resolutions are nominally set by adhering to the design support principle of practicality (that is, design solutions must be economically feasible and technically readily-available). Insulation values, for example, ranging from 1.5 to 4.5 m^2K/W in step of 0.5 m^2K/W are readily available on the market.

TABLE 3.1 **Demand and distribution side design parameters**

Parameters	Design Range	Levels of Investigation
Insulation (Thermal resistance, Roof)	1.5 – 4.5 m^2K/W	7
Insulation (Thermal resistance, Wall)	1.5 – 4.5 m^2K/W	7
Construction Types (Roof)	STL or CONC	2
Construction Types (Wall)	STL or CONC	2
Surface Reflectance (as absorptance, Roof)	0.2 – 0.8	4
Surface Reflectance (as absorptance, Wall)	0.2 – 0.8	4
Surface Reflectance (as absorptance, Ceiling)	0.2 – 0.8	4
Surface Reflectance (as absorptance, Wall Int.)	0.2 – 0.8	4
Overall heat transfer coefficient (Glazing)	2 or 5 U-value	double- or single-glazed
Daylighting (as % of roof area)	0 – 15 %	4
Transpired solar collector (as % of south wall)	0 – 100 %	6

Table 3.1 also includes the reflectance of both the roof and the exterior wall surfaces for consideration. However, it should be pointed out that PV modules (to be discussed in next section) act as shading devices for the roof and the addition of transpired solar collector blocks the south wall surface, the significance of the impact of the reflectance of the exterior surfaces needs further investigation.

3.2 Generation side considerations

By relying on energy conservation alone, it is almost impossible to achieve the goal of a zero energy building, not to mention, an energy producing building. Industrial halls, in many cases, operate all day long (CIBSE, 2012b). Lighting energy consumption, which could be drastically reduced during the day with the help of daylighting through skylights, cannot be reduced after dusk. Amidst all means of energy saving measures, on-site renewable energy generation is necessary to make up the energy deficit.

Photovoltaics (PV), solar thermal systems, and wind turbines are all common renewable energy generation technologies for the built environment (REN, 2013). The applicability of any of these technologies has to take into account the unique situations of industrial halls.

These technologies will generate electrical energy, thermal energy, or both. Electrical energy is a very useful source of energy as it is demanded by most manufacturing processes and for lighting purposes. On the other hand, the need for thermal energy greatly depends on the types of manufacturing processes as well as heating and cooling demand.

PV system is to be investigated, since it generates electricity that is of immediate demand (for lighting or manufacturing purposes), it could be readily deployed and attached to the rooftop with no alteration to the building design (as long as the roof has enough load bearing capacity for the added weight), and its application can be scaled according to need. In addition, industrial halls are usually of similar height. They are spaced apart in a suburban setting with open fields where the performance of PV systems is not hampered by shading of surrounding buildings. Therefore, grid-connected PV system is the technology of choice of this research to demonstrate the possibility towards energy producing building. The investigation of PV systems fulfills the assessment principle of universal applicability and scalability.

Although demand side design parameters work together to achieve energy saving and exhibit certain interdependencies, they are in principle acting within their own individual domains (lighting, heating, cooling, and ventilation). From the example presented in Section 3.1.3, there are indirect factors (such as unwanted heat gain or loss) that relate the skylight coverage and energy performance of buildings under varying insulation values. However, increase or decrease in skylight coverage will not have a direct impact on the performance of insulation. By contrast, design parameters for PV systems work together as nuts and bolts of a system and are worth further explanation from the system design perspective. Interaction between tilt angle of and spacing between PV modules is a good example to illustrate the dependency and is further explained in subsequent sections.

3.2.1 Photovoltaic (PV) system conventional design approach

Using the conventional design approach based on rule of thumb design principle, PV systems may not harness the full potential of the available solar energy nor optimize the use of the limited available space in which the PV modules are installed.

According to the conventional design approach, the sizing of PV systems is usually based on rated characteristics of the equipment. For example, watt peak (W_P), the nominal value used for sizing of PV systems, is the nameplate power that a PV module can generate under the Standard Test Conditions (STC) of 1,000 W/m^2 irradiance and 25°C cell temperature (CEC, 2001). In reality, the irradiation peaks at different values according to installation locations and varies hour-by-hour throughout the year. In most cases, sizing of PV systems is based on either the annual average or the worst month average irradiance values at the installation location. Therefore, the actual performance of PV systems might not match or even come close to the design performance.

As a rule of thumb, PV systems that have to satisfy a rather constant year-round load could have the arrays tilted to the angle of latitude at the installation location in order to maximize the annual performance. If PV systems have to satisfy a winter-dominant load, the angle of latitude plus 15° is suggested; on the other hand, if PV systems have to satisfy a summer-dominant load, the angle of latitude minus 15° is recommended (NABCEP, 2012).

For PV systems with multiple rows, the PV modules of the row in front will cast a shadow on the modules of the rows behind, and thus reduce the overall generation efficiency. This issue of self-shading is more apparent at higher latitudes. The conventional approach tries to avoid the shading during part of the day by imposing a minimum required spacing between the rows of PV modules (NABCEP, 2012). The spacing is commonly specified by a separation factor, which is the ratio of the spacing and height (H, see **FIGURE 3.3**). Therefore, for the same separation factor, the taller the height, the wider the spacing.

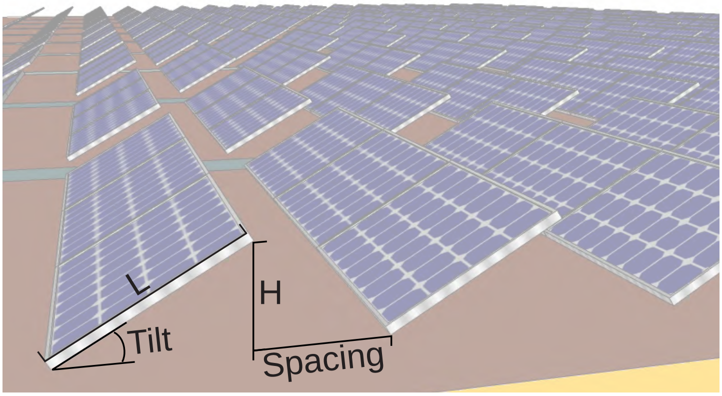


FIGURE 3.3 *Configuration of PV system*

For Amsterdam, at a latitude of 52.4°N, a separation factor of 10 is necessary to avoid shading between 9AM and 3PM (NABCEP, 2012). That is, for a limited space, only a few rows of PV modules can be installed according to this conventional design approach.

3.2.2 PV system design considerations

PV systems are commonly deployed on a horizontal surface such as that depicted in Figure 3.3, with multiple rows of PV modules tilted at an angle and separated by a spacing. The main design objective is to maximize the energy generation, and the main design limitation during the design phase will be the aforementioned self-shading effect of the adjacent tilted PV array.

Effect of shading and bypass diodes

To complicate the issue further, the reduction in energy generation due to shading is not in direct proportion to the area being shaded. In large PV systems, like those deployed on the rooftops of industrial halls, PV modules are connected in series or parallel to achieve the desired voltage and current output. If an individual module is partially shaded, or some of the connected modules are shaded while others are not, then a mismatch will occur between those shaded and non-shaded portions. Hot spots will be developed due to current flowing from the non-shaded cells / modules to the shaded ones. The exact effect depends on the configuration of the PV modules and how they are connected.

To prevent the damaging effect of hot spots due to unavoidable shading in many situations, bypass diodes are installed to divert the flow away from the shaded portions. Each bypass diode usually serves around 30 to 40 cells depending on manufacturers. The groups of PV cells are typically arranged along the short side of the rectangular module. Since the shading due to adjacent rows of PV begins at the bottom and progresses towards the top, PV modules are commonly deployed with their long side attached to the ground so that the sequence of bypass diodes can handle the slowly increasing shaded area from the bottom up.

3.2.3 Computational simulation approach

The default setting assumes a PV cell efficiency of 15.7%, which is quite typical among commonly available flat-plate monocrystalline PV modules (IRENA, 2013). The energy generation results can be scaled to different efficiencies.

Three bypass diodes per PV module are assumed. In other words, each bypass diode serves a third of the PV surface area from the bottom up. Depending on the configuration of the PV system, and thus the heat accumulation of the hot spots, bypass diodes might respond differently. Correspondence with practitioners indicates that the bypass diode will have full effect (thus completely disabling the corresponding connected PV cells) if the relevant area is more than 55% shaded. The effect of the shading and bypass diodes is taken into account in the simulation model.

The computational approach studies three parameters — the tilt angle, the PV module length, and the spacing. The investigation is applied to the same building as discussed in Section 3.1.1. Amsterdam, is located at a latitude of 52.4°, therefore, a design range of the tilt angle from 0° (that is, lying flat on the horizontal surface) to 56° is investigated. PV modules are commonly available in a limited choice of sizes. Commercially available modules come in nominal lengths (the short side of the module) of 0.4 m, 0.6 m, 0.8 m, and 1.0 m, all of which are being investigated. The investigation is being applied on the same hypothetical rooftop as before with dimensions of 100 m (south facing) x 40 m. For maintenance purposes, a minimum spacing of 0.5 m between rows is imposed. Therefore, for a PV module length of 0.4 m, a maximum of 40 rows could be installed on a rooftop with a depth of 40 m. Spacing is in fact a derived quantity based on the number of rows and the available rooftop area. **TABLE 3.2** summarizes the design parameters.

This computational simulation approach not only examines the hour-by-hour variation of irradiation with the aforementioned self-shading / bypass diode effect, but also considers the diffuse portion of the solar radiation, which is best received on a horizontal surface.

TABLE 3.2 **Design parameters of PV systems**

Parameters	Design Range	Notes
Length of PV module	0.4 m, 0.6 m, 0.8 m, 1.0 m	nominal length for commercially available PV modules
Tilt angle	0° to 56°	in increment of 2°
Number of rows (spacing)	max. 40 rows (max. 39.6 m)	for a hypothetical rooftop with a depth of 40 m, and to accommodate a minimum spacing of 0.5 m (maximum spacing reflects an installation of one row of PV modules of a length of 0.4 m)

3.3 Sensitivity analysis

Based on the list of demand and distribution side parameters in Table 3.1, a full investigation of all possible different combinations of design parameters at the suggested resolutions of investigation is too computationally intensive (more than one hundred thousand configurations). Especially, it might not be worth the effort if the massive investigation provides little additional information. Moreover, if the investigation is to be carried out for all discussed process loads (from 5 to 300 W/m^2, as presented in Table 2.1) and occupancy schedules, there could be over 2 million cases to be investigated for a climatic location. On the other hand, a full investigation of generation side design parameters at the suggested resolution involves less than 5 thousand configurations, and the investigation is independent of the process loads and occupancy schedules of the industrial halls analyzed.

When a massive investigation is not practically feasible, a sensitivity analysis can be carried out to identify parameters that have the greatest influence on the performance (in this case, energy performance). For building performance investigations that involve large datasets, Latin Hypercube Sampling (LHS) is an efficient means of reducing the size of the investigation to a smaller sample set (Struck, 2012). However, it becomes apparent in later discussions on monotonicity and rank transformation that any sampling technique will result in missing points in the rank and subsequently nonlinearity in the data. As seen in the prior investigation illustrated in Figure 3.2 (energy consumption due to varying roof insulation values), the relationship between energy consumption (output) and any of the studied design parameters (input) is monotonic. A monotonic relationship is which the output will move in one direction (increase or decrease) with respect to an increase in input. In such case, a reduced size investigation can be made with reduced resolution for each of the parameters.

3.3.1 Monotonicity and rank transformation

The design parameters relevant to industrial halls are given in different units. From Figure 3.2, without considering the units, daylighting induces an energy consumption variation from 7.8 to 10.4 by varying from 0 to 15, while roof insulation induces a variation from 8.6 to 9.2 by varying from 1.5 to 4.5. Energy consumption is in the same units of $Wh/m^2 \cdot h$ in both cases, but the units for daylighting and insulation are not the same. This difference in units might cause problems in sensitivity ranking. A possible solution is to apply rank (on same range) to each of the design parameters. For example, a ranking from 1 to 10 (the exact numerical value is not important) is assigned for the smallest insulation value to the largest insulation value, respectively. Since all design parameters are ranked on the same basis, their relationship with the energy consumption can then be cross compared. **FIGURE 3.4** presents on the same diagram the change in energy consumption due to a change in each of the design parameters from their smallest to their largest values.

A display of rank transformed relationships as in Figure 3.4 can confirm monotonic relationships between inputs and outputs, which is one of the criteria in performing a successful regression based sensitivity analysis (Saltelli and Sobol, 1995).

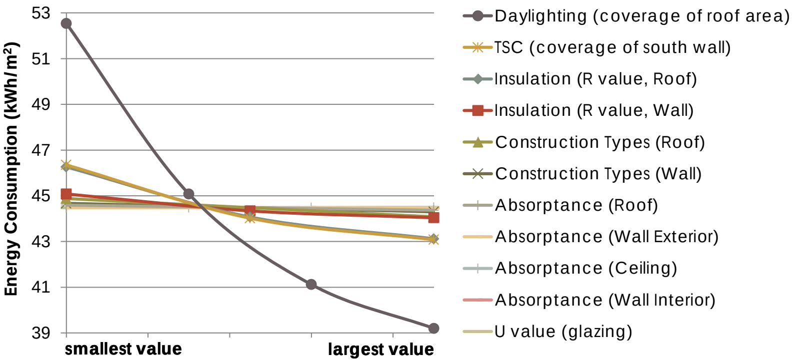


FIGURE 3.4 *Comparison of impact of different design parameters on energy consumption*

3.3.2 Linearity and rank transformed output

Even though the relationships are monotonic, it can be observed from Figure 3.4 that some of the relationships are nonlinear. Regression based sensitivity analysis also requires the input-output relationship to be linear otherwise the resulting Standardized Regression Coefficient (SRC) might perform poorly. Rank transformation can also be applied to the output to linearize the relationships. For example, the lowest energy consumption is assigned as 1 and the second lowest energy consumption is assigned as 2. The resulting Standardized Rank Regression Coefficient (SRRC) represents the strength of the monotonic relationship rather than the strength of the linear relationship (Helton and Davis, 2002). For the presented dataset, rank transformation improves the coefficient of determination (R^2) from 0.924 to 0.988.

3.3.3 Partial correlation

In the discussion of the integrated design approach, it is suggested that there could be interdependency between design parameters. That is, the effect of one parameter, affects the design trend of the others. In some cases, parameters might even be dependent on each other. For example, the performance of daylighting is dependent on the type of glazing, which is represented by the U-value of glazing in this investigation. Such correlations between input parameters will have an impact on the sensitivity ranking. An investigation of partial correlations will remove the correlation that is due to mutual association among parameters. Hamby (1994) suggests that the Partial Rank Correlation Coefficient (PRCC) is a good metric for ranking the sensitivity for parameters that are monotonically but nonlinearly related.

3.3.4 Comparison on sensitivity results based on different sensitivity analysis procedures

The above discussion presents the different procedures to take care of linearity and partial correlation if input-output relationships are monotonic. **TABLE 3.3** presents the coefficients and the corresponding rankings generated by following the different sensitivity analysis procedures just described. Here are the resulting coefficients:

- PRCC — Partial Rank Correlation Coefficient
- SRRC — Standardized Rank Regression Coefficient
- PCC — Partial Correlation Coefficient
- SRC — Standardized Regression Coefficient

The absolute rank order is in fact not a subject of interest. From the table, influential design parameters can be easily identified since their coefficients are an order of magnitude more than the non-influential ones. However, it can be observed that the rank order is different if the dataset has been rank transformed (rankings of PRCC and SRRC versus those of PCC and SRC). Even though, the difference in rank order is small and is based on tiny changes in the values of the coefficients, the presence of a difference suggests that rank transformation to linearize the relationship does have an impact on the sensitivity ranking.

The previous discussion of the integrated design approach described the interdependency among design parameters, with particular reference to the effect of daylighting on heating and

TABLE 3.3 **Sensitivity results — coefficients and rankings (in bracket) based on different sensitivity analysis procedures**

Parameters	PRCC	SRRC	PCC	SRC
Daylighting (as % of roof area)	-0.99 (1)	-0.87 (1)	-0.99 (1)	-0.94 (1)
Transpired solar collector (as % of south wall)	-0.96 (2)	-0.38 (2)	-0.90 (2)	-0.24 (2)
Insulation (Thermal resistance, Roof)	-0.93 (3)	-0.27 (3)	-0.85 (3)	-0.19 (3)
Insulation (Thermal resistance, Wall)	-0.66 (4)	-0.10 (4)	-0.46 (5)	-0.06 (5)
Construction Types (Roof)	-0.60 (5)	-0.08 (5)	-0.47 (4)	-0.06 (4)
Surface Reflectance (as absorptance, Roof)	-0.38 (6)	-0.05 (6)	-0.25 (6)	-0.03 (6)
Construction Types (Wall)	-0.35 (7)	-0.04 (7)	-0.19 (7)	-0.02 (7)
Surface Reflectance (as absorptance, Wall Ext.)	-0.07 (8)	-0.01 (8)	-0.03 (8)	-0.00 (8)
Surface Reflectance (as absorptance, Ceiling)	0.005 (9)	0.001 (9)	0.001 (9)	0.000 (9)
Overall heat transfer coefficient (Glazing)	0.003 (10)	0.000 (10)	0.000 (11)	0.000 (11)
Surface Reflectance (as absorptance, Wall Int.)	0.001 (11)	0.000 (11)	0.000 (10)	0.000 (10)

cooling, and therefore, insulation as well. After removing the correlation that is due to mutual association among parameters, partial correlation coefficients offer meaningful insight into those interdependent parameters. For example, the coefficient for roof insulation increases from -0.27 (SRRC) to -0.93 (PRCC).

Surface reflectance

Earlier discussion suggests that the addition of transpired solar collectors will block the south wall surface from solar exposure and thus reduce the overall impact of exterior wall surface reflectance on heating and cooling load. The relatively small sensitivity coefficients of the exterior wall reflectance support this notion.

The effect of tilted PV modules acting as shading devices has not been considered in this sensitivity analysis (which does not include generation side considerations); the benefit in reducing cooling demand is not known. However, as seen from Figure 3.1, cooling demand due to external factors is insignificant in the climate of Amsterdam, such a shading effect is not investigated in this research (and cooling demand as a result of raised internal heat gain will not be benefited much from shading devices). Nevertheless, since the effect of roof reflectance on heating and cooling load is tightly tied with the shading effect of the PV modules, they should be studied together under an integrated design approach. However, in subsequent investigations regarding the search for design solutions (Chapter 5), some simulation approaches require the decoupling of the demand side investigation from generation side investigation to reduce computational resources; the consideration of roof reflectance precludes such decoupling. Even though the sensitivity coefficients of the roof reflectance are comparatively higher than those of other surface reflectances, they are still lower than those of most other design parameters. Therefore, roof reflectance and other surface reflectances of even lesser significance are not being considered in subsequent investigations and are assumed to have a typical reflectance value of 0.4.

3.3.5 Identification of influential design parameters

The purpose of a sensitivity analysis is to limit the scope of the investigation to those influential design parameters so as to reduce the computational effort within practical limits without losing output resolution. From the PRCC presented in Table 3.3, it is quite clear what those influential design parameters are. **FIGURE 3.5** presents the PRCC in a tornado chart.

A tornado chart is an illustrative way to provide an at a glance view for identifying influential parameters. **TABLE 3.4** lists the selected influential design parameters to be studied in the subsequent investigations.

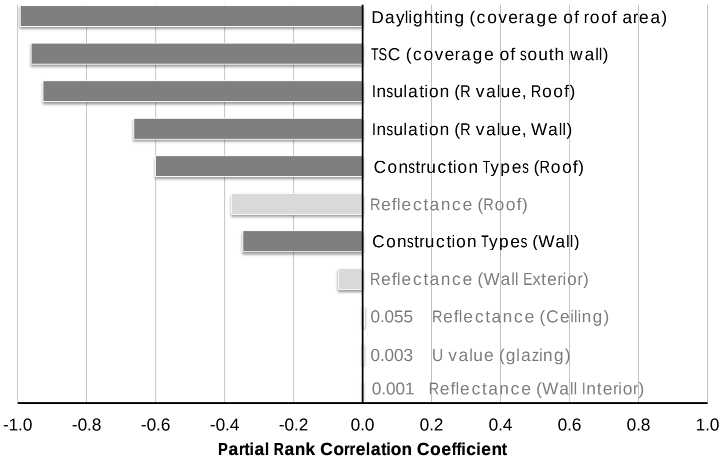


FIGURE 3.5 *Tornado chart showing the sensitivity (ranking based on PRCC) of the demand and distribution side design parameters.*

TABLE 3.4 Final list of influential demand and distribution side design parameters

Parameters	Design Range	Levels of Investigation
Insulation (Thermal resistance, Roof)	1.5 – 4.5 m^2K/W	7
Insulation (Thermal resistance, Wall)	1.5 – 4.5 m^2K/W	7
Construction Types (Roof)	STL or CONC	2
Construction Types (Wall)	STL or CONC	2
Daylighting (as % of roof area)	0 – 15 %	4
Transpired solar collector (as % of south wall)	0 – 100 %	6

Based on these design parameters and the corresponding resolutions, there could be four thousand possible configurations for each studied process load and occupancy schedule. For all discussed process loads and occupancy schedules for one climatic location, the investigation is limited to a manageable 70 thousand cases, which is much less than the originally suggested 2 million cases.

3.4 Concluding remarks

This chapter provides an in-depth discussion of the demand, distribution, and generation side design parameters. It has been shown that the selection of design parameters depends very much on the geometry and construction method of the buildings, or more specifically, the typical buildings of the local market. Therefore, for each component of the simulation model framework, a thorough review of the local situation for the typical case has to be performed to identify the design parameters. The discussion of surface reflectance and shading effect of PV modules highlights the importance of considering the local situation. In a hotter climate of lower latitude countries (as opposed to the mild climate of Amsterdam at higher latitude), surface reflectance and shading effect should not be ignored.

The heating, cooling, and lighting energy demands (as a result of altering demand side parameters) have to be satisfied by equipment and systems that are specified by the distribution side parameters. The resulting energy consumption will be supplemented by energy generation. The energy flow / conversion between modules (i.e. the conversion between energy demand and consumption, and the conversion between energy sources) is summarized in **FIGURE 3.6**.

An integrated design approach is necessary if there is inter-dependency or even dependency among design parameters. Moreover, an integrated design approach facilitates the design decision process by providing a full selection of comparably performing but largely different solutions. The designers can then use this to make their choice according to their own set of objective performance criteria.

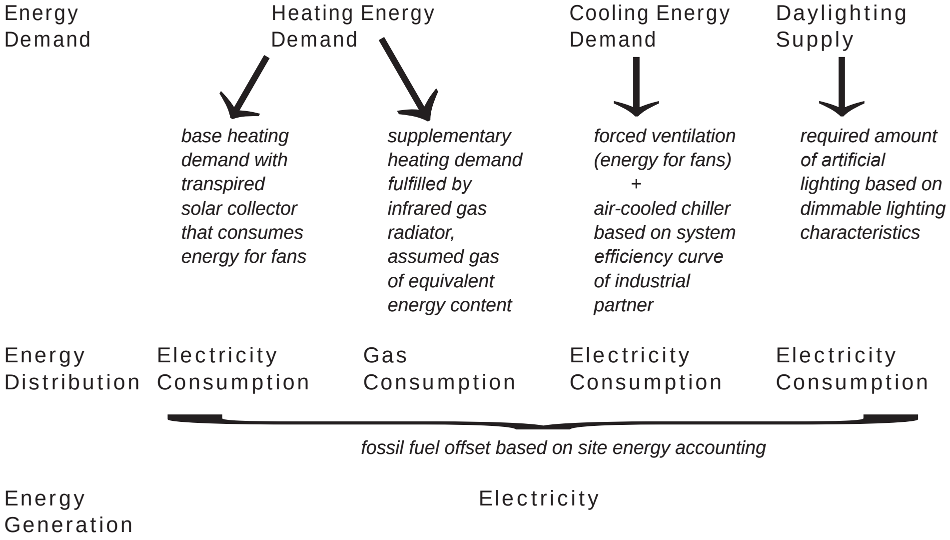


FIGURE 3.6 *Linkage between energy demand, energy distribution, and energy generation as they are related in this research*

Sensitivity analysis is an effective method for limiting the scope of the investigation to only the most influential design parameters. It allows an investigation of highly influential design parameters at high resolution, and at the same time, satisfies practical constraints such as limitations in computational power and time. Regression based sensitivity analysis can be performed if the inputs and outputs exhibit a monotonic and linear relationship. Scatter plot of inputs and outputs for each of the design parameters graphically confirms monotonicity of the relationship. If the relationship is monotonic, rank transformation can be utilized to linearize the relationship. If design parameters are interdependent or even dependent on each other, partial correlation can be investigated to remove the mutual association. Due to concerns in linearity and partial correlation, the Partial Rank Correlation Coefficient (PRCC) is a good metric for sensitivity ranking.

By finalizing the design parameters to be included in the virtual simulation models, this chapter completes the parametric representation of the physical characteristics of the studied industrial halls.

4

Performance Evaluation – Design Objectives Based on Derived Performance Indicators

THE SIMULATION BASED ASSESSMENT DEVELOPED at this point focuses on the energy simulation models and the corresponding design parameters. The output of the simulation models is the energy consumption and generation for different configurations of industrial halls. The amount of energy (consumed or generated) is the sole direct performance indicator of the simulation models. On the other hand, energy consumption affects the cost of operation, which can be a performance indicator of much interest to the designers. Energy consumption also has an impact on the environment, depending on the sources of energy. Either financial cost or environmental impact is a derived performance indicator that is based on energy performance and other assumed parameters, which are explored in this chapter.

4.1 Energy as a performance indicator

The only output of the simulation models is energy consumption and generation. However, energy itself does not represent a “quality” that is meaningful in the design decision process. Energy needs to be translated into another performance indicator or a performance / design goal on which the decision can be based.

4.1.1 Tangible quality in making informed design decisions

In the design decision process, the decision variable being investigated (quantified by performance indicators) must be tangible with respect to the decision to be made. Capital investment on renewable energy systems and the corresponding financial return on the investment exemplify the desired quality of tangibility. In this particular example, the decision involving capital investment and the performance indicator measuring financial return are both quantified in the same monetary unit. The amount of predicted financial return and the decision to commit the capital investment are related in a straightforward and causal manner.

In this respect, energy consumption itself does not represent a tangible quality in the design decision process. In other words, reducing energy consumption does not yield a tangible return in its own right. On the other hand, evaluating the energy savings and translating that into energy cost savings provides meaningful, tangible, and crucial information for the designers. In fact, the LEED green building rating system specifically requires the energy saving potential to be expressed in terms of energy cost savings (USGBC, 2009). Cost effectiveness of design solutions is discussed in Section 4.2.

Energy is intangible with respect to the design decisions because energy does not cause a direct impact on matters that are of concern in the design decision process, such as the aforementioned financial cost or environmental impact. In fact, energy has no financial impact if it is free and does not raise an environmental concern if it is from sustainable sources.

Conversely, those concerns do not exist if the building does not consume any energy, since there is no more financial or environmental impact related to energy consumption. In such a case, achieving statuses such as "net zero energy" can be an accomplishable and tangible "goal" that facilitates the design decision process.

4.1.2 Net zero energy building (NZEB) as a design goal

As depicted in Figure 3.6, industrial halls typically consume electricity and gas depending on how heating, cooling, and lighting demands are to be fulfilled. Energy consumption can be satisfied by local energy generation to achieve the status of NZEB.

There are numerous definitions of NZEB and different ways to account for the amount of energy from different sources. NREL (2009b) provides in-depth discussion on the various definitions and accounting methods. In this research, the site NZEB definition is adopted, in which the renewable energy generated on site shall be able to fulfill the energy consumed in a year. The adoption of site NZEB has a few implications. First, the accounting period is the whole year. Energy generation might fall short in some periods when energy has to be drawn from the electricity grid, while excess electricity has to be sent back to grid during other periods. The building is qualified as NZEB as long as the net energy flow is zero or in excess for the whole year. Second, site NZEB ignores the values of different fuels at the sources. For example, due to transmission and generation loss, electricity is more valuable at the source than when accounted at site. Since the environmental impact of energy generation and transmission also depends on the generation mix of the local grid, this consideration is further discussed in the subsequent section on environmental impact. Third, if the cost of electricity and the price of selling back electricity to the grid are the same, and if there is no difference in cost and price at different periods of time, then a site NZEB is also a cost NZEB too. However, Lee et al. (2013) pointed out that the cost-benefit of having on-site generation varies greatly if there are different price structures for peak / non-peak periods and for buying / selling of electricity.

With the adoption of the site NZEB definition, site energy accounting allows fuels from different sources to be offset at a one-to-one ratio. Therefore, the amount of gas consumption presented in Figure 3.6 can be directly offset with electricity generation from the PV systems. In order to achieve the goal of NZEB, the PV system can be sized to fulfill energy consumption.

4.1.3 Achieving the design goal of NZEB with PV systems

There are three studied parameters for PV systems — tilt angle, PV module length, and spacing. From Figure 3.3, it can be imagined that for a less inclined tilt angle and a tighter spacing, higher generation capability per unit area of rooftop (or per design capacity) might be possible.

From an investment point of view, tilt angle or spacing are not the parameters of interest since they do not indicate the worthiness of the investment of PV systems. In practice, energy generation capability (the potential annual energy generation of the PV system in kWh) determines how much return the PV system can yield, while energy generation capacity (the design capacity at peak in kW_P) of the PV system defines the amount of capital investment. Therefore, there could be two design objectives for PV systems:

Energy yield

Maximizing the energy yield is to maximize the energy generation capability (kWh) per energy generation capacity (kW_P). This design objective helps promote higher return for the same amount of capital investment.

Energy generation density

Maximizing the energy generation density is to maximize the energy generation capability (kWh) per unit space (m^2) available for the installation. The rooftop (or any installation space) is a limiting factor on how much PV can be installed. Depending on the financial resources and the economic benefits, this design objective helps fit the maximum amount of PV within the limited available space, which is an unexplored valuable resource. In the context of buildings, the energy being generated is most likely prioritized for local consumption. If a PV system is installed on the rooftop of a single-storey structure, as for many industrial halls, the area ratio between the rooftop and floor area is one to one. Sustainable building design goals, such as NZEB, can be achieved by matching the energy generation density (kWh/m^2 of the rooftop for PV installation) with the energy use intensity (EUI, kWh/m^2 of the building floor area).

To illustrate the computational simulation approach of Chapter 3, and to demonstrate the design goal of NZEB, an ad-hoc study has been performed. Based on the design parameters presented in Table 3.2, an ad-hoc study investigates a few different configurations out of the many thousands of possible configurations.

TABLE 4.1 presents a comparison between results obtained from the conventional design approach and the ad-hoc study using computational simulation. In this example, a PV array of 1.0 m length is installed. With the conventional design approach, a tilt angle of 52° and a spacing of 8 m between rows of PV arrays are assigned according to the rule of thumb design principle. This configuration rated at a design unit capacity of 22 W_P/m^2 returns a predicted energy generation density of 16.5 kWh/m^2·yr at a yield of 742 kWh/kW$_P$ annually.

The recommended configuration according to the conventional design approach never fully utilizes the available rooftop space, nor generates energy at the highest yield. In Table 4.1, two ad-hoc configurations are proposed. At the same unit design capacity (22 W_P/m^2), one configuration can generate energy at a higher yield of 778 kWh/kW$_P$, which is 5% more efficient than the conventional design approach. Since the cost of PV systems installation is

TABLE 4.1 **A comparison of energy generation performance of PV systems designed according to conventional design approach and computational simulation approach**

	Length (m)	**Tilt Angle (°)**	**Spacing (m)**	**Design Unit Capacity (W_P/m^2)**	**Energy Yield (kWh/kW_P)**	**Energy Generation Density (kWh/m^2-yr)**
conventional design approach						
	1.0	52	8	22	742	16.5
computational simulation approach						
same kW_P	1.0	30	8	22	778	17.3
max. density	1.0	14	0.8	89	742	66.0

commonly reported in units of cost per watt peak, the ad-hoc configuration is also more cost effective than the conventionally designed one. The energy yield of the second ad-hoc configuration is exactly the same (742 kWh/kW_P) as the conventionally designed configuration, but offers a much higher generation density of 66.0 kWh/m^2yr. The PV array is efficiently packed into the available space and generates four times the amount of energy at the same energy yield.

The computational simulation approach for PV systems offers two main advantages over the conventional design approach: by first providing time-varying evaluated solutions (vs rule of thumb recommendations as discussed in Section 3.2.1), and second by addressing practical considerations regarding yield, space limitations, and NZEB design goal, which could not be achieved with the conventional design approach.

By matching the energy generation density to EUI, NZEB can be achieved. Minimizing energy consumption together with maximizing energy generation can indeed be treated as relevant design objectives if the ultimate design goal is to achieve NZEB.

4.2 Cost effectiveness of design solutions

Industrial halls are, in general, ready-to-build structures that are meant to serve a single purpose or function. Cost effectiveness is one of the gauges for economic performance and is in practice a major determining factor in design decisions. That is, the investment in energy saving or generation measures shall in return bring forth a financial reward that could compensate the cost, if not make a profit.

Cost effectiveness can be evaluated in relative terms. With no consideration of any energy saving or generation measures, industrial halls can be built according to the specification of a baseline building, to which other studied configurations can be referenced and compared. In the Netherlands, building standard NEN 7120 (NNI, 2009) Energieprestatie van gebouwen — Bepalingsmethode (Energy performance of buildings — Determination method) defines the methodology for determining the energy performance of a building and provides prescribed values for some of the design parameters that have already been discussed in Section 3.1. The prescribed values are summarized in TABLE 4.2.

TABLE 4.2 **NEN 7120 prescribed values**

Parameters	Prescribed Values
Insulation (Thermal resistance, Roof)	3.5 m^2K/W
Insulation (Thermal resistance, Wall)	3.5 m^2K/W
Daylighting (as % of roof area)	–
Transpired solar collector (as % of south wall)	–

From an economic performance point of view, the absolute cost of construction of the baseline building does not play a role in the design decisions, since it is the amount of capital that has to be invested if no particular design options are selected. On the other hand, the investment of a newly proposed configuration (with energy saving or generation measures) can be compared to the investment of the baseline-building configuration. It is the difference between the two configurations, the proposed design and the baseline building, that represents the additional investment required for the energy saving or generation measures.

Likewise, the absolute cost of the energy consumption of either configuration is not of interest from the design decision point of view. It is the difference between the two configurations that represents the actual energy cost saving (or energy cost deficit) of the proposed configuration. In practice, capital investment is normally paid up front at the time of construction while energy cost saving can only be realized in the subsequent years during the lifespan of the energy saving and generation measures. A summation of the two does not yield meaningful results.

4.2.1 Cost of investment

There are many methods to evaluate the cost effectiveness of an investment. In evaluating the different energy saving and generation measures, it is important to compare the different measures on an equal basis. Simple payback period is a common metric to gauge cost effectiveness of an investment. Simple payback period is the period of time in which the net benefit of an investment compensates the original investment; that is, the period of time the investment takes to pay for itself. It is calculated by dividing the investment with the cash inflow per accounting period, by assuming there is the same amount of return for each accounting period. If the accounting period is on annual basis, then the simple payback period is evaluated in terms of number of years.

However, simple payback period does not allow comparison between different measures. First of all, it does not account for the financing cost, such as the incurred interest of the loan on the investment. If one design solution requires higher investment than the others, the financial impact becomes more significant; the omission of financial cost discriminates some solutions from the others.

Lifespan of the investment

Moreover, every measure has a definite lifespan. Simple payback cannot handle cases in which the payback period is longer than the lifespan of the equipment itself. An example is PV systems, which normally have a lifespan of 20 years. A comparison between different solutions with longer payback period beyond the lifespan is not meaningful.

Also, it is not correct to compare different energy saving or generation measures if two or more measures have different lifespans and are shorter than that of the building. For example, consider a case where measure A has a lifespan of 10 years, measure B has a lifespan of 25 years, while the building itself has a lifespan of 50 years. During the timeframe of 50 years, is it fair to compare 5 cycles of measure A together with 2 cycles of measure B? Within that 50 year timeframe, either measure A or B evolves, faces changes in prices, or is eliminated. A quick comparison based on a simplified method, such as that of simple payback period, does not provide a fair view of different measures.

Financial cost and amortization

A capital investment on an asset (e.g. equipment) is an expenditure that is supposed to create future benefits. Regardless of how the investment is actually financed, the asset is presumed to carry a finite lifespan and depreciate over time. In other words, the capital investment can be treated in accounting terms by having an equal amortized investment cost over the lifespan of the asset. The **Amortized Cost of an Investment**, I_A can be calculated with a discount rate, r, for the number of years of the life-cycle, n, based on the initial capital investment, I, with **EQUATION 4.1**.

$$I_A = I/\left[\frac{(1+r)^n - 1}{r(1+r)^n}\right]$$

EQUATION 4.1

In practice, the European Union publishes each quarter a base rate for each of the member states. Normally, the reference rate is assumed to be 100 basis points over the base rate (up to a 1,000 basis point for borrowers with very poor credit rating). Such a reference rate can be used as a discount rate (EU, 2008) for calculating amortized cost as in Equation 4.1. Currently, the base rate for the Netherlands is 0.66% (EC, 2013a).

The above amortization procedure provides a fair basis of comparison for different energy saving and generation measures. The costs of those measures, *m*, can be summed and weighed against the cost of the baseline building, with **EQUATION 4.2**, to arrive at the **Amortized Relative Investment Cost.**

$$\begin{matrix}\mathit{Amortized\ Relative} \\ \mathit{Investment\ Cost}\end{matrix} = \sum_{m} I_A - I_{A,baseline\ building} \qquad \text{EQUATION 4.2}$$

4.2.2 Life-cycle cost-benefit analysis

The operating cost of the building can be evaluated for any fixed accounting period. An annual period allows seasonal variations to be taken into account. The amortized investment cost of any energy saving and generation measures can also be evaluated annually (according to Equation 4.2) based on the lifespan of the respective measures.

Operating cost

The operating cost is limited to that of electricity and gas energy consumption, which are the outputs of the simulation models. The predicted energy consumption, separately for electricity and gas, for each of the studied configurations can be compared to that of the baseline building. The difference between the two is the net energy savings or deficit in electricity and gas that can be paired with the respective utility prices to arrive at the **Annual Relative Operating Cost** with respect to the baseline building. **EQUATION 4.3** depicts the relationship. Utilities can involve electricity and gas, and include multiple suppliers. Energy consumption and utility price are evaluated for each supplier.

$$\begin{matrix} Annual\ Relative \\ Operating\ Cost \end{matrix} = \sum_{Utilities} \left[\left(\begin{matrix} Energy \\ Consumption \end{matrix}_{configuration} - \begin{matrix} Energy \\ Consumption \end{matrix}_{baseline} \right) \times \begin{matrix} Utility \\ Prices \end{matrix} \right]$$

EQUATION 4.3

Annualized relative cash flow

The above amortization procedure allows the evaluation of investment cost of different measures with different lifespans on the same basis. Both investment cost and operating cost are treated as positive values. Operating cost can be negative if the investment brings forth energy savings with respect to the baseline building. Investment cost can also be negative if the investment in the proposed configuration costs less than the investment in the baseline building.

If the sum of operating cost and amortized investment cost is negative, the investment yields a net benefit, though it is counterintuitive to have a negative number to represent benefit. An unbiased economic performance indicator for a particular configuration of industrial hall can be expressed in terms of **Annualized Relative Cash Flow**, which is defined as the inverse sum of Annual Amortized Relative Investment Cost and Annual Relative Operating Cost as in EQUATION 4.4.

$$\begin{matrix} Annualized\ Relative \\ Cash\ Flow \end{matrix} = -\left(\begin{matrix} Annual\ Amortized\ Relative \\ Investment\ Cost \end{matrix} + \begin{matrix} Annual\ Relative \\ Operating\ Cost \end{matrix} \right)$$

EQUATION 4.4

4.3 Environmental impact due to carbon emissions

Environmental impact due to carbon emissions is the main cause of concern rather than the energy consumption itself. In fact, operational energy can be expressed in terms of carbon emissions.

4.3.1 Energy consumption and carbon emissions

The environmental impact depends on the sources of energy, which in turn, depend on the energy mix of the power generation of the country or location. Carbon emissions due to either electricity or gas consumption can be evaluated with the country specific CO_2 emission factors, which are listed in TABLE 4.3.

TABLE 4.3 CO_2 emission factors of electricity and gas consumption in the Netherlands

	CO_2 emission factors (kg CO_2/kWh)
Electricity consumption	0.415 IEA (2012)
Gas consumption	0.202 EU (2010)

In terms of energy consumption, there is no distinction between two design solutions based on different energy saving and energy generation measures if the net amount of energy (according to site NZEB definition) is the same. And there is no distinction between the two design solutions in terms of energy cost if the price of purchasing or selling the energy is the same.

Since there is no clear carbon neutral definition, there can be an issue in evaluating energy saving and generation measures in terms of carbon emissions. Although energy generation from renewable sources does not incur operational carbon emissions, it only helps reduce the building's carbon emissions if either:

1. The amount and time of energy generation match those of energy consumption. This scenario is very unlikely since demand and generation might not occur at the same hour. **TABLE 4.4** highlights the potential issue.
2. The accounting of carbon neutrality follows the same accounting principle as site NZEB where surplus energy generation is converted to carbon credit to offset energy consumption at another time.

Both Design Solution 1 and 2 consume the same amount of operational energy. However, Design Solution 1 achieves the same amount through energy generation, while Design Solution 2 relies only on energy saving. Design Solution 2 incurs much lower operational carbon emissions since this solution reduces the energy consumption in the first place instead of balancing it with energy generation that does not potentially match the consumption at the exact hour and amount (values shown in Table 4.4 assume

TABLE 4.4 **A comparison between two different design solutions; one with energy generation and one with energy saving only**

Parameters	Design Solution 1	Design Solution 2
Insulation (Thermal resistance, Roof, m^2K/W)	1.5	3.5
Insulation (Thermal resistance, Wall, m^2K/W)	1.5	3.5
Construction Types (Roof)	CONC	STL
Construction Types (Wall)	CONC	STL
Daylighting (as % of roof area)	0	15
Transpired solar collector (as % of south wall)	0	100
Total Energy Consumption (kWh/m^2)	57.7	38.0
Energy Generation (kWh/m^2)	19.7	0
Operational Energy (kWh/m^2)	38.0	38.0
Operational Carbon Emissions (kg CO_2/m^2)	21.4	14.5

no matching). In this example, it can be observed that it is the design objective (e.g. minimizing operational carbon emissions) that dictates the selection of design solutions.

Since energy demand and generation matching involves detailed knowledge of how the building is operated, which is outside the scope of this research, subsequent analysis of carbon emissions therefore follows the same accounting principle as site NZEB.

4.3.2 Life-cycle considerations regarding embodied energy and carbon

Energy saving and generation measures can help reduce operational carbon emissions. This notion tends to ignore the embodied energy, or embodied carbon, that is entrenched in the manufacturing processes of the building materials and equipment. For example, the manufacturing of PV modules involves a lot of logistics and excavation activities. Even though the environmental impact of excavating rare earth for PV module manufacturing might sound like a very special case, survey data of embodied energy or embodied carbon associated with the production of many building materials and equipment are readily available and shall not be ignored. The assessment can be biased if it only considers the energy generating capability of PV systems without looking into the embodied energy in the manufacturing of the many components of PV systems. A life-cycle assessment approach that covers the whole lifespan from the manufacturing of the components to the end-of-life treatment of the system, provides a better glimpse into the actual benefit of any energy saving or generation measure. Such approach involves the investigation of:

- the embodied energy involved in the acquisition, processing, manufacturing, and transportation of building materials during the construction phase;
- the operational energy of the building; and
- the demolition energy in the destruction, removal, and recycling of building materials.

An evaluation at the three different phases ensures a fair comparison among different design solutions. The same idea can be applied to the building structure. The simplicity in the construction of industrial halls limits the variety of building materials being used, and at the same time, increases the proportion of each of them. Either concrete or steel, depending on the construction, constitute a significant portion of the structure of industrial halls; whereas steel, concrete, aluminum, plastic, wood, glass, gypsum and other building materials share similar and much smaller proportion in office buildings. Therefore, a study to compare embodied energy in the structure of industrial halls is potentially significant.

Embodied energy of the structure

In practice, buildings come to their end-of-life usually not because of any structural issue, but rather because the original purpose of the buildings is no longer relevant, and the existing buildings no longer support their new roles and functions. The possibility of remodeling depends largely on how flexible the construction of the original buildings is to adapt to their new roles. Concrete structures can only be modified to a certain extent at a cost that might be greater than the building of new structures. By contrast, steel structures, which in many cases, are bolted together, facilitate deconstruction and reuse. Readapting existing buildings for other purposes, or reusing existing building materials for the construction of a new building not only saves new materials from being used, but also cuts the associated environmental impacts of producing and transporting those materials.

Embodied energy in building materials

For concrete, the bulk of the required materials are natural materials like sand or crushed rock. The binding agent cement is also a major component of concrete. In fact, CO_2 emissions in the cement industry account for 5% of global man-made CO_2 emissions (CDIAC, 2009). Cement can be replaced by industrial waste products like fly ash, blast-furnace slag, and silica fume (induced as additives) for up to a certain percentage. The replacement not only improves the quality of concrete but also eliminates the environmental impacts of having to dispose the otherwise disposed waste products.

Steel contains both virgin and recycled contents. The energy required to make virgin steel is more than three times of that to make recycled steel from scrap material (BSRIA, 2011). The proportion of recycled content of the new materials is an indicator of sustainability. Since the demand for steel products is greater than the supply of scrap steel, it is necessary to have a certain percentage of virgin steel in any steel product. Data of embodied energy for some building materials are available from public sources.

Case study of embodied energy in the structure of industrial halls

Even though embodied energy data are widely available, there are certain difficulties in evaluating the embodied energy of the whole building structure due to the uncertainties in input assumptions. Possible uncertainties can be categorized into the following:

Variation in the construction

Due to the diversity of industries (each imposing different structural requirements) and the variations in construction techniques, the amount of materials used in the building structure may vary.

Location specific deviation from embodied energy values contained in the database

Currently embodied energy data are available from various sources. The data can be a nationwide average of another country or a value for a specific case. For example, the Athena's database (Athena, 2010) suggests that the embodied energy of building assemblies varies among cities ranging from ±5% of the national average for US cities to ±10% for Canadian cities. Since location specific data are most likely not available, the suggested variation implies that the use of embodied energy values from these databases will result in an inevitable deviation from the local situation.

Uncertainty in recycled or replacement content of building materials

The embodied energy of virgin steel is quite different from that of recycled steel. However, the exact recycled content of steel products varies from one production lot to the next. Likewise, the exact amount of replacement content in cement cannot be generalized. Unless job specific information is available, the recycled or replacement content of steel and concrete products shall be treated as values over an uncertainty range rather than a single value.

Lee et al. (2011) conducted a case study to analyze the embodied energy of the structure of industrial halls by considering the aforementioned uncertainties in the input assumptions. In that case study, the evaluation is demonstrated with three hypothetical structures:

- Steel structure — steel cladding on steel frame with steel deck on steel joist,
- Concrete structure — reinforced concrete wall with concrete deck on steel joist, and

- Hybrid structure — reinforced concrete wall with steel deck on steel joist.

Monte Carlo simulation is a means to evaluate outcomes based on uncertainties in input assumptions, by randomly selecting values for the input assumptions according to the probability distribution of the uncertainties. Details of the input assumptions and the corresponding uncertainties can be found in the article. The embodied energy of the three hypothetical building structures evaluated in the case study is presented in **FIGURE 4.1**.

The embodied energy is presented as per unit area and per year of the lifespan of the studied industrial hall, in the units of kWh/m^2·yr. The results suggest that if the building last for 50 years, the embodied energy of the concrete structure is in the neighborhood of 4.9 kWh/m^2·yr, while that of the steel structure is 2.4 kWh/m^2·yr. That is, the embodied energy of the concrete structure is significantly more than that of the steel or the hybrid structure. Because of the vast amount of steel utilized in any of the three structures, the uncertainty in the recycled content of steel causes the most impact on the resulting embodied energy. The comparatively larger roof surface (as compared to the wall surface) also makes the mass of the roof in steel a very influential input parameter.

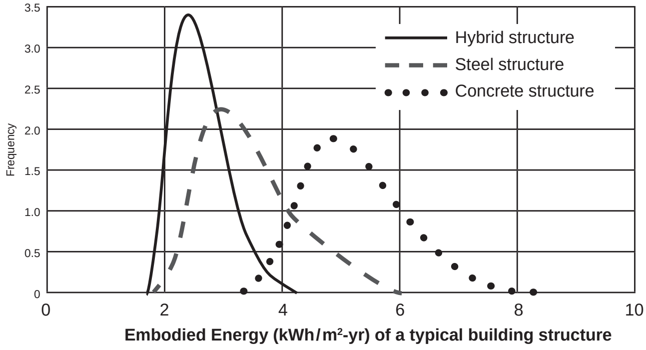


FIGURE 4.1 *Probability distribution of embodied energy of the three exemplary building structures (data source, Lee et al., 2011)*

By taking the same design solutions in Table 4.4 as examples, TABLE 4.5 provides a snapshot of how embodied carbon in a building structure compares with operational carbon emissions. The operational energy consumption values have been translated to carbon emission values with country specific CO_2 emission factors. The embodied carbon footprints of the building materials are taken from various databases (BSRIA, 2011; Ecocosts, 2007).

TABLE 4.5 **Embodied carbon as a percentage of the annualized net carbon emissions of two exemplary design solutions**

Parameters	Design Solution 1	Design Solution 2
Operational Carbon Emissions (kg $CO_2/m^2\cdot yr$)	21.4	14.5
Annualized Embodied Carbon Footprint (kg $CO_2/m^2\cdot yr$)		
Structure	2.8	0.8
PV system	1.9	–
Embodied Carbon as a % of Net Carbon Emissions	18%	5%

As observed from TABLE 4.5, the embodied carbon of the structure is relatively insignificant as compared to the net carbon emissions. In other words, the uncertainty distribution of embodied energy as displayed in Figure 4.1 has little effect on the life-cycle net environmental impact, which is based on the sum of both operational and embodied energy consumption (and the corresponding carbon emissions). In view of the difficulties in gathering location and job specific data for embodied carbon and the low impact found in studying the uncertainties, subsequent analysis on embodied carbon adopts the deterministic approach and relies on the best available data.

As suggested earlier in this section, the manufacturing of PV modules also incurs embodied energy (with an average of 242 kg CO_2 per m^2 of PV module, according to BSRIA, 2011). Since a PV system has a shorter lifespan (20 years) than the building

(50 years), the annualized carbon footprint can be significant. As in Table 4.4, carbon emission reductions due to energy generation have not been included in Table 4.5. If they are included, the operational carbon emissions will be reduced by 6.9 kg $CO_2/m^2 \cdot yr$, which is enough to compensate the extra carbon footprint of the PV system. In subsequent investigations, net carbon emissions based on site energy accounting are used as the performance indicator for the environmental impact.

4.4 Risk analysis of predicted performance

The previous discussion on embodied energy reveals that many of the assumed input values are in fact uncertain in nature. For example, the exact embodied energy in the steel structure depends on a number of parameters including the recycled content, the distance between steel fabrication facilities and construction site, and many other factors. It is worth noting that at the end of life of a steel structure, some of the components can be reused which require less energy for demolition, sorting, and transportation only, while the rest can be recycled to make new steel products of equal or better grade. Average values of embodied energy or embodied carbon are quite readily available in the databases for some countries, but more detailed survey data such as the aforementioned transport distance between the manufacturing facility and the jobsite are not generally accessible.

4.4.1 Robustness of product design versus risk in building design solutions

Due to the lack of more detailed information, use of average values as inputs to the simulation models is required and nonetheless provides a fair prediction of the performance. However, such prediction falls short in revealing how well the design solution performs if the inputs change in an uncertain manner.

It is understandable that the magnitude of the uncertainties in inputs is not predictable and yet the occurrence of such uncertainties is highly anticipated. However, in most cases, it is not in the hands of the designers to eliminate or lessen such uncertainties. Those inputs can be global parameters such as electricity prices to local parameters such as material supply.

Robust design

A robust design is a means to reduce the potential deviation (both an increase and a decrease) from the predicted performance by improving the design itself without trying to mitigate the uncertainties (Taguchi et al., 2005). The original robust design approach is applied to the manufacturing process, in which a tighter cluster of deviation is preferable over scattered deviation (Taguchi and Clausing, 1990). However, building design (in terms of energy conservation) has a different need for “robustness” as compared to the manufacturing process. In a manufacturing process, a product must be produced according to the specification. A product, with a deviation in any direction (e.g. bigger or smaller, if size is the performance indicator) is perceived as having poor quality if it is the end product or regarded as non-functional if it is a component to be fitted in a system together with other components, in which one is dependent on the others. For example, a bigger or smaller bolt simply will not fit into the nut of certain size. However, in building design, if energy consumption is the performance indicator, it is generally accepted that the lower the energy consumption the better. That is, lower energy consumption will be perceived as better than higher consumption if the comfort level can be maintained. Moreover, the fact of having lower energy consumption does not have an impact on other aspects of building operation (except on the cost of operation). Unlike bolts that have to be fitted into nuts, energy consumption results are not going to be fed into other performance evaluations.

In the practical sense, the designers are not concerned too much with whether the building operates at lower than predicted energy consumption due to uncertainties. It is an issue only if the building operates with higher than predicted energy consumption.

Therefore, the robustness consideration related to uncertainties from a building design perspective is very different from the original intention of robust quality for the manufacturing process, at least from the designer's point of view.

Risk analysis

From the above discussion, the design decision process for buildings can be treated as a two-step process. First, the predicted performance has to be acceptable to the designers. The designers expect the predicted performance to be the actual performance, even though, in most cases, there could be a shortfall in the actual performance. Second, the potential shortfall has to be quantified and conveyed to the designers, and be an integral part of the design decision process.

In fact, this second step raises the question of uncertainties in the inputs, in which the uncertainties are intrinsically not ascertainable in the first place. The legitimate question then becomes how to objectively evaluate the impact of such uncertainties and facilitate informed design decisions. Without redefining a robustness indicator, which has to be different from that for the manufacturing processes; risk analysis is an alternative and objective means to assess the impact of such uncertainties.

4.4.2 Uncertainty in input parameters

From previous sections, the derived performance indicators are evaluated based on many input assumptions. Since cost effectiveness is the biggest concern to designers for industrial halls, the following discussion focuses on the risk associated with the predicted performance of cost effectiveness. For example, the derived performance indicator of cost effectiveness (the annualized relative cash flow) is evaluated using three economic parameters: discount rate, electricity price and gas price. Commonly referenced rates can be the current rates, historical average rates such as the 10-year average rates, or historical high or low rates. TABLE 4.6 summarizes some of these commonly referenced rates in the Netherlands based on data of the last 10 years.

TABLE 4.6 10-yr high, average, and low values for discount rate, electricity price, and gas price in the Netherlands

Rates	10-yr high	10-yr average	10-yr low
Discount Rates (%) (EC, 2013a)	6.42	4.59	1.66
Electricity Price (€/kWh) (EC, 2013b)	0.135	0.118	0.107
Gas Price (€/kWh) (EC, 2013b)	0.044	0.040	0.029

To evaluate the impact of uncertainty in input parameters, designers often evaluate the impact of the "worst-case scenario". In most business situations, such as investing in a piece of machinery or operating a production line, the highest interest rate for the investment or highest energy cost for the operation always comprises the "worst-case scenario". Therefore, intuitively and understandably, historical high rates (a combination of high discount rate, high electricity price, and high gas price) might be mistakenly identified as the "worst-case scenario". **TABLE 4.7** presents a comparison between two different design solutions with their respective annualized relative cash flow under two different scenarios of 10-yr high rates and 10-yr low rates.

For Design Solution 1, the high rate scenario yields better relative cash flow; while for Design Solution 2, the high rate scenario yields much poorer relative cash flow (negative return). The relationship between economic performance of the design solutions and the values of the economic input parameters could not be easily correlated. That is, higher rates or lower rates do not necessarily impact the economic performance negatively or positively, respectively. From Table 4.7, it can be observed that there is no clear common "worst-case scenario". Therefore, it is not possible to evaluate the impact of uncertainties in input parameters with a deterministic approach (with one set of assumed "worst-case" scenario inputs).

TABLE 4.7 **A comparison between two different design solutions under two different scenarios of high and low rates**

Parameters	Design Solution 1	Design Solution 2
Insulation (Thermal resistance, Roof, m^2K/W)	1.5	3.5
Insulation (Thermal resistance, Wall, m^2K/W)	3.5	3.5
Construction Types (Roof)	CONC	STL
Construction Types (Wall)	CONC	STL
Daylighting (as % of roof area)	0	15
Transpired solar collector (as % of south wall)	0	100
Annualized Relative Cash Flow (€/m^2)		
10-yr high rate scenario	0.25	(0.73)
10-yr low rate scenario	0.09	0.35

Table 4.7 also suggests that some design solutions are more susceptible to uncertainties and result in much wider changes in predicted performance. In fact, Design Solution 2 even yields negative return under a high rate scenario and a rather decent return under a low rate scenario.

Needless to say, the choice of applying historical high rates, historical average rates, or a scenario of whatever combination of rates lies greatly in the designer's own subjective judgment and personal preference without an objective means to evaluate if such combination is indeed the "worst-case scenario" or a fair representation of the reality.

4.4.3 Stochastic approach

The impact of the uncertainties in input parameters has to be evaluated for many different uncertainty scenarios. For economic performance, different uncertainty scenarios can be those of different combinations of discount rate, electricity price and gas price.

Uncertainty in input parameters can be based on statistical or historical data of past years. Through time, some rates can have a higher probability of occurrence than others. **FIGURES 4.2** to **4.4** present the historical probability distribution of discount rate, electricity price and gas price for the past ten years.

From Figure 4.2, it can be observed that it is more likely to have the discount rate higher than 4.75%. Therefore, when considering uncertainty in any of the input parameters, the likelihood of occurrence of the uncertainty values shall be taken into account.

Correlation among input parameters

From the distributions of the above three economic parameters, discount rates are clustered around 2.50 and 5.75%, while electricity prices are clustered around the lower end, and gas prices are clustered around the higher end. There could be some degree of correlation among the three parameters. For example, the electricity prices might be related to the gas prices and discount rates. Since the exact correlation among input parameters is unknown and is beyond the scope of this research, the impact of uncertainties can possibly be evaluated based on existing available data by either assuming:

- The input parameters are fully independent of each other. That is, each of the input parameters is not correlated to the others. If there is no correlation among input parameters, Monte Carlo simulation, which randomly creates combinations according to the probability distributions of each of the input parameters, can be deployed.

- The input parameters are completely correlated to each other. In such a case, the possible combinations of input parameters are limited to the historical occurrences of recorded combinations of the input parameters.

The comparison between the two assumptions is further explored in Appendix A.4. In this research, input parameters are assumed to be fully independent, and Monte Carlo simulation is deployed and discussed in the following sections.

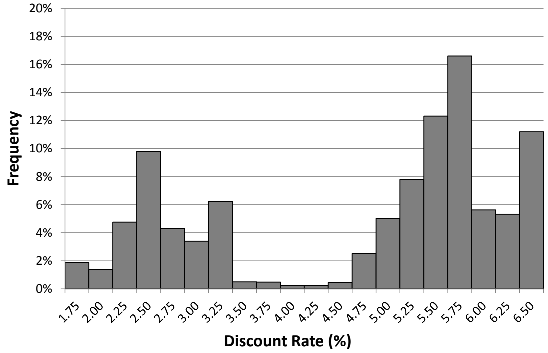


FIGURE 4.2 *Probability distribution of discount rate of the past ten years*

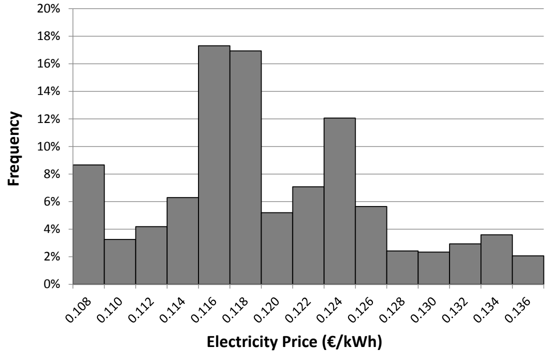


FIGURE 4.3 *Probability distribution of electricity price of the past ten years*

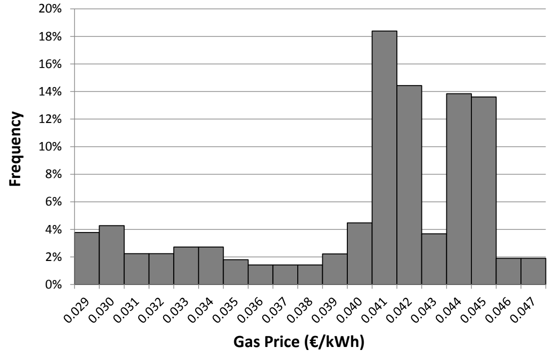


FIGURE 4.4 *Probability distribution of gas price of the past ten years*

Monte Carlo simulation as applied to time series data

Monte Carlo simulation can be applied to estimate the possible impact due to uncertainties, by randomly selecting values of the input parameters according to the probability distribution of the occurrence, and making combinations that are going to be fed into the simulation models to evaluate new possible outcomes. Since input parameters are assumed to be fully independent, some extreme combinations of input parameters are possible; for example, a very high discount rate together with a very low electricity price. In this research, a Monte Carlo simulation with 1,000 random combinations is performed with Latin Hypercube Sampling (LHS), in which values are sampled from segments that break up the range of values according to the probability distribution. LHS ensures values are sampled according to the probability distribution. In this example of economic performance study, the outcome is 1,000 different annualized relative cash flows under different economic scenarios (combinations of economic input parameters), for each of the design solutions. **FIGURE 4.5** presents the probability distribution of the annualized relative cash flow for one of the design solutions.

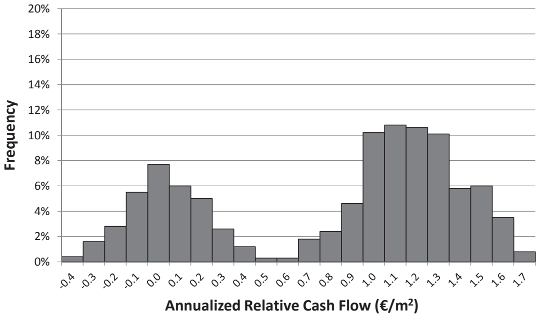


FIGURE 4.5 *Probability distribution of annualized relative cash flow for one of the design solutions*

4.4.4 Risk indicator

The predicted performance shall be based on a reference scenario, for example, the 10-year average rates. It can also be based on any other reference scenario that the designers deem appropriate. Since the reference scenario is selected by the designers, the predicted performance for this reference scenario can also be treated as the designers' expected outcome.

Risk is generally defined as the product of the magnitudes of the possible adverse consequences and the likelihood of occurrence of each of the consequences (Stamatelatos, 2000; Wreathall and Nemeth, 2004). The adverse consequence, in economic performance terms, is the potential shortfall from the predicted performance. That is, the designers will be satisfied with anything equal to or better than the predicted performance, and any shortfall from the predicted performance becomes an adverse consequence.

FIGURE 4.6 depicts a case where the designers opt for the 10-year average rates as the reference scenario. For that reference scenario, the particular design solution (of Figure 4.6) yields an annualized relative cash flow of 0.731 €/m^2. Any possible outcome, according to the probability distribution, that is on the left of 0.731 €/m^2 in Figure 4.6 is a potential shortfall.

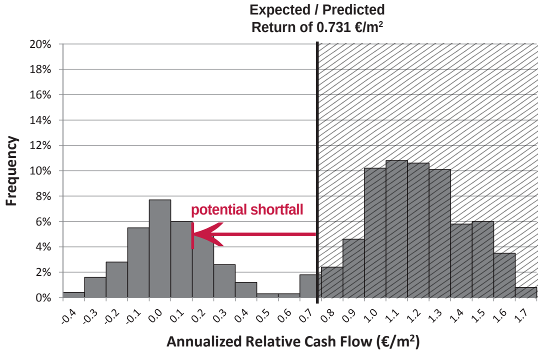


FIGURE 4.6 *An example to depict the relationship between expected return, potential shortfall, and the risk with respect to the expected return*

The risk (with respect to the expected return) is defined by **EQUATION 4.5**, where *n* is the number of bins that represent the distribution with values smaller than the expected return.

$$Risk = \sum_n \left\{ \begin{bmatrix} potential\ shortfall \\ (w.r.t. predicted\ performance) \end{bmatrix}_n \times \begin{bmatrix} frequency\ of \\ occurrence \end{bmatrix}_n \right\}$$

EQUATION 4.5

While annualized relative cash flow as defined in Section 4.2.2 serves well as the performance indicator for economic performance, risk as defined above acts as the performance indicator to objectively quantify the economic impact (of uncertainties) that is of concern to the designers. Decisions shall not be based only on the predicted cash flow, but also on the acceptable level of risk, as quantified by this risk indicator.

Other descriptive statistics from the probability distribution such as the lower quartile, the upper quartile, as well as the 10th and 90th percentiles, provide additional information on the impact of uncertainties in input parameters, which can also be useful in the design decision process.

Applications of risk indicator

One possible application of a risk indicator is to provide an objective evaluation of the potential short fall. **TABLE 4.8** presents an example, in which risk indicators can also be used to expose hidden pitfalls in design solutions and serve as the differentiating factor in making informed choices among different design options.

From this example, it can be observed that even though the two design solutions provide almost the same relative cash flow, the risk incurred by Design Solution 2 is two orders of magnitude more than that of Design Solution 1. From this illustration, it can be seen that economic performance alone does not provide sufficient information for informed design decisions. The risk indicator provides additional information that helps differentiate similarly performing solutions. In other words, amidst the non-predictable but anticipated variation in economic and energy market parameters, the risk indicator is a differentiating and determining factor in the design decision process.

TABLE 4.8 **A comparison between two different design solutions with very similar economic performance but different risks**

Parameters	Design Solution 1	Design Solution 2
Insulation (Thermal resistance, Roof, m^2K/W)	3.0	2.0
Insulation (Thermal resistance, Wall, m^2K/W)	2.0	2.0
Construction Types (Roof)	STL	CONC
Construction Types (Wall)	STL	CONC
Daylighting (as % of roof area)	0	15
Transpired solar collector (as % of south wall)	60	20
Predicted Annualized Relative Cash Flow (€/m^2)	0.173	0.172
Risk (€/m^2)	(0.002)	(0.152)

4.5 Concluding remarks

Based on the energy consumption and generation outputs of the simulation models, derived performance indicators that represent economic performance and environmental impact have been defined in this chapter.

It is suggested that utilizing **Energy Consumption** as a performance indicator is not tangible enough to provide a basis for making informed design decisions. Rather, achieving an energy related status such as NZEB to nullify the consideration of energy cost and energy associated environmental impact constitutes a tangible design goal.

Economic performance can be evaluated with life-cycle cost-benefit analysis and expressed in terms of **Annualized Relative Cash Flow**. This annualized value considers both the amortized cost of the investment and the ongoing operating cost of the building, and therefore, allows a fair comparison of the cost effectiveness of different energy saving and generation measures with different lifespans.

The relationship between energy consumption and operational carbon emissions has been discussed. **Net Carbon Emissions** also consider the embodied carbon footprint of the building materials. It has been shown that there are large uncertainties in input assumptions when estimating embodied carbon; however, the uncertainties are neglected due to their relatively insignificant impact on the net carbon emissions (the assumption is based on current operational energy consumption predictions, but embodied carbon can be significant when operational energy consumption is further reduced).

The evaluation of cost effectiveness also faces large uncertainties in input assumptions. In fact, it has been demonstrated that the uncertainties in economic parameters cause significant deviation from the predicted annualized relative cash flow to the point where an originally profitable design solution can become a non-profitable one. Through stochastic risk analysis, this chapter proposes a **Risk** indicator to represent the risk level associated with the investment.

Design objectives based on derived performance indicators

This chapter explains in detail the development of various performance indicators that cover aspects from the economic performance to the environmental impact of industrial halls. The establishment of these performance indicators allows industrial halls to be objectively designed and assessed with the following design objectives:

- Minimizing Energy Consumption or Maximizing Energy Generation towards achieving design goals such as NZEB
- Maximizing Annualized Relative Cash Flow
- Minimizing Net Carbon Emissions
- Minimizing Risk

The next chapter discusses the exploration and assessment of design solutions based on these design objectives.

5

Design Solutions Search — Objective Exploration and Assessment

CHAPTER 3 SUGGESTS MEANS TO REPRESENT THE BUILDING in design parameters and limit the scope of the investigation to a relevant design space. Chapter 4 proposes design objectives that could objectively differentiate one solution from another. This chapter furnishes the simulation based assessment methodology with a computational approach that could search through the relevant design space and identify the design solutions according to the established design objectives.

There are two possible systematic approaches: the optimization approach and the comprehensive design space exploration approach. These systematic approaches contrast with the heuristic approach used in current practice that is based on experience, rule of thumb guidance, or best judgment.

5.1 Optimization approach

Based on the ranges and levels of investigation for the design parameters as presented in Table 3.2 and 3.4, there are 21 million possible configurations for each climate / process load / occupancy schedule scenario if the demand and distribution side investigation (with 4,704 configurations) and the generation side investigation (with 4,640 configurations) are studied together. A complete search through (by performing simulation for) all the configurations is indeed computationally intensive. At a rate of around one minute of simulation time per configuration, a complete coverage will take more than forty years to complete. With this in mind, optimization is investigated for reducing the number of configurations simulated.

5.1.1 Computational advantage of performing optimization

Optimization can be deployed to search for the optimized design solutions according to the design objectives without the need to cover the whole design space. The discussion here refers to genetic algorithm based optimization.

Konak et al. (2006) summarizes a list of genetic algorithms that can be utilized to effectively search for design solutions out of the larger design space. At a rate of around one minute of simulation time per configuration, a more extensive coverage of the design space and a global search of the design solutions are both feasible and desirable over fast convergence. Multi-objective Genetic Algorithm (MOGA) proposed by Fonseca and Fleming (1993) is used in this research for its relatively straightforward approach for ensuring proper coverage, even though it may not be the most computationally efficient algorithm.

To demonstrate the computational advantages of performing optimization, an optimization is conducted to:

- Minimize Net Carbon Emissions
- Maximize Annualized Relative Cash Flow

In this example, an initial search space of 50 configurations is generated with Latin Hypercube Sampling (LHS). As the optimization progresses through generations, MOGA will move to a more likely search space. Deviation of the current search space from the previous one depends on the mutation setting, which has to strike a balance between fast convergence and consideration of all possibilities. The optimization ceases to identify any new design solutions for the last few generations. The optimization is set to stop after 40 generations. Out of the 2,000 studied configurations, there are only 1,353 unique design solutions since some of the configurations are being carried over from one generation to another based on the mutation setting.

When using optimization, if some parameters are more influential than others, it can be the case that some parameters have a much higher chance of being investigated at each of the levels, while other parameters might remain at a certain value. In other words, due to the limited number of configurations being simulated, it is impossible to draw design trends for each of the design parameters being studied (to be discussed later under Section 5.2.2 on full factorial design). The end result of the optimization approach is the optimized design solutions only.

Contrasting optimized design solutions with baseline building

FIGURE 5.1 presents all configurations (with different combinations of values of the aforementioned design parameters as presented in Table 3.2 and 3.4) that have been studied.

Each grey diamond in Figure 5.1 presents a unique configuration, which is represented by the corresponding values of net carbon emissions and annualized relative cash flow. The optimized design solutions, which are also known as Pareto solutions, are represented by the olive diamonds. Pareto solutions are design solutions that cannot be improved in one performance aspect without worsening another. In this particular example, as can be observed from the figure, there is no lower net carbon emission solution without reducing the annualized relative cash flow among these Pareto

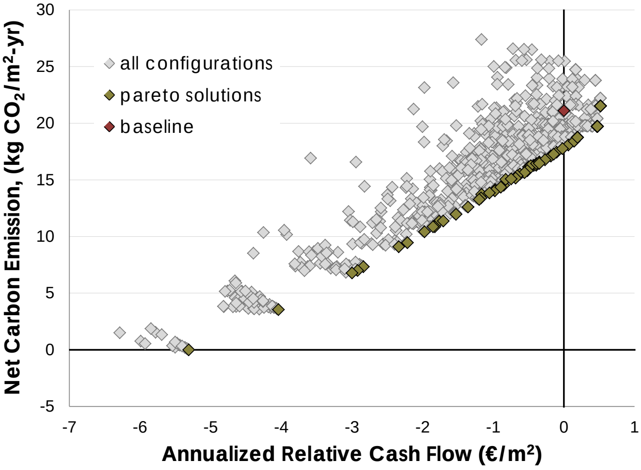


FIGURE 5.1 *Design solutions obtained by optimization as compared to the design solution of the baseline building*

solutions. Selection among these solutions is a trade-off between the desired level of environmental impact and return of cash flow that is left to the designers.

There is indeed a wide range of optimized design solutions available for the designers, from solutions with positive annualized relative cash flow but high carbon emissions to very costly solutions with lots of energy generation (thus much lower carbon emissions). It is difficult to make a business case to generate excessive energy at a huge loss. **TABLE 5.1** suggests two distinctly different design solutions, namely, the “zero-cost” solution and the carbon neutral solution that might be attractive to the designers. The design solutions are stacked against the baseline-building configuration to reveal the percentage of savings.

A carbon neutral building is a common design goal that is even mandatory for certain types of buildings in some locations. The negative annualized cash flow indicates the building owners / operators suffer a loss every year to achieve carbon neutrality

TABLE 5.1 **Performance of two design solutions in terms of annualized relative cash flow, energy consumption, and net carbon emissions as compared to the baseline building**

Parameters	Baseline	Zero-Cost Solution	Carbon neutral Solution
Insulation (Thermal resistance, Roof, m^2K/W)	3.5	1.5	1.5
Insulation (Thermal resistance, Wall, m^2K/W)	3.5	1.5	1.5
Construction Types (Roof)	STL	STL	STL
Construction Types (Wall)	STL	STL	STL
Daylighting (as % of roof area)	0	10	10
Transpired solar collector (as % of south wall)	0	0	0
PV installation (m^2)	0	202	2184
Annualized Relative Cash Flow (€/m^2)	–	0.0	(5.3)
Energy Consumption (kWh/m^2·yr)	53.4	52.9	(4.4)
saving over Baseline	–	1%	108%
Net Carbon Emissions (kg CO_2/m^2·yr)	21.1	17.8	0.0
saving over Baseline	–	16%	100%

as compared to the baseline-building configuration. Since the investigation is based on design parameters of discrete values, there could be cases where energy generation is slightly under or over the energy consumption. As shown in Figure 5.1, there are gaps between solutions. Therefore, a design solution with exactly zero carbon emissions might not exist.

There could also be environmentally conscious designers who prefer to lower the carbon emissions as much as possible without incurring a financial burden. The zero-cost solution demands capital investment on PV systems up front, but offers financial benefits in subsequent years (i.e. the operational financial benefits cancels out the annualized capital investment cost). Even with this zero-cost solution, a saving of 16% on carbon emissions can be achieved.

In this example, design solutions are quickly identified by the optimization process through searching 2,000 configurations. Compared to 21 million possible configurations of different combinations of demand side, distribution side, and generation side design parameters, 2,000 simulation runs suggest that the optimization approach indeed offers significant computational advantages. In fact, based on an integrated design approach with so many different design parameters, it is almost impossible to search for design solutions without performing optimization.

As a side note, it is suggested in Section 4.2.1 that different energy saving and generation measures of different lifespans must be evaluated using amortized cost rather than simple payback period. In the above example, a PV installation with an assumed lifespan of 20 years is the only energy saving and generation measure that has a shorter lifespan than the building. The above carbon neutral solution includes a PV installation with a simple payback period of almost 24 years, which is 4 years beyond what is assumed for the lifespan of the PV panels (the long payback period is partially attributable to the low industrial electricity price). The proposed performance indicator — annualized relative cash flow, considers the shorter lifespan of PV systems and allows a fair comparison between different configurations.

5.1.2 Limitation of applicability of optimization with derived performance indicators

The optimization approach requires full knowledge of what is to be optimized. There are two issues associated with the requirement of full knowledge. First of all, the design objectives must be clearly defined before an optimization is performed. In the above example, the optimization is conducted to:

- Minimize Net Carbon Emissions
- Maximize Annualized Relative Cash Flow

The resulting optimized design solutions only work for the defined design objectives. For example, the solutions that yield the maximum annualized relative cash flow might not have the shortest simple payback period even though both are derived performance indicators of economic performance. There could be other derived performance indicators (other than those discussed in Chapter 4) that are relevant for a particular situation but are not considered at the evaluation stage. If a design objective to minimize simple payback period or a constraint that excludes design solutions with long payback periods are indeed desired, then another optimization has to be performed.

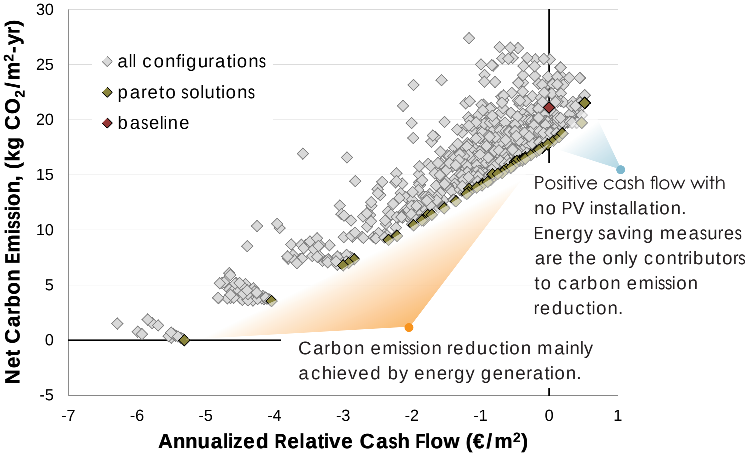
Since the definition of design objectives (based on derived performance indicators) is considered at the evaluation stage rather than left to the design decision stage, the designers are somewhat constrained. They are either deprived of the chance to define their own design objectives or are being forced to perform another optimization if another design objective is deemed desirable at a later stage. This goes against the assessment principle of design decision facilitation.

Second, the derived performance indicators rely on the values of the input assumptions. Derived performance based on one set of input assumptions is not valid under another set of assumptions (Section 5.2.1 demonstrates this argument with an example). In fact, there is a clear distinction between the direct performance indicator (i.e. energy consumption), and the derived performance indicators, such as the aforementioned annualized relative cash flow. Energy consumption and generation values are direct outputs of the simulation models based on different designers specified design parameters. On the other hand, the proposed derived performance indicators depend on the value of numerous external scenario parameters that are beyond the control of the designers. Hopfe (2009) distinguishes the two types of parameters in detail. The previous chapter also presents the wide range of uncertainty associated with many of these scenario parameters.

The second issue is more problematic and eminent. For example, consider the annualized relative cash flow where an investigation of this indicator requires knowledge of the discount rate and utility rates which fluctuate with time. Optimized design solutions based on one set of rates are guaranteed to be invalid when rates change. This is contradictory to the assessment principle of universal applicability.

The computational advantage of performing optimization is definitely attractive. However, the two issues described above severely limit the application of optimization for assessment of industrial halls. This dilemma raises the question of whether a few million configurations must be investigated. In fact, if demand and distribution side parameters and generation side parameters are to be investigated separately, then there are only few thousand configurations for each separate investigation instead of a few million configurations for one combined investigation.

The above optimization example is presented again in **FIGURE 5.2**. Figure 5.2 roughly categorizes the design solutions into two groups. One group of solutions does not include PV installation;



Positive cash flow with no PV installation. Energy saving measures are the only contributors to carbon emission reduction.

Carbon emission reduction mainly achieved by energy generation.

FIGURE 5.2 *Design solutions categorized into groups with either no or some PV installations* carbon emission reductions are a result of energy saving measures. The positive annualized relative cash flow of these solutions also suggests that the corresponding design options are cost effective. The other group includes certain amount of PV capacity. It can be observed that while the PV installation offers significant carbon emission reductions, and even enables design solutions to achieve carbon neutrality, a high capacity installation incurs a large negative cash flow.

Previous sections argue that it is not practical to generate excessive energy at a huge loss. Instead of aimlessly seeking the design solution with the lowest carbon emissions, business practice suggests achieving tangible design goals such as a carbon neutral building or NZEB. To achieve those design goals, the demand and distribution side investigation can be decoupled from the generation side investigation. In fact, other than the potential cooling energy reduction due to the shading effect of PV modules (ignored in this research based on climate of Amsterdam with low cooling demand), there is no linkage between the building energy simulation model and the energy generation simulation model that requires a combined investigation. The integrated investigation is purely economically motivated. It can be for some cases that energy generation measures might be more cost effective than energy saving measures, or vice versa. However, the demonstration in Figure 5.2 suggests that the design solutions are clustered into two distinct groups of design solutions with either no or some PV installations, instead of one mixed group of design solutions with different contributions of energy saving and generation measures. Based on this observation, a carbon neutral building or NZEB can be achieved by first picking the most desirable design solutions based on a demand and distribution side investigation and making up the energy deficit with energy generation solutions. The next section on comprehensive design space exploration presents a fuller account of how this is implemented.

5.2 Comprehensive design space exploration approach

With predefined design objectives and fixed input assumptions, optimization does not offer the flexibility which would otherwise be possible with derived performance indicators. By contrast, a comprehensive design space exploration approach that covers all configurations in the design space offers great flexibility to the designers.

5.2.1 Full factorial design that covers the entire design space of the investigation

If the parameters are discrete variables (i.e. each parameter is defined by a finite set of values), then there is a known set of combinations (configurations of building designs) based on the assigned ranges of values and resolutions in the investigation. Based on Table 3.4, there are altogether 4,704 possible configurations for the demand and distribution side investigation for each climatic location, process load, and occupancy schedule scenario. The comprehensive design space exploration approach can be accomplished using a full factorial design which will consider all combinations of the design space. Since every possible combination is investigated, this approach tends to avoid the bias found in the heuristic approach that is constrained by experience and eliminates the aforementioned limitations of optimization.

Databases of energy consumption

Evaluated results from the full factorial design can be made available as databases that contain all the configurations with different values for the design parameters, input assumptions, as well as direct and derived performance indicators. Due to the characteristics of industrial halls, simulation results for one building can be readily applied to another building of the same configuration in the same climatic location. In other words, the goal is to facilitate the design decision process by presenting the results in the form of databases, upon which future designs can be based without having to consider every design on a case-by-case basis.

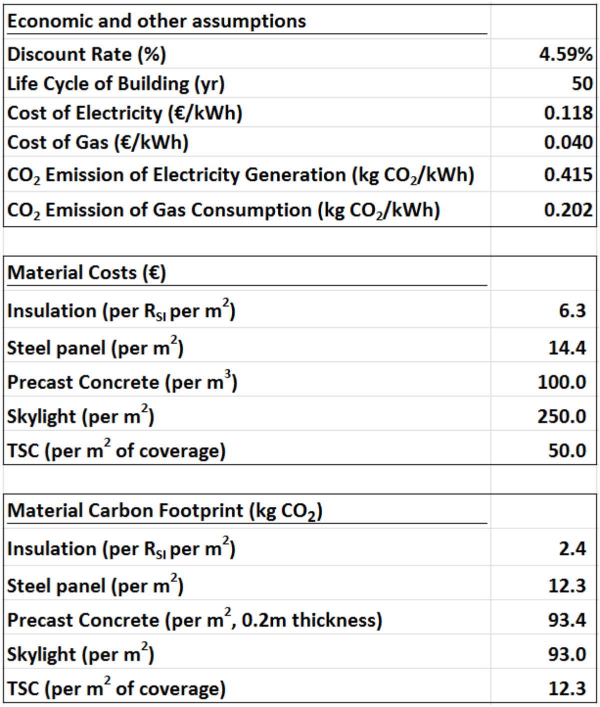
Flexibility in specifying input assumptions to evaluate derived performance

Valuable design decision information can be drawn from the derived performance indicators. However, such derived performance is very much dependent on the input assumptions and the resulting selection of design solutions can be completely different if there is a change in input assumptions.

Spreadsheet style databases allow the flexibility of specifying input assumptions. **FIGURE 5.3** presents a dummy interface where the users of a database can specify input assumptions. **FIGURE 5.4** depicts a snapshot of the corresponding database. As users specify the input assumptions, the values of the derived performance indicators change accordingly. Input assumptions can be based on the user's own experience such as billed utility rates or the user's expectations regarding future anticipated material costs.

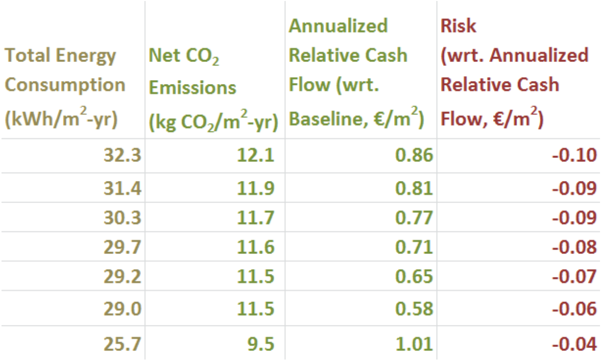
Table 4.7 presents two arbitrary design solutions where the resulting annualized relative cash flow is completely opposite when the design solutions are subject to two different scenarios of 10-yr high rates and 10-yr low rates. With full factorial design, the effect of input assumptions can be seen for all studied configurations. **FIGURE 5.5** presents the scatter plots of Net Carbon Emissions versus Annualized Relative Cash Flow for all configurations under two different scenarios of 10-yr high rates and 10-yr low rates (10-yr high rates and 10-yr low rates are defined in Table 4.6.)

It can be observed that the 10-yr high rate scenario induces a much wider variation in annualized relative cash flow with design solutions ranging from (1.6) to 1.3 €/m^2. With the aforementioned database, users can observe the impact on derived performance indicators based on their own choice of input assumptions, such as the economic rate scenario just demonstrated here.



Economic and other assumptions	
Discount Rate (%)	4.59%
Life Cycle of Building (yr)	50
Cost of Electricity (€/kWh)	0.118
Cost of Gas (€/kWh)	0.040
CO_2 Emission of Electricity Generation (kg CO_2/kWh)	0.415
CO_2 Emission of Gas Consumption (kg CO_2/kWh)	0.202
Material Costs (€)	
Insulation (per R_{SI} per m^2)	6.3
Steel panel (per m^2)	14.4
Precast Concrete (per m^3)	100.0
Skylight (per m^2)	250.0
TSC (per m^2 of coverage)	50.0
Material Carbon Footprint (kg CO_2)	
Insulation (per R_{SI} per m^2)	2.4
Steel panel (per m^2)	12.3
Precast Concrete (per m^2, 0.2m thickness)	93.4
Skylight (per m^2)	93.0
TSC (per m^2 of coverage)	12.3

FIGURE 5.3 *Input assumptions for derived performance indicators*



Total Energy Consumption (kWh/m^2-yr)	Net CO_2 Emissions (kg CO_2/m^2-yr)	Annualized Relative Cash Flow (wrt. Baseline, €/m^2)	Risk (wrt. Annualized Relative Cash Flow, €/m^2)
32.3	12.1	0.86	-0.10
31.4	11.9	0.81	-0.09
30.3	11.7	0.77	-0.09
29.7	11.6	0.71	-0.08
29.2	11.5	0.65	-0.07
29.0	11.5	0.58	-0.06
25.7	9.5	1.01	-0.04

FIGURE 5.4 *Direct and derived performance indicators that provide objective assessment of design solutions*

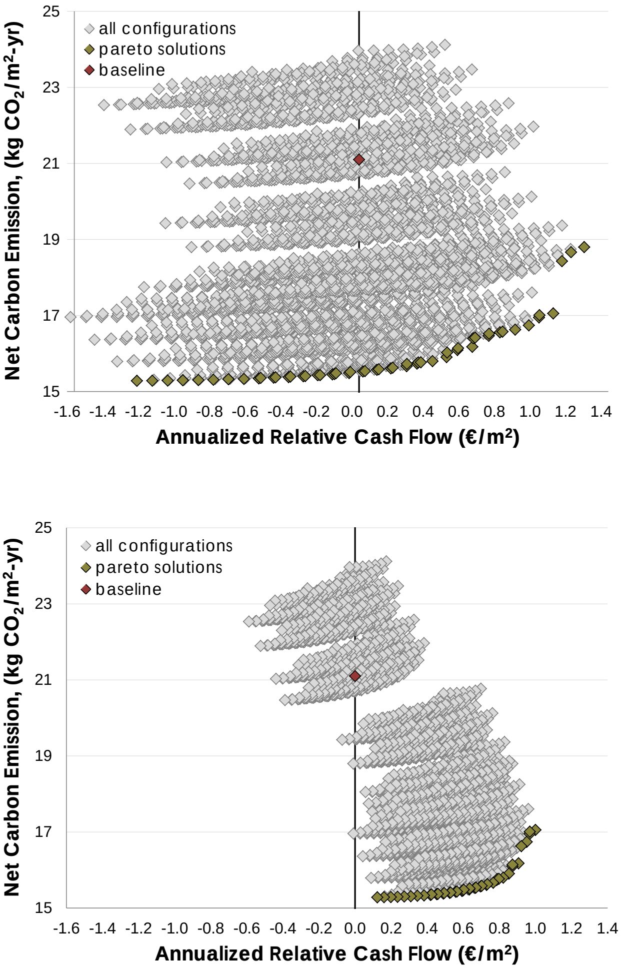


FIGURE 5.5 *Scatterplots of Net Carbon Emissions versus Annualized Relative Cash Flow of design solutions under two different scenarios of high (top) and low (bottom) rates*

5.2.2 Design solutions and design trends

In Figure 5.5, Pareto solutions are denoted by the olive diamonds. TABLE 5.2 presents the Pareto solutions with the highest and the lowest annualized relative cash flow under scenarios of 10-yr high rates and 10-yr low rates.

The design solution that yields the highest cash flow (1.3 €/m^2 in this example) under the high rate scenario might not yield the highest cash flow (only 0.87 €/m^2 in this example, as compared to the highest cash flow of 1.1 €/m^2 returned by another design solution) under the low rate scenario (the opposite rate scenario in this case). Table 4.7 also demonstrates the idea that design solutions that perform well in one scenario might perform poorly in another scenario. However, there could be cases in which the

TABLE 5.2 Design solutions with the highest and lowest annualized relative cash flow under two different scenarios of high and low rates

Parameters	Annualized Relative Cash Flow under **10-yr high rate scenario**		Annualized Relative Cash Flow under **10-yr low rate scenario**	
	Highest	**Lowest**	**Highest**	**Lowest**
Annualized Relative Cash Flow (€/m^2)	1.3	(1.2)	1.0	0.1
under opposite rate scenario	0.87	0.1	1.1	(1.2)
Net Carbon Emissions (kg CO_2/m^2·yr)	18.8	15.3	17.1	15.3
Insulation (Thermal resistance, Roof, m^{2}K/W)	1.5	4.5	1.5	4.5
Insulation (Thermal resistance, Wall, m^{2}K/W)	1.5	4.5	1.5	4.5
Construction Types (Roof)	STL	STL	STL	STL
Construction Types (Wall)	STL	STL	STL	STL
Daylighting (as % of roof area)	5	15	5	15
Transpired solar collector (as % of south wall)	0	100	80	100

performance of a design solution is not greatly affected by the input assumptions. The highest annualized relative cash flow design solution under the low rate scenario offers a very similar return under the high rate scenario (1.0 and 1.1 €/m^2, respectively).

It has been demonstrated that a full factorial design offers a very comprehensive view of the whole design space and allows exploration under varying input assumptions. The result is a truly unbiased design support tool that facilitates objective design and assessment. With the vast amount of information provided in the database, designers can select a design solution according to their desired level of performance for each of the performance indicators.

Observation of design trends

From the building designer's point of view, the vast amount of data allows design trends to be observed. That is, what is the impact of each design parameter on each of the performance indicators?

In a full factorial design, each level of a design parameter is being investigated with the same set of combinations of different levels of other design parameters. Therefore, from the resulting data of a full factorial design, it is possible to observe design trends for each of the design parameters. In fact, observing design trends is one of the key advantages of performing a full factorial design.

FIGURE 5.6 presents a design trend showing how the total energy consumption (the total of heating, cooling, ventilation, and lighting consumption) changes with respect to the variation in the level of roof insulation. Since roof insulation is only one of the design parameters and the full factorial design includes an investigation of all other design parameters, the value of the energy consumption with respect to each level of roof insulation represents the average of all the configurations (combinations of different levels of other varying design parameters) at that roof insulation level.

In this example, a full factorial design involves 4,704 configurations; therefore, at any particular roof insulation level (total 7 levels) the

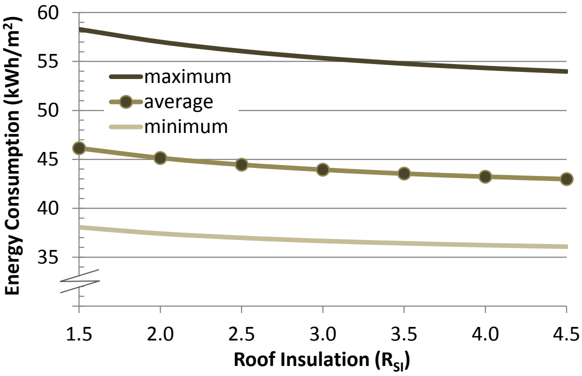


FIGURE 5.6 *Design trends that indicate changes in total energy consumption with respect to changes in the level of roof insulation*

energy consumption value represents the average value of the energy consumption for 672 possible configurations of other design parameters. The maximum and the minimum energy consumption values for those 672 configurations at each of the roof insulation levels are also shown in Figure 5.6.

Under current practice, a design trend for a particular design parameter is commonly identified by keeping all other design parameters fixed (e.g. a fixed level of daylighting). Czitrom (1999) exemplifies the potential pitfalls of such "one-factor-at-a-time" (OFAT) investigations. Section 3.1.3 also points out the potential bias in OFAT investigations as related to this research. Such bias is demonstrated in **FIGURE 5.7**. In this example, the configurations are assumed to be a steel construction with no transpired solar collector (TSC), and with wall insulation kept at 3.0 m^2K/W. The configurations are investigated at two fixed daylighting levels — 0% and 15% of roof area. In fact, a building with no TSC and daylighting is considered to be quite typical under current practice.

Figure 5.7 reveals that the energy consumptions for halls with no daylighting are almost as high as the maximum values of the

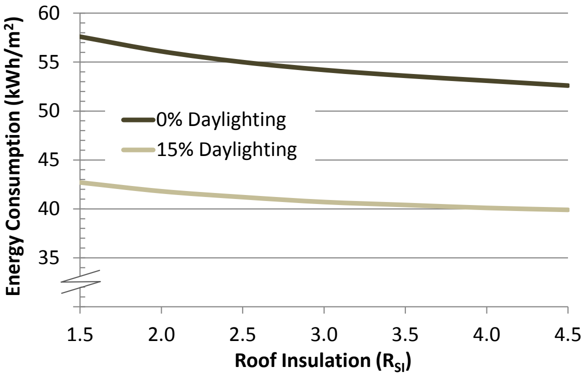
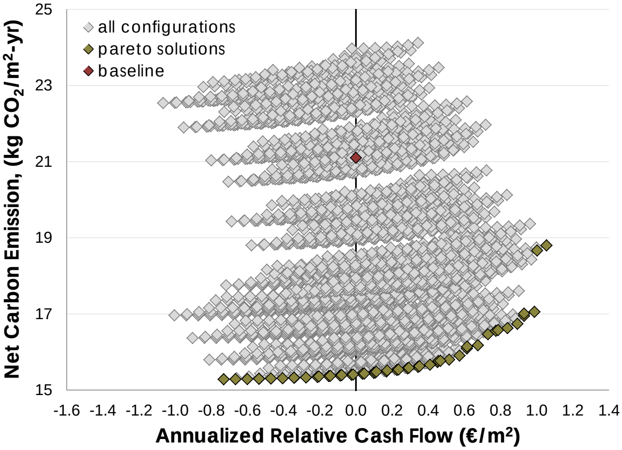


FIGURE 5.7 *Design trends that indicate changes in total energy consumption with respect to changes in the level of roof insulation corresponding to 0% and 15% roof area of daylighting with all other design parameters kept fixed*

672 configurations as observed in Figure 5.6. In this example, it is important to note that OFAT investigation with fixed values of design parameters provides a significantly misleading representation of the actual design trend. For example, the seemingly common (under current practice) configurations with no daylighting are in fact the extreme cases having a high level of energy consumption. On the other hand, a full factorial design makes available simulation data for each of the studied configurations and thus ensures the integrity and representativeness of the observed design trends.

5.2.3 Optimization revisit — a comparison to full factorial design

There are pros and cons in performing optimization. The computational advantage is obvious especially if the design space is so large that a full factorial design is simply not computationally feasible. However, other than the previously mentioned limitations of optimization, there is also a concern as to whether or not optimization can effectively identify all Pareto solutions. **FIGURE 5.8** offers a comparison of design solutions using the two approaches. The design solutions shown in the top figure are generated using



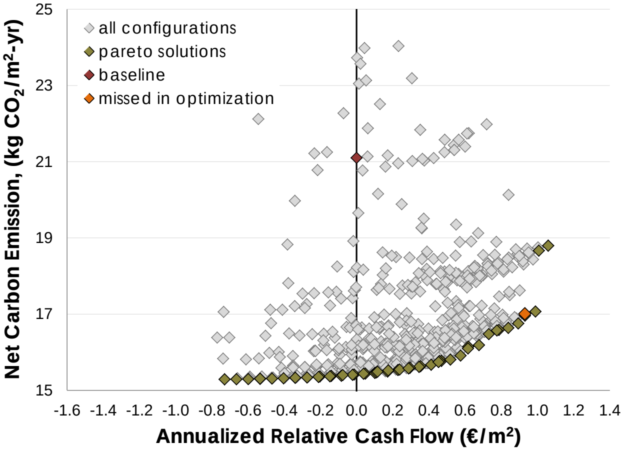


FIGURE 5.8 *Scatterplots of Net Carbon Emissions versus Annualized Relative Cash Flow of design solutions generated by the comprehensive design space exploration approach (top) and the optimization approach (bottom)*

the comprehensive design space exploration approach with full factorial design. That is, the design solutions in this figure represent the full collection of all possible configurations.

With the optimization approach (bottom figure), “almost” all Pareto solutions are identified by searching through a mere 611 unique configurations, instead of the whole design space of 4,704 configurations. The optimization is set up with an initial search space of 50 configurations and carried out for 100 generations; therefore, a total of 5,000 configurations are studied and of these configurations, 611 are unique). MOGA cannot find any better solutions after the 38th generation. The example is based on an input assumption of a 10-year average rate scenario.

The computational time saving of 87% (611 configurations versus 4,704 configurations) is hard to ignore. However, a comparison of the Pareto solutions generated by the two different approaches suggests that the optimization approach fails to identify “all” Pareto solutions. Optimization misses 1 solution (marked by the orange diamond) out of the 51 obtainable Pareto solutions. In this particular example, the optimization process is not set to stop until completing 100 generations. As the optimization progresses through generations, MOGA, a fairly common genetic algorithm, will move to a more likely search space for each new generation. Deviation of the current search space from the previous one depends on the mutation setting, which has to strike a balance between fast convergence and the consideration of all possibilities. **FIGURE 5.9** depicts how the optimization progresses in this example.

In the first 10 generations, MOGA is able to identify 28 Pareto solutions. However, from the 38th generation till the 100th generation, MOGA is not able to “mutate” to another search area to find the missed Pareto solution. In fact, in this research, MOGA is set to mutate slowly to encourage in-depth coverage of the whole design space. The slow mutation is reflected in the number of repeated configurations in each generation (611 unique

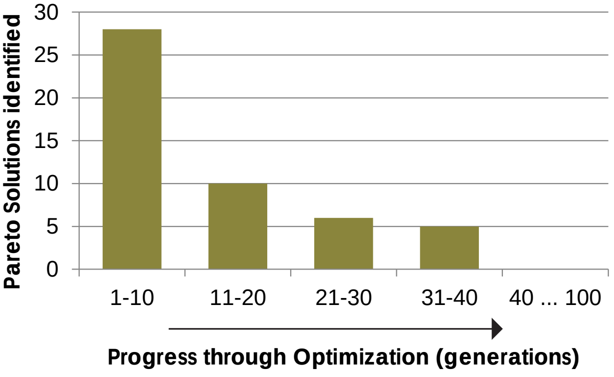


FIGURE 5.9 *Number of Pareto solutions identified as the optimization progresses through generations*

configurations versus 4,389 repeated configurations, out of the 5,000 configurations being studied).

There are many commonly deployed optimization algorithms with their own strengths and weaknesses. Fine tuning the mutation and evolution settings for genetic algorithms is also case dependent and is more of an art than a science. A full discussion of optimization techniques is beyond the scope of this research; however, an interesting fact is that the configuration of the missed Pareto solution is quite similar to the configurations of a few Pareto solutions that have already been identified. There is no apparent reason why that particular solution is missed even though its neighboring design space has already been searched and yielded some promising solutions.

The example presented demonstrates two characteristics of optimization with genetic algorithms. First, there is no guarantee the identified Pareto solutions represent all obtainable Pareto solutions in the design space. A rather extensive search in this example results in only 1 miss out of 51. In other cases, the proportion of missed Pareto solutions can be high (and yet cannot be predicted) for a far less exhaustive search such as the one presented in Section 5.1.1 with just 1,353 unique configurations studied out of the possible 21 million configurations.

Second, it is also not possible to predict what kind of configuration is more likely to be missed; therefore, the problem is not just about missing some Pareto solutions. The bigger problem is the inability to estimate the proportion of missed Pareto solutions out of all obtainable Pareto solutions, and more importantly, the lack of knowledge of the configurations of the missed Pareto solutions.

If the intention of performing optimization is to search for optimized design solutions as long as they are optimally performing in all design objectives, then the computational advantage of performing optimization does make it a sound approach. On the other hand, if the designers are interested in the details of the configurations and make the decision based on their preferences regarding particular energy saving and generation measures rather than simply fulfillment of the design objectives, then full factorial design is a well-suited approach that offers such comprehensive information for the design decision process.

5.3 Concluding remarks

The examples presented in this chapter showcase the effectiveness of the optimization approach in searching for design solutions if the input assumptions and design objectives are known to the designers and not likely to change in the future. However, as a generalized simulation based assessment methodology (under the premise of universal applicability and scalability), the optimization approach lacks the flexibility offered by the comprehensive design space exploration approach, in which the energy performance of the full spectrum of configurations is available and the derived performance can be found via post-processing. The actual presentation of data for the comprehensive design space exploration approach can be a spreadsheet style database that allows users to assign their own input assumptions that represent their particular circumstances.

The computational advantage of performing optimization is significant particularly if the design space is large enough that covering the complete design space is not computationally feasible (where feasibility depends on computational resource and time constraints such as for the illustrative rate of around one minute of simulation time per configuration in which a complete coverage of 21 million possible configurations will take more than forty years to complete). However, it can be observed that the effectiveness of searching the design space in a limiting fashion via optimization comes at a cost of missing Pareto solutions which could otherwise be identified with a comprehensive design space exploration.

On the other hand, a comprehensive design space exploration with full factorial design not only allows the defining of design objectives and the assigning of input assumptions to be postponed to the design decision stage, but also identifies the full set of all obtainable Pareto solutions for the complete design space. This is the approach of choice that fulfills the assessment principles of universal applicability and scalability. In effect, the full factorial design introduced in this chapter defines the size of the design space of an investigation. The practical issue of having an unfeasibly large design space could be solved using sensitivity analysis (presented in Section 3.3) which reduces the scope of the investigation to a limited number of influential design parameters. In fact, the sensitivity analysis and thus the compilation of the final list of design parameters have to take into account the size of the design space and the available computational resources so that a full factorial design with acceptable resolution can be performed within the available means.

6

Applicability and Usefulness of Simulation Based Assessment for Design Support — a Case Study

In previous chapters, the development of the building energy simulation based assessment methodology has been presented: the parametric representation in Chapter 3, design objectives in Chapter 4, and design solutions search in Chapter 5. This chapter demonstrates the application of the assessment methodology. With a case study, the applicability and usefulness of the assessment methodology to the design of industrial halls is demonstrated by presenting the significant performance advantages of the proposed design solutions (offered by the assessment methodology) over solutions based on the current design practice. Analyzed design trends and graphical presentation of data further demonstrate the potential capabilities of the assessment methodology. Throughout this chapter, a warehouse in Amsterdam is selected for the case study and is operated on a 2-shift operation unless stated otherwise.

6.1 Simulation based assessment — an overview

Even though local situations are different from country to country, and region to region, the simulation based assessment involves a few generalized steps, which can be universally applied to local situations. The assessment shall include a thorough review of the local construction practice of industrial halls and come up with a list of design parameters that cover the demand side, distribution side, and generation side (discussed in Section 3.1 and 3.2). Each design parameter is described by a set of discrete values that represent the readily available sizes of the respective building components (for example, amount of insulation at certain m^2K/W). Building configurations are comprised of combinations of different values of the studied design parameters.

The investigation involves Full Factorial Design (Section 5.2) that covers the whole design space of all possible configurations based on different design parameters with sets of discrete values. Sensitivity Analysis (Section 3.3) is used to identify the influential design parameters so as to limit the scope of the investigation so that it is feasible to complete a full factorial design with the available computational resources. Based on the characteristics of the dataset (i.e. monotonic, nonlinear, and mutually associated parameters), the Partial Rank Correlation Coefficient is found to be an appropriate means to rank sensitivity.

The direct performance indicator is energy consumption, which is the output of the simulation models. Derived performance indicators are evaluated based on values of both the input assumptions (external scenario parameters) and the direct performance indicator. Derived performance indicators cover design aspects on cost effectiveness (Section 4.2), environmental impact (Section 4.3), and risk (Section 4.4). The post-processing of energy consumption data to arrive at these derived performance indicators involves purpose specific concepts such as Amortized Cost, Cost-benefit, Embodied Energy and Carbon, and generalized approaches such as Life-cycle Analysis and Stochastic Risk Analysis. Design

Objectives (e.g. to minimize or to maximize any of the performance indicators) are also assigned.

By performing a full factorial design, performance data for all configurations are made available and can be presented in a spreadsheet style database. Pareto solutions are identified based on the fulfillment of design objectives. Designers can select design solutions from the pool of Pareto solutions based on their own preferences regarding the design objectives. Through data analysis, design trends (i.e. impact on a performance indicator under varying design parameters) can be drawn. Design trends of the design parameters offer insightful information for building designers.

The simulation based assessment methodology just described is depicted as a flowchart in FIGURE 6.1. The assessment methodology is developed in such a way that can be applied to situations other than the case study. Figure 6.1 highlights the generalized steps to be followed with reference to concepts and approaches that are explained in detail in their respective sections.

6.2 Single objective design trend observation

With a full factorial design, a vast amount of data are available. Section 5.2.2 proposes that design trends, which study the impact of each design parameter on each of the performance indicators, can be drawn from aggregated data of thousands of configurations (by taking the average value of the configurations made up of combinations of other design parameters). A total of 24 single objective design trends can be drawn for the 6 design parameters with 4 performance indicators each.

6.2.1 Energy related design trends

Annual operational energy consumption is commonly expressed in the unit of kWh/m^2; however, if occupancy patterns range from 1-shift of work to full-time operation, then the annual total energy consumption among different

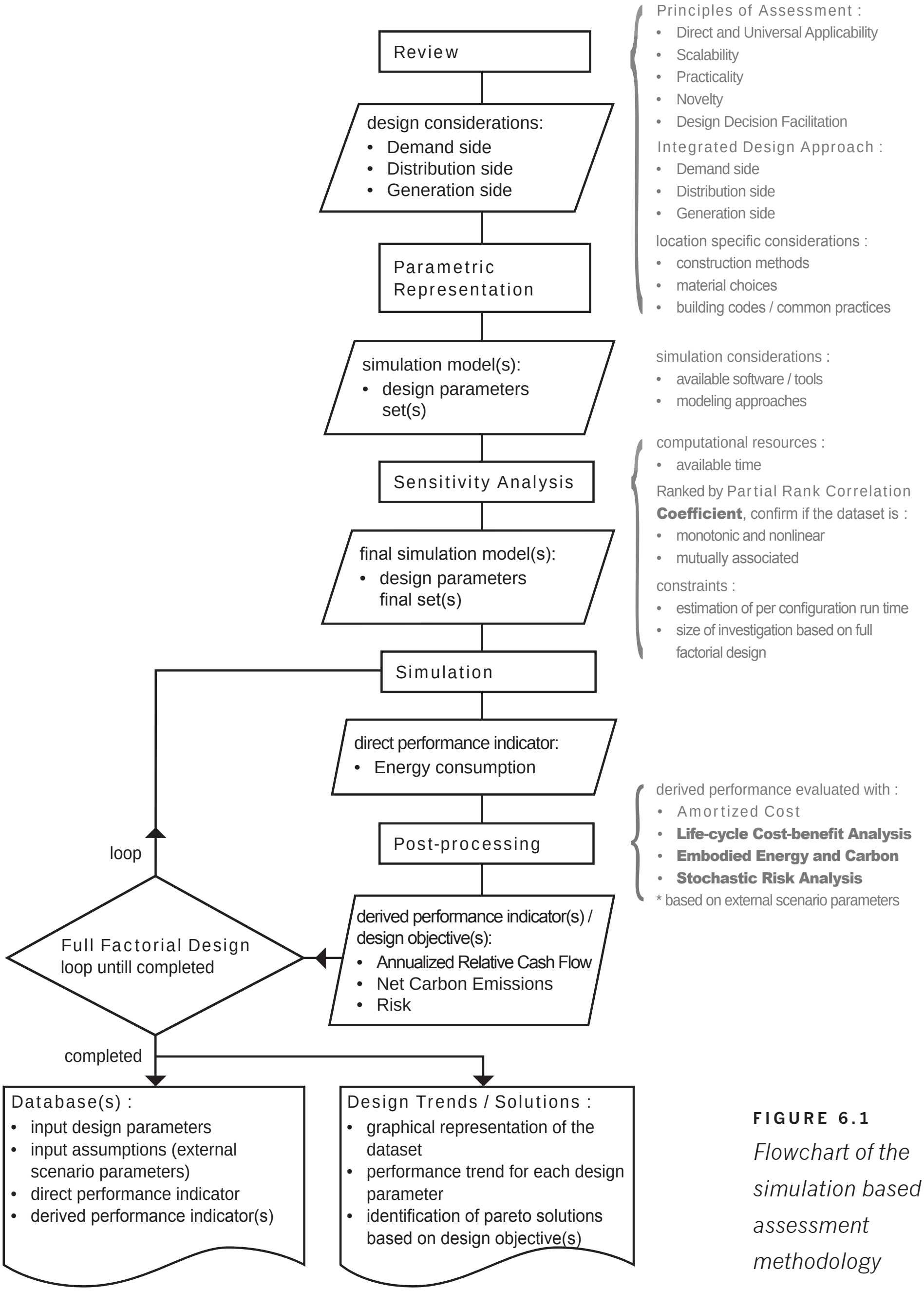


FIGURE 6.1

Flowchart of the simulation based assessment methodology occupancy patterns can differ by an order of magnitude. The annual energy consumption can be divided by the operating hours (e.g. 5,008 hours for a 2-shift operation) to calculate an hourly average energy consumption (in the unit of $Wh/m^2 \cdot h$). This hourly value allows a fairer comparison of performance between different occupancy patterns and provides useful information for the designers since the unit cost of the product is directly proportional to the hourly cost of the energy instead of the annual sum. Although it is true that $Wh/m^2 \cdot h$ is in effect W/m^2, they represent two conceptually different entities, in which the former represents the amount of energy consumed for each hour (and thus the energy cost as it appears on the utility bill). On the other hand, W/m^2, which is the power per unit area, does not offer the same practical meaning. The same concept also applies to carbon emissions, cash flow, and risk. It is the per operating hour unit values that are of interest to the operators in a manner similar to hourly wages. **FIGURE 6.2** presents the design trend for energy consumption with respect to changes in the level of roof insulation.

It can be observed that the hourly energy consumption is highest under 2-shift operation. In fact, it is paramount to observe the

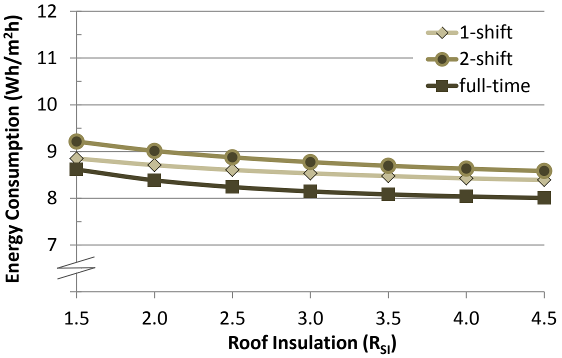


FIGURE 6.2 *Design trend that indicates changes in total energy consumption with respect to changes in the level of roof insulation*

intricate relationship between heating, cooling, and lighting, as well as among different design parameters. **FIGURE 6.3** contrasts the annual heating energy consumption (top) and hourly heating energy consumption (bottom) for different levels of roof insulation. In general, demand for heating is comparatively low for a 1-shift schedule with operation during the day (warmer hours). This is reflected in the annual heating energy consumption for the 1-shift operation. For a full-time operation, quite many of the operating hours are during the night, when the heat loss to the surroundings

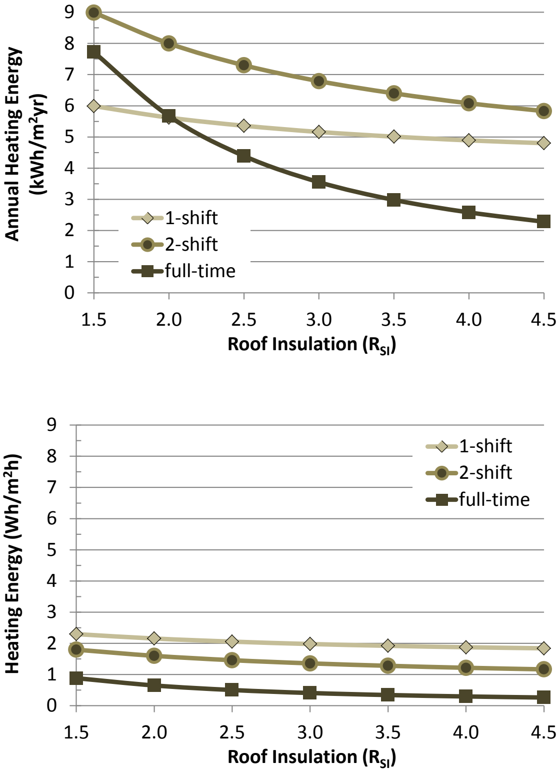


FIGURE 6.3 *Annual heating energy consumption (top) and hourly heating energy consumption (bottom) with respect to changes in the level of roof insulation*

is high for a significant portion of time. However, non-stop operation ensures continuous heat gain from the process load. With lesser insulation, the annual heating energy consumption of the full-time operation is higher than the 1-shift operation due to the longer operating hours (8,760 versus 2,610 hours) and a larger portion of night hours, but the annual heating energy consumption drops significantly (even lower than that of the 1-shift operation) at higher insulation levels since heat gain from the non-stop process load is retained inside the hall.

A similar trend can be observed for 2-shift operation, where annual heating drops significantly with a higher level of insulation. However, for 2-shift operation, the halls are exposed to colder temperatures during the night and have no internal heat gain during non-operating hours; therefore, the effect of insulation is not as significant as in full-time operation. After dividing by the operating hours, a 1-shift operation consumes the largest amount of hourly heating energy while full-time operation consumes the least.

Lighting energy follows a different pattern. Unlike heating, in which heat gain can be dissipated or retained through time, daylighting only offers instantaneous lighting energy savings. Daylighting brings significant savings in lighting energy during the day, and therefore yields immediate benefit at just 5% coverage. During the day, extra skylights unnecessarily provide lighting above the required 500 lx level, but are helpful in the early morning or late evening hours when the sun is dim. That is, the additional amount of skylight extends the hours of useful daylighting. In fact, the difference between occupancy patterns only affects the number of available daylighting hours. As seen from **FIGURE 6.4**, with extended daylighting hours with a larger amount of skylight, annual lighting energy consumption (top) is reduced more under a full-time operation than under either 2-shift or 1-shift operation.

After dividing by the operating hours, the marginal benefit of prolonged daylighting hours does not compensate for the fact that a full-time operation requires artificial lighting during the night

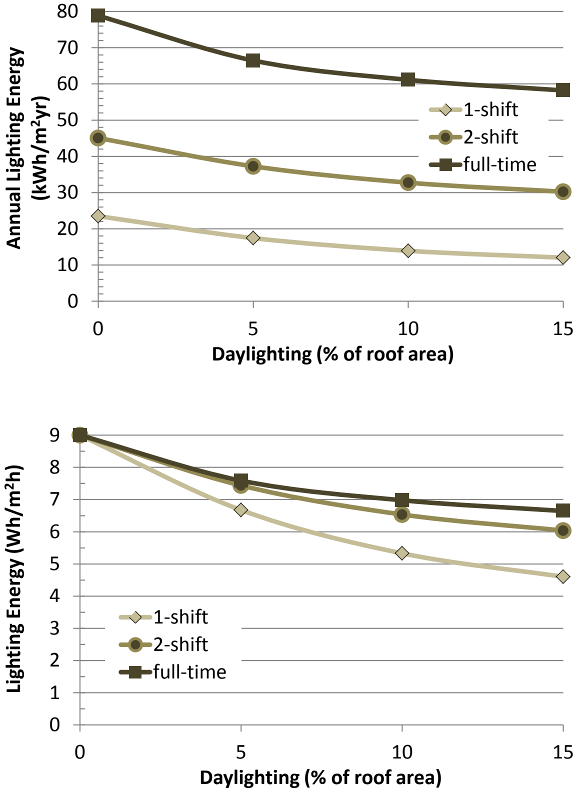


FIGURE 6.4 *Annual lighting energy consumption (top) and hourly lighting energy consumption (bottom) with respect to changes in daylighting level*

when there is no available daylighting. The 1-shift operation still consumes the least amount of hourly lighting energy.

For industrial halls with low process loads such as a warehouse, lighting constitutes a significant portion of total energy consumption. **FIGURE 6.5** puts the numbers into perspective and depicts the lighting energy under different levels of roof insulation. The lighting energy is not expected to change at all with respect to changes in the level of roof insulation. The gaps between the parallel lines among

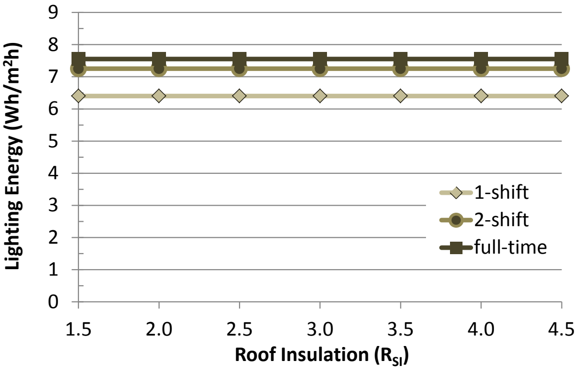


FIGURE 6.5 *Hourly lighting energy consumption with respect to changes in the level of roof insulation*

different occupancy patterns represent the marginal advantage of having daylighting for one occupancy pattern over the others.

When stacking the hourly heating energy consumption of Figure 6.3 (bottom) on top of the hourly lighting energy consumption of Figure 6.5, hourly total energy consumption as depicted in Figure 6.2 can be realized (both cooling and ventilation are comparatively negligible in this case). It is interesting to note that full-time operation incurs the lowest heating energy and highest lighting energy, while 1-shift operation incurs the highest heating energy and lowest lighting energy. As a result, hourly total energy consumption (Figure 6.2) under 2-shift operation is the highest regardless of the level of roof insulation.

6.2.2 Carbon related design trends

In this research, life-cycle carbon emissions consider both the operational carbon (determined by energy consumption based on CO_2 emissions factors) and the embodied carbon of the design solution. Minimizing net life-cycle (annualized) carbon emissions is one of the design objectives as discussed in Section 4.3.

The operational carbon follows the design trends of the previously discussed operational energy consumption. Since net carbon emissions also include the embodied carbon, the effectiveness in reducing net carbon emissions of each of the design components (as related to each design parameter) is considered. A certain design solution may reduce the operational carbon significantly, but at the same time incurs a higher level of embodied carbon, the net carbon emissions reflects the relationship between operational and embodied carbon, and offers one single value to indicate the environmental impact. **FIGURE 6.6** contrasts the performance in terms of operational energy consumption (top) and net carbon emissions (bottom) for a roof constructed of either steel or concrete.

The enclosure can be a steel construction or a concrete construction (200 mm of concrete in this case study). Steel panels and a concrete layer do not have a practical reason to coexist; therefore, dotted lines in Figure 6.6 are there to conveniently display the different levels of performance between the steel construction and the concrete construction and not to suggest there is any in-between value among the two different types of constructions.

From Figure 6.6, it can be observed that the performance difference (less than 2%) in terms of energy consumption is minimal. However, when the embodied carbon of the structures is also considered, the performance difference in terms of life-cycle carbon emissions ranges from 4% (full-time operation) to 19% (1-shift operation) between the two different types of constructions.

Embodied carbon is a fixed value attached to the building structure based on construction methods and material choices. When this fixed value is divided by the operating hours, it is proportionally more significant when divided by the smaller number of operating hours of a 1-shift operation than the larger number of operating hours of a full-time operation. Therefore, the aforementioned performance difference in net carbon emissions is more significant under a 1-shift operation.

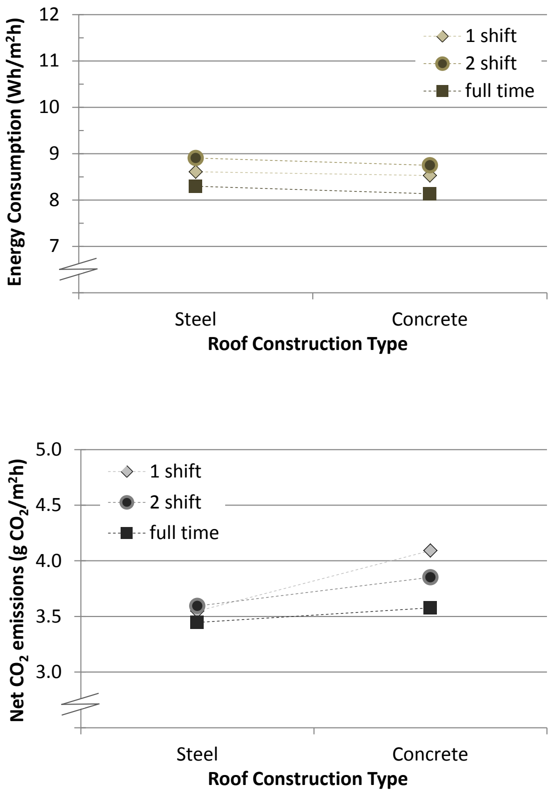


FIGURE 6.6 *Design trends that indicate changes in total energy consumption (top) and net carbon emissions (bottom) among two roof construction types, steel and concrete*

From this example, it is quite clear that the selection of materials or construction methods shall not be based on one performance indicator. The performance can exhibit an opposing trend if it is based on another performance indicator.

6.2.3 Cost related design trends

Cost effectiveness, which considers both the capital investment cost and the operating cost, can be expressed in terms of the annualized relative cash flow. A negative value signifies the design solution incurs a loss, which is definitely not a viable proposition for investment. If the investment is purely profit driven, the higher the annualized relative cash flow of a design solution the better. Similar to net carbon emissions, there is a fixed component involved in the evaluation of annualized relative cash flow. Annualized relative cash flow indicates if the saving in operating cost is worth the corresponding spending in the fixed capital investment cost. **FIGURE 6.7** compares the hourly performance in terms of operational energy consumption (top) and annualized relative cash flow (bottom) for different levels of daylighting.

As discussed in detail in Section 6.2.1, daylighting exhibits greater hourly energy savings under a 1-shift operation, since the lighting reduction happens mainly during the day when a 1-shift schedule is in operation. However, in terms of capital investment, the more hours that yield a benefit (no matter how marginal or insignificant the benefit is), the more the investment has been diluted over the operating hours. Therefore, full-time operation offers the highest hourly return (in terms of annualized relative cash flow) regardless of the daylighting level.

In this example for daylighting, skylights covering 5% of the roof area offer a greater cash flow than a greater coverage of 15%. It is, therefore, not cost effective to opt for a higher level of daylighting based on the current cost of skylights (this observation concurs with ASHRAE Standard 90.1's compliance path that limits skylight coverage to less than 5%, ASHRAE, 2007b). Since energy performance improves with higher daylighting levels, it could be the case that a higher level of daylighting is cost effective if the cost of the skylights decreases. The proposed database gives users the flexibility to input their own assumptions regarding material prices and other rates.

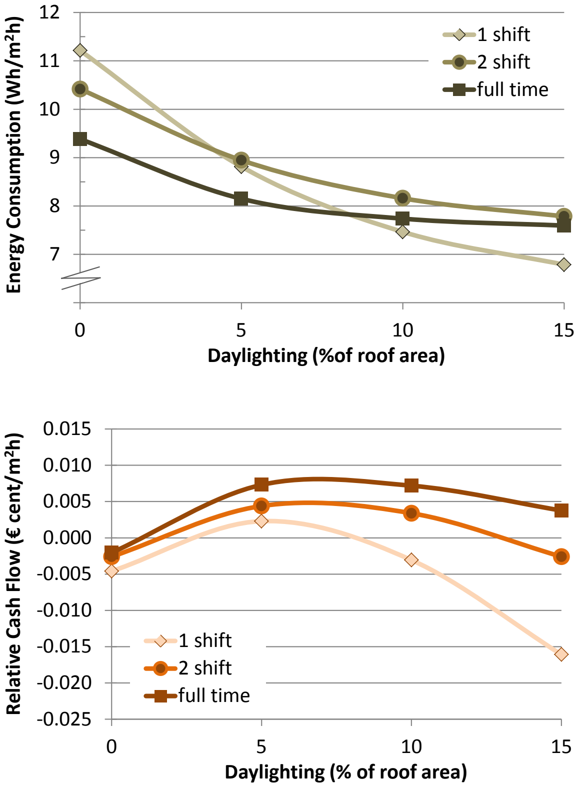


FIGURE 6.7 *Design trends that indicate changes in hourly total energy consumption (top) and hourly average of the annualized relative cash flow (bottom) with respect to changes in the daylighting level*

6.2.4 Risk related design trends

Both net carbon emissions and annualized relative cash flow are derived performance indicators that depend on the values of external scenario parameters. The relationships between the derived performance indicators and the external scenario parameters are direct and discrete (i.e. the relationships are one-to-one based on simple arithmetic).

By contrast, (economic) risk is dependent on the amount of capital investment and the interest rate (which follows a probability distribution rather than a deterministic value) applied to finance the investment. **FIGURE 6.8** depicts risk performance that displays a “bumpy” response with respect to different levels of roof insulation. The relationship between the design parameter and the corresponding risk is complex, and the observed design trend does not offer a conclusive “trend” for the designers. The inconclusive nature of the results is further demonstrated in the next section.

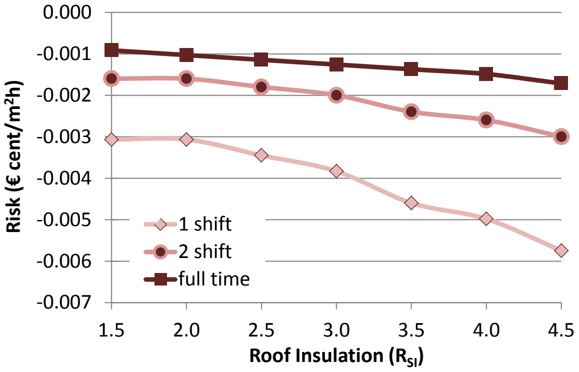


FIGURE 6.8 *Design trend that indicate changes in hourly average risk with respect to changes in the level of roof insulation*

6.3 Single objective design solutions

From the above demonstration, design trends provide indispensable guidance in helping building designers develop design ideas based on the performance indicators discussed above. Even though design trends are drawn from aggregated data from thousands of configurations, the design trend observations are limited to one design parameter at a time. If roof insulation of 4.5 m^2K/W is found to save the most energy, and similarly so is daylighting covering 15% of roof area, is it true that a combination of the two will save the most energy? **TABLE 6.1** proposes hypothetical configurations for each of the performance indicators, based on the best performing value of each design parameter from each of the single objective design trends (assuming 2-shift operation).

TABLE 6.1 Hypothetical configurations (for 2-shift operation) of the "best design solutions" based on the best performing value of each design parameter from each of the single objective design trends

Parameters	Lowest Energy Consumption	Lowest Net Carbon Emissions	Highest Annualized Relative Cash Flow	Least Risk / actual least risky solution
Energy Consumption (kWh/m^2)	36.1	37.5	50.2	58.3 / 53.4
Net Carbon Emissions (kg CO_2/m^2)	17.0	15.3	18.8	22.0 / 21.1
Annualized Relative Cash Flow (€/m^2)	(1.00)	(0.73)	1.05	0.72 / 0
Risk (€/m^2)	(0.29)	(0.25)	(0.04)	(0.01) / 0
Insulation (Thermal resistance, Roof, m^2K/W)	4.5	4.5	1.5	1.5 / 3.5
Insulation (Thermal resistance, Wall, m^2K/W)	4.5	4.5	1.5	1.5 / 3.5
Construction Types (Roof)	CONC	STL	STL	STL / STL
Construction Types (Wall)	CONC	STL	STL	STL / STL
Daylighting (as % of roof area)	15	15	5	0 / 0
TSC (as % of south wall)	100	100	0	0 / 0

As seen from Table 6.1, a combination based on the best performing value of each design parameter for a single objective design trend does turn out to be the solution that yields the best performance for that particular design objective. Observed design trends, can indeed serve as a means to identify design solutions. Since risk is a rather complex derived performance indicator (see discussion in

Section 6.2.4), a combination of the best performing values of the design parameters does not generate the best performing design solution in terms of the risk.

6.3.1 Design solutions of similar performance

As a matter of fact, even though the hypothetical configurations perform the best for each of the design objectives, they are not necessarily the only choices to achieve such a high level of performance. **FIGURE 6.9** presents the top 2% performers (i.e. the top 94 configurations out of the full set of 4,704 configurations) for each design objective.

The parallel plot presented in Figure 6.9 allows a quick overview of the kinds of configurations that yield a certain level of performance. Since only the top 2% performers are included in the figure, the performance of the presented configurations is indeed very close to the performance of the “best design solution” (indicated by the black line) with respect to each design objective (except the annualized relative cash flow, which yields over a wider range from 1.05 €/m^2 to 0.74 €/m^2).

Risk can never be positive since it reflects a potential shortfall from the predicted value. In this research, risk (defined in Section 4.4) is evaluated relative to the annualized relative cash flow. Therefore, risk is presented using the same scale as used for the cash flow so that the magnitude of the potential shortfall relative to the cash flow can be easily identified.

TABLE 6.2 summarizes the range of each design parameter within the set of top 2% design solutions (94 solutions) for each design objective. Ranges of the performance are also indicated.

The so-called “best design solutions” are only the best with respect to the corresponding design aspect. It can be observed that the top 2% performers for both energy consumption and net carbon emissions are those with 15% daylighting level. By contrast, the top 2% performers for risk (the design solutions with the least risk)

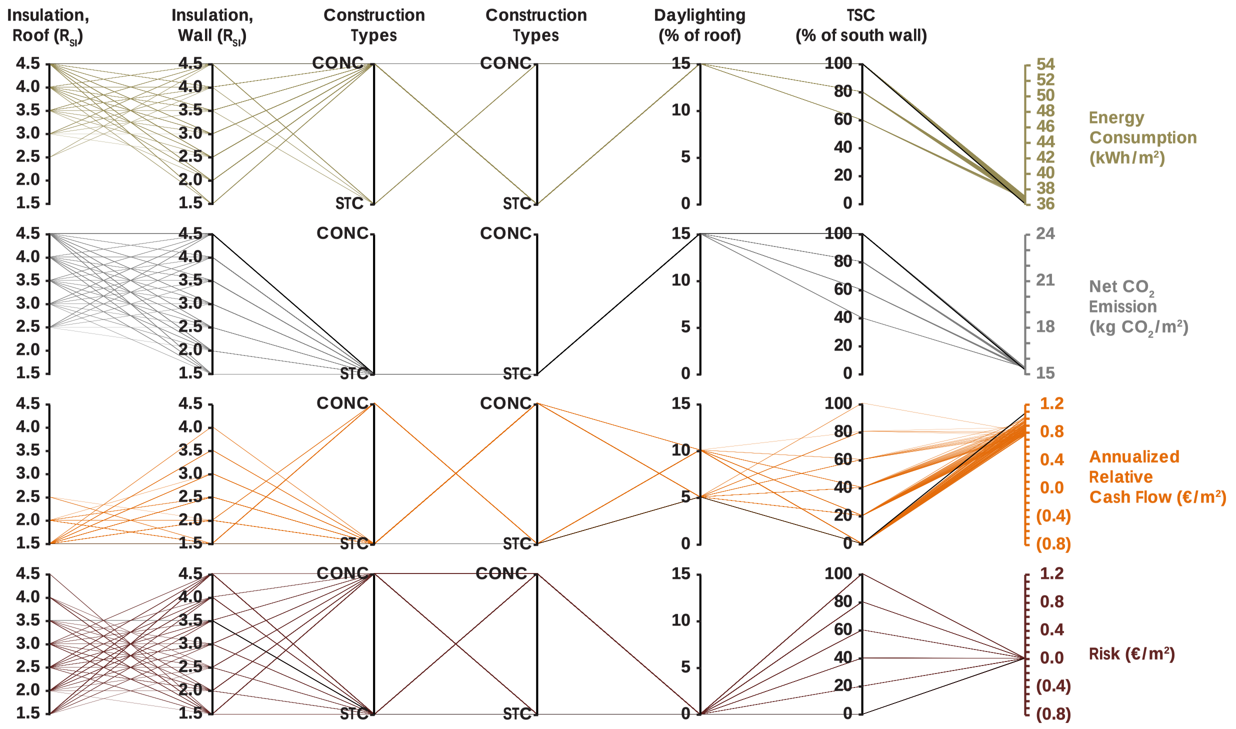


FIGURE 6.9 *Parallel plots that present the configurations and the resulting performance for the top 2% of design solutions with respect to each design objective*

TABLE 6.2 **Summary of configurations for the top 2% performers for each design objective with design ranges for each for the design parameters**

Parameters	Energy Consumption (kWh/m²)	Net Carbon Emissions (kg CO_2/m²)	Annualized Relative Cash Flow (€/m²)	Risk (€/m²)
	36.1 – 37.1	15.3 – 15.5	0.74 – 1.05	(0) – (0.01)
Insulation (Thermal resistance, Roof, m²K/W)	2.5 – 4.5	2.5 – 4.5	1.5 – 2.5	1.5 – 4.5
Insulation (Thermal resistance, Wall, m²K/W)	1.5 – 4.5	1.5 – 4.5	1.5 – 4.0	1.5 – 4.5
Construction Types (Roof)	STL or CONC	STL	STL or CONC	STL or CONC
Construction Types (Wall)	STL or CONC	STL	STL or CONC	STL or CONC
Daylighting (as % of roof area)	15	15	5 – 10	0
TSC (as % of south wall)	60 – 100	40 – 100	0 – 100	0 – 100

are those with no daylighting at all. The top 2% performers for each design objective are of different configurations. Design solutions that work best in one design aspect may not work well for another design aspect.

6.4 Multi-objective design solutions

Figure 6.9 presents single objective design solutions that perform well in one design aspect only. As demonstrated, these solutions do not perform well in other design aspects since they are selected based on one design objective only.

Energy saving or carbon reduction can always be improved if cost is not an issue. In practice, cost is always an important consideration.

The cost effectiveness of any proposed measure signifies if such a measure is worth adopting or not. The concept of Pareto design solutions is introduced in Section 5.1.1. Pareto solutions are design solutions that cannot be improved in one design objective without worsening another. Since cost effectiveness (in terms of annualized relative cash flow defined in Section 4.2) is also one of the studied performance indicators, Pareto solutions that consider both energy performance and cost effectiveness allow the designers to select one solution over another by making trade-off decisions based on an objective performance comparison. **FIGURE 6.10** presents the parallel plots of Pareto solutions that are based on the four design objectives, namely:

- Minimizing the annual energy consumption
- Minimizing the net carbon emissions
- Maximizing the annualized relative cash flow
- Minimizing the risk (less negative and closer to zero)

There are altogether 425 design solutions (out of a total of 4,704 possible configurations) that are considered as Pareto solutions for the above four design objectives. Since these Pareto solutions are based on all design objectives, the set of 425 configurations is the same across the four design objectives as demonstrated in Figure 6.10 (contrasted with Figure 6.9, where there are different sets of configurations for each design objective). Among the Pareto solutions, some are better performing in certain aspects than in others and wide ranges of performance are possible. The “best solutions” of the single objective design solutions are by definition always included in the set of Pareto solutions, since the single objective “best solution” simply represents one extreme case of the Pareto solutions in which the performance is the best in that single performance aspect and cannot be the best in any other performance aspect. These single objective design solutions are highlighted by black lines.

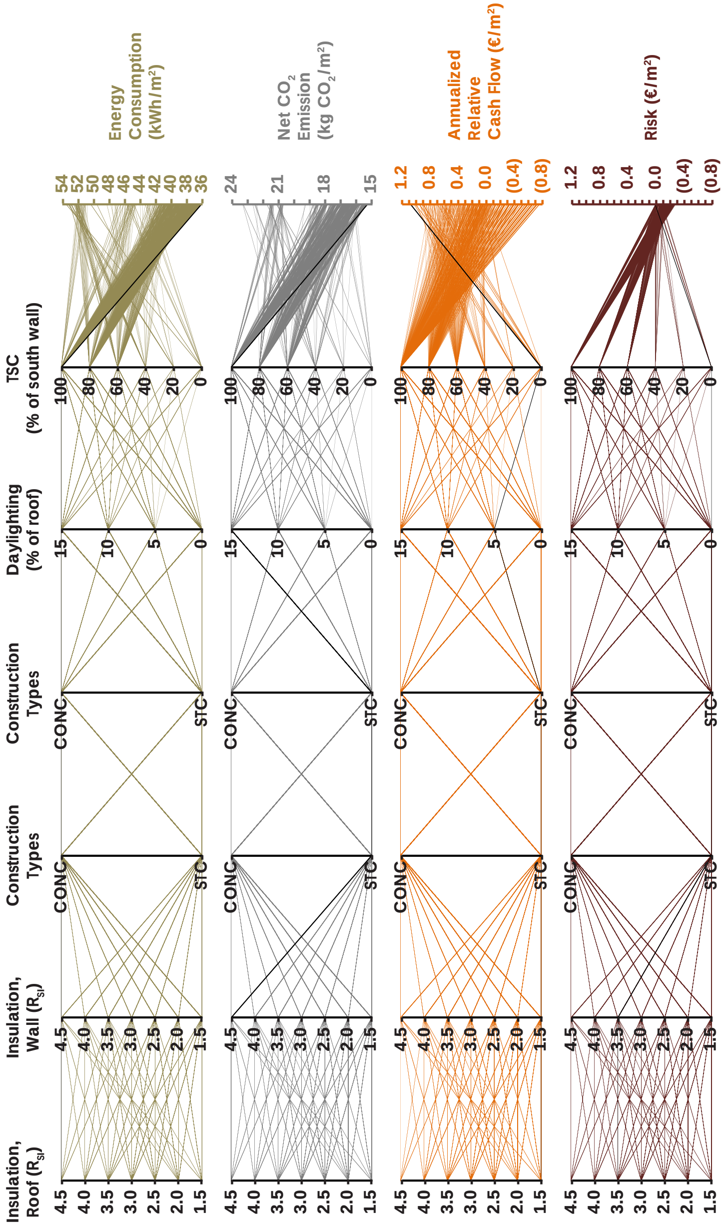


FIGURE 6.10 *Parallel plots that present the configurations and the resulting performance (with respect to each design objective) for the Pareto design solutions (total 425 Pareto solutions in this case study) that fulfill all studied design objectives*

6.4.1 Characteristics of multi-objective design solutions

Ninety-four is 2% of 4,704; however, 425 (number of Pareto solutions) is just an arbitrary number that represents the number of configurations of this particular Pareto solution set. Due to the characteristics of the data, there could be many more or far fewer Pareto solutions for another scenario (e.g. full-time operation, instead of the studied 2-shift operation). Since all four design objectives are considered together, the Pareto solutions need not be among the best performers in any single design objective, but rather are the “best alternatives” when trade-offs with other design objectives are considered.

As indicated in Figure 6.10, the range of performance of the Pareto solutions for each design objective can be wide (e.g. energy consumption from the best performance of 36.1 kWh/m^2 to the worst performance of 53.4 kWh/m^2). Among those Pareto solutions, some solutions are better performing in certain design aspects than in others. **TABLE 6.3** presents the design summary of the best 94 Pareto solutions for each design objective (the best 94 solutions of the 425 Pareto solutions sorted for each design objective). Ninety-four is just an arbitrary number in this example to facilitate comparison with the top 2% single objective design solutions of the same number.

The range of performance of the Pareto solutions for each design objective is much reduced (e.g. energy consumption from the best performance of 36.1 kWh/m^2 to the worst performance of 38.0 kWh/m^2 among these 94 best performing Pareto solutions in terms of energy consumption). This much-reduced performance range is still a bit wider than the performance range of the single objective design solutions (Table 6.2).

The configurations of these solutions follow similar patterns to those of the single objective design solutions. In Table 6.3, design parameters that exhibit tighter ranges (than those of the same design parameters as the single objective solutions) are highlighted in orange. Those showing wider ranges are indicated in green.

TABLE 6.3 Summary of 94 best performing Pareto solutions for each design objective with design ranges for each for the design parameters

Parameters	Energy Consumption (kWh/m^2)	Net Carbon Emissions (kg CO$_2$/m^2)	Annualized Relative Cash Flow (€/m^2)	Risk (€/m^2)
	36.1 – 38.0	15.3 – 16.0	0.49 – 1.05	(0) – (0.04)
Insulation (Thermal resistance, Roof, m^{2}K/W)	**2.0 – 4.5**	**1.5 – 4.5**	1.5 – 2.5	**1.5 – 3.5**
Insulation (Thermal resistance, Wall, m^{2}K/W)	1.5 – 4.5	1.5 – 4.5	**1.5 – 3.0**	1.5 – 4.5
Construction Types (Roof)	STL or CONC	STL	STL or CONC	STL or CONC
Construction Types (Wall)	STL or CONC	**STL or CONC**	STL or CONC	STL or CONC
Daylighting (as % of roof area)	15	15	**5 – 15**	**0 – 5**
TSC (as % of south wall)	**80 – 100**	**0 – 100**	0 – 100	0 – 100

Since Pareto solutions consider all design objectives at the same time, a tighter range indicates the respective design parameter is a major contributor to the corresponding design objective, and a wider range indicates the respective design parameter is essential to provide trade-off alternatives.

Since the selection of a particular Pareto solution involves the consideration of trade-offs among design objectives, which is highly dependent on the designer's preference, the selection process should be case dependent and should not be generalized. On the other hand, the design summary as presented in Table 6.3 can be transformed into a descriptive summary (TABLE 6.4) that indicates the recommended levels for certain design parameters. Design parameters with no recommended level simply imply these parameters can be assigned any value within their design ranges, which only affects the trade-off, but not the corresponding design objective. By contrast, the recommended level (if indicated, for certain design parameters) should be followed to achieve the best performance for the corresponding design objective.

TABLE 6.4 **Descriptive summary of the best performing Pareto solutions for each design objective indicating the recommended level (or the lack of) for each design parameter**

Parameters	Energy Consumption (kWh/m^2)	Net Carbon Emissions (kg CO$_2$/m^2)	Annualized Relative Cash Flow (€/m^2)	Risk (€/m^2)
Insulation (Thermal resistance, Roof, m^{2}K/W)	–	–	low	–
Insulation (Thermal resistance, Wall, m^{2}K/W)	–	–	–	–
Construction Types (Roof)	–	STL	–	–
Construction Types (Wall)	–	–	–	–
Daylighting (as % of roof area)	high	high	–	low
TSC (as % of south wall)	high	–	–	–

6.5 From design solutions to building configurations

When multiple design objectives are considered at the same time, the Pareto solutions are in fact trade-off solutions, where the selection among these solutions is a matter of a trade-off decision made between each of the design objectives according to designer's preference.

From the design decision process point of view, the difficulty lies with the fact that there are far too many possible design solutions (even just the Pareto solutions number 425) for the designers to select from. Figure 6.10 provides a good overview which relates building configurations to the corresponding performance for each design objective. However, it only presents a one-direction data flow from the building configuration to the corresponding performance, but not the other way around.

In fact, the designers care less about the exact configuration, but are more concerned with the performance and the benefits brought forth by the performance. Depending on their preference, designers will have their own desired set of performance combinations (e.g. a very high cash flow solution with low risk and not too much energy consumption and carbon emissions). Figure 6.10 only indicates the range of performance with respect to each design objective, but not the trade-off among design solutions. Designers need to know the exact trade-off at their desired level of performance for their prioritized design objective (e.g. how poor is the energy performance for the highest cash flow solution). One possible method is to create a graphical representation that displays all Pareto solutions with respect to all four design objectives.

FIGURE 6.11 presents the Pareto solutions for all four of the design objectives that have been discussed thus far. Each of the color filled triangles represents one configuration. All 4,704 configurations are displayed in the figure, in which most of the configurations are too high in terms of energy consumption or net carbon emissions, or too low in terms of annualized relative cash flow. The triangles that are outlined in black are the Pareto solutions. These are Pareto solutions for the 2-shift operation only, but some configurations are Pareto solutions under all three occupancy schedules and are displayed in solid black. These Pareto solutions satisfy all four design objectives at once in the sense that each solution will yield better performance in one design objective than any other (non-Pareto solution) configurations if the other three design objectives are fixed at certain values (i.e. one objective versus the other three, or two objectives versus the other two). For example, if an annual energy consumption of 44 kWh/m^2·yr (or below) and a net carbon emissions of 17 kg CO$_2$/m^2·yr (or below) are deemed satisfactory for the designers, then there will be no solution having an annualized

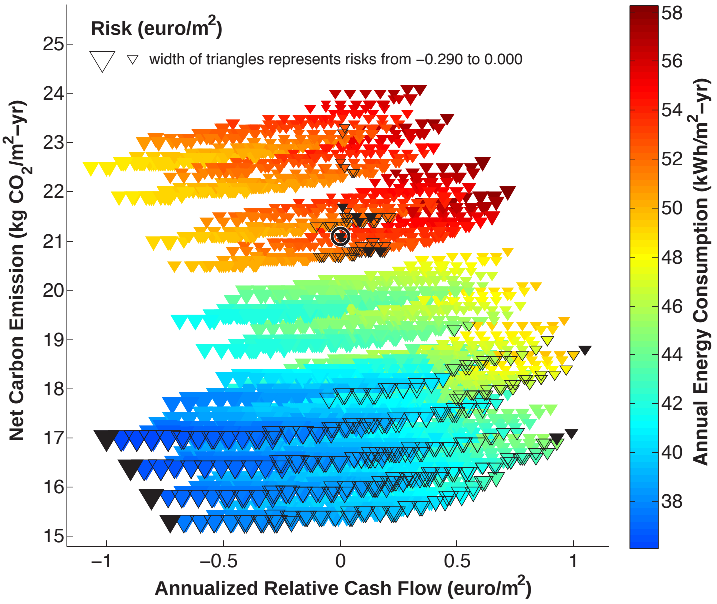


FIGURE 6.11 *Pareto solutions (shown as solid black or with a black outline) with respect to four design objectives among all the studied configurations (color filled triangles)*

relative cash flow of more than 0.89 €/m²-yr and risk less than (0.05) €/m²-yr.

Designers can also opt to pick the solution that offers the best (or close to the best) performance for the prioritized design objective and select from a variety of trade-off performance values for the other three design objectives. With Figure 6.11, the choice rests with the designers to select the solutions that offer the desired combination of performance among design objectives.

This graphical representation demonstrates that the flow of data can begin with the performance data (users can select the triangle with their desired performance levels in all four design objectives) and lead to the exact building configuration (easily identified with sorted performance data). This direction of data flow matches the natural path of the design decision process. After all, the ultimate goal of the assessment methodology is to facilitate informed design decisions.

NZEB design solution

The design solutions based on demand side or distribution side energy saving measures still consume a certain amount of energy (e.g. the lowest is 36.1 kWh/m^2 in this case study). This energy deficit must be matched by energy generation to make the industrial hall achieve the status of NZEB. Pareto solutions for rooftop PV energy generation that maximize both energy yield and energy generation density may be able to match this energy deficit. Section 4.1.3 provides a detailed explanation regarding matching the energy consumption with the energy generation density (both in terms of kWh/m^2). In short, the trade-off is a lower energy yield if higher generation density is needed.

6.6 Simulation based assessment in practice

Pre-calculated results from the full factorial design can be made available in the form of databases. Design trends can be observed with data analysis. Design solutions can also be presented in an easily recognizable way that facilitates objective energy design and assessment of industrial halls in everyday practice.

6.6.1 Relevance and applicability of the assessment methodology in practice

The industrial partner for this research project, Bouwen met Staal, has launched a beta version of the database online as a webtool, which practitioners can access and utilize for design solutions. Such a webtool fulfills the principles of support for objective design and assessment in terms of direct and universal applicability, scalability, practicality, novelty, and design decision facilitation.

The comprehensiveness and the objective nature of the databases, and the flexibility in input assumptions allow unmatched versatility in the assessment. However, this added flexibility also comes as a burden to the users as they might not have full knowledge of the input assumptions. For example, it is almost impossible for the building designers or industrial hall owners to predict the future interest or utility rates. Random assignment of input assumptions does not help identify direction of impact on derived performance due to input assumptions. The risk indicator helps reveal the impact of the assumptions without relying on the user's input. Initial feedback on the webtool has been positive, even though the development of the webtool itself is still at the beta stage and is outside the scope of this research.

6.6.2 Performance advantages of design solutions offered by the assessment methodology

An assessment methodology can only be useful if it leads to design solutions that offer significant performance advantages over existing solutions proposed by current practices. The single objective design solutions (presented in Table 6.1), which are also included in the Pareto solutions set, offer quite significant performance advantages over the baseline building for the respective objective while including trade-offs for other objectives. For example, the lowest energy consuming solution offers an energy savings of 32% over the baseline building, while the lowest carbon emissions solution reduces carbon emissions by 19%; however, both solutions have a negative cash flow with high risk.

TABLE 6.5 presents the performance of the baseline building and two other solutions that offer advantages in most design aspects (the performance improvement over baseline building is highlighted in bold). The "simply better" solution, in fact, offers improvements in all design aspects. Though the improvements are not significant, they come with a tiny financial return with the same zero economic risk as the baseline building.

The performance of the greatest annualized cash flow solution (also one of the single objective design solutions) is presented again in Table 6.5. This solution offers 6% energy savings and 11% carbon emission reductions over the baseline building at a high annualized return of 1.05 €/m^2·yr with a minimal risk of 0.04 €/m^2·yr.

TABLE 6.5 Pareto solutions that excel in most design objectives offer advantages over baseline building

Parameters	Baseline Building Solution	Simply Better Solution	Highest Annualized Relative Cash Flow
Energy Consumption (kWh/m^2)	53.4	53.0	50.2
Net Carbon Emissions (kg CO_2/m^2)	21.1	21.0	18.8
Annualized Relative Cash Flow (€/m^2)	0.00	0.02	1.05
Risk (€/m^2)	0.00	0.00	(0.04)
Insulation (Thermal resistance, Roof, m^{2}K/W)	3.5	4.5	1.5
Insulation (Thermal resistance, Wall, m^{2}K/W)	3.5	4.5	1.5
Construction Types (Roof)	STL	CONC	STL
Construction Types (Wall)	STL	CONC	STL
Daylighting (as % of roof area)	0	15	5
TSC (as % of south wall)	0	100	0

The designers should select solutions according to their own needs. The above examples demonstrate the possible advantages offered by the design solutions proposed by the simulation based assessment methodology.

6.6.3 A comparison between predicted performance and the corresponding green building rating

Though operational energy performance is the main focus of this research, it is considered within the larger context of sustainability. Therefore, the investigation also considers the environmental impact of the design solutions in terms of carbon emissions. On the other hand, green building rating systems mainly consider prescriptive based factors instead of performance based factors. Even though the preliminary evaluation is based on objective performance evaluation, it will be translated into rating points by a conversion using prescriptive based factors. The LEED (USGBC, 2009) green building rating system is taken as an example (LEED is generally applied to non-residential new construction with no specific rating system for industrial halls). The energy performance of buildings is considered under the Energy and Atmosphere (EA) category, while the environmental impact of construction material choice is considered under the Materials and Resources (MR) category. **TABLE 6.6** presents again some of the previously discussed design solutions and compares the predicted performance with the corresponding points obtained under LEED for the aforementioned two categories.

The EA points for energy performance improvement are awarded according to a scale based on the percentage improvement over the baseline building. The scale has a cap at 48%. Improvement over the baseline building beyond 48% will not bring forth any extra LEED points. Artificial caps are applied to almost all LEED sub-categories. For example, 2 points are awarded for recycled content up to 20% under the MR category. The 20% recycled content mark is readily achievable for industrial halls which are constructed with simple steel or concrete assemblies that are typically high in recycled content. The recycled content ranges of the building materials common for industrial halls simply far exceed the prescribed percentage. In other words, improvement in material choice for industrial halls simply cannot be reflected under the LEED system. For example, a very high recycled content of more than 90% is

TABLE 6.6 **A comparison of predicted performance of design solutions with obtained LEED points under the EA and MR categories**

Parameters	Baseline Building Solution	Lowest Energy Consumption	Lowest Net Carbon Emissions	Highest Annualized Relative Cash Flow
Energy Consumption (kWh/m^2)	53.4	36.1	37.5	50.2
Net Carbon Emissions (kg CO$_2$/m^2)	21.1	17.0	15.3	18.8
Annualized Relative Cash Flow (€/m^2)	0.00	(1.00)	(0.73)	1.05
Risk (€/m^2)	0.00	(0.29)	(0.25)	(0.04)
% Improvement over Baseline (Energy)	–	32%	30%	6%
% Improvement over Baseline (Carbon Emissions)	–	19%	27%	11%
LEED – EA (as points)	0	11	10	0
LEED – MR (as points)	2	2	2	2
LEED – EA (as % of total)	0	10%	9%	0
LEED – MR (as % of total)	2%	2%	2%	2%
Insulation (Thermal resistance, Roof, m^{2}K/W)	3.5	4.5	4.5	1.5
Insulation (Thermal resistance, Wall, m^{2}K/W)	3.5	4.5	4.5	1.5
Construction Types (Roof)	STL	CONC	STL	STL
Construction Types (Wall)	STL	CONC	STL	STL
Daylighting (as % of roof area)	0	15	15	5
TSC (as % of south wall)	0	100	100	0

possible for steel. The same is not true for office buildings with complex constructions, where steel, concrete, aluminum, plastic, wood, glass, gypsum and other building materials share similar and much smaller proportions in the structure.

Another issue is that points under the LEED system are awarded in a limited number of levels (e.g. two levels with 10% or 20% of recycled content). The limited number of levels does not reflect the possible range of performance. The net carbon emissions performance improvement over the baseline building for the three design solutions presented in Table 6.6 ranges from 11% to 27%. Performance improvement in terms of percentage captures the incremental difference from one solution to another. LEED points awarded in limited number of levels with an artificial cap simply cannot capture the incremental difference.

The above illustration only intends to demonstrate the arguments. Actual LEED assessment covers a much wider scope and makes different assumptions and definitions. For example, LEED defines the baseline building according to ASHRAE Standard 90.1 (ASHRAE, 2007b), which stipulates thermal resistance values of 3.3 and 2.3 m^2K/W for the roof and wall, respectively. Whereas a value of 3.5 m^2K/W is assumed for both the roof and wall for the baseline building in this research. Net carbon emissions defined in this research also cover more aspects than just the recycled content demonstrated under the MR sub-category. However, regardless of the exact configurations of the baseline building or the exact definitions of performance indicators, arguments presented in the above illustration still hold true. For example, structural steel can have a recycled content as high as 90% (SRI, 2008). Whether the performance indicator for the environmental impact is the net carbon emissions with broader coverage or the recycled content of limited scope, LEED points simply do not cover the range and resolution of the performance of industrial halls. To apply LEED effectively to industrial halls, a new rating system specific for this type of building would be beneficial.

6.7 Concluding remarks

The simulation based assessment methodology depicted in Figure 6.1 can offer design solutions that are otherwise not adopted by current practice and not possibly made available through the heuristic and deterministic approach. The full factorial design approach ensures full coverage of the design space and thus promotes flexibility in making input assumptions for many of the derived performance indicators. Such flexibility is crucial to fulfill the assessment principle of direct and universal applicability. Though presenting and delivering the results of the assessment methodology are not part of this research, it has been demonstrated that the results can be graphically summarized in a useful way to facilitate informed design decisions. The designers are empowered to do what they perform best — creating designs, rather than gathering data or processing information.

With a few design solution examples, it is demonstrated that the design solutions proposed by the assessment methodology offer many performance advantages over designs based on current practice. Moreover, it has been shown that assessments based on LEED (a representative green building rating system) do not represent the actual performance of industrial halls.

7

Closure

The main objective of this research is to develop a building energy simulation based assessment methodology for design support of industrial halls. The focus of the thesis is the development process itself, and the outcome is the resulting simulation based assessment methodology. This closure completes the investigation of the research by contrasting the initial expectation of the research with the actual outcomes and findings, and provides directions for future work.

7.1 Conclusions

To achieve the main objective, Chapter 1 suggests identifying issues in terms of energy in the energy design and assessment of industrial halls, formulating the computational simulation based assessment methodology that could work towards energy optimized industrial halls, and demonstrating the applicability and the usefulness of the assessment methodology.

The initial expectation can be grouped into three categories:

- Fulfillment of the principles of assessment
- Applicability of the assessment methodology for industrial halls
- Usefulness of the assessment methodology to the users (different groups of personnel involved in the design decision process of industrial halls)

Fulfillment of the principles of assessment

Based on the unique characteristic of industrial halls and the issues facing the energy design of industrial halls, Chapter 2 suggests five principles of assessment that must be fulfilled:

- Direct and Universal Applicability
- Scalability
- Practicality
- Novelty
- Design Decision Facilitation

Since the methodology emphasizes the use of readily available building materials and common construction methods (Chapter 3 gives a full account in the selection of design parameters), the offered design solutions shall also be readily buildable — **practicality** is in fact an integral part of the methodology. Chapter 5 explains the reasons to adopt the comprehensive design space exploration approach. With such an approach, raw data for all configurations are available to the users and are not critically constrained by assumptions made by the building designers. With the availability of raw data and comprehensive coverage of the design space, the assessment is **directly and universally applicable**. Appendix A.3 suggests that once an industrial hall attains a certain size, the per unit area performance does not change drastically with an increase in the size of the hall. With known limitations, the proposed assessment methodology offers a certain degree of **scalability**. The proposed assessment methodology is indeed **novel**, since current practice provides nothing comparable in terms of both sophistication and comprehensiveness. In fact, current practice does not offer much guidance in encouraging energy saving, not to mention, achieving carbon reduction, or promoting cost effectiveness. All of these design objectives are investigated in Chapter 4 and demonstrated with a case study in Chapter 6. The following presents how this novel assessment methodology **facilitates informed design decisions.**

Applicability of the assessment methodology for industrial halls

The applicability of the assessment methodology for industrial halls can only be judged by the quality of the design solutions offered by the assessment. The advantages in deploying this simulation based assessment methodology are shown via the demonstration in Chapter 6, in which the resulting design solutions display better performance than the designs based on current practice in terms of any of the design objectives.

In Chapter 1, it is mentioned that current green building rating systems might not be applicable to industrial halls. It is also suggested that assessment must not be biased towards any design options. Since the assessment methodology adopts the comprehensive design space exploration approach, all configurations are evaluated to study the performance in terms of all of the design objectives and there is no “missed” configuration that has not been considered by the assessment. With the comprehensive set of available data, bias in the designs can be mitigated. A comparison between performance data of design solutions offered by the assessment methodology and the corresponding points obtained through LEED green building rating systems also confirms the initial doubt concerning whether green building rating systems can be applied directly to industrial halls.

Usefulness of the assessment methodology to the users

The users of the methodology are the only ones who can appraise the usefulness of the assessment. The assessment methodology has considered multiple operational scenarios (e.g. occupancy patterns and process loads), multiple design options (e.g. skylights and TSC), and multiple design objectives (e.g. maximizing cost effectiveness and minimizing environmental impact). Since these multi-dimensional considerations are made together with the practitioners who have experience with the design of industrial halls according to local situations (discussion in Section 2.2), the developed assessment methodology serves those practitioners' needs. In fact, the success of the assessment methodology rests largely on the involvement of local practitioners.

Chapter 6 also demonstrates the importance of the presentation of data. Although, the presentation of data is not part of the scope of this research, it affects the effectiveness of the delivery of ideas and thus the usefulness of the assessment methodology.

In summary, the approach of the simulation based assessment methodology can be characterized as a systematic exhaustive search for design solutions with stochastic risk analysis (Section 6.1 gives a full account of the assessment methodology). This approach offers much more valuable and unbiased information for the designers as compared to a heuristic and deterministic approach, and provides much improved design solutions over the rule of thumb based current practice.

7.2 Future work

Energy design and assessment of industrial halls have long been neglected by the current building construction practice. This research approaches the topic in a way that is interesting to the users by offering a ready to deploy simulation based assessment methodology. Current energy policy promotes investigations that study the performance of various combinations of energy related measures and methods to account for varying occupancy patterns and operating conditions. Even though the systematic exhaustive search for design solutions and stochastic risk analysis approach in this research is in line with the direction of current energy policy, there are still areas that need further investigation and work that requires further refinement.

7.2.1 Research related to current energy policy

The current research only covers essential approaches and concepts that are necessary to develop the assessment methodology. The following items are some of the research topics that are not essential but are worth investigating to enhance the proposed assessment methodology by exploring different means to facilitate informed design decisions.

Extended application of stochastic risk analysis

In this research, stochastic risk analysis has been applied to study the impact of uncertainties in economic parameters. However, stochastic risk analysis can also be applied to any input parameter with known uncertainty. Embodied carbon in building materials is one such parameter. Due to the use of multiple suppliers, a buildings material always contains varying levels of embodied carbon depending on sources and manufacturing processes for that material. A probability distribution of embodied carbon can be obtained for the local situation (from a list of known suppliers based on existing contracts). With a stochastic risk analysis approach for embodied carbon, the database can be further enhanced to include a risk indicator for net carbon emissions. By contrast, a deterministic approach based on Building Information Modeling (BIM) is a viable means for evaluating the environmental impact for a particular construction job (versus a generalized regional database for a local situation).

Occupancy pattern variation is in fact a big issue. As suggested in Section 2.3.6, the occupancy pattern of industrial halls falls into discrete schedules in terms of number of shifts. Performance of a hall with a 1-shift operation is quite different from a hall with a full-time operation. In this research, performance is evaluated using a single occupancy pattern for the whole year. In reality, there will be variation in occupancy patterns. Such variation happens monthly or at most weekly, but seldom daily. The same assessment methodology can be applied; however, the energy performance data shall be stored with a finer time step, such as monthly, rather than annually. A historical probability distribution of occupancy patterns (e.g. monthly) can be used as a stochastic input to post-process the monthly energy performance data.

Integrated design by post-processing performance data

In Chapter 5, the advantages of performing a full factorial design have been explained. However, due to computational resource limitations, a full factorial design necessitates the separation of the generation side investigation from the demand and distribution side investigation. It is possible to achieve an energy performance goal such as NZEB by matching the energy generation density of the generation side design solution to the energy consumption of the demand and distribution side design solution. Both design solutions are in fact Pareto solutions (of the generation side investigation and the demand / distribution side investigation).

However, the separate investigation implies that the combination of the two design solutions might not be a Pareto solution for the combined performance. Conversely, a combined investigation might suggest reducing energy consumption with a higher level of daylighting rather than increasing energy generation with PV modules, but the configuration with a higher level of daylighting might not be itself a Pareto solution under a separate demand / distribution side investigation.

In the case study, there are 4,704 different configurations for the demand and distribution side investigation and 4,640 different configurations for the generation side investigation. In total, there would be 21 million different combinations to be simulated for a combined analysis. Section 5.1 already states that a full factorial investigation is practically impossible. However, through post-processing of energy performance data from the separate investigations, combined derived performance indicators (combined net energy consumption / generation, combined carbon emissions, and combined annualized relative cash flow) can be evaluated within the available computational resources. Such an investigation may or may not offer NZEB design solutions, but will generate Pareto solutions for the integrated design (from demand to generation side) that fulfill all four design objectives.

Double loop optimization to ensure reliability of design

Reliability based design optimization (RBDO) deploys a double loop optimization with the outer loop for the design optimization (such as those conducted in Section 5.1) and the inner loop for studying the reliability of the design. As suggested in Section 4.4 with respect to risk analysis, it is impossible for the designers to know which scenario (high rates or low rates) is the worst-case scenario. With double loop optimization, the inner loop evaluates the worst case for the subject of interest. That is, if economic risk is indeed a concern, the double loop optimization will return the predicted performance of all design objectives in the outer loop (the varying design parameters are evaluated on a deterministic set of economic parameters, e.g. 10-year average rates). The double loop optimization will return the worst annualized relative cash flow in the inner loop based on the design solution configuration defined in the outer loop and the stochastic inputs on historical values of economic parameters.

Double loop optimization is not only used to investigate economic risk. It can be any performance indicator where reliability is a concern. With such an approach, designers can select the design solution with the best performance (e.g. highest annualized relative cash flow) even for the worst-case scenario as long as it is within the designer's risk tolerance level.

Quantifying benefits of waste heat recovery

A few research and innovation targeted areas are identified under the Horizon 2020 roadmap (EU, 2013) to achieve various long term energy goals. Waste heat recovery from industrial facilities is specifically identified as a potential resource to be exploited. The exact implementation is very case specific and requires in-depth investigation of the manufacturing process of interest. Such investigation goes against the assessment principle of direct and universal applicability identified in this work and does not match the theme of this research.

However, the potential benefits of waste heat recovery are hard to ignore and likely affect the design decisions. A black-box modelling approach to quantify the benefits of waste heat recovery might be appropriate. Waste heat can be expressed in terms of generic qualities such as the amount and temperature of the discharge fluid. The focus is not on how to recoup the heat (which requires case specific investigations) but on the benefits such waste heat can bring and the corresponding implication for the design of industrial halls. For example, an industrial hall with a large amount of available waste heat should favor designs with a higher heating demand than those with a lower heating demand. With the inclusion of waste heat recovery, a more realistic and fairer comparison (among design solutions) in terms of energy, environmental, and cost performance can be achieved.

7.2.2 Research related to industrial applications

The current research demonstrates how to implement the assessment methodology in the form of databases or present complex results in diagrams. Below is a description of potential application areas that requires further research.

User interface for design solution exploration

Section 6.5 presents Figure 6.11 as a static diagram where the designers can use it to identify design solutions that satisfy their performance requirements. However, the building configurations corresponding to those design solutions still have to be manually selected from the database. In practice, the selection process is not straightforward and prone to error.

A better solution is to implement the database and the diagram as an app for a tablet computer. Designers can select any design solution, and the computer will return the building configuration. The returned building configuration can be presented in the form of sliders (one slider for each design parameter). Designers can slide away from the solution and see in real time the impact on the performance by varying the configuration (e.g. increasing or decreasing the amount of roof insulation). This interactive app explores the full potential of what can be offered by the comprehensive database of performance information.

Building Information Modeling (BIM) integration

BIM has been used for construction project management to facilitate the tracking of building materials. Organizations, such as Athena Sustainable Materials Institute (Athena, 2010), which develop databases for embodied energy of building materials, propose a future generation of databases that should be integrated with BIM to allow designers to immediately assess the embodied energy of the project when the design is conceptualized and when the design is modified.

The spreadsheet style energy consumption database illustrated in Section 5.2 allows the users to input their own assumptions for economic and environmental parameters. If the job specific values for some of these parameters, such as the cost and embodied energy of building materials, were available with future BIM tools, then there would be no more guess work for the designers regarding input assumptions. A full integration of the energy consumption database into such a future BIM tool would provide timely and precise information to the designers. The designers could assess the total life-cycle energy consumption or net carbon emission of a building with such an enhanced BIM tool. In practice, local green building councils or construction industry associations could compile the list of building materials from local suppliers with local cost and environmental information. Together with the energy consumption database, such information would facilitate the selection of the best locally available building materials.

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Appendix A

Concerns regarding Simulation Approaches

CHAPTER 2 INTRODUCES THE MULTIDISCIPLINARY computational simulation approach as a basis to develop an assessment methodology for design support of industrial halls. Building energy simulation, though widely deployed to study office buildings, is not commonly used to investigate the performance of industrial halls. Section 2.3 presents the characteristics of industrial halls and raises a few concerns regarding how simulation can be applied to industrial halls. Section 4.4 proposes risk analysis as a tool to study uncertainties in input parameters; there are also concerns in how to conduct the analysis. This appendix addresses those concerns with fit-for-purpose validations to support the choice of approaches made during the development of the assessment methodology.

A side note on computational simulation tools applied in this research

The developed simulation based assessment methodology is independent of any simulation tools. The same assessment methodology can be applied using many different simulation tools. Nevertheless, since the examples and design solutions presented in this research are generated with specific simulation tools, the tools used in this research are presented here for convenient reference.

Based on the simulation model framework defined in Table 2.2, the investigation involves a building energy simulation model, a lighting simulation model, and a PV energy generation simulation model. In the investigation of the demand side parameters, the domains of heating, cooling, and lighting are covered. The building energy simulation program TRNSYS is used to perform the energy analysis for heating and cooling demand. Hourly energy consumption is evaluated and aggregated for the year.

The introduction of daylight will have an impact on the heating and cooling energy demand in addition to the lighting demand. The effect of daylighting introduced through skylights can be independently evaluated through two separate simulation models. A model in TRNSYS considers the effect of daylighting on heating and cooling by taking into account the amount of solar heat gain being introduced through the glazing and the reflectivity of the surfaces.

A DAYSIM lighting simulation model evaluates the illuminance level on the work surface for each hour due to daylighting at different locations inside the building and for different amounts of skylight coverage. Based on the illuminance level, lighting energy is then calculated by a proprietary program written in MATLAB.

Chapter 5 introduces the ideas of optimization and comprehensive design space exploration, which are

> conducted using an automation platform. MODEFRONTIER is selected as the platform of choice for its vast selection of optimization algorithms, and its flexible connectivity to building energy simulations and post-processing tools, namely, TRNSYS, DAYSIM and MATLAB, which are used in this research. For each simulation, MODEFRONTIER will, based on the configuration, prepare simulation files for each tool.

The following sections address previously raised concerns regarding the simulation approaches.

A.1 Division of zones for industrial halls with single non-partitioned space

Section 2.3 portrays the studied industrial halls as large single-storey structures with non-partitioned space and uniformly distributed process loads. Since the process load and lighting load (and the negligible occupant load) are the only internal factors that affect heating and cooling demand, uniformly distributed loads imply the geometry of halls only affects the response to external environmental factors.

The external surfaces are the roof and walls. Section 2.3.4 suggests that the impact of external factors through the roof becomes dominant for larger single-storey halls, since the roof surface increases at the same rate as the floor area, while wall surfaces increase at a disproportionate rate. By contrast, office buildings are subject to greater external factors through the disproportionally larger wall surfaces. In energy performance investigations for office buildings, the concepts of multiple zones (perimeter and core zones) are meant to separate areas that are under greater influence from external factors from areas that are under greater influence from internal factors. On the other hand, spaces for industrial halls are naturally single non-partitioned zones to accommodate the layout of manufacturing equipment and to facilitate logistics. The question is raised as to whether such a large non-partitioned space can be simulated with a single-zone or a multi-zone model.

A.1.1 Comparison of a single-zone and a multi-zone model

The investigation is based on the typical building as defined in Section 2.3.8, which is 100 m (L) by 40 m (W) by 6 m (H). The large space can be modelled as a single zone or multiple zones, in which qualities such as temperature are treated as bulk properties having the same value throughout each of the investigated zones. In reality, there could be temperature variation at different locations within a zone. From thermal comfort point of view, dissatisfaction caused by vertical temperature gradient between head and feet of the occupants presented in ASHRAE Standard 55 (ASHRAE, 2004) is not an issue for industrial halls since there is no requirement to curb the percentage of dissatisfied occupants. Moreover, case studies of a few large spaces (IEA, 1998) indicate that such temperature gradient is just a mere few degree Celsius difference, which is insignificant as compared to the wide allowable temperature range and temperature fluctuation rate for industrial halls. From energy performance point of view, amidst likely variations in temperature across the space, it is believed that such variations do not greatly impact the energy consumption. This proposition is to be tested by contrasting the energy performance results of a single-zone model with that of a multi-zone model.

For a multi-zone model, each of the zones is subject to different external or internal factors. For this fit-for-purpose validation, the single non-partitioned space is divided into 18 virtual simulation zones as depicted in **FIGURE A.1**. In the vertical dimension, with a height of 6 m, the space is equally divided in 2 levels of 3 m each. The lower level represents the activity area of the workers. Temperature fluctuation in the lower zones is more of a concern than fluctuation in the upper zones. Process loads are applied to the lower zones, while lighting loads are applied to the upper zones. External factors affect the exterior surfaces. As discussed in Section 2.3.3, windows are not commonly installed as the benefit

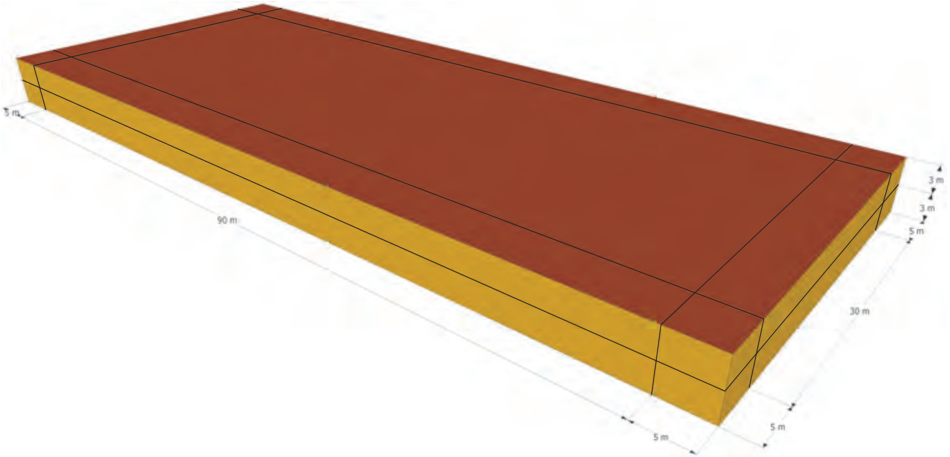


FIGURE A.1 *Multi-zone simulation model divides the space into 18 zones (perimeter and core zones in 2 levels)*

provided by daylighting through vertically placed windows is limited. With no windows, modeling of perimeter zones is supposedly redundant (argument to support modeling as a single zone). For the multi-zone model, perimeter zones are defined as spaces located within 5 m from the exterior walls based on ASHRAE's definition (2007b).

The energy performance of a space is subject to greater external factors if the space has a lower process load. As process load increases, external factors assert much less impact. Under a 1-shift operation, the space is cycled between sessions with a mix of internal / external factors and sessions with no internal factors at all. On the other hand, the space is subject to internal factors all the time under full-time operation. The most extreme operational scenarios are the four combinations of extreme occupancy patterns (1-shift and full-time) and process loads (5 W/m^2 and 300 W/m^2) based on the defined values.

The objective of the fit-for-purpose validation is to evaluate if the difference in energy performance (heating and cooling demand) predicted by the two models falls within a reasonable range and thus allows the deployment of either one of the models. Simulations have been carried out for the four extreme operational scenarios, and the corresponding energy performance (heating and cooling demand under ideal control without consideration of distribution systems) is presented in TABLE A.1.

TABLE A.1 Energy performance under four different operational scenarios. Percentage differences of the predictions of the single-zone from those of the multi-zone models are presented in brackets

Single-zone model:

Energy performance (MJ/m^2-yr)	$5W/m^2$ / 1-shift	$5W/m^2$ / full-time	$300W/m^2$ / 1-shift	$300W/m^2$ / full-time
Heating	67	9	0	0
Cooling	0	40	2,280	8,949
Lighting	85	284	85	284
Total	152 (-3%)	333 (-3%)	2,365 (-7%)	9,233 (-3%)
Heating and Cooling	67 (-6%)	49 (-22%)	2,280 (-7%)	8,949 (-3%)

Multi-zone model:

Energy performance (MJ/m^2-yr)	$5W/m^2$ / 1-shift	$5W/m^2$ / full-time	$300W/m^2$ / 1-shift	$300W/m^2$ / full-time
Heating	55	13	0	0
Cooling	16	47	2,446	9,187
Lighting	85	284	85	284
Total	156	344	2,531	9,471
Heating and Cooling	71	60	2,446	9,187

The objective of this fit-for-purpose validation is not to differentiate if one model is better than the other, but to confirm that the difference between the two models is not large enough as to require further investigation. In fact, the more complicated multi-zone model should not be perceived as providing more accurate results than the single-zone model. The two models simply treat surfaces and spaces in different manners. Since process and lighting loads are applied to some of the zones but not the others in the multi-zone model, the different behaviors of the two models in heating and cooling are reasonable and are more apparent for lower process load cases as observed in Table A.1. Even if heating and cooling energy demand are presented as separate entries, the worst percentage difference between the two models (22% at most) is considered acceptable for the following reasons.

> *Efficiency of distribution side equipment*
>
> The heating and cooling energy performance is presented as energy demand rather than the energy consumption of electricity and gas. The predictions are based on the evaluation of heating and cooling demand under ideal control without the consideration of distribution equipment. With the distribution side equipment studied in this research (Section 3.1.2), the energy consumption of heating and cooling will be much less, and its impact on the total energy consumption is comparatively negligible (by contrast, lighting energy performance is presented as the electrical energy consumption for lighting).
>
> *Percentage difference relative to total energy performance*
>
> As stated in Section 3.1, this research focuses primarily on energy demand and generation rather than on distribution. The configurations of the building and the corresponding impact on total energy performance as well as other derived performance indicators are the subjects of interest, rather than the configuration of the heating and cooling equipment. Lighting is one of the largest energy consumers, particularly for lower process load halls, where the greatest percentage difference between the two models exists. Energy saving measures, such as the installation of skylights, yields percentage changes in performance that are an order of magnitude more than the percentage difference between the two models.

The percentage difference between the total values predicted by the two models is less than 10%. At the lower end, for the scenario of a 300 W/m^2 hall operating full-time, a percentage difference of 3% is almost negligible. Therefore, in this research, the single-zone model is adopted for future investigation because it requires fewer computational resources with little difference in energy performance prediction when compared to the multi-zone model.

A.2 Simulation time step and reporting period

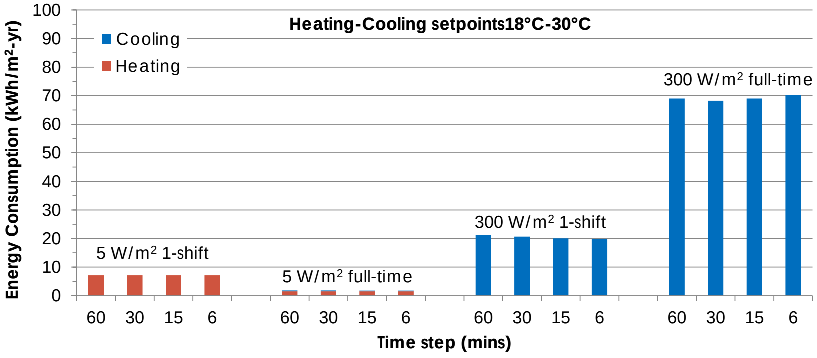
Two types of time steps are of interest — the simulation time step and the reporting period.

A.2.1 Loose thermal comfort requirement and simulation time step

As proposed in Section 2.3.2, the loose thermal comfort requirements (wider acceptable temperature range of 18°C to 30°C, and more frequent temperature fluctuation) of industrial halls may allow the simulation to be carried out with a larger time step. The possibility depends on two issues. First, is whether or not the larger time step yielding energy performance prediction results similar to the results using a finer time step. “Finer” and “larger” are relative terms. It is not true that the finer the simulation time step the better. In reality, distribution side equipment operates on a control scheme in discrete time intervals, usually in the range of 10 to 30 mins. Too fine a simulation time step only makes the simulation results become detached from reality.

Second, is whether or not the simulation executable at all with a larger time step. In the previous section, the time step is not an issue for a simulation that is used to study the energy demand adopting an ideal control strategy. However, for an investigation of energy consumption with distribution side equipment, there could be a case in which a larger time step will make a simulation run terminates prematurely since the calculation does not converge after exceeding a predefined number of iterations. In extreme operational conditions, this issue is more apparent, since the calculation is based on results from the previous time step. A larger time step might yield a value that cannot be handled by the defined equipment of a certain size (as opposed to the case with no size limitation under the ideal control strategy).

For the same four extreme operational scenarios previously discussed, simulations for different time steps are carried out to study if there is any impact on the predicted energy performance and if the simulation is executable at all. Time steps of 60, 30, 15, and 6 mins are studied. **FIGURE A.2** summarizes the results. For comparison purposes, simulations are repeated at a tighter



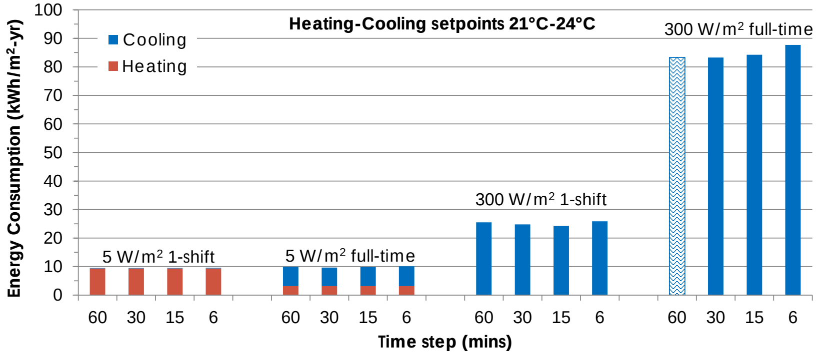


FIGURE A.2 *Energy consumption prediction under different time steps and operational scenarios* thermal comfort requirement with heating and cooling setpoints of 21°C and 24°C, respectively.

First of all, it is interesting to note that there is no significant difference in the predicted energy performance among different time step settings, especially for the lower process load scenarios. At higher process loads, getting rid of the excess heat becomes difficult, particularly if the halls are operating full time. With a tighter thermal comfort requirement, a lot of heat has to be removed for the 300 W/m^2 full-time operation, and the simulation does not converge (marked by the blue pattern bar) for the defined equipment simulated at a larger time step of 60 mins.

Since a time step of 30 mins does match the time interval for many control systems and provides results similar to those based on a simulation with a finer time step, the 30 mins time step is adopted in this research for its computational performance advantages.

A.2.2 Hourly reporting period

Throughout this research, an annual reporting period is adopted since it is assumed that the purchasing cost of electricity from the grid is the same as the selling price of electricity back to the grid. The following discussion helps understand the dynamic between the purchasing cost and selling price if energy generation is involved in the designs.

Energy generation and cost dynamics

Imagine the case where the generated energy cannot be stored or sold back to the grid, then the extra amount of energy generated beyond the amount being consumed is basically wasted. In fact, it is particularly problematic for many renewable energy sources since most of them depend on natural resources that are not constantly available. Electricity generation from solar PV is one such case. It is fortunate that most industries operate during the day when the sun is shining. However, there are occasions such as during the weekends when there is minimum demand for the generated energy. This raises the question whether the PV system should be sized to fulfill the basic energy demand or be oversized to maximize energy generation. In many countries, there is a feed-in tariff (FIT) to subsidize the renewable energy investment. The FIT, administered under different schemes, is the premium rate at which the utilities promised to buy electricity back from grid-connected local generation of renewable energy. The premium rate is higher than the electricity rate and is usually guaranteed for a fixed number of years. Therefore, environmental benefits aside, the main advantage or the determining factor to deploy renewable energy systems is the potential economic benefit that might be gained as a result of savings in the electricity cost or earnings from the FIT.

FIGURE A.3 depicts a PV system deployment for a typical summer day. The figure indicates that the amount of energy generated might not match the amount consumed at each of the hours. In this example, the energy surplus (the positive area bounded by the "Exported Energy" line) is roughly equal to the energy deficit (the negative area bounded by the "Exported Energy" line). In other words, the sum of the surplus and deficit is nearly zero for this particular day.

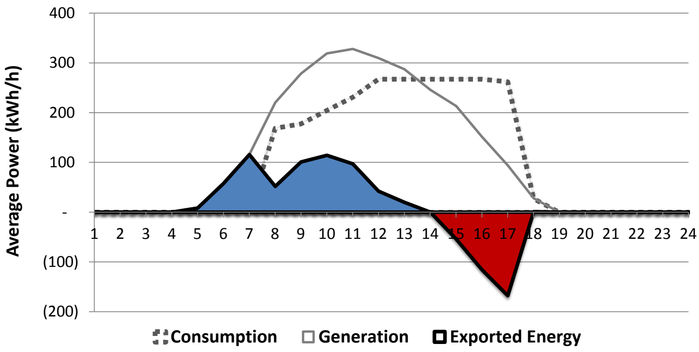


FIGURE A.3 *Energy consumption and generation profile for a typical summer day (Lee et al., 2013)*

On the other hand, the income (positive, if exporting at the feed-in tariff for the hours of surplus; negative, if purchasing from the grid at the price of electricity for the hours of deficit) is calculated for each of the hours in **FIGURE A.4**. If the FIT rate is higher than the electricity price, then it is clear that there is a net income for the day (the positive area is more than double of the negative area bounded by the "Income" line).

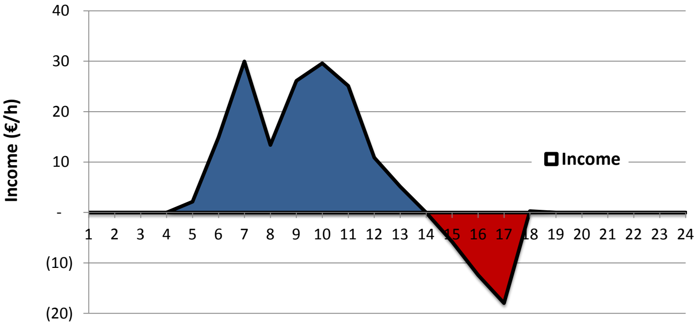


FIGURE A.4 *Income as a result of exporting surplus electricity (negative, if purchasing from the grid) for the same day of Figure A.3 (Lee et al., 2013)*

Lee et al. (2013) concludes that if there is a differential between purchasing and selling prices of energy, then an hour-by-hour cost-benefit analysis is necessary to study the economic viability of the energy generation measures. In such a case, an hourly reporting period for the building energy simulation is deemed necessary to facilitate the cost-benefit analysis.

A.3 Scalability of design

In Section 2.3.4, it is suggested that the influence of external factors through the roof becomes dominant for large single-storey structures. For that reason, it is further suggested that performance results can be expressed per unit floor area, and the total energy performance of halls can be obtained by scaling this per unit area performance value with the floor area.

A.3.1 Roof dominancy and minimum floor area to support scalability

For a single-storey building, the roof surface increases at the same rate as the floor area, while wall surfaces increase at a disproportionate rate. **FIGURE A.5** presents roof area as a percentage of all exposed surface areas. These hypothetical halls (**TABLE A.2**) follow a width-to-depth aspect ratio of 2.5 as suggested in Section 2.3.8.

Based on the current building stock, a floor area of 4,000 m^2 is arbitrarily considered as typical (roof area is also 4,000 m^2 for a single-storey hall). From Figure A.5, It can be observed that as floor area increases beyond 4,000 m^2, each doubling in floor area only

TABLE A.2 **Hypothetical halls with a width-to-depth aspect ratio of 2.5**

Width	Depth	Floor Area
25	10	250
50	20	1,000
75	30	2,250
100	40	4,000
125	50	6,250
150	60	9,000
250	100	25,000

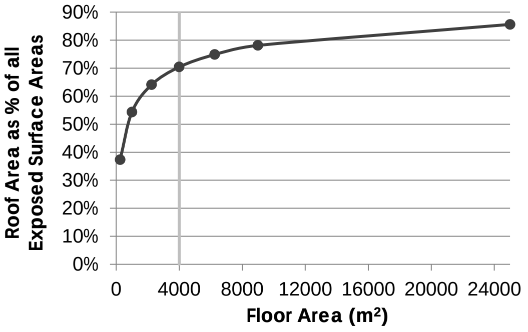


FIGURE A.5 *Roof area as a percentage of all exposed surface areas for halls of different sizes* causes a single digit increase in roof area as a percentage of all exposed surface areas (e.g. from 70% to 77% when the floor area increases from 4,000 m^2 to 8,000 m^2). On the other hand, the roof area as a percentage of all exposed surface areas decreases quite drastically as the floor area gets smaller than 4,000 m^2.

To identify a hall size in which per unit energy performance values can be scaled, simulations are carried out for halls of these different sizes with a process load of 5 W/m^2 operating on a 1-shift schedule. **FIGURE A.6** presents the results.

The hall size for scaling has been found to be 4,000 m^2 (arbitrarily) for the case study building, which coincidently is also the typical size for industrial halls. The percentage change in energy demand is less than 5% with every size increment beyond 4,000 m^2. This insignificant change has not yet reflected the even smaller change if energy consumption (considering distribution equipment) is evaluated as opposed to energy demand. Moreover, lighting energy consumption is accounted per unit area regardless of the size of the halls. Therefore, it can be concluded that a per unit area performance value drawn from the investigation of a 4,000 m^2 hall can be scaled for larger size halls without significant loss in fidelity.

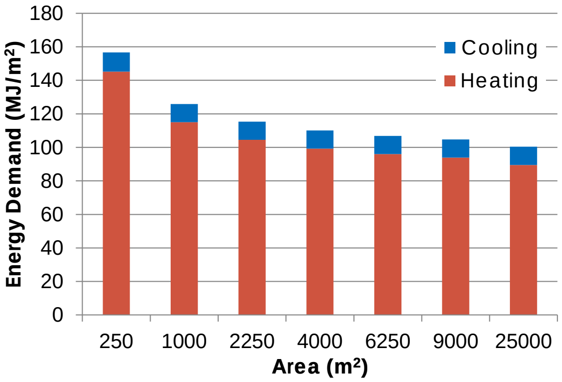


FIGURE A.6 *Per unit area heating and cooling energy demand for halls of different sizes*

As the size of the halls increases beyond 100,000 m^2 (arbitrarily), the effect of wall related elements becomes nullified. In a practical sense, halls larger than 100,000 m^2 are not common and are outside the scope of this research. For those mega-sized halls, the geometry and the size of the halls depend more on the necessity to fulfill the functionality (e.g. to accommodate certain manufacturing process) rather than to lower energy consumption.

A.4 Treatment of historical values for risk analysis

Risk analysis is introduced in Section 4.4 and the Monte Carlo Simulation (MCS) approach is adopted based on the assumption that there is no correlation among input parameters. However, there is a concern regarding whether the input parameters are somewhat correlated to each other. In the extreme case, the input parameters can be completely correlated to each other.

A.4.1 A comparison between Monte Carlo simulation and historical combination evaluation on the predicted performance

The stochastic risk analysis is based on inputs of historical values, for example, historical electricity prices, gas prices, and discount rates. MCS, which assumes input parameters are fully independent of each other, will randomly create combinations according to the probability distributions of each of the input parameters. Section 4.4.3 describes the making of 1,000 random combinations with Latin Hypercube Sampling (LHS). Figure 4.2 to Figure 4.5 illustrate the results of the process. Some extreme combinations of input parameters are possible; for example, a very high discount rate together with a very low electricity price. For economic performance, the average annualized relative cash flow can be evaluated based on these 1,000 random combinations of historical electricity prices, gas prices, and discount rates.

In practice, it is difficult to determine the correlation from the available data. If the studied economic input parameters are indeed fully correlated, then the only possible combinations of input parameters will be those recorded historically. If monthly values are recorded for the past ten years, then there will be 120 recorded combinations of input parameters. Average annualized relative cash flow can also be evaluated based on these 120 historical combinations of rates.

The implication of either deploying MCS or historical combination evaluation can be assessed by evaluating the average annualized relative cash flow with both approaches and observing the difference between the two approaches. The assessment has been carried out to evaluate the average annualized relative cash flow for all of the 4,704 different building configurations as suggested in Section 5.2.1 with a full factorial design of design parameters listed in Table 3.4.

FIGURE A.7 presents the average annualized relative cash flow evaluated through either MCS or historical combination evaluation for all 4,704 configurations. The annualized relative cash flow evaluated with the deterministic combination (with 10-yr average rates) is also presented for comparison. The data are ranked by

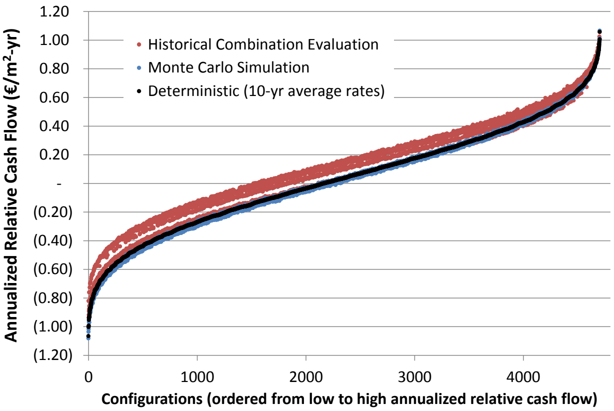


FIGURE A.7 *A comparison of predicted annualized relative cash flow based on the three approaches — Monte Carlo Simulation, historical combination evaluation, and deterministic approach* the combinations from the lowest to the highest annualized relative cash flow based on the deterministic combination.

It can be observed from Figure A.7 that historical combination evaluation tends to yield a higher annualized relative cash flow than those obtained by MCS or the deterministic approach. From the designer's perspective, the interest is not in determining the correlation, or in judging whether MCS or historical combination evaluation is more representative than the other. The interest is in how stochastic risk analysis helps facilitate informed design decisions. By following the same line of thought as with the risk indicator in Section 4.4.4 that the designers will be satisfied with anything equal to or better than the predicted performance, the approach that returns more conservative results is deemed appropriate. MCS, as observed in Figure A.7, returns lower cash flow for almost all configurations than historical combination evaluation.

To facilitate the design decision process, it is also important to differentiate similarly performing design solutions. Figure A.7 only displays the "average" value of the annualized relative cash flow of the 1,000 values being evaluated under MCS. **FIGURE A.8** presents the 10th to 90th percentile range of these 1,000 values for each configuration. The deterministic values are also presented.

For those best performing configurations (with higher cash flow), the ranges are relatively small. However, for those poorer performers, the ranges can be large (the largest range is from -0.05 to -1.78 €/m^2·yr). The possible large uncertainties in economic performance (in terms of annualized relative cash flow) further support the need for a risk indicator defined in Section 4.4.4.

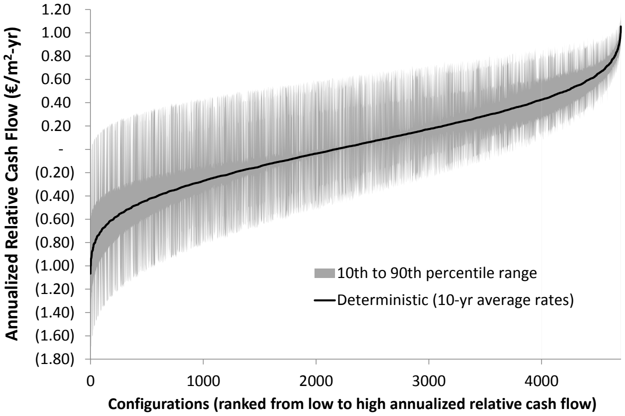


FIGURE A.8 *10th to 90th percentile range of the 1,000 different values (evaluated under MCS) of annualized relative cash flow for each of the 4,704 configurations*

Curriculum Vitae

BRUNO LEE was born in 1970 in Hong Kong. He earned his first degree in Computer Engineering from the University of British Columbia in 1995, and his second degree with distinction in Building Engineering from Concordia University in 2007. He was awarded the Building Engineering Medal for graduating first in class and his involvement in research activities and extracurricular activities (e.g. as president of ASHRAE — American Society of Heating, Refrigerating and Air-Conditioning Engineers, Concordia University student branch 2006-2007). His interest in sustainable and energy efficient design in building has been further demonstrated by winning the Undergraduate Student Research Awards for two consecutive years (2005 and 2006) from NSERC — Natural Sciences and Engineering Research Council of Canada.

He graduated from the Pennsylvania State University (Penn State) in 2009 with a M.S. in Architectural Engineering. His thesis titled "Simulation-based Performance and Life-cycle Cost Evaluation of In-duct Ultraviolet Germicidal Irradiation (UVGI) Systems" was supervised by Professor W.P. Bahnfleth and the work was partially supported by an ASHRAE Graduate Student Grant-In-Aid Award.

His PhD research work, supported by Materials innovation institute (M2i), was conducted in the Department of the Built Environment (Unit of Building Physics and Services) at the Eindhoven University of Technology (TU/e) under the supervision of Professor J.L.M. Hensen. Being a researcher focusing on scientific investigation, he recognizes the importance of practical application and societal relevance. His strong collaboration with industrial partners exemplifies his awareness. Based on his PhD work, he submitted two research proposals, which were both accepted and funded by the industry.

He was involved in IEA Annex 54 — Analysis of Micro-generation and Related Energy Technologies in Buildings, and in amending the Netherland's building code NEN 7120 (Energy Performance of Buildings · Calculation Method) with relevant inputs regarding industrial halls. He was also a visiting researcher at the Institute of Industrial Science at the University of Tokyo for two months in 2012.

Bruno's interest in sustainable built environment is not limited to research work. On the professional front, Bruno is accredited as a LEED AP BD+C. He is also a Chartered Engineer (CEng, CIBSE — Chartered Institution of Building Services Engineers).

List of Publications

JOURNAL PUBLICATIONS:

Bruno Lee, Marija Trcka, and Jan L.M. Hensen (2014). **Building energy simulation and optimization: A case study of industrial halls with varying process loads and occupancy patterns.** *Building Simulation: An International Journal, 7(3), 229–236*

Bruno Lee and William P. Bahnfleth (2013). **Effects of installation location on performance and economics of in-duct ultraviolet germicidal irradiation systems for air disinfection.** *Building and Environment, Volume 67, 193–201*

Bruno Lee, Marija Trcka, and Jan L.M. Hensen (2013). **Rooftop photovoltaic (PV) systems: a cost–benefit analysis study of industrial halls.** *International Journal of Low-Carbon Technologies, 0, 1–8*

Bruno Lee, Marija Trcka, and Jan L.M. Hensen (2012). **Rooftop photovoltaic (PV) systems for industrial halls: Achieving economic benefit via lowering energy demand.** *Frontiers of Architectural Research, 1(4), 326-333*

Bruno Lee, Marija Trcka, and Jan L.M. Hensen (2011). **Embodied Energy of Building Materials and Green Building Rating Systems: a Case Study for Industrial Halls.** *Sustainable Cities and Society, 1(2), 67-71*

JOURNAL PUBLICATIONS (UNDER PREPARATION):

Bruno Lee and Jan L.M. Hensen. **Maximizing energy generation potential of photovoltaic (PV) systems on large flat roof surfaces in a suburban setting.**

Bruno Lee and Jan L.M. Hensen. **Automated design solution search approaches towards cost effective energy optimized industrial halls.**

Bruno Lee and Jan L.M. Hensen. **Full-factorial design space exploration approach for multi-criteria decision making of the design of industrial halls.**

CONFERENCE PROCEEDINGS:

Bruno Lee, Marija Trcka, and Jan L.M. Hensen (2013). **Towards Zero Energy Industrial Halls — Simulation and Optimization with Integrated Design Approach.** *Building Simulation 2013 - 13th Conference of the International Building Performance Simulation Association, pp. 1339-1346, Chambery, France, Aug 2013*

Bruno Lee, Marija Trcka, and Jan L.M. Hensen (2013). **Building Energy Simulation and Optimization of Industrial Halls.** *ASHRAE 2013 Winter Conference, pp. 1-8, Dallas, USA, Jan 2013*

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Bruno Lee, Marija Trcka, and Jan L.M. Hensen (2012). **PV-systemen voor industriele hallen.** *TVVL Magazine, 41(5), 26-28*