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Developing a risk indicator to quantify robust building design

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Abstract

Many modern buildings are rated high under green building rating systems based on their predicted energy performance. However, the actual performance, in many cases, deviates from the prediction. The discrepancy is mainly due to difference between assumptions in the building design and actual operating conditions. It is, therefore, important not only to seek energy efficient building designs but also robust designs that perform consistently even under varying conditions. This paper proposes a design approach that incorporates a risk indicator into the existing energy performance evaluation process and demonstrates it with a case study for industrial halls in Amsterdam, the Netherlands.

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Keywords: robust building design; risk analysis; automated design space exploration; building energy performance simulation; industrial halls;

1. Introduction

Many modern buildings are rated high under green building rating systems based on their predicted energy performance. However, the actual performance, in many cases, deviates from the prediction [1]. The discrepancy between the actual and predicted performance leads to doubt towards deploying building performance simulation for building design and hence mistrust towards green building rating [2]. In fact, the discrepancy could be due to difference between assumptions in the building design and the actual operating conditions. Occupancy pattern is one of the uncertain operating factors [3], which is commonly modeled with deterministic assumption [4]. Achieving energy efficient design requires an integrated design approach that involves a vast array of design parameters and investigates

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the collective impact of the combination of those design parameters [5]. Out of the many combinations, certain combinations perform robustly under varying occupancy pattern while many combinations exhibit great deviation from predicted performance under ever-changing operating conditions. To ensure robust and energy efficient design, a building design approach that considers ever-changing operating conditions is necessary [6].

This paper will deploy automated design space exploration for a large design space with risk analysis to quantify risk for the different combinations of building design. Based on the vast amount of energy performance data generated, a design approach that incorporates risk indicator into existing energy performance evaluation will be developed, leading to straightforward identification of robust designs under varying conditions and occupancies. The risk indicator serves the purpose of quantifying the potential discrepancy between the predicted and actual performance of a particular design, and therefore, provides a practical and tangible means to promote robust building design. Minimizing energy consumption and minimizing risk can be two design objectives to facilitate the decision making process. The approach is illustrated by a case study of industrial halls in Amsterdam, the Netherlands.

2. Automated design space exploration with risk analysis

In order to mitigate bias towards certain designs over others, an automated approach that exhaustively search over a large design space by varying a finite set of design parameters is proposed. To effectively illustrate the newly developed design approach within the limited length of this paper, a case study of industrial halls is purposed for its simple geometry and construction methods such that the number of design parameters related to energy performance can be greatly reduced. With a limited number of parameters, it is possible to investigate each parameter quantitatively by observing the predicted performance through adjusting the quantity of the subject of interest. An example is to vary the skylight coverage and observe the impact on energy consumption in lighting, heating and cooling. The development and the definition of the risk indicator is presented in section 2.4.

2.1. The baseline building model

The case study includes a hypothetical building (measures 100m x 40m x 6m) that represents a typical rectangular shape industrial hall in Amsterdam, the Netherlands, which is classified as ASHRAE climate zone 5 with a warm summer and a mild winter. The baseline building fulfills the requirement specified in ASHRAE standard 90.1 [7] with few noted exceptions, where the requirement for office buildings are not applicable to industrial halls. The building is built either with steel cladding on a steel frame or with concrete. ASHRAE standard 90.1 mandatory provisions assign the wall and roof insulation with a minimum resistance value of 2.3 and 3.3 m^2K/W respectively (resistance value is investigated over a range in the next subsection). Ventilation rate at 0.55 $L/s\text{-}m^2$ is adopted according to ASHARE standard 62.1 [8]. Steel frame or concrete construction is in general quite airtight and infiltration is mainly due to opening of doors (particularly for warehouses). Infiltration rate is evaluated dynamically in the simulation by assuming a constant opening of a 0.1m by 3m gap on the entrance side (assumed to be facing south). Fluorescent lighting with a lighting power density (LPD) of 9 W/m^2 is assigned according to ASHRAE standard 90.1. Certain aspects of daylighting are discussed in the standard, but no value is prescribed to specify or to recommend the amount of daylighting. For an industrial hall kind of environment, current guideline [9] recommends that the temperature of the space has to 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 for workers performing light work. Actually, some of the aforementioned 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.

2.2. Design parameters

The building might not attain optimal energy saving with prescribed default values of the standard. Table 1 presents the ranges of values for each design parameter that is to be investigated in this study. The ranges and resolutions are nominally set and are within practical range; that is, any configuration based on possible combination of these values can be readily built. The study also includes transpired solar collector (TSC), which could be a potentially effective means of heating [10], 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. These six design parameters are identified through a sensitivity analysis as the more influential parameters than others, which from a much longer list of parameters [5].

Table 1. Design parameters and their ranges of values under investigation.

Design Parameters	Design Ranges	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)	Steel or Concrete	2
Construction Types (Wall)	Steel or Concrete	2
Skylight Coverage (as % of roof area)	0 – 15 %	4
Transpired Solar Collector (as % of south wall)	0 – 100 %	6

An automated design space exploration involves an exhaustive search of design solutions through the design space made by all possible different combinations of design parameters at the suggested resolutions of investigation. Based on values in Table 1, there are 4,704 possible design solutions. It is the collective impact of different design parameters that make some solutions to consume much less energy than other solutions. Some solutions exhibit higher cooling energy consumption with lower heating energy consumption, while other solutions behave the other way round. In this paper, it is the total energy consumption, including cooling, heating, and lighting, that is of interest.

2.3. Operating Scenarios

As discussed, it is hard to ignore the impact of operating conditions to the energy performance. Over time, the building space might not even serve the original intended purposes. A robust building design shall be able to maintain similar performance level even under varying operating conditions. For industrial halls, internal heat gain, which depends on the process load, affects the cooling and heating energy consumption quite significantly. The process load depends very much on the industry occupying the space (as opposed to office buildings with comparatively typical plug load). Table 2 organizes the industries into three groups of representative industries in terms of arbitrary process loads that are derived from annual process energy consumption and occupancy schedule published by CIBSE [11].

Table 2. Three groups of industries from low to high representative process loads.

Arbitrary Process Load (W/m^2)	Representative Industries
5	Distribution
25	Engineering, Light Manufacturing
50	Lab, Plastics, General Manufacturing, Textiles, Electronics, Chemical Factory

Occupancy schedule is highly varying. For logistics warehouses, a two-shift work schedule is quite common, whereas warehouses for storage purpose operate on a 1-shift operation. Both types of warehouses assume a 5 W/m^2 process load. If the industrial hall is optimized for a particular process load and occupancy schedule, for example, a 2-shift operation at a process load of 5 W/m^2, the energy performance at a different occupancy schedule and process load will be different. 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.

2.4. Risk indicator

Assume an industrial hall is designed for a 2-shift operation at a process load of 5 W/m^2, there is no guarantee that the building is operating under the same scenario throughout its life-span. It is fair to assume that the industry might stay or change to a lower or a higher process load one. The same variability applies to occupancy schedule, which depends on economic cycles, product demands, and industry specific characteristics.

Annual operational energy consumption is commonly expressed in the unit of kWh/m^2; however, if occupancy schedules range from 1-shift of work to full-time operation, then the annual total energy consumption among different occupancy schedules 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^2h). This hourly value allows a fairer comparison of performance between different occupancy schedules and at the same time provides useful information for the building designers since the unit cost of the product is directly proportional to the hourly cost of the energy instead of the annual sum.

Comparing energy performance of a building design under different occupancy schedules on a fair ground, it is interesting to note that some design solutions perform better under certain occupancy schedules but not the others. It is therefore important to investigate the energy performance of a building not at just one occupancy schedule and process load, but for all possible combinations of occupancy schedules and process loads. There are nine different combinations in this case study and have to be investigated for all 4,704 design solutions.

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 [12-13]. The adverse consequence, in energy performance terms, is the potential surge in predicted energy consumption. That is, the building designers will be satisfied with anything equal to or less than the predicted energy consumption value, and energy consumption above the predicted value is considered to be an adverse consequence.

Fig. 1 depicts a case where the designers opt for a 2-shift operation at a process load of 5 W/m^2 as the reference scenario. For that reference scenario (dark blue bar), the particular design solution (of Fig. 1) incurs an energy consumption of 8.11 Wh/m^2h. The other eight occupancy schedule / process load combinations are either consuming more or less than the reference scenario. Any energy consumption value that is on the right of reference scenario in Fig. 1 and above the 8.11 Wh/m^2h consumption level are considered to be undesirable (an adverse consequence). The undesirable portion of energy consumption is bounded by the red arrows.

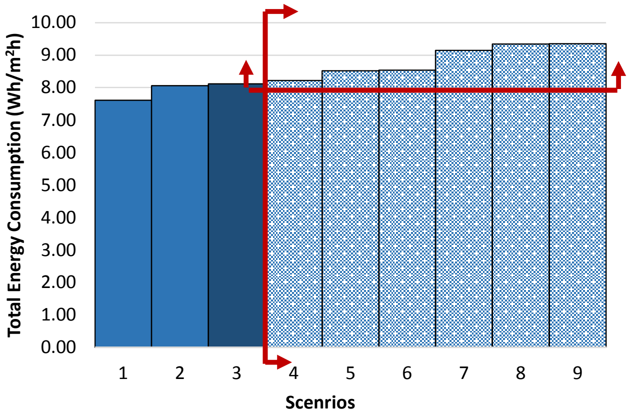

Fig. 1. An example to depict the undesirable energy consumption with respect to the reference scenario.

The likelihood of occurrence in this case study is assumed to be of equal chance for each operating scenario. Based on the aforementioned definition, a risk indicator is evaluated for each of the 4,704 design solutions. The risk indicator is to provide an objective and quantitative evaluation of the potential surge in energy consumption of a design solution. It also serves as the differentiating factor in making informed choices among different design solutions.

3. Results and discussion

The newly developed automated design space exploration workflow with risk analysis is applied to the case study industrial hall to identify the Pareto solutions that consume the least amount of energy (for cooling, heating, and lighting) and maintain their predicted performance over the course of life span even under varying operating conditions. Pareto solutions are design solutions that cannot be improved in one performance aspect without worsening the other. In this paper, energy performance is one aspect, while risk is the other performance aspect. For the 4,704 different possible design solutions, both total energy consumption and the corresponding risk have been evaluated for each solution. In Fig. 2, each blue dot presents a unique solution (combination of design parameters of different values), which is denoted by the total energy consumption and the risk. The orange dots highlight the Pareto solutions. It can be observed that there are 90 design solutions that offer very similar performance of a low predicted energy consumption level of 6.75 Wh/m^{2}h (the building is designed for the reference scenario of a 2-shift operation at a process load of 5 W/m^2). Out of those solutions, the Pareto solution incurs a risk of 0.48 Wh/m^{2}h; that is, the energy performance of the building will likely be 7.23 Wh/m^{2}h due to the potential changes in operating conditions in the future. Some non-Pareto solutions incur a higher risk of 0.59 Wh/m^{2}h and a likely energy consumption of 7.33 Wh/m^{2}h. As observed from Fig. 2, some solutions even incur a very high risk of almost 1 Wh/m^{2}h.

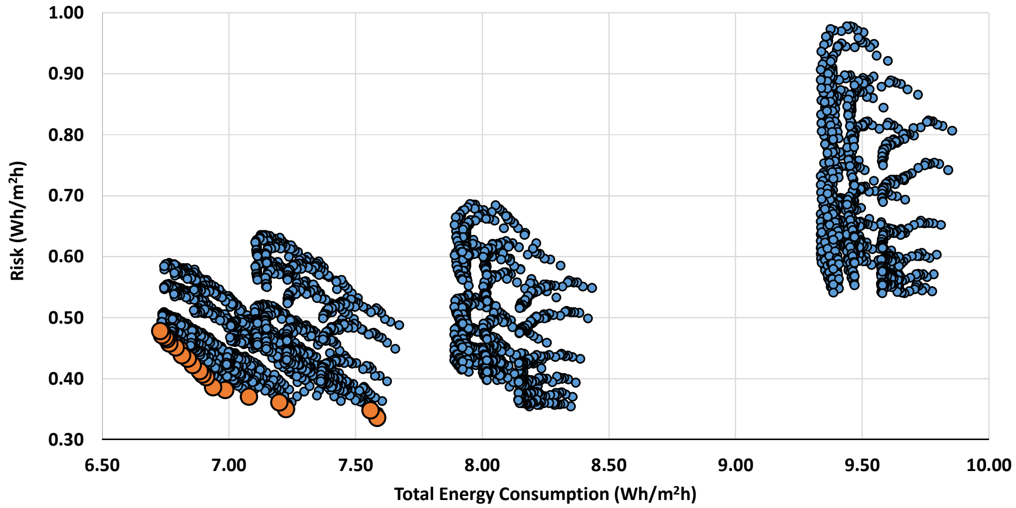

Fig. 2. Scatterplots of Risk versus Total Energy Consumption of all 4,704 design solutions.

Judging from the distribution of the design solutions, the solutions can be roughly drawn into 4 groups, namely, the Pareto solutions, the low, medium, and high energy consumption solutions, according to the energy performance. Table 3 summarizes the design configurations for the 4 groups by presenting the values of the design parameters corresponding to design solutions with min., avg., and max. energy consumption within each group. Even though the 6 selected design parameters are the relatively influential ones according to the sensitivity analysis, results from Table 3 suggests that skylight coverage is the main factor influencing the total energy consumption.

Table 3. Summary of design configurations for four groups of design solutions.

		Roof Ins. (m2K/W)	Wall Ins. (m2K/W)	Roof Construction	Wall Construction	Skylight Coverage (%)	TSC (% of south wall)
Pareto Solutions	Min.	***1.5***	***1.5***	***0***	***0***	***10***	***100***
	Avg.	***2.5***	***2.1***	***0.16***	***0.16***	***14.6***	***100***
	Max.	***4.5***	***4***	***0.2***	***0.2***	***15***	***100***
Low Energy Consumption Solutions	Min.	1.5	1.5	0	0	***10***	0
	Avg.	3	3	0.1	0.1	***12.5***	50
	Max.	4.5	4.5	0.2	0.2	***15***	100
Med. Energy Consumption Solutions	Min.	1.5	1.5	0	0	***5***	0
	Avg.	3	3	0.1	0.1	***5***	50
	Max.	4.5	4.5	0.2	0.2	***5***	100
High Energy Consumption Solutions	Min.	1.5	1.5	0	0	***0***	0
	Avg.	3	3	0.1	0.1	***0***	50
	Max.	4.5	4.5	0.2	0.2	***0***	100

Design solutions ranging from low to high energy consumption prevail the whole design space; that is, design parameters (except skylight coverage) exert minimal impact on energy consumption. From design point of view, no clear design trends (values in normal typeface) can be drawn for those design parameters. On the other hand, it can be observed that low, medium, and high energy consumption is a result of having skylight coverage of 10-15%, 5%, and 0% respectively.

However, distinctive design trends (values highlighted by bold-italic typeface) can be observed for Pareto solutions: 100% coverage of south wall with TSC, 15% coverage of skylight, preferably concrete construction, and comparatively lower thermal resistance value. In fact, the Pareto solutions are just the less risky low energy consumption solutions (both groups cover the same range of energy consumption). This preliminary results (without further review of each individual configuration) seem to indicate that low thermal resistance and high thermal mass offer more robust design solutions.

4. Conclusion

This paper has illustrated a design approach that involves automated design space exploration and risk analysis. Risk, based on results of the case study, can potentially signifies designs with notable increase in predicted energy consumption. Such an increase is significant enough to make a supposedly very energy efficient design solution not as efficient as other originally not efficient solutions. The risk indicator, as presented in this paper, only considers nine different operating scenarios; however, more scenarios can be incorporated as appropriate and be treated stochastically if the probability of occurrence is known. This single number indicator offers an objective and quantitative means to represent robustness of building design and avoids the clumsiness of presenting performance data for each and every investigated scenario. Demonstrated with the case study, the risk indicator facilitates building design decisions based on objective and data driven reasoning. The results also suggest that the design approach is able to identify robust building designs that are among the top energy performers and yet perform consistently under varying operating conditions.

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