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Building energy simulation and optimization: A case study of industrial halls with varying process loads and occupancy patterns

Research Article

Bruno Lee[1,2] (✉), **Marija Trcka**[2,*], **Jan L.M. Hensen**[2]

1. Materials innovation institute (M2i), Delft, the Netherlands

2. Department of the Built Environment, Eindhoven University of Technology (TU/e), Eindhoven, the Netherlands

** Marija Trcka is currently at United Technologies Research Center (UTRC), East Hartford, CT 01608, USA*

Abstract

Industrial halls are mainly low-rise rectangular-shaped structures of simple construction. The relatively loose requirements in space conditioning and the comparatively high internal heat gain make the approach in industrial hall design quite different from that of office building design. The simplicity in building geometry and construction method allows the investigation of energy consumption for building services to be limited to a few demand-side parameters, namely, resistance of the roof and wall insulation, airtightness, and amount of daylighting. This paper investigates the impact of varying these demand-side parameters on the energy consumption for space conditioning and lighting for a typical industrial hall. Through building energy simulation, such impacts can be investigated, and by applying optimization, the configurations of the most optimal combinations of demand-side parameters with the lowest energy consumption can be identified. The result suggests that there is a significant energy-saving potential. For industrial halls, energy consumption for building services can be very sensitive to changes in the process load and occupancy pattern, which in reality, fluctuate widely due to economic cycles, and other factors. Optimized design solutions for industrial halls intended for a particular process load and occupancy pattern might not perform as predicted due to potential changes. To account for potential changes, uncertainty analysis can be performed to determine if the optimized design solutions are in fact robust enough to such changes and to identify solutions that are less susceptible to uncertainty.

Keywords

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1 Introduction

The industrial sector is one of the heaviest consumers of energy. In the USA, the sector used up 32% of the total energy consumption in 2009 (LLNL 2010), while in Europe, this sector consumed 24% in the same year (Eurostat 2011). Some of this energy was consumed in the manufacturing processes, while much of the rest was spent in lighting and space conditioning. Industrial halls, which are mainly single floor structures, maintain a relatively high roof-to-floor area ratio as compared to other types of buildings. Thermal comfort is seldom a concern for industrial halls, in which space conditioning (cooling and heating) is provided to maintain the building within a reasonable or legally allowable temperature range. By contrast, saving in energy consumption for space conditioning and for lighting is a big issue since even a modest percentage reduction in energy consumption could be translated into a large monetary sum.

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 building. In fact, what is potentially an energy efficient design for office buildings might not be appropriate for high internal heat gain halls.

Moreover, the comparatively simple building geometry and construction method of industrial halls, as compared to office buildings, allow the investigation of energy consumption for space conditioning to be limited to a small number of demand-side parameters (e.g. insulation value of walls), where a change in value of some of the parameters

E-mail: b.lee@tue.nl

affects the overall energy consumption significantly.

Furthermore, single floor structures allow energy saving measures, such as daylighting through skylight, to be applied to the whole building area, as opposed to only the area of the top floor as in many multi-floor buildings. Investigating the benefit of daylighting, and the corresponding impact on cooling and heating energy is crucial.

To demonstrate the unique nature of industrial halls, this paper will present a case study for a typical industrial hall, which will be investigated with representative heat gains for three different groups of industries. The case study will include computational building performance simulation and optimization to identify the building design solutions on demand-side parameters that will minimize the total energy consumption of cooling, heating, and lighting. However, because of the great uncertainty associated with the process load and occupancy pattern, the optimized design solutions will be analyzed with a variety of process loads and occupancy patterns to investigate the robustness of the solutions. This paper presents some of the results of an on-going project "Sustainable Energy Producing Steel Frame Industrial Halls", which also studies other energy related operation aspects.

2 Simulation, optimization, and uncertainty analysis

This section presents the case study that involves energy performance simulation, optimization, and uncertainty analysis of a typical industrial hall.

2.1 The case study building

The case study includes a hypothetical building that represents a typical industrial hall in Amsterdam, the Netherlands, which measures 40 m (W) × 100 m (D) × 6 m (H). Figure 1 depicts a graphical representation of a typical industrial hall with skylight. Hypothetical process load scenarios are considered with reference to CIBSE Guide F (CIBSE 2004), which covers a range of industries that are representative in the Netherlands, from distribution (with a process load in the neighborhood of 5 W/m^2) to chemical / electronics (45 W/m^2) to rubber / furniture (125 W/m^2).

The building is constructed with steel cladding on a steel frame in Amsterdam (classified as ASHRAE climate zone 5), which has a warm summer and a cold but not severe winter. The baseline building is assigned with insulation according to ASHRAE Standard 90.1 (ASHRAE 2007a) mandatory provisions; the insulation for the wall and the roof requires a minimum resistance value of R_{SI}-2.3 and R_{SI}-3.3 respectively. ASHARE Standard 62.1 (ASHRAE 2007b) suggests a ventilation rate at 0.55 L/(s·m^2). For typical steel frame industrial halls, an infiltration rate from 0.1 to 0.5 ACH is expected (ISSO 2002). For the baseline building (since a specific value is not prescribed by the standard), simulations in steps of 0.1 ACH were performed, and the average of the predicted energy performance values across the five infiltration rates is applied.

Workers are assumed to perform light work. For an industrial hall type environment, a current guideline (ARAB 2006) recommends that the temperature of the space must be maintained under 30℃ to protect workers from heat stress and heating has to be provided only if the space drops below 18℃ during occupied hours. For this study, the baseline investigation assumes full-time operation (that is, operating 24/7 for a total of 8760 hours) for the above mentioned process load scenarios.

ASHRAE Standard 90.1 suggests a lighting power density (LPD) of 14 W/m^2 for manufacturing facility without qualifying the required lighting level or type of lighting. In order to maintain a lighting level of 500 lx (CEN 2002), fluorescent lighting with a more conservative LPD of 16 W/m^2 is assumed. No value is prescribed to specify or to recommend the amount of daylighting, other than to limit the amount of skylight to 5% of gross roof area.

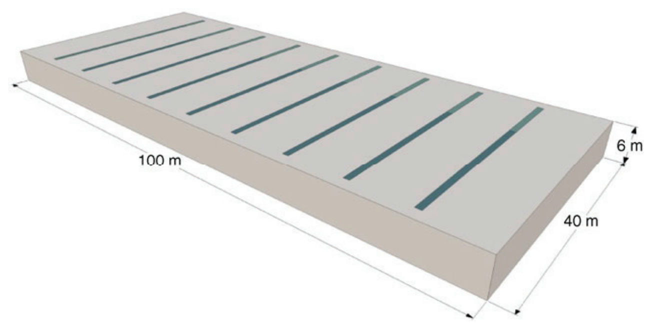

Fig. 1 Graphical representation of a typical industrial hall with skylight

2.2 Demand-side design parameters

The building might not be optimally designed in terms of energy consumption if it is designed according to the default values as prescribed by the ASHRAE standard. For example, insulation intended to isolate the space from the external elements might not be desirable for a building with high internal heat gain, in which the heat is preferably to be dissipated rather than be retained. As another example, limiting the skylight to only 5% of the roof area might not have explored the full potential of energy saving in lighting with a higher percentage of skylight. Therefore, by exploring different design values for each of the parameters, a reduction in energy consumption might be possible at a design value other than what is prescribed by the ASHRAE standard. Table 1 lists the demand-side design parameters that are to be investigated in this study and presents the ranges of

Table 1 Demand-side design parameters

Parameter	Design range	Level of investigation
Resistance of roof insulation	0–**3.3**–5.0 (R_{SI})	11
Resistance of wall insulation	0–**2.3**–5.0 (R_{SI})	11
Airtightness (as infiltration rate)	0–0.5 (ACH)	11
Daylighting (as % of roof area)	0–15 (%)	4

values for each parameter. These values deviate quite a bit from what are prescribed by the ASHRAE standards but are within practical ranges; custom made construction is not necessary to implement any of these specifications. Values prescribed by the standard and applied to the baseline building are highlighted in bold (no prescribed value for airtightness and daylighting). An evaluation of different configurations (combinations of different values of each parameter) will provide a clear view as to which could be the most energy efficient configurations.

In practice, airtightness is not a directly implementable quality. Airtightness can only be achieved through a combination of procedures, such as the use of a continuous barrier, proper workmanship at joints, and installation of weather seals, which are subjected to challenges of wind, pressure differential, and temperature gradient. In this paper, airtightness is arbitrarily defined in terms of a year-round constant infiltration rate, which is a derived measure for airtightness and allows fair comparison between different design solutions.

Due to the heat released from the processes, in practice, cooling is the predominant factor in HVAC energy consumption if the industrial halls are not located in an extremely cold climate. Since this paper is focused on demand-side parameters only, both cooling and heating are simulated under ideal control, that is, the energy demand predicted by the simulation is the theoretical amount of energy that must be removed to cool and must be added to heat the building according to the temperature setpoint. In practice, forced ventilation with heat recovery is a common system for industrial halls in a moderate climate, in which the halls can be efficiently cooled by drawing in ambient air at a lower temperature. Because of the comparatively low ambient temperature in Amsterdam even during the hottest days, and a rather high cooling setpoint of 30℃, the building can be effectively cooled with forced ventilation, which is assumed to operate at a constant system COP of 10. Cooling energy consumption is therefore calculated as one-tenth of what is demanded. Heating energy consumption is assumed to be the same as the demand.

Lighting is also a major energy consumer in buildings. Daylighting (through double-glazed translucent skylights) is an effective means of lessening the reliance on artificial lighting that is dimmed with a sensor control switch. 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 (double-glazed skylight has a much lower resistance value than most of the studied values of roof insulation, which is being replaced by skylight). The exact benefit of daylighting is evaluated in this paper after a thorough study that considers the impact on cooling and heating.

2.3 Energy performance analysis

The building energy performance simulation program TRNSYS is used to perform the energy analysis for cooling and heating demands. Energy consumption by the hour is evaluated and aggregated for the year. The baseline building model is created according to the specification just discussed. For each alternative design solution, energy performance of cooling and heating is evaluated for a new combination of values within the range for each of the studied demand-side design parameters. Such new combinations of values can be considered as feasible contenders or alternatives to the baseline building if they exhibit lower energy consumption.

DAYSIM is used to evaluate the illuminance level on the work surface for each hour due to daylighting at different locations inside the building and for different configurations of halls under investigation. Based on the illuminance level, lighting energy consumption is then calculated by a proprietary program written in MATLAB according to the dimmable lighting characteristics suggested by Rubinstein et al. (2010).

2.4 Optimization

Optimization is deployed to search for the optimized design solutions (most energy efficient configurations) that consume the least amount of total energy for cooling, heating, and lighting. Each configuration is a unique combination of different values of each of the design parameters at the assigned ranges and levels. For example, the industrial hall is investigated for 11 levels of roof insulation value, from R_{SI}-0.0, R_{SI}-0.5 till R_{SI}-5.0. With four design parameters and at the current resolution of investigation (see Table 1, the number of levels for each parameter), there could be 5324 different configurations. A complete search through all the configurations is computationally intensive. With appropriate algorithms, optimization techniques can determine the optimized design solutions without the need to cover the whole design space.

MODEFRONTIER is selected as the platform of optimization for its vast selection of optimization algorithms, and its flexible connectivity to energy performance simulations and post-processing tools, namely, TRNSYS, DAYSIM and MATLAB in this case study. For each simulation, MODEFRONTIER will, based on the configuration, prepare simulation files for each tool. Out of the many available algorithms in MODEFRONTIER, MOGA (multi-objective genetic algorithm) is chosen as the optimization algorithm. Though it is more commonly deployed for multi-objective optimization, its efficiency in searching for global optimums (Poles et al. 2004) makes it a good candidate for this case study, even though the case study is a single objective optimization that minimizes the total energy consumption.

An initial search space of 40 configurations (to ensure an upper and a lower value for each parameter) 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 a fast convergence and the consideration of all possibilities. In this case study, the adaptive evolution option (an option in MOGA) is selected. The optimization converged at the last few generations without further improvement. The optimization is set to stop after 15 generations. By evaluating only 600 configurations (15 generations of 40 each), the amount of computation with optimization is far less than what is required for a comprehensive evaluation of the whole design space of 5324 configurations.

2.5 Uncertainty analysis

The single most dominant source of heat gain is the process loads of the manufacturing processes, which is not a static value but rather a dynamic one that fluctuates widely due to seasonal factors, economic cycles, product demands, industry specific characteristics, or even a change in manufacturing technology. And for the same reasons, industrial halls can be occupied with just one-shift of work to full-time operation. Table 2 presents the different variations in process load and occupancy pattern that will be investigated in this study. The energy consumption results of these variations will then be compared to those of the baseline building, in which the facility is operated full-time.

Table 2 Variations from baseline investigation in process load and occupancy pattern

Variation	Deviation
Lower process load	−20% (throughout the year)
Higher process load	+20% (throughout the year)
Seasonal process load	+20% (Apr. 1 till Sept. 30), −20% otherwise
Two shifts	Monday–Friday, 06:00–22:00 (total 5008 hours)
One shift	Monday–Friday, 08:00–18:00 (total 2610 hours)

As opposed to the general sense of robust quality in a manufacturing process as suggested by Taguchi and Clausing (1990), in which tighter cluster of deviation is preferable over scattered deviation, building design (in terms of energy conservation) has a different need of "robustness" as compared to the manufacturing process. In a manufacturing process, a product must be produced according to specification. A product, with a deviation in any direction (e.g. bigger or smaller, if size is the performance indicator) will be perceived as having poor quality if it is the end product or be 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 another. However, in building design, if energy consumption is the performance indicator, it is generally accepted that the lower the energy consumption the better. The amount of energy consumption does not have an impact on other aspects of building operation except directly affecting the cost of operation.

In practical sense, the building operators are not concerned too much on whether the building will operate at a lower energy consumption than the predicted value due to uncertainties in operation matters. It will be an issue if and only if the building is operating at a higher energy consumption than the predicted one. Therefore, the robustness consideration from a building design perspective is very different from the original intention of robust quality for the manufacturing process, at least from the building operators' point of view. It is outside the scope and not the intention of this paper to develop a gauge for "robustness" in building design in terms of energy conversation. However, with the aforementioned variations in operation scenarios that represent likely uncertainties facing industrial hall operation, this paper explores a potential area, which is often neglected in building design.

3 Results and discussion

The energy consumption comprises that for cooling, heating, and lighting. In general, because of the moderate climate and the rather loose requirements for space conditioning, energy consumption for cooling and heating is comparatively low as compared to that for lighting. Table 3 presents the predicted energy consumption values for cooling, heating, lighting, and the total, for each of the three process load scenarios. In the table, two values are presented, one for the baseline building, and the other for the most optimized design solution (after a search through 600 configurations). The percentage savings for the optimized design solution is also presented.

In fact, from Fig. 2, it can be observed that quite a number of other configurations could also arrive with similar total energy consumption as those most optimized

Table 3 Cooling, heating, lighting, and total energy consumption for both the baseline building and the most optimized design solution for each of the three process load scenarios

Scenarios	Cooling (kWh/(m²·yr))	Heating (kWh/(m²·yr))	Lighting (kWh/(m²·yr))	Total (kWh/(m²·yr))
5 W/m²				
Baseline	15	0	140	155
Optimized	10	2	104	115
Saving (%)	33%	—	26%	25%
45 W/m²				
Baseline	49	0	140	189
Optimized	20	1	104	124
Saving (%)	60%	—	26%	34%
125 W/m²				
Baseline	119	0	140	259
Optimized	58	0	104	162
Saving (%)	51%	—	26%	37%

design solutions. The characteristics of these configurations will be discussed in the next section. What is encouraging to note is that with just changes in the design values of the four demand-side design parameters, a savings of 25% to 37% in total energy consumption over the baseline building can be obtained for the studied process load scenarios. The most optimized design solutions offer a consistent 26% savings in lighting over the baseline building, and also offer significant savings in cooling.

From Table 3, it can be observed that the most optimized design solutions with higher process loads virtually require no heating at all. As the process load increases, the primary concern is to dissipate the excess internal heat gain as much and as quickly as possible, and as a result, energy consumption for cooling becomes a dominant factor. In the baseline building, no daylighting is adopted. Since lighting comprises the largest slice of energy consumption, the most optimized design solution suggests that a 15% roof coverage with daylighting results in the least total energy consumption for all process load scenarios. By contrast, depending on the process load, energy consumption and thus the design solutions addressing issues in cooling and heating are vastly different.

3.1 Characteristics of the optimized design solutions

The building is subject to process loads ranging from 5 W/m² to 125 W/m². With an increase in process load, it is harder for buildings to dissipate the corresponding heat gain. As a result, solutions that work best for a certain process load might not perform well for other process loads. Figure 2 presents design solutions within 2% deviation of

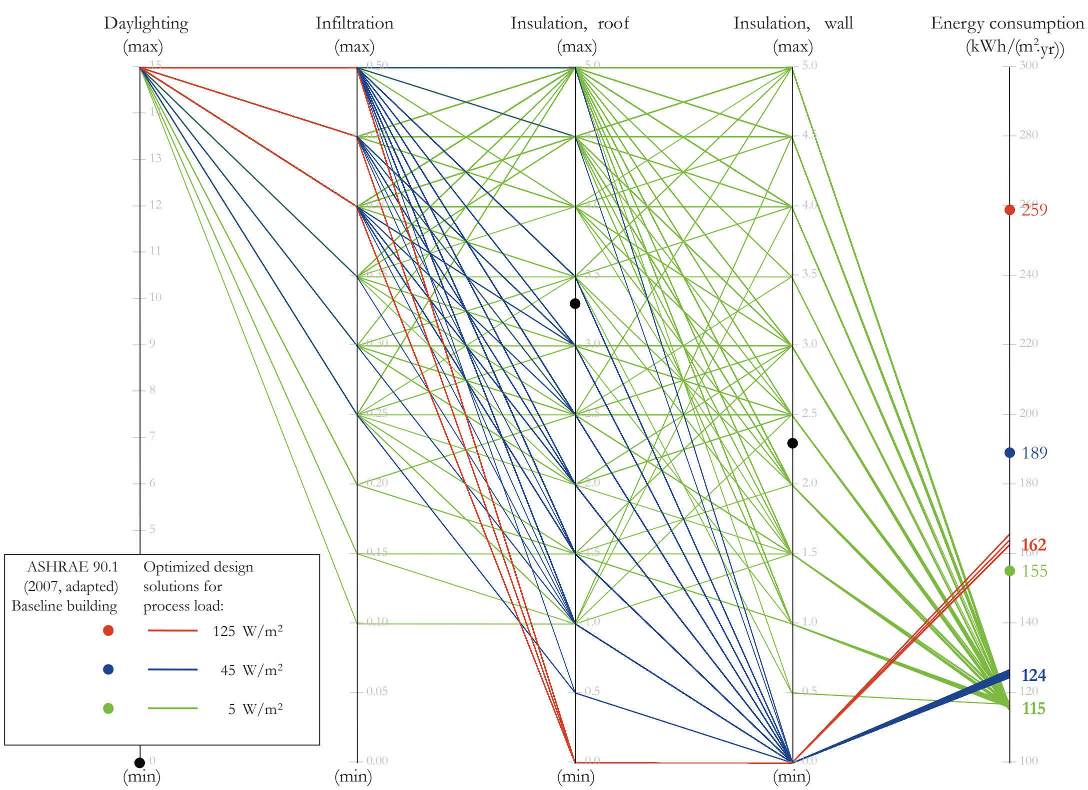

Fig. 2 Optimized design solutions (within 2% deviation of the most optimized design solution) and baseline building configuration of industrial halls for each of the three process load scenarios

the most optimized design solution for each of the three process load scenarios. Each parallel line represents a design solution for a different combination of values of the four demand-side parameters. The ASHRAE Standard 90.1 baseline building is represented by the dots.

In order to achieve an energy performance that is within 2% deviation from the total energy consumption of the most optimized design solution, there are not many options available for halls with high process loads, such as those of 125 W/m^2; heat has to be dissipated as effectively as possible by having high infiltration rate and no insulation. On the other hand, there is a vast variety of possible options available for the low process load halls, since some design solutions opt for more cooling with no heating, while others favor less cooling with a bit of heating. As a result, a variety of different configurations could have similar performance. The scenario with a process load of 5 W/m^2 best illustrates the complex scene behind this characteristic. Insulation and infiltration are not the determining factors; since for quite a number of different combinations of insulation and infiltration, the total energy consumption remains similar as long as the halls are fitted with high levels of daylighting. However, an inspection into the numerical values of cooling and heating energy consumption reveals that even though the total energy consumption is within 2% of 115 kWh/m^2, cooling energy consumption ranges from 9 to 14 kWh/m^2 and heating energy consumption ranges from 0 to 5 kWh/m^2 for the many possible solutions.

With a process load of 45 W/m^2, cooling becomes more prominent. Around twenty possible configurations are within 2% of the 124 kWh/m^2 of total energy consumption of the most optimized design solution. With just one exception, all other configurations consume 19 to 23 kWh/m^2 for cooling and 0 to 2 kWh/m^2 for heating. Design favors high infiltration rate at an average of 0.44 ACH, no wall insulation, and an average roof insulation of R_{SI}-2.2. Such configurations as compared to that of the baseline building, offer a significant saving in cooling energy (up to 60%).

As the process load increases to 125 W/m^2, heating is no longer required for all studied solutions. Cooling energy consumption ranged from 58 to 62 kWh/m^2 for the top 2% performers. Halls with no insulation dissipate heat more efficiently. In general, higher coverage of the roof with skylights for daylighting will lower the lighting energy consumption at the expense of higher solar heat gain, and thus an increase in cooling energy consumption. As process load increases, the amount of solar heat gain induced through the skylight is hard to ignore and has to be dissipated together with the internal heat gain of the process load. The main concern is to reduce the overall thermal resistance to promote heat dissipation. Since the skylight is assumed to be double-glazed, for solutions with no insulation, reducing the amount of skylight helps reduce the overall thermal resistance (single-glazing with lower thermal resistance has not been evaluated in this paper). It is interesting to note that if daylighting coverage is reduced from 15% to 10%, lighting energy increases from 104 kWh/m^2 to 109 kWh/m^2; but at the same time, cooling energy decreases by 1 kWh/m^2.

The optimization process has evaluated 600 different configurations for each process load scenario. Each of these configurations will consume a different amount of cooling and heating energy. To illustrate the issue of the inter-dependent nature between cooling and heating, Figure 3 puts into order the 600 configurations, from the least energy consuming (in terms of cooling and heating) configuration to the most energy consuming configuration, for each of the three process load scenarios.

It can be observed that, for most of the configurations studied, no heating is necessary especially as process load increases. For the low process load scenario of 5 W/m^2, the induced heat gain by process load is not sufficient to maintain the space temperature, and excess energy has to be spent on heating if the halls are not well insulated. Therefore, the worst design solutions are those with no insulation. For the process load scenario of 45 W/m^2, the additional internal heat gain somewhat compensates the heat loss through the building envelope, therefore, for this scenario the design solutions with no insulation consume much less energy than similarly configured solutions under the low process load scenario. As process load increases beyond 125 W/m^2,

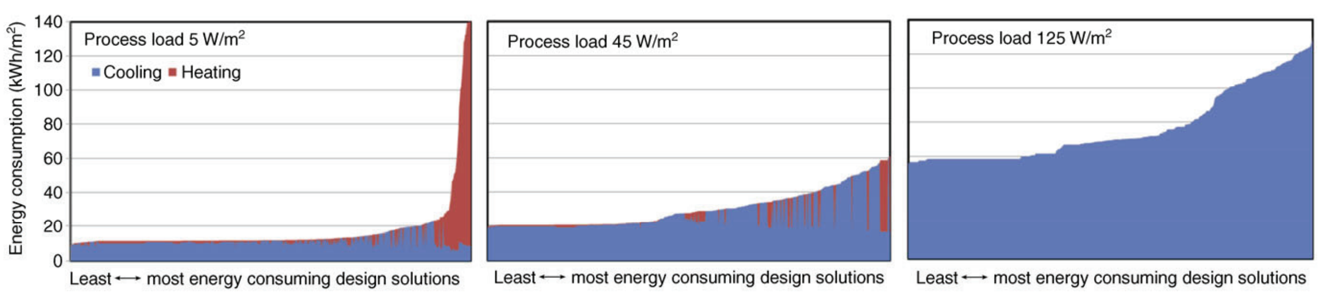

Fig. 3 Energy consumptions for cooling and heating, with configurations arranged from the least amount to the highest amount, for each of the three process load scenarios

heating is absolutely not necessary.

In practice, little insulation and high infiltration rate might induce undesirable effects such as condensation, contamination, local discomfort, and acoustic issue. Depending on design priority and preference, an integrative approach, which considers other performance issues than energy efficiency alone, should be adopted.

3.2 Robustness of the optimized design solutions

The results demonstrate that optimized design solutions offer significant savings over buildings complying with the ASHRAE Standard 90.1 prescriptive building envelope option by altering just a few demand-side parameters. However, optimized design solutions for industrial halls projected for a particular process load and occupancy pattern might not perform as predicted due to anticipated but unascertainable changes in the load and the pattern.

Annual energy consumption is commonly expressed in units of kWh/m^2; however, if occupancy patterns range from one-shift of work to full-time operation, then the annual total energy consumption among different occupancy patterns can differ by an order of magnitude. Therefore, the energy consumption per operating hour (that is, in the unit of Wh/(m^2·h)) allows a fairer comparison between different occupancy patterns and provides more information for the building operators since the unit cost of the product is directly proportional to the hourly cost of the energy instead of the annual sum. Number of operating hours for one-shift and two-shift operation is presented in Table 2.

As previously demonstrated, solutions that work best for a certain process load might not perform well for other process loads. Therefore, it is important to investigate if the optimized design solutions perform similarly under a variety of process loads and occupancy patterns. Figures 4 to 6, present the ten most optimized design solutions for each of the three process load scenarios, which are ranked from the lowest to the highest energy consumption (comparatively,

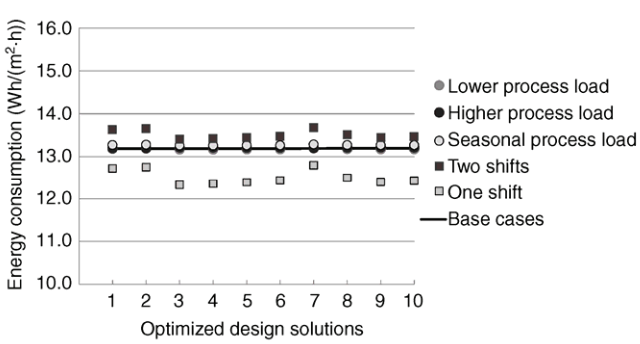

Fig. 4 Energy consumption of the ten most optimized design solutions for the 5 W/m^2 process load scenario with variations in process load and occupancy pattern

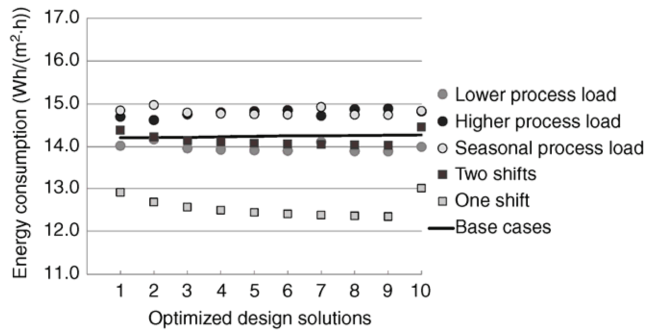

Fig. 5 Energy consumption of the ten most optimized design solutions for the 45 W/m^2 process load scenario with variations in process load and occupancy pattern

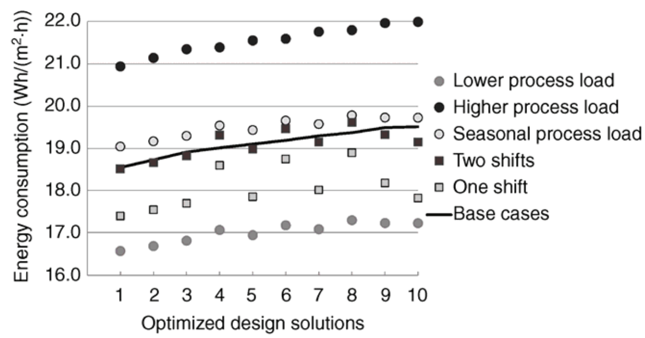

Fig. 6 Energy consumption of the ten most optimized design solutions for the 125 W/m^2 process load scenario with variations in process load and occupancy pattern

within this optimized group of configurations). On the same diagrams, energy consumption for the variations (as specified in Table 2) in process load and occupancy pattern is also presented.

The most optimized design solution for the scenario with a process load of 5 W/m^2 consumes 13.2 Wh/(m^2·h) during occupied hours. If full-time operation is not required, energy consumption per occupied hour increases to 13.6 Wh/(m^2·h) for a two-shift operation and decreases to 12.7 Wh/(m^2·h) for a one-shift operation. This information is crucial for building operators since an increase in per unit cost will affect the marginal profit, and in this particular case, a decision has to be made as to whether a two-shift operation is indeed a profitable alternative. The energy consumption of design solution 3 differs from the most optimized design solution by less than 0.03%. And the worst variation for a two-shift operation consumes only 13.4 Wh/(m^2·h). Even though solution 3 is not the most optimized solution, it is in fact the more robust one. In this low process load scenario of 5 W/m^2, it can be observed that the occupancy pattern is the determining factor. By contrast, ±20% variation in process load has limited effect, since the dominant factors are related to the weather and the lighting, which are tied in with the occupancy pattern.

The scenario with a 45 W/m^2 process load best illustrates the intricate relationship between cooling and heating demands. Some design solutions opt for more cooling with no heating, while others favor less cooling with a bit of heating, and the total energy consumption across the ten optimized solutions is quite similar. Those solutions with an anticipated heating load will perform better even under seasonal process load (less process load during the winter), but will consume more under higher process load (throughout the year) since heat gain is more difficult to dissipate with those solutions (more insulation). Under this medium process load scenario, the choices of design solution might depend on the anticipated manufacturing pattern, such as a seasonal production cycle.

For the process load scenario of 125 W/m^2, heating is no longer required for all solutions studied. An increase in the process load will induce an almost proportional increase in energy consumption. The effect of each of the demand-side design parameters becomes more prominent; changes in configurations will result in a wider spread in total energy consumption among different solutions. Out of the ten optimized solutions, the most optimized one consumes significantly less energy for the base cases, and also performs quite similarly to other solutions under different variations.

4 Conclusion

The industrial sector is one of the heaviest consumers of energy; therefore, any slight percentage saving in energy consumption could be translated into a large absolute sum. This paper demonstrates how building performance simulation and optimization can help to achieve the goal of lowering energy consumption for industrial halls. Findings from this paper also provide evidence for the otherwise intuitive notion that a high level of insulation does not help buildings with high process load to dissipate the excess internal heat gain. There is also the potential for significant energy savings over ASHRAE baseline buildings simply by altering just a few demand-side design parameters. The savings are mainly due to the poor performance of the baseline building, which is prescribed without considering the unique characteristics of industrial halls. Findings from this paper also demonstrate that the most optimized design solutions will not have the same performance under different process loads and occupancy patterns. Even though robustness itself is a yet to be defined term, this paper demonstrates the importance of performing an uncertainty analysis to evaluate the robustness of the optimized design solutions and to identify solutions that are less susceptible to uncertainty. Inclusion of HVAC systems and generation systems in future studies will provide a more comprehensive view on how to achieve the ultimate goal of net-zero energy or energy producing industrial halls.

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