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Building Energy Simulation and Optimization of Industrial Halls

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ABSTRACT

Industrial halls are characterized with their rectangular shape and relatively simple construction, as contrasted with office buildings with similar floor area. Industrial halls are usually subject to high energy demand due to the many manufacturing processes, lighting, and the corresponding amount spent on space conditioning. Thermal comfort is seldom a concern for industrial halls. By contrast, saving in energy consumption for lighting and space conditioning is a big issue since even the modest percentage change in energy consumption could be translated into a large monetary sum.

With relatively loose requirement in space conditioning, and comparatively high internal heat gain; the approach in industrial hall design is quite different from that of office building. In fact, what poses to be an energy efficient design for office buildings might not be appropriate for high internal heat gain halls. The simplicity in the building geometry and the construction method allow the investigation of energy demand for space conditioning to be limited to a few number of demand side parameters (e.g. insulation value of walls); in which, change in values in some of the parameters presents a significant impact on the overall energy demand.

This paper investigates the impact of varying different demand side parameters on the energy demand for space conditioning and lighting for a typical industrial hall. Through building energy simulation, such impact can be investigated; and by applying optimization, the configurations of the most optimal combinations of parameters with the lowest energy demand can be identified. The result indicates that the energy demand of the least efficient configuration can be more than double of that of the optimized design solution. This paper will also explore green building assessment systems such as LEED, in terms of energy performance, with the studied industrial hall as an example. The huge energy saving brought by the optimized design solution over the baseline building of LEED suggests that there might be a potential deficiency of LEED rating system at its current state as it applies to industrial halls.

INTRODUCTION

The industrial sector is one of the heaviest consumers of energy. In the United States, the sector consumed 32% of the total energy consumption in 2009 (LLNL, 2010), while in Europe, this sector consumed 24% in 2009 (Eurostat, 2011). Some of the energy from this amount 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 (heating and ventilation) is provided to maintain the building within a reasonable or legally allowable temperature range. By contrast, saving in energy consumption for space conditioning and that for lighting is a big issue since even the modest percentage reduction in energy consumption could be translated into a large absolute monetary sum.

With relatively loose requirement in space conditioning, and comparatively high internal heat gain; the approach in industrial hall design is quite different from that of office building. In fact, what poses to be 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 building, allow the investigation of energy demand for space conditioning to be limited to a few number of demand side parameters (e.g. insulation value of walls), in which, change in values in some of the parameters affects the overall energy demand 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 multi-floor buildings. Investigating the benefit of daylighting, and the corresponding impact on ventilation 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, and will apply computational building performance simulation and optimization to identify the building design solutions on demand side parameters that will minimize the total energy consumption of ventilation, heating, and lighting. Predicted energy performance of the optimized design solutions will be compared to that of a baseline building prescribed by ASHRAE standard 90.1 (ASHRAE, 2007a) as required by LEED (USGBC, 2009) certification process under the Energy and Atmosphere category. This paper presents some of the results of an on-going project "Sustainable Energy Producing Steel Frame Industrial Halls", which also studies other operation energy related aspects.

SIMULATION AND OPTIMIZATION FOR INDUSTRIAL HALLS

This section will present the case study that involves energy performance simulation and optimization of an industrial hall, and comparison to the energy performance of a baseline building prescribed by ASHRAE standard 90.1.

The Case Study

The case study includes a hypothetical building, which represents a typical rectangular shape industrial hall in Amsterdam, the Netherlands. Process load at three different levels are applied to the case study building to cover a range of industries that are representative in the Netherlands. The baseline building is set up according to the requirement specified in ASHRAE standard 90.1 with few noted exceptions, to be discussed in later section, in which the requirement for office buildings are not applicable to industrial halls.

The Building. The hypothetical building measures 40 m (131 ft, W) x 100 m (328 ft, D) x 6 m (20 ft, H). Hypothetical scenarios are considered according to CIBSE Guide F (CIBSE, 2004) that covers industries from warehouse / distribution (with a process load close to 5 W/m^2 or 1.6 Btu/hr-ft^2) to electronics (45 W/m^2 or 14.3 Btu/hr-ft^2) to rubber / furniture (125 W/m^2 or 39.6 Btu/hr-ft^2). And in order to maintain a lighting level of 500 lx or 46 fc (CEN, 2002), fluorescent lighting with a lighting power density (LPD) of 16 W/m^2 (5.1 Btu/hr-ft^2) is assigned.

The workers are assumed to perform light work. For an industrial hall kind of environment, current guideline (ARAB, 2006) recommends that the temperature of the space has to be maintained under 30°C (86°F) to protect workers from heat stress and heating has to be provided only if the space drops below 18°C (64°F) during occupied hours. Occupancy pattern depends on seasonal factors, economic cycles, industry specific characteristics, and others. In order to facilitate comparison among design options and different scenarios, full-time operation is assumed for all cases.

The building is built with steel cladding on a steel frame. The baseline building is assigned with insulation according to ASHRAE standard 90.1 mandatory provisions; the insulation for the wall and the roof requires a minimum resistance value of R$_{SI}$-2.3 (R-13.0) and R$_{SI}$-3.3 (R-19.0) respectively. Ventilation rate at 0.55 L/s-m^2 (0.1 cfm/ft^2) is adopted according to ASHARE standard 62.1 (ASHRAE, 2007b).

For a typical steel frame industrial hall, usually an infiltration rate from 0.1 to 0.5 ACH is expected (ISSO, 2002). For the baseline building (since specific value is not prescribed by the standard); simulation in step of 0.1 ACH has been performed, and the average of the predicted energy performance values across the five infiltration rates is applied.

Certain aspects of daylighting are discussed in the standard, but no value is prescribed to specify or to recommend the amount of daylighting; therefore, no daylighting is assumed for the baseline building. The building is located in Amsterdam, the Netherlands, which is classified as ASHRAE climate zone 5 (ASHRAE, 2007a) with a warm summer and a cold but not severe winter that is similar to cities in the United States like Boston, MA, or Pittsburgh, PA.

Demand side design parameters. The building might not be optimally designed in terms of consuming the lowest energy; if it is designed according to the default values as prescribed by the standard. For example, insulation intends to isolate the space from the external elements might not be desirable for building with high internal heat gain, in which the heat is needed to be dissipated than to retain. **Table 1** lists the demand side design parameters that are to be investigated in this study and presents the ranges of values for each parameter. These values are within practical range; that is, no custom made construction is necessary to implement any of these specifications. Any configuration based on possible combination of these values can be readily built. Values assigned for the baseline building are highlighted in bold. There is no prescribed value for airtightness. In practice, airtightness is not an implementable quality that can be applied the same way as insulation is to be installed. Instead, airtightness can only be achieved through a combination of procedures, such as use of continuous barrier, proper workmanship at joints, and installation of weather seals. In this paper, airtightness is arbitrarily defined in terms of infiltration rate, which is a derived measure for airtightness.

With the heat released from the processes, in practice, cooling is the predominant factor in HVAC energy demand if the industrial halls are not located in extreme cold climate. Since this paper is focus on demand side parameters only, both cooling and heating are assumed to be under ideal control; that is, the energy demand predicted by the simulation is the theoretical amount of energy needed to be removed to cool and to 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. Based on previous studies of the authors on forced ventilation on industrial halls, cooling energy demand is translated into cooling energy consumption by a rather conservative factor of 10, which can be considered as a cooling system running at a constant efficiency. Heating energy consumption is assumed to be the same as the demand.

Lighting is also a major energy consumer in buildings. Daylighting (through diffuse skylight) is an effective means to lessen the reliance on artificial lighting that is dimmed with sensor control switch. The saving in energy for lighting will be somewhat offset by the additional cooling load due to heat gain during the day and heating load due to heat loss during the night particularly in the winter. The exact benefit of daylighting can be evaluated only after a thorough study with consideration of HVAC influences.

Energy Performance Analysis

The building energy performance simulation program TRNSYS is used to perform the energy analysis for cooling and heating demand. Energy demand 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 at each of the 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).

Optimization. Optimization is deployed to search for the optimized design solutions that consume the least amount of total energy for cooling, heating, and lighting. With four design parameters, there could be hundreds of thousands of different configurations. A complete search through all the configurations is computational intensive.

With appropriate algorithms, optimization can search for the optimized design solutions without the need of covering 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 simulation and post-processing tools, namely, TRNSYS, DAYSIM and MATLAB in this case study. For each simulation, MODEFRONTIER will base 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 optimum (Poles, 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 values for each parameters) 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. 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.

LEED Credits Evaluation

Green Building Rating (GBR) systems available today, in general, concern about energy conservation. However, these systems differ greatly in their purposes and scopes; and as a result, the amount of points available and the criteria to obtain the points are quite different. In this paper, only the LEED system (USGBC, 2009) will be explored.

Under the LEED 2009 Rating System (part of version 3 certification program), 35 points can be obtained under the "Energy and Atmosphere" (hereafter referred as "EA") category and worth more than 30% of all available points. Out of the 35 points, 19 points are awarded to EA Credit 1 — Optimizing Energy Performance. In order to obtain points with EA Credit 1, the proposed building has to demonstrate that there is an energy cost saving as compared to the baseline building. An energy cost saving of 10% over the baseline building is the minimum requirement. Points are awarded starting from 1 point based on 12% saving up to 19 points based on 48% saving.

The energy cost saving can be demonstrated with a whole building energy simulation. A comparison between the energy performance of the optimized design solutions and that of the baseline building will be performed. Since only demand side design parameters are considered, energy cost is directly proportional to energy consumption. By contrast, if energy generation is considered, energy cost depends on the choice of generation technologies (with different feed-in tariffs, and different import and export pricing structures), and therefore, can no longer be assumed to be directly proportional to energy consumption. In this paper, saving in energy consumption is discussed rather than that in energy cost, to preclude exposure to fluctuation in energy price and currency exchange. Other energy related credits are also available, include that for use of on-site renewable energy, use of green power, and others, which are outside the scope of this paper.

Baseline building model for industrial hall. A baseline building has to be set up according to ASHRAE standard 90.1 Appendix G in order to apply for EA Credit 1. Since energy is primarily used for manufacturing processes, direct applicability of the standard for industrial halls is not granted. The major differences between a standard baseline building in climate zone 5 and the studied hypothetical baseline building are described in this section.

The most notable exception is the baseline HVAC system type, in which the standard prescribes packaged VAV system for nonresidential building of the studied floor size. For the purpose of this paper, that is, to investigate the effect of varying demand side design parameters; the inclusion of a specific HVAC system type will mask the investigation in a way that the effect of those parameters on cooling and heating load is largely dependent on the efficiency and characteristic of the HVAC system. Therefore, cooling and heating on ideal control is adopted, instead.

As stated previously, industrial halls are maintained above 18°C (64°F) and under 30°C (86°F). This rather loose requirement for space conditioning comes as a contrast to the range of 21°C (70°F) to 24°C (75°F) as suggested by the standard. Moreover, no hot water demand is assumed for industrial halls (hot water for manufacturing processes is outside the scope of the standard). Precision works are performed inside industrial halls; a lighting level of 500 lux (46 fc) is desirable. Therefore, a higher LPD of 16 W/m^2 (5.1 Btu/hr-ft^2) is assigned (based on recommendation of industrial contacts), as opposed to the 12 W/m^2 (3.8 Btu/hr-ft^2) as suggested by the standard for nonresidential conditioned space.

RESULTS AND DISCUSSION

The energy consumption is comprised of that for cooling, heating, and lighting. In general, because of the moderate climate and the rather loose requirement for space conditioning, energy consumption for cooling and heating is comparatively low as compared to that for lighting. **Table 2** presents the predicted energy consumption values for cooling, heating, lighting, and the total of all of each, 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, i.e. 15 generations of 40 samples). The percentage saving of the optimized design solution is also presented.

Halls with higher process load virtually require no heating at all. As process load increases, the primary concern is to dissipate the excess internal heat gain as much and as quick as possible; and 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.

Characteristics of Optimized Design Solutions

The building is subject to process loads ranging from 5 W/m^2 (1.6 Btu/hr-ft^2) to 125 W/m^2 (39.6 Btu/hr-ft^2). 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 1** presents design solutions within 2% deviation of the most optimized design solution for each of the three process load scenarios. Each parallel line represents a design solution of a different combination of values of the four demand side parameters. 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 load, such as those of 125 W/m^2 (39.6 Btu/hr-ft^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; and that results in halls having similar performance for a variety of different configurations. Scenario of 5 W/m^2 (14.3 Btu/hr-ft^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 stays similarly, as long as the halls are fitted with high level of daylighting. However, an inspection into the numerical values of cooling and heating energy consumption will discover that even though the total energy consumption is within 2% of 115 kWh/m^2 (36.6 Btu/ft^2, the most optimized design solution); cooling energy consumption ranges from 9 to 14 kWh/m^2 (2.9 to 4.4 Btu/ft^2) and heating energy consumption ranges from 0 to 5 kWh/m^2 (0 to 1.6 Btu/ft^2) for the many possible solutions.

As process load increases to 125 W/m^2 (39.6 Btu/hr-ft^2), heating is no longer required for all studied solutions.

Halls with no insulation dissipate heat more efficiently. In general, higher coverage of roof with skylight for daylighting will lower the lighting energy consumption in the expense of higher solar heat gain, and thus an increase in cooling energy consumption. However, as process load increases, the amount of heat gain induced through the skylight becomes negligible as compared to that of the process load. In order to cope with the excess internal heat gain, the main concern is not to reduce solar heat gain during the day, but to reduce the overall thermal resistance to promote heat dissipation. Since skylight is assumed to be double-glazing with U_{SI}-2.89 (U-0.50); therefore, for solutions with no insulation, reducing the amount of skylight helps reducing the overall thermal resistance (single-glazing with lower thermal resistance has not been evaluated in this paper). Some solutions indicate that a 10% coverage with skylight is also desirable.

To illustrate the issue of the interdependent nature between cooling and heating, **Figure 2** puts into order the different design solutions, from the least energy consuming (in terms of cooling and heating) one to the most energy consuming one, for each of the three process load scenarios.

It can be observed that for most studied configurations, no heating is necessary; especially as process load increases. For the low process load scenario of 5 W/m^2 (1.6 Btu/hr-ft^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 (14.3 Btu/hr-ft^2), the additional internal heat gain somewhat compensates the heat loss through the building envelope, and therefore, the worst design solutions (with no insulation) for this scenario consume much less energy than similarly configured solutions under the low process load scenario. As process load increases beyond 125 W/m^2 (39.6 Btu/hr-ft^2), heating is absolutely not necessary.

Improvement over LEED Baseline Building

With changes in the four demand-side design parameters, a percentage saving of 25% to 37% in total energy consumption can be obtained for the studied process load scenarios. Optimized design solutions offer a consistent 26% saving in lighting over the baseline building, and offer significant saving in cooling, ranging from 33% for the low process load halls to 51% for the high process load ones.

In the case study, cooling energy consumption is assumed to be one-tenth of that of the theoretical cooling energy demand. In practice, forced ventilation with heat recovery is a common system for industrial halls in a moderate climate. The cooler ambient air in the summer months is in general more than sufficient to remove the excess heat gain due to the process load and to maintain the rather high setpoint temperature of 30°C (86°F). Under this premise, cooling energy consumption can be drastically reduced percentage wise, particularly for high heat gain halls. The standard prescribes packaged VAV for the baseline building (buildings that are less than 5 floors and are between 2,300 m^2 (25,000 ft^2) and 14,000 m^2 (150,000 ft^2)), which operates at an efficiency that is an order of magnitude lower than that for forced ventilation. Therefore, if the proposed building is assigned with forced ventilation, it is reasonable to believe that, many design solutions will be able to obtain the full 19 LEED points with saving of more than 48% in energy consumption over the baseline building with packaged VAV.

And from the results of the analysis, applying a single set of prescribed insulation levels for all buildings (for a particular climate zone and construction type) does not seem to serve the purpose; that is, the baseline building can perform quite poorly particularly under high process load. Because of the poor performance of the baseline building, particularly for high process load scenarios; LEED points are awarded indiscriminately with just little changes in few demand side design parameters (such as insulation), and are insensitive to additional effort made for further improvement since full LEED points are already obtained. Therefore, if obtaining LEED certification is the sole motive for building owners, then under current LEED rating system, there is no incentive to make significant energy cutting measures.

CONCLUSION

Industrial sector is one of the heaviest consumers of energy; any slight percentage saving in energy consumption will be translated into a large absolute sum. This paper shows 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 to the otherwise intuitive notion that high level of insulation might not work well with high internal heat gain buildings. This paper also demonstrates the potential deficiency of current LEED rating system, particularly for industrial halls, which might award points that do not truly reflect any significant improvement in energy consumption. The root of the issue lies in a poorly performed baseline building, which is prescribed without considering the unique circumstances of industrial halls.

Future work

In this study, only a few demand side design parameters are investigated. Incursion of HVAC systems and generation systems will provide a more comprehensive view on how to lower energy consumption for industrial halls. As process load increases, the predicted energy consumption becomes more sensitive to changes in input parameters. Other than the four studied parameters, there are assumed and prescribed values for many more parameters. Changes in those values will have a large impact in the predicted energy performance. An uncertainty analysis in the more significant parameters will help to select the design solutions that are more robust and less susceptible to uncertainty.

REFERENCES

ARAB. 2006. Artikel 148, Titel II - Algemene bepalingen betreffende de arbeidshygiëne alsmede de veiligheid en de gezondheid van de arbeiders. Brussels: Algemeen Reglement voor de arbeidsbescherming.

ASHRAE. 2007a. Standard 90.1 — Energy Standard for Buildings Except Low-Rise Residential Buildings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. 2007b. Standard 62.1 — Ventilation for Acceptable Indoor Air Quality. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

CEN. 2002. EN 12464-1, Light and lighting – Lighting of work places – Part 1: Indoor work places. Brussels: Comité Européen de Normalisation.

CIBSE. 2004. CIBSE Guide F Energy efficiency in buildings. London: Chartered Institution of Building Services Engineers.

Eurostat. 2011. Final Energy Consumption, by Sector. http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/ data/main_tables, accessed May 11, 2011.

ISSO. 2002. Handboek Installatietechniek. Rotterdam: Instituut voor Studie en Stimulering van Onderzoek op het gebied van gebouwinstallaties

LLNL. 2010. Estimated U.S. Energy Use in 2009. Livermore: Lawrence Livermore National Laboratory.

Poles, S. 2004. MOGA-II Performance on Noisy Optimization Problems. International Conference on Bioinspired Optimization Methods and their Applications, Ljubljana, Slovenia

Rubinstein, F., L. Xiaolei, D.S. Watson. 2010. Using Dimmable Lighting for Regulation Capacity and Contingency Reserves in the Ancillary Services Market. A Feasibility Study. PIER Buildings End-Use Energy Efficiency Program.

USGBC. 2009. LEED 2009 for New Construction and Major Renovations Rating System with Alternative Compliance Paths For Projects Outside the U.S. Washington, DC: U.S. Green Building Council.
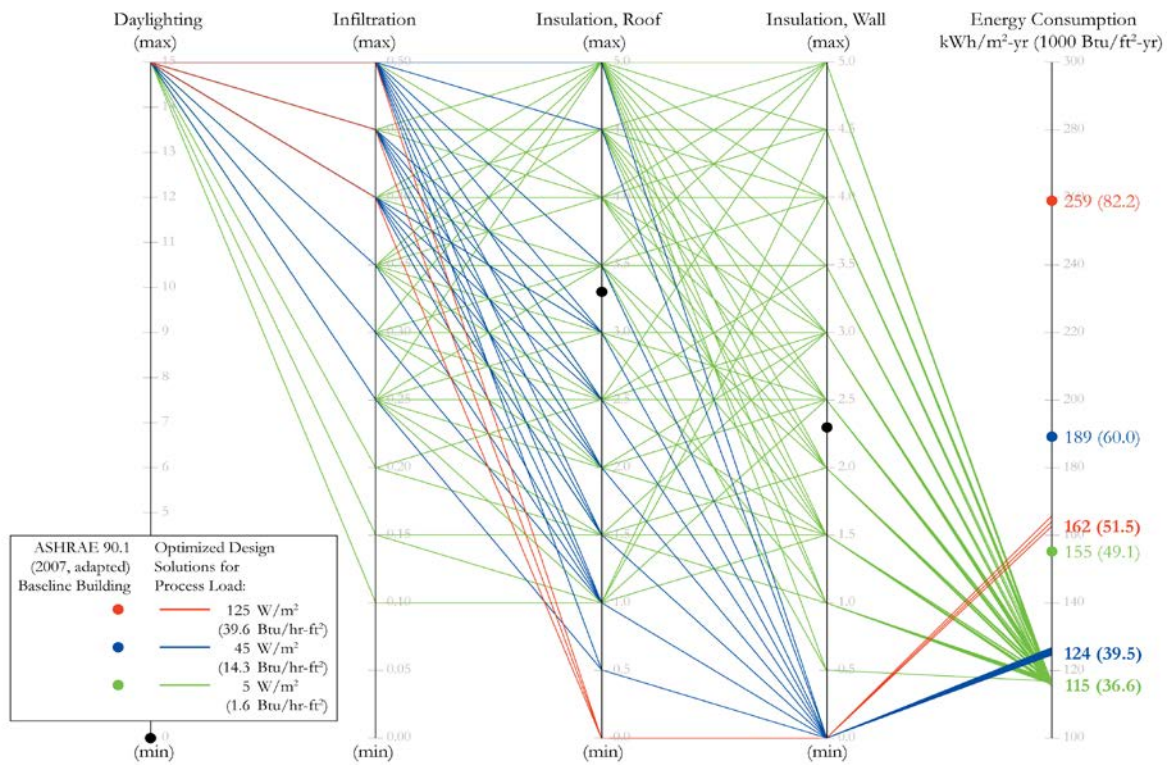
Table 1. Demand Side Design Parameters

Parameters	Design Range (SI units)	Design Range (IP units)
Resistance of roof insulation	0 – **3.3** – 5.0 (R_{SI})	0 – **19.0** – 28.5 (R)
Resistance of wall insulation	0 – **2.3** – 5.0 (R_{SI})	0 – **13.0** – 28.5 (R)
Airtightness (as infiltration rate)	0 – 0.5 (ACH)	0 – 0.5 (ACH)
Daylighting (as % of roof area)	**0** – 15 (%)	**0** – 15 (%)

Table 2. Energy Consumption for Cooling, Heating, Lighting, and the Total

Scenarios	Cooling kWh/m^2-yr (1000 Btu/ft^2-yr)	Heating kWh/m^2-yr (1000 Btu/ft^2-yr)	Lighting kWh/m^2-yr (1000 Btu/ft^2-yr)	Total kWh/m^2-yr (1000 Btu/ft^2-yr)
5 W/m^2 (1.6 Btu/hr-ft^2)				
Baseline	15 (4.7)	0 (0.0)	140 (44.4)	155 (49.1)
Optimized	10 (3.2)	2 (0.5)	104 (33.0)	115 (36.6)
Saving (%)	33%	-	26%	25%
45 W/m^2 (14.3 Btu/hr-ft^2)				
Baseline	49 (15.6)	0 (0.0)	140 (44.4)	189 (60.0)
Optimized	20 (6.2)	1 (0.3)	104 (33.0)	124 (39.5)
Saving (%)	60%	-	26%	34%
125 W/m^2 (39.6 Btu/hr-ft^2)				
Baseline	119 (37.8)	0 (0.0)	140 (44.4)	259 (82.2)
Optimized	58 (18.5)	0 (0.0)	104 (33.0)	162 (51.5)
Saving (%)	51%	-	26%	37%

Figure 1   Optimized design solutions and baseline building configuration of industrial halls for each of the three process load scenarios
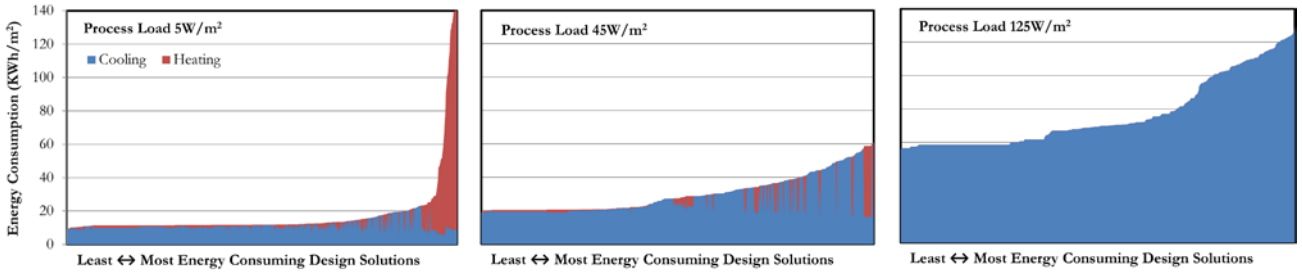
Figure 2 Energy consumptions for cooling and heating, in the order from the least amount to the highest amount, for each of the three process load scenarios.