Are Optimized Design Solutions Robust Enough? A Case in Point — Industrial Halls with Varying Process Loads and Occupancy Patterns

B.Lee[1,2,*], M.Trcka[2] and J.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

ABSTRACT

Industrial halls are mainly low-rise rectangular shape structures of simple construction. Manufacturing processes, lighting, and the corresponding amount of energy spent on space conditioning to remove the excess heat gain, all contribute to the high energy demand of industrial halls. Since thermal comfort is seldom a concern; the relatively loose requirement in space conditioning and the comparatively high internal heat gain make the approach in industrial hall design quite differs from that of office building design.

The simplicity in the building geometry and the construction method allow the investigation of energy demand for building services to be limited to a few number of demand side parameters (e.g. insulation value of walls). Through building performance simulation and optimization, this paper will identify the most optimal combinations of values of demand side parameters that will minimize the total energy consumption of ventilation, heating, and lighting for a typical industrial hall.

For industrial halls, energy demand for building services could be very sensitive to changes in the process load and occupancy pattern, which in reality, fluctuate widely due to seasonal cycles, and other factors. 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. To take into account such possible 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.

[*] Corresponding author email: b.lee@m2i.nl. M. Trcka is currently a senior research scientist at United Technologies Research Center (UTRC), East Hartford, CT, United States

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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 sum.

With relatively loose requirement in space conditioning, comparatively high internal heat gain, rather simple building geometry and construction method, and single floor structures that allow effective deployment of energy saving or generation measures; 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 single most dominant source of heat gain is the process load 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.

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 process loads. Through computational building performance simulation and optimization, this paper will identify the building design solutions on demand side parameters that will minimize the total energy consumption of ventilation, heating, and lighting. However, because of the great uncertainty in process load and occupancy pattern, the optimized design solutions will be challenged 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 operation energy related aspects.

SIMULATION, OPTIMIZATION, AND UNCERTAINTY ANALYSIS

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

The case study building

The case study includes a hypothetical building, which represents a typical industrial hall in Amsterdam, the Netherlands, that measures 40 m (W) x 100 m (D) x 6 m (H). Hypothetical scenarios are considered with reference to CIBSE Guide F (CIBSE 2004), which cover a range of industries that are representative in the Netherlands, from distribution (with a process load in the neighbourhood of 5 W/m^2) to chemical / electronics (45 W/m^2) to rubber / furniture (125 W/m^2). And in order to maintain a lighting level of 500 lx (CEN 2002), fluorescent lighting with a lighting power density of 16 W/m^2 is assigned as suggested by industrial sources.

The building is built with steel cladding on a steel frame. For the location of Amsterdam, which is classified as ASHRAE climate zone 5 with a warm summer and a cold but not severe winter; ASHRAE standard 90.1 (ASHRAE 2007a) prescribes minimum resistance values of R_{SI}-2.3 and R_{SI}-3.3 for the wall and the roof respectively. 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. 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).

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 to protect workers from heat stress and heating has to be provided only if the space drops below 18°C during occupied hours. Actual process load and occupancy pattern depend on many previously described factors. For this study, the baseline investigation assumes full-time operation at the above mentioned process load scenarios.

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 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 ranges; custom made construction is not necessary to implement any of these specifications. Values prescribed by the standard are highlighted in bold (no prescribed value for airtightness and daylighting). In practice, airtightness is not a directly implementable quality. 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.

Table 1. *Demand side design parameters*

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

Since this paper is focus on demand side parameters only, both cooling and heating are assumed to be under ideal control. In practice, forced ventilation with heat recovery is a common system for industrial halls in a moderate climate, in which 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 heat gain or heat loss. The exact benefit of daylighting can be only evaluated after considering these thermal side effects.

Energy performance analysis

The building energy performance simulation program TRNSYS is used to perform the energy analysis for cooling and heating demands. Energy demand by the hour is evaluated and aggregated for the year. DAYSIM is used to evaluate the illuminance level on the work surface at each of the hour due to daylighting. 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 thousands of different configurations. A complete search through all configurations is computational intensive. With appropriate algorithms, optimization can search for the optimized design solutions without 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 simulation and post-processing tools, namely, TRNSYS, DAYSIM and MATLAB.

Out of the many available algorithms in MODEFRONTIER, MOGA (multi-objective genetic algorithm) is chosen as the optimization algorithm. Though it is commonly deployed for multi-objective optimization, its efficiency in searching for global optimum (Poles 2004) makes it a good candidate, 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 parameter) is generated with Latin Hypercube Sampling. 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 is set to stop after 15 generations.

Uncertainty analysis

There will be great uncertainty in the process load as a result of operating more or fewer production lines, or variation in the occupancy pattern that ranges from 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.

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

Variations	*Deviations*
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
One-shift	Monday – Friday, 08:00 – 18:00

RESULTS AND DISCUSSION

The energy consumption comprises 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 3 presents the predicted total energy consumption values, for each of the three process load scenarios, and of both the most optimized design solution and the building with ASHRAE standard 90.1 prescribed envelope. The most optimized design solution is the result of a search through 600 configurations, i.e. 15 generations of 40 samples; the optimization converged at the last few generations without further improvement.

Table 3. *Total energy consumption (cooling, heating, lighting) of the optimized design solution / that of the building with ASHRAE standard 90.1 prescribed envelope*

Scenarios	*Energy consumption, Wh/m^2h (percentage saving)*
5 W/m^2	13.2 / 17.7 (25%)
45 W/m^2	14.2 / 21.6 (34%)
125 W/m^2	18.5 / 29.6 (37%)

Annual energy consumption is commonly expressed in the unit of kWh/m^2. In this study, the energy consumption per operating hour (that is, in the unit of Wh/m^2h) allows a fairer comparison between different occupancy patterns and provides more information for the operation owners since the unit cost of the product is directly proportional to the hourly cost of the energy instead of to an annual sum.

It can be observed from the results that optimized design solutions offer significant saving over building with ASHRAE standard 90.1 prescribed envelope. In general, as process load increases, the primary concern is to dissipate the excess internal heat gain as much and as quick as possible. Therefore, a high insulated and airtight hall does not perform well. Similarly, solutions that work best for a certain process load might not perform well for other process loads. Figure 1 to Figure 3, present the ten most optimized design solutions with the least total energy consumptions for each of the three process load scenarios. On the same diagrams, energy consumptions for the variations in process load and occupancy pattern are also presented.

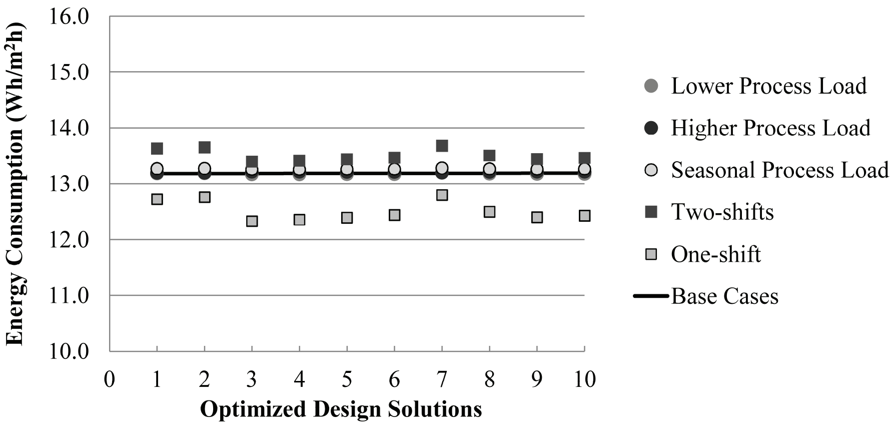

***Figure 1**. Energy consumption of optimized design solutions for the $5W/m^2$ process load scenario with variations in process load and occupancy pattern.*

The most optimized design solution for the scenario with process load of $5W/m^2$ consumes 13.2 Wh/m^2h for each occupied hour. If full-time operation is not required, energy consumption per occupied hour increases to 13.6 Wh/m^2h for a two-shift operation and decreases to 12.7 Wh/m^2h for a one-shift operation. This information is crucial for operation owners since an increase in per unit cost will affect the marginal profit; and in this particular case, decision has to be made to see if a two-shift operation is indeed a profitable one.

The energy consumption of design solution case 3 is less than 0.03% different from the most optimized design solution. And the worst variation of having two-shift operation consumes only 13.4 Wh/m^2h. 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 $5W/m^2$, it can be observed that 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 occupancy pattern.

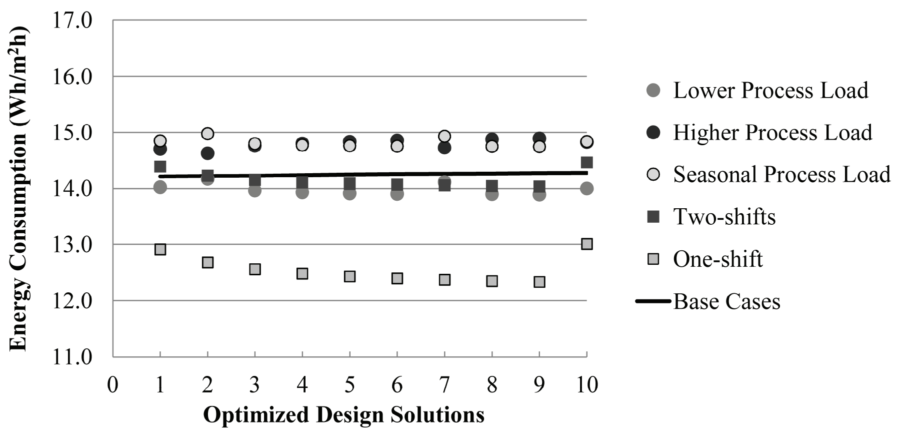

Figure 2. *Energy consumption of optimized design solutions for the 45W/m^2 process load scenario with variations in process load and occupancy pattern.*

Scenario of 45W/m^2 best illustrates the intricate relationship between cooling and heating demands. Some design solutions opt for more cooling with no heating, while others favour less cooling with a bit of heating; and the total energy consumption across the ten optimized solutions are quite similar. Those solutions with anticipated heating 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 seasonal production cycle.

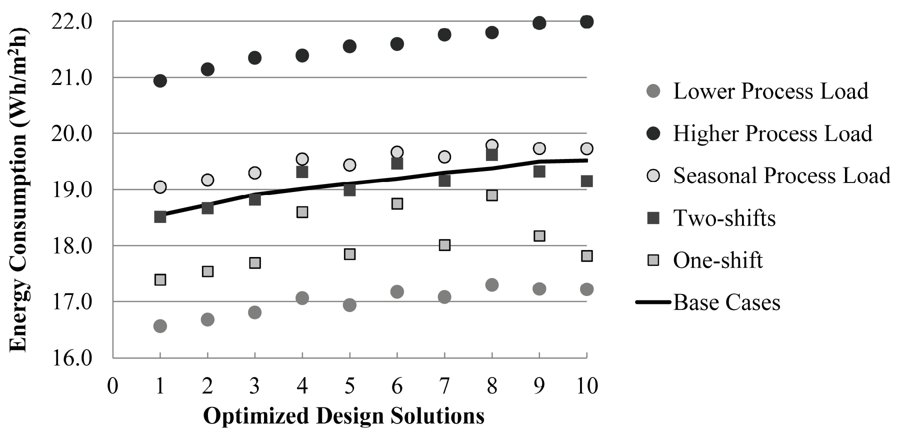

Figure 3. *Energy consumption of optimized design solutions for the 5W/m^2 process load scenario with variations in process load and occupancy pattern.*

For the process load scenario of 125 W/m^2, heating is no longer required for all studied solutions. Increase in process load will induce 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.

CONCLUSION AND IMPLICATIONS

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 demonstrate that the most optimized design solutions might not perform well under different process loads and occupancy patterns. An uncertainty analysis can be deployed to evaluate the robustness of the optimized design solutions and identify solutions that are less susceptible to uncertainty. Incursion of HVAC systems and generation systems in future studies will provide a more comprehensive view on how to lower energy consumption for industrial halls.

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