Full-factorial design space exploration approach for multi-criteria decision making of the design of industrial halls

Bruno Lee[1,2,*], Navid Pourmousavian[1], Jan L.M. Hensen[2]

[1] Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec, Canada

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

* Corresponding author. Tel: +1-514-848-2424 ext. 5399
Fax: +1-514-848-7965
E-mail address: bruno.lee@concordia.ca

Abstract

Industrial halls pose high energy saving potential that is not yet explored under current design practice. Common design approaches such as parametric study or optimization are largely constrained by the assumptions and do not promote flexibility in the decision making process. Based on the unique characteristics of industrial halls, this paper develops a full factorial design space exploration approach to support multi-criteria design decision making. Energy performance, environmental impact, and cost effectiveness are studied over the whole life cycle. The approach is demonstrated with a case study of a warehouse in Amsterdam. Design parameters of interest are the insulation values, construction types, skylight coverage and transpired solar collector coverage. The results indicate that this approach offers design solutions that might not be otherwise identified. The non-case-specific one-time investigation allows objective space of derived performance to be generated dynamically based on even changing information or inputs specified by the users at the time of making the decision. This new design support approach facilitates designers to assess feasibility of any design solution based on their own desired set of performance requirement under different probable scenarios in the future.

1 Introduction

Industrial halls studied in this paper, are relatively simple single-storey rectangular shaped building structures with large floor area. They are commonly constructed in suburban industrial settings in Europe and North America according to current practices without considering sustainability issues. The heuristic approach or an optimization approach, which work very well for other building types might not fully address the issues facing the design of industrial halls. In fact, as a particular building type, industrial halls pose certain characteristics that might require special considerations and offer opportunities for significant energy performance gain. However, there is a lack of research in quantifying the impact of energy saving measures as they are deployed on industrial halls (not to mention the collective impact on the overall performance due to the combinations of these measures), a design support approach for industrial halls is needed to be developed.

Industrial sector accounts for 26% of the total energy consumption in 2011 in Europe [1] and 31% in the same year in the US [2]. Energy is used for both the manufacturing processes and the operation of buildings. In one report [3], non-manufacturing process activities account for 15% of the energy consumed, out of which, more than 80% is consumed on lighting and space conditioning. Understandably, industrial halls are not expected to be conditioned to the same comfort level as required for office buildings, cooling energy for halls with higher process loads can also be significant, on the other hand, lighting energy can be substantial for halls with lower process loads. Even though energy is one of the most significant contributors to sustainability, most industrial halls are not following energy codes or standards since most building standards do not apply to industrial buildings. Energy saving potential or emerging energy generation technologies for industrial halls are seldom explored [4].

Awareness in sustainability issues in buildings has accelerated the development of green building rating systems such as LEED [5], BREEAM [6], and others. These systems cover all life-cycle phases from

construction to demolition, and different design aspects from energy efficiency to material choice. However, these systems are mainly catered for office buildings. Their applicability to industrial halls is unclear. It is particularly the case for operational energy consumption since it constitutes a significant portion of the life-cycle energy consumption of industrial halls. LEED points related to operational energy performance does not faithfully represent the significance of operational energy for industrial halls under the current LEED point conversion scheme. Contribution of embodied energy in the building materials to the total life-cycle energy consumption also cannot be ignored. Because of the large floor area, saving in operational energy consumption implies compelling financial benefit for the building owners. In this paper, multi-objective life-cycle analysis is deployed to facilitate informed design decisions in terms of energy performance (including both embodied energy in the building materials and operational energy), environmental impact and cost effectiveness of operational energy related measures for industrial halls. In fact, current European energy policy actually states that performance should be considered for the whole life-cycle of buildings in terms of energy, environmental, and cost [7]. The investigation should include an exhaustive exploration of different design options, such as choices of material, types of constructions, and sizes of components. A building energy simulation based design support approach is developed to systematically assess the aforementioned performance aspects for the whole life-cycle.

2 Current practice in industrial hall design

Published design guides [8 – 11] provide recommendations for many of the design options. ASHRAE design guide [8] suggests a 30% energy savings for a warehouse over ASHRAE Standard 90.1 [12]. TargetZero design guide [11] manages to achieve zero carbon emissions through aggressive energy generation. In both design guides, design options are grouped into improvement packages to achieve the stated design goal. For example, it is recommended to have a roof insulation with a thermal resistance of 3.5 m^2K/W and a skylight coverage of 5% - 7% of gross roof area for a warehouse in the Netherlands (ASHRAE Climate Zone 5). These improvement packages indeed achieve significant energy

saving. However, the heuristic and deterministic approach associated with the development of these packages fails to consider the followings:

- ***Multiple operational scenarios***: there are operational scenarios other than the assumed one. For example, skylight coverage favors day-shift operation, but not full-time operation.

- ***Multiple design objectives***: other than energy efficiency, there could be other design objectives such as lowering cost and reducing carbon emissions. In other words, there could be other improvement packages at different performance levels of cost effectiveness and carbon emissions that could achieve the same energy efficiency level.

- ***Multiple design options***: the previous notion also highlights the fact that there may be improvement packages that could achieve better energy efficiency at the same cost. Current design guides that focus on energy efficiency alone tend to ignore the many potential design options that could serve different combinations of design objectives.

2.1 Multi-objective optimization approach in current practice

As opposed to heuristic approach studying limited number of improvement packages, multi-objective optimization offers a systematic and computational efficient way to search through the design space for optimized design solutions [13]. The only outcome of the optimization approach is the optimized design solutions.

In practice, the optimization approach requires full knowledge of what is to be optimized. This requirement of full knowledge creates two issues. The first issue: the objective function must be defined before performing an optimization, which implies that the resulting optimized design solutions perform well only for the studied performance indicator. For example, the solutions that optimized for annualized relative cash flow (to be defined later) might not have the shortest simple payback period even though both are performance indicators of cost effectiveness. There are many other performance indicators of cost effectiveness than the two mentioned here. Each of these indicators serves a particular purpose that might not have been well considered at the time the indicator is assigned. The

issue is especially problematic at early-design stage of the buildings, in which there is an iterative process between design evaluation and design decision. Sometimes, it is not at all apparent what could be the suitable performance indicator at the time of the evaluation; it is not until a later stage that the performance indicator is found to be insufficient to support the decision making to achieve the design objective. New round of optimization has then to be performed for each additional performance indicator, which causes significant overhead in the design process and dissuades innovative design that more often than not requires uncommon evaluation procedure and performance indicator.

2.2 Performance aspects, performance indicators, and design objectives

Unlike evaluation of energy performance, evaluation of certain performance aspects are depending on other performance aspects. Performance indicators for those performance aspects are therefore termed as "derived performance indicators". For example, the cost effectiveness of energy saving measures is in fact a derived function of energy saving and a few input assumptions such as utility prices, which change from time to time. Derived performance indicators are only valid for the assumed set of values and not for another set of values. In fact, there is a conceptual difference between direct performance indicators (e.g. energy consumption) and derived performance indicators (e.g. cash flow), in which the results of direct performance indicators are the direct outputs of the simulation models based on designer-specified design parameters, while the results of derived performance indicators are depending on the values of external scenario parameters that are outside the control of the designers. Hopfe differentiates in details between design and scenario parameters [14]. This second issue has a prolong effect over the lifespan of the design. If the annualized relative cash flow is the performance indicator, the investigation requires knowledge of the utility rates which change over time. Optimized design solutions are no longer valid when utility rates change.

With predefined design objectives and fixed input assumptions, the optimization approach severely limits the flexibility which would otherwise be possible with derived performance indicators. This paper

proposes a full-factorial design space exploration approach, which covers all configurations in the design space, to offer greater flexibility to the designers and promote informed design decisions.

3 Development of the full factorial design space exploration approach

The goal of this paper is to develop an approach to support multi-criteria decision making of the design of industrial halls. A suitable approach should be catered for the characteristics of the building type of interest. The unique characteristics of industrial halls allow a systematic exhaustive search through the whole design space. The observation of the characteristics of industrial halls plays an important role in developing the approach and forms an integral part of the methodology.

3.1 Observing the characteristic of industrial halls

Industrial halls as a particular building type house a variety of industries from retails, to logistics, to heavy industry. The interest of this paper is the operational energy design (limited to heating, cooling, and lighting) and not the activities (e.g. manufacturing processes) of the buildings.

- *Loose thermal comfort requirements*: Thermal comfort is not a concern in the design of industrial halls, where the space is needed to be maintained within legally allowed temperature range to prevent heat stress [15]. A Belgian guideline [16] explicitly sets a temperature range of 18°C to 30°C for workers performing light work. There is also no regulation to how the temperature is allowed to fluctuate. Energy efficient equipment, even with loose temperature control, can be a viable alternative to more common heating and cooling equipment for office buildings.

- *Simple geometry and construction methods:* Rectangular shaped structures serve most functions well, from manufacturing to storage. The relatively low land cost in industrial areas also favors the construction of single-storey building [18]. In fact, single-storey layout facilitates logistics of the manufacturing process, from receiving raw materials, to transporting between different operations, to delivery of products. Skylights (as opposed to windows) allow daylight to cover the entire floor area and is an effective means to introduce daylight [19]. Roofs and walls are commonly built in

simple construction of steel (e.g. steel sandwich panels) or concrete (e.g. precast panels with insulation on the outside, such as EIFS - Exterior Insulation and Finish Systems). Walls of steel sandwich panels or concrete panels can be considered as continuous air and vapor barriers with high airtightness [20, 21]. With simple geometry and construction methods, the design parameters related to the energy performance of industrial halls have been greatly reduced. With a limited number of parameters, it is possible to investigate each parameter quantitatively.

- *Single-storey structure:* Wall surfaces cover a significant portion of the building enclosure for office buildings. By contrast, the roof-to-floor area ratio is equal to one for single-storey industrial halls. Both external factors (e.g. solar radiation) and internal factors (e.g. process load) are proportional to the floor area. Orientation also does not play an observable role for industrial halls in the absence of windows. For industrial halls of typical or larger size, unit area performance value of a generic industrial hall can be scaled and applied to another industrial hall of the same design configuration.

- *Sparsely built and monotonous sites:* Industrial parks covering large area are generally flat to facilitate logistics and laying out of equipment. Business issues (e.g. low land cost and reserve for future expansion) and practical considerations (e.g. large loading area) result in industrial areas that are sparsely built. Land-to-building ratios of 2 to 10 are quite common. In such setting, there is no interactive relationship (e.g. shading effect) between an industrial hall and its neighboring buildings in terms of energy performance. This characteristic further supports the previous notion that performance results of one hall can be applied to other halls of the same construction and location.

- *Discrete occupancy patterns:* In general, industrial halls are not densely occupied, ranging from approximately 2 to 0.2 occupants/100 m^2 [23, 24]. The occupant load factor is significantly less than that of office buildings, ranging from 5 to 60 occupants/100 m^2 based on the function of the office space [25]. Office buildings are subject to more uncertain occupancy patterns, spontaneous events will result in working overtime or leaving early for individual workers, teams of workers, or one of the companies in a building. By contrast, an industrial hall is typically occupied by a single company

that follows a very discrete and regular occupancy pattern, in which the whole space is either occupied or not occupied. Workers cannot exercise any individual preference on building operation (e.g. opening of a window). Occupancy pattern can be modelled in terms of shifts of work [26].

3.2 Investigation with a systematic quantitative approach

Quantitative approach investigates the performance by observing the predicted value through altering the quantity of the subject of interest. An example in this paper is to alter the coverage of skylights and observe the changes in energy consumption. Because of the aforementioned characteristics, this approach can be applied systematically to industrial halls. With only a limited set of design parameters (each component has high physical presence) for industrial halls, sensitivity analysis is applied to identify the most influential parameters that have high impact on energy consumption. In reality, design parameters are discrete variables (i.e. defined by a finite set of values such as R_{SI} 2, 2.5, … 4.5 for insulation). For each investigation, there will be a known set of configurations, which are the combinations of different design parameters at their assigned ranges of values and resolutions. A full factorial design space exploration approach will evaluate the energy performance for each and every configuration by performing an automated sequential evaluation through the design space.

3.3 Derived performance indicators

The approach described thus far is based on energy performance simulation with the corresponding design parameters as inputs to the simulation models. Energy consumption for each configuration of industrial halls is the direct performance indicator from the simulation model. From the designers' point of view, cost effectiveness is more of an interest and is composed of the cost of the capital investment, and the cost of the operation, which is a derived quantity of the energy consumption. Depending on the sources of energy, energy consumption has an impact on the environment. Both the cost effectiveness and environmental impact are derived performance indicators based on energy performance and other assumed inputs.

- ***Cost effectiveness of design solutions:*** From a project feasibility point of view, an investment in energy saving measures shall bring forth financial benefit that could ideally make a profit or at least compensate the initial investment. Performance indicator for cost effectiveness shall therefore be able to demonstrate the cost-benefit of such investment. Cost effectiveness can be investigated in relative terms with respect to a baseline building configuration to which other studied configurations can be compared with. A baseline building is the one that is built according to current building standard with no particular consideration of energy saving measures. With respect to cost effectiveness, the absolute cost of the baseline building will not affect the decision since it is the capital investment that has to be made if no particular energy saving measures are considered. It is the additional cost (or in some cases, discount) of a newly proposed configuration that is of interest from the design decision point of view. By the same token, the absolute cost of the energy consumption of either the baseline building configuration or the proposed configuration is not of interest to the designers. It is the difference between the two configurations that represents the actual energy cost saving or deficit of the proposed configuration.

  There are many methods to evaluate cost effectiveness of an investment, which is paid up front at the time of the construction. In the subsequent years, energy cost saving is realized through the lifespan of the energy saving measures. It is particularly an issue since the lifespans of different energy saving measures are not the same and are shorter than the lifespan of the building. Simple payback period, a common metric to gauge cost effectiveness, is calculated by dividing the investment with the annual cash inflow (if the accounting period is a year). This metric does not account for the financial cost, the different lifespans among different measures, and the fact that the payback period can be longer than the lifespan of the equipment itself. This paper proposes Annualized Relative Cash Flow as the performance indicator for cost effectiveness as it offers a fair comparison among different energy saving measures of different lifespans.

Regardless of the financing method, the asset with a finite lifespan depreciates over time. That is, the capital investment can be treated by having an equal amortized investment cost over the lifespan of the equipment. The Amortized Cost of an Investment, I_A of an initial investment, I, can be calculated with a discount rate, r, for the number of years of the life-cycle, n, with Equation 1.

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

A discount rate is 100 basis points over the base rate, which is published by the European Union for each of the member states every quarter [27]. The total cost of these measures (simple summation of amortized costs of different measures, m) can be weighed against the cost of the baseline building, with Equation 2, to arrive at the Amortized Relative Investment Cost.

$$\begin{matrix} Amortized\ Relative \\ Investment\ Cost \end{matrix} = \sum_m I_A - I_{A,baseline\ building} \qquad \text{Equation 2}$$

The operating cost is based on electricity and gas energy consumption from the simulation models. The predicted electricity and gas consumption for each of the studied configurations can be compared to that of the baseline building. The difference between the two is the net energy savings or deficit in electricity and gas. Together with the utility prices, the Annual Relative Operating Cost can be calculated with Equation 3. Utilities can involve multiple resources and include multiple suppliers. Energy consumption and utility price are evaluated for each supplier.

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

Equation 3

The relative operating cost is negative if there is net energy savings with respect to the baseline building. The relative investment cost can also be negative if the proposed configuration costs less than the baseline building. An unbiased performance indicator for cost effectiveness proposed by this paper — Annualized Relative Cash Flow is defined as the inverse sum of Annual Amortized Relative Investment Cost and Annual Relative Operating Cost as in Equation 4.

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

Equation 4

- **Environmental impact due to carbon emissions:** Environmental impact depends on the sources of energy, which from a regional perspective, depends on the energy mix of power generation of the location. Carbon emissions is often used to gauge environmental impact and is more of a concern than the energy consumption itself. Carbon emissions due to either electricity or gas consumption can be expressed in terms of country specific CO_2 emissions factors listed in Table 1.

Table 1 CO_2 emissions factors of electricity and gas consumption in the Netherlands

	CO$_2$ emissions factors (kg CO$_2$/kWh)	
Electricity consumption	0.415	[41]
Gas consumption	0.202	[42]

In terms of energy consumption, there is no distinction between electricity and gas energy consumption if the net amount of consumption (according to site NZEB definition) is the same. However, when converted to carbon emissions, different energy saving measures will have different environmental impact due to difference in electricity and gas consumption. In this paper, the accounting of carbon neutrality follows the same accounting principle as site NZEB where energy consumption is converted to carbon emissions and accounted for the whole year.

Energy saving measures can only reduce operational carbon emissions. However, embodied energy or embodied carbon, which is entrenched in the acquisition, processing, manufacturing, and transportation of the building materials and equipment, is hard to ignore. Actually, survey data of embodied energy or embodied carbon of many building materials and equipment are readily available. These survey data are aggregated data of the region, and therefore, are specific to the location. In this paper, embodied carbon footprints of the building materials are taken from two databases, one from the United Kingdom [28] and one from the Netherlands [29]. These data correspond well with the case study building proposed in the next section, which is located in the Netherlands and presumed to be built with local building materials. For industrial halls, simple construction implies only a few building materials (e.g. steel and concrete in various forms and skylights if applicable) are being used and each constitutes a rather significant portion of the structure. A life-cycle approach included both embodied and operational carbon emissions provides a better picture of the benefit of the energy saving measures.

Based on the characteristics of industrial halls, a full-factorial design space exploration approach that facilitates multi-criteria decision making has been developed. The approach follows European policy [7] to consider multiple criteria in terms of energy, environmental, and cost for the whole life-cycle of buildings. The full-factorial design space exploration approach has no pre-defined set of agenda (as contrasted with optimization approach in earlier discussion) and thus promotes greater flexibility in exploring design options. The design support based on full-factorial design space exploration approach is summarized as a flowchart in Figure 1. The implementation of the design support and details of the steps involved are illustrated with a case study in section 4.
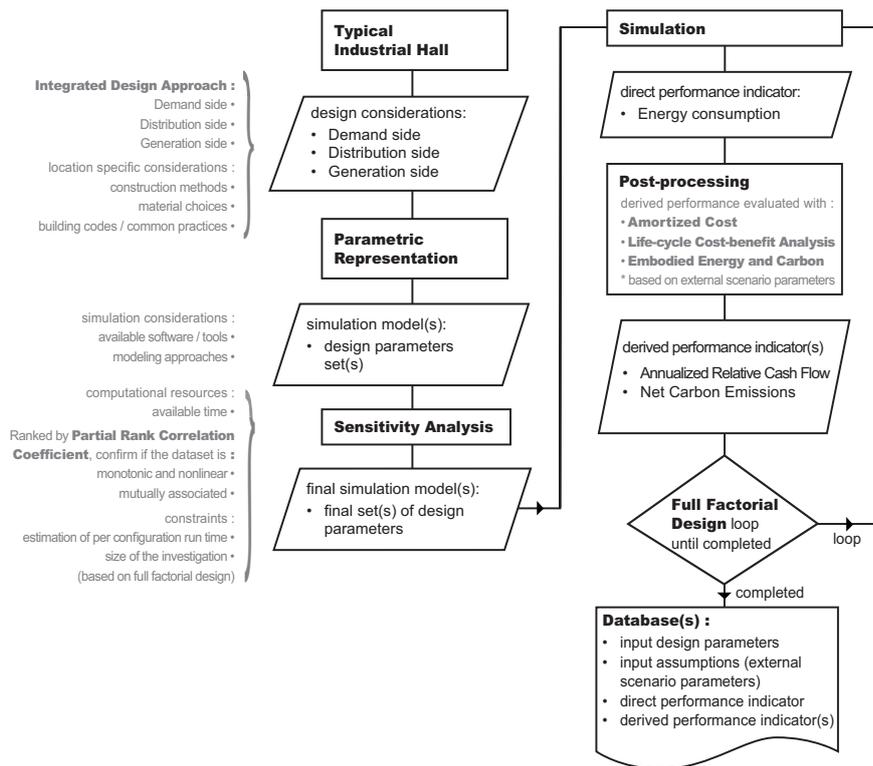
Figure 1 Flowchart of the design support with the full-factorial design space exploration approach

4 Case study

The case study involves the setup of the baseline building and the full-factorial design space

investigation of energy saving measures of industrial halls. The baseline building is set up according to

the prescriptive values proposed by international and national organizations or regulatory bodies for the

many aspects of the building design, such as the thermal resistance of insulation and glazing, the

infiltration rate, the ventilation rate and many other parameters [12, 22, 25, 30 – 32]. Most of these

values are climate specific and subject to change with technological advancements and higher

performance requirements. Many of the referenced documents have actually been updated to current

years. However, for the purpose of composing the baseline building for industrial halls, older documents

are adopted since they represent what is readily available in the market.

The case study building is a warehouse in Amsterdam (logistics is one of the main Dutch industries) with

a process load of 5W/m² (arbitrary value based on energy benchmarks cited by Chartered Institution of

Building Services Engineers, CIBSE [33]). A rectangular shape hall with an arbitrary dimension of 100 m

(W) x 40 m (D) x 6 m (H) is adopted in this paper since the size is midway in the range of 2,343 to 5,672

square meter per building enclosure as published by U.S. Energy Information Administration through its

Manufacturing Energy Consumption Survey [34] for a variety of industries. Bouwen met Staal (the Dutch

steel construction organization), through correspondence, further suggests a width-to-depth aspect

ratio of 2.5 and a size increment of 20 m. Figure 2 is a graphical representation of a typical industrial hall
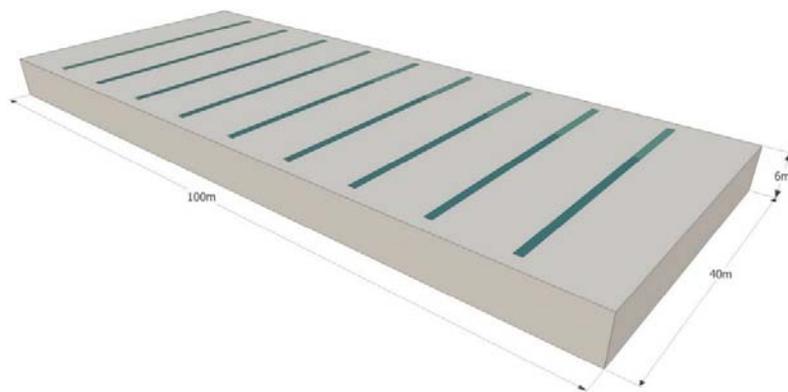
with skylights.

Figure 2 Graphical representation of a typical industrial hall with skylights

4.1 Design parameters

The relationship between energy consumption (output) and any of the studied design parameters

(input) is monotonic. However, some of the relationships are nonlinear. There are also interdependency

among design parameters. That is, the effect of one parameter, affects the impact on performance of

others. Lee [17] discusses extensively the various common metric to gauge the relative influence of each

design parameter and suggests that Partial Rank Correlation Coefficient (PRCC) is applicable to the

design of industrial halls. Through sensitivity analysis with PRCC, six design parameters have been

identified as the most influential ones. They are the insulation values of the roof and walls, construction

types (steel or concrete) of the roof and walls, skylight coverage and transpired solar collector coverage.

In fact, the PRCC is -0.350 for the least influential design parameter being studied in this paper

(construction types of walls) whereas the PRCC is 0.007 for the most influential one not being studied

(surface reflectance of walls). Table 2 presents the studied design parameters with their respective ranges and resolutions of the investigation.

Table 2 List of influential design parameters with their design ranges and resolutions

Parameters	Design Range	Baseline	Levels of
Insulation (Thermal resistance, Roof)	1.5 – 4.5 m²K/W	3.5 m²K/W	7
Insulation (Thermal resistance, Wall)	1.5 – 4.5 m²K/W	3.5 m²K/W	7
Construction Types (Roof)	STL or CONC	STL	2
Construction Types (Wall)	STL or CONC	STL	2
Skylights (as % of roof area)	0 – 15 %	0%	4
Transpired solar collector (as % of south wall)	0 – 100 %	0%	6

Steel sheets are assumed to have no thickness and no thermal resistance. Concrete is assumed to have a thickness of 0.2 m with a density of 2400 kg/m³, a thermal conductivity of 2.1 W/m-K, and a thermal capacity of 1 kJ/kg-K. For newly built industrial halls, steel and concrete constructions can be considered as quite airtight with infiltration mainly comes as a result of opening doors, which is more of an operation issue. A constant infiltration rate of 0.2 ACH is assumed [22].

As depicted in Figure 1, skylights are installed on the rooftop to introduce daylight and are measured in terms of a percentage of the rooftop area in this paper. CIBSE provides guidance in the design of daylighting [36]. A lighting power density (LPD) of 9 W/m² is assumed (e.g. with fluorescent lighting) and will be dimmed according to the lighting level by following the dimmable lighting characteristics suggested by Rubinstein [37]. Since skylights are introduced, the U-value of the glazing as well as the reflectance of the interior surfaces affect energy performance, but are both found to be much less influential than other design parameters.

4.2 Heating and cooling

As suggested, the heating and cooling requirements of an industrial hall are quite different from an office building in two ways — a wider acceptable temperature range and higher allowable temperature

fluctuation rate. Since the requirement is loose, the choice of heating and cooling equipment may follow other priorities, such as energy performance and cost. In many cases, heating and cooling equipment serve not only the function of space conditioning, but the need of the manufacturing process, which is beyond the scope of this paper. The default equipment selection is, therefore, based on the current best practice instead of an in-depth parametric study.

- *Cooling:* Forced ventilation with heat recovery is common for industrial halls in a moderate climate, in which halls can be effectively cooled by drawing in ambient air at a lower temperature. Multiple fans are installed to draw in ambient air for cooling purposes and to fulfill the minimum outdoor air ventilation requirements [25]. The fans are controlled by a feedback controller, which moderates the fan output to maintain space at the desired temperature. The fans are rated at 2kW per 10,000 L/s of air flow, which is in the mid-range in terms of energy efficiency [38]. Supplemental cooling is provided by precooling the outdoor air with a mechanical system that includes an air-cooled chiller when forced ventilation fails to cool down the building. The COP of the system depends on the temperature and humidity. The relationship between COP and temperature / humidity is based on actual measured data [39].

- *Heating:* Local heating using suspended infrared gas radiators is very common for industrial halls. The radiators are the only equipment that consume gas. Building configurations that demand more heating will have an impact on carbon emissions. Transpired solar collector (TSC) is a potentially effective means [40, 41] of heating with solar energy. 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). TSC is the only piece of equipment investigated in the case study. It is investigated with coverage on the south wall from 0% to 100% as indicated in Table 2. The only energy consumption for the system is that of the fans (same efficiency as indicated under Cooling), which draw in and distribute the heated air.

For the case study, the logistic warehouse is presumed to be operated in 2-shift: Mon - Sat, 06:00 - 22:00 for a total of 5,008 hours a year. The building energy simulation program TRNSYS is used to perform the energy analysis for heating and cooling demand. Climate data is based on typical meteorological year weather data (in TM2 format) for Amsterdam-Schiphol. Hourly energy consumption is evaluated and aggregated for the year. The introduction of daylight will have an impact on the heating and cooling energy demand in addition to the lighting demand. The effect of daylighting introduced through skylights can be independently evaluated through two separate simulation models. A model in TRNSYS considers the effect of daylighting on heating and cooling by taking into account the amount of solar heat gain being introduced through the glazing and the reflectivity of the surfaces. A DAYSIM lighting simulation model evaluates the illuminance level on the work surface for each hour due to daylighting at different locations inside the building and for different amounts of skylight coverage. Based on the illuminance level, lighting energy is then calculated by a proprietary program written in MATLAB. Derived performance indicators for cost effectiveness and environmental impact will be post-processed based on results of the energy performance. The loose thermal comfort requirement allows the simulation to be carried out with a larger time step. Lee suggests that a 30 mins time step is appropriate since such time step matches the time step for many control systems and provides energy consumption results similar to those based on a simulation with a finer time step. Lee further suggests that the whole non-partitioned space of industrial halls can be investigated as a single zone after comparing energy consumption results of a few different zonal arrangements [17].

5 Results and discussions

A full factorial design space exploration provides vast amount of performance data for the designers to make informed design decision with observed design trends [17] to multi-criteria decision making support. This paper only focus on the decision making support.

5.1 Multi-criteria decision making support

In this paper, six design parameters and 4,704 different configurations have been investigated. Even though single parameter design trends and voxel diagrams are all effective means to present energy performance of the parameters of interest, it is not at all possible to visualize the combined effect of four or more parameters, and more importantly, not able to present performance of other design aspects such as cost effectiveness and environmental impact. In fact, for either design trends or voxel diagrams, the design workflow is from the configuration (a single parameter or a combination of parameters) to the performance. That is, the designers inspect the configurations one at a time and select the one that fits the performance requirement. In reality, this conventional design workflow to treat performance as a dependent variable of the configuration is counterintuitive in a sense that the designers care only about the performance but not the exact composition of the configuration.

This paper proposes a design workflow to facilitate the designers to select the desired performance (combination of performance in terms of energy, environmental, and cost) from a comprehensive set of performance data. Figure 3 illustrates one possibility of such design workflow. Designers simply select from the diagram their desired combination of performance (energy, environmental, and cost). The corresponding configuration can be numerically displayed at the point of selection or graphically displayed as a dashboard. The user interface can readily be implemented as a tablet application or web tool, however, the implementation is beyond the scope of this paper.
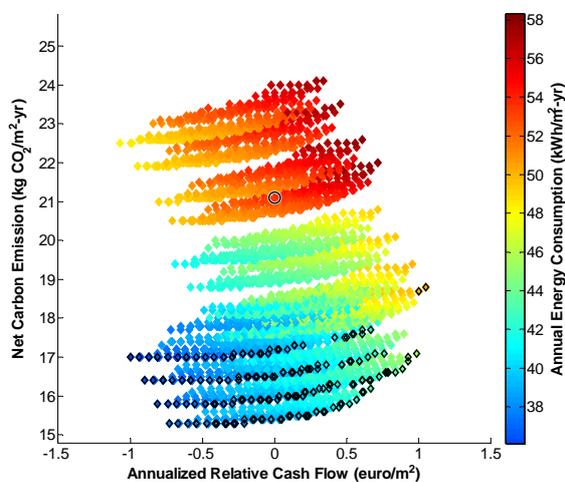
Figure 3 Pareto solutions (shown with black outline) with respect to three design objectives among all studied configurations (color diamonds)

Performance data for all 4,704 studied configurations are displayed in one single diagram. There is no bias in the design process since the choice of the designers is absolutely based on performance data driven reasoning. The baseline building configuration is highlighted in a circle. It can be observed that the baseline building performs very poorly in any of the three design objectives. In fact, most of the configurations are too high in terms of energy consumption or net carbon emissions, or too low in terms of annualized relative cash flow. Configurations outlined in black are the Pareto solutions (also known as trade-off solutions), which are the design solutions that cannot be improved in one design objective without worsening another. There are 192 Pareto solutions out of the 4,704 configurations (shown as color diamonds).

The previous discussion on optimization points out the fact that optimization is valid only for the scenario assumed at the time of the investigation. For example, the input data assumed for the investigation as presented in Figure 3 are listed in Table 3 under Scenario 0. Cost and carbon values are current values in the Netherlands at the time of the investigation. If the investigation is by means of an optimization, then the whole investigation will be nullified if any one of the assumed values changes. For example, an increase in electricity price, which is very likely from time to time. A seemingly computationally efficient approach of doing optimization is not effective at all, if it is necessary to be redone from time to time due to any change, big or small, in any of the input assumptions.

Table 3 Input assumptions for four different scenarios (values with changes are bold and underlined)

Scenarios	0	1	2	3
	Economic and other assumptions			
Discount Rate (%)	4.59%	4.59%	4.59%	4.59%
Life Cycle of Building (yr)	50	50	50	50
Cost of Electricity (€/kWh)	0.118	**0.107**	**0.135**	0.118
Cost of Gas (€/kWh)	0.040	**0.044**	**0.029**	0.040

CO$_2$ Emissions of Electricity Generation (kg CO$_2$/kWh)	0.415	**0.229**	**0.781**	0.415
CO$_2$ Emissions of Gas Consumption (kg CO$_2$/kWh)	0.202	**0.202**	**0.202**	0.202
Material Costs (€)				
Insulation (per R$_{SI}$ per m^2)	6.3	6.3	6.3	6.3
Steel panel (per m^2)	14.4	14.4	14.4	14.4
Precast Concrete (per m^3)	100.0	100.0	100.0	100
Skylights (per m^2)	250.0	250.0	250.0	**180**
TSC (per m^2 of coverage)	50.0	50.0	50.0	**30**
Material Carbon Footprint (kg CO$_2$)				
Insulation (per R$_{SI}$ per m^2)	2.4	2.4	2.4	2.4
Steel panel (per m^2)	12.3	12.3	12.3	**8**
Precast Concrete (per m^2, 0.2m thickness)	93.4	93.4	93.4	93.4
Skylights (per m^2)	93.0	93.0	93.0	93.0
TSC (per m^2 of coverage)	12.3	12.3	12.3	**8**

Because of the characteristics of industrial halls — sparsely built and monotonous sites, for example, the same investigation can be reapplied to any other industrial hall in the same geographic location. With the previously introduced derived performance indicators, a change in the scenario (e.g. a change in the electricity price, energy mix of power generation, or material cost) only implies a change in the inputs to dynamically regenerate the database. That is, a whole new database of performance data and the corresponding graphical display can be dynamically generated by updating the inputs. Table 3 present three more hypothetical scenarios that might be of interest to the readers. Scenario 1 could represent a scenario where renewable energy becomes the norm with low electricity price (in fact, generation cost for PV has been significantly reduced over the years). Carbon emissions of electricity generation is low since it is mainly from renewable energy sources. Scenario 2 is the opposite of Scenario 1 where gas price is low (e.g. due to newly discovered gas field) and electricity generation is primarily based on fossil fuel power plants. Scenario 3 is a case where prices of both skylights and TSC have dropped due to technological advancement. Higher recycled content also lowers the carbon footprint of steel. Numerical values listed in Table 3 are taken from various sources [7, 28, 29, 42, 43] and represent realistic situations. Figure 4 (left) and (right) represent design solutions for Scenario 1 and 2 respectively.
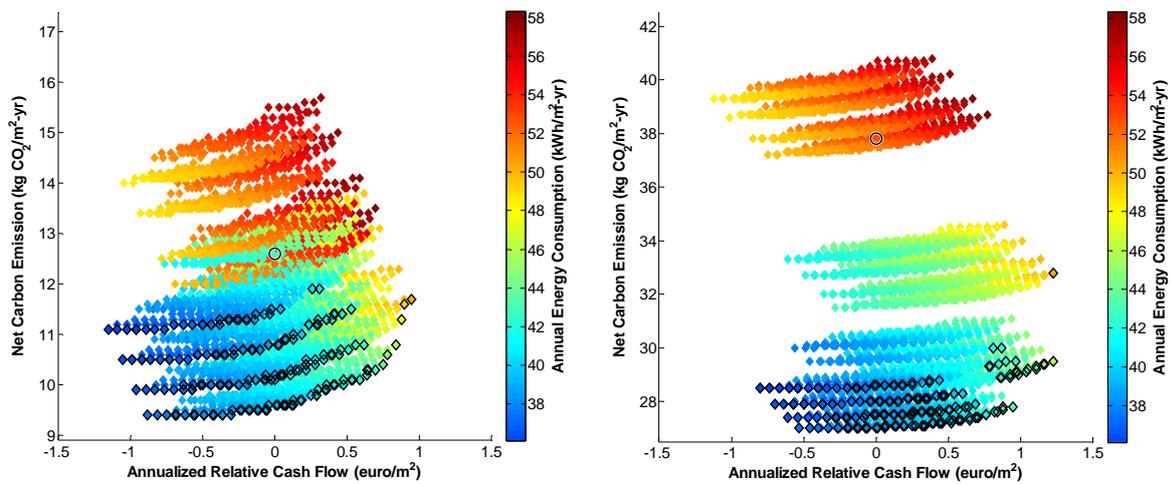
Figure 4 Design solutions of Scenario 1 and 2

Total energy consumption is the direct performance indicator and is the result of building performance simulation. The range of values for total energy consumption stays the same for all diagrams since the total energy consumption is not affected by changes in scenarios. On the other hand, net carbon emissions and annualized relative cash flow are derived performance indicators, and therefore, affected by changes in scenarios.

For Scenario 1, since energy is generated from renewable sources, the environmental impact (as carbon emissions) is low in general. The performance gap in environmental impact between the baseline building and Pareto solutions is also much reduced. Around a net carbon emissions of 12 - 13 kg CO_2/m^2-yr, there are configurations with high energy consumption (> 56 kWh/m^2-yr) and low energy consumption (< 44 kWh/m^2-yr). This piece of information is very important for the decision makers, since for the same carbon footprint, it is more than natural to select configurations with less energy consumption. In fact, the two clusters of configurations refer to the group with high insulation level, no skylight and no TSC, and the group with high coverage of skylights and TSC.

In fact, skylight coverage is a very effective means to reduce energy consumption in a mild climate. For Scenario 2, the whole cluster of configurations with high carbon emissions and energy consumption is the one with no skylight coverage at all. High carbon emissions for those configurations is expected

since energy mix is basically based on fossil fuel. The higher electricity price also favors configurations with higher energy savings. Configurations with higher skylight coverage fit exactly the bill.

Scenario 3 is quite similar to Scenario 0. With reduction in material cost and carbon footprint, the results are in general a shift towards more positive cash flow and a small reduction in net carbon emissions. Figure 5 depicts such scenario.
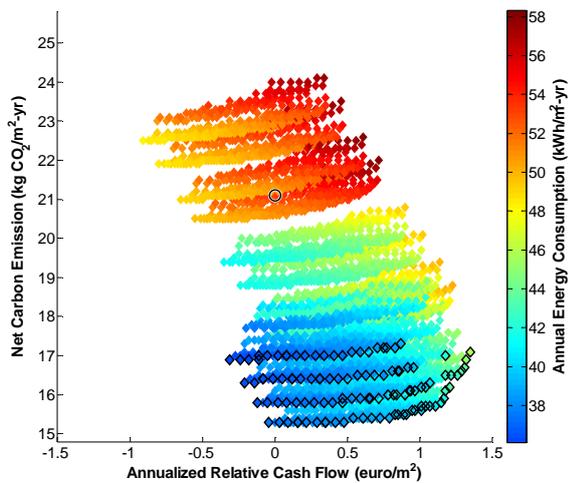

Figure 5 Pareto solutions of Scenario 3

The four diagrams presented here exemplify the flexibility and relevancy of the proposed design support, in which the designers are in full control of what they want (desired performance). Table 4 highlight some of the design solutions to further illustrate this new design support approach. Baseline Design configuration and its performance under all four discussed scenarios are presented in column 1. By definition, the cash flow must be zero since the Baseline Design is the reference case with standard configuration and no energy saving measures. If a heuristic approach is adopted, it is very natural to keep insulation (according to building code) and construction (a steel building) the same as the Baseline Design and install a maximum amount of skylights and TSC as in Design Solution 1. In fact, if carbon emissions is the main concern, Design Solution 1 also offers the lowest carbon emissions under all for scenarios. In this example, either the heuristic approach or the proposed approach (with lowest carbon emissions as the only goal) will come to the same Design Solution 1. However, due to the excessive amount of skylights and TSC, Design Solution 1 comes with a very high initial cost in which subsequent

energy cost savings cannot cover (even with a 29% energy saving over the Baseline Design, the annualized relative cash flow is quite negative under three out of four scenarios). However, from Figure 3 to 5, it can be observed that for very similar carbon emissions performance, there are quite many alternative design solutions that yield positive cash flow. Design Solution 2 is one of such alternative solutions, where its carbon emissions performance is almost the same as that of Design Solution 1, but its cash flow is significantly improved with substantial net return under all four scenarios. Design Solution 2 achieves its performance by reducing the amount of insulation in a way that the capital investment is reduced (as compared to the Baseline Design) and yet the impact on energy performance is minimal. It is particularly advantageous to deploy Design Solution 2 if the prices for skylights and TSC are low (Scenario 3).

Cash flow for Design Solution 3 is almost zero under all four scenarios. That is, this concrete building solution costs almost nothing and performs almost the same as the Baseline Design. Design Solution 4 offers the highest cash flow among the 4,704 different configurations. This solution in fact performs better than the Baseline Design in terms of both energy and carbon emissions.

Table 4 Design solution examples and their performance under the four different scenarios

Parameters	Baseline Design	Design Solution 1	Design Solution 2	Design Solution 3	Design Solution 4
Insulation (Thermal resistance, Roof, m²K/W)	3.5	3.5	2.0	2.0	1.5
Insulation (Thermal resistance, Wall, m²K/W)	3.5	3.5	2.5	3.0	1.5
Construction Types (Roof)	STL	STL	STL	CONC	STL
Construction Types (Wall)	STL	STL	STL	CONC	STL
Daylighting (as % of roof area)	0	15	15	0	5
Transpired solar collector (as % of south wall)	0	100	100	40	0
Annualized Relative Cash Flow (€/m²)					

Original	0.00	-0.34	0.15	0.01	1.05
Scenario 1	0.00	-0.49	0.00	0.01	0.95
Scenario 2	0.00	-0.13	0.38	0.00	1.23
Scenario 3	0.00	0.35	0.85	0.07	1.23
Net CO_2 Emissions (kg CO_2/m^2-yr)					
Original	21.1	15.3	15.5	23.2	18.8
Scenario 1	12.6	9.4	9.6	14.7	11.7
Scenario 2	37.8	27.0	27.2	40.0	32.8
Scenario 3	21.1	15.3	15.5	23.2	18.8
Total Energy Consumption (kWh/m^2-yr)	53.4	38.0	39.3	52.7	50.2

These few design solution examples are drastically different from one another in terms of design objectives (minimizing energy and carbon emissions, and maximizing cash flow), multi-criteria decision making (e.g. achieving certain carbon emissions level and maximizing the cash flow), practical consideration (e.g. zero cost), and construction types (steel verse concrete), and are made possible with the full factorial design space exploration approach.

6 Conclusion

Industrial halls are large consumers of energy, small percentage saving could be translated into a large absolute sum and have a huge impact to the society. In fact, the case study presented in this paper suggests that it is possible to introduce significant energy savings and carbon emissions reduction with minimal cost.

The unbiasedness of the investigation, the identification of potentially desirable design solutions, and the flexibility in the decision making process is entirely depending on the suitability of the design support approach, which is in turn depending on the building type of interest. Industrial halls as a particular building type pose certain characteristics that allow full factorial design space exploration approach to be deployed in a non-exclusive and flexible manner. With a comprehensive set of energy performance data, the proposed approach allows databases of derived performance to be dynamically generated based on even changing information or inputs specified by the users at the time of making

the decision. Other than offering potentially beneficial design solutions, this newly proposed design support approach with dynamically generated databases changes the design workflow of industrial halls in two ways: 1) investigation could be a non-case-specific one-time effort for a particular geographic location, and 2) design evaluation and decision making are no longer two separate processes in iteration. With the new approach, designers, decision makers, and project stakeholders can assess feasibility of any design solution based on their own desired set of performance requirement (e.g. design objectives, derived performance indicators) under different potential scenarios.

There are indeed advantages in adopting full factorial design space exploration approach, however, the approach is only possible due to the very unique characteristics of industrial halls. This paper demonstrates that observing characteristics and understanding design requirement of the building type of interest (in this case, industrial halls) are in fact the most crucial steps in developing a suitable design support approach.

Acknowledgements

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