Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Building and Environment 40 (2005) 1126–1139
BUILDING AND ENVIRONMENT
www.elsevier.com/locate/buildenv

A methodology for design of environmentally optimal buildings by variable grouping

S. Pushkar, R. Becker*, A. Katz

Department of Structural Engineering and Construction Management, Faculty of Civil and Environmental Engineering,
Technion – Israel Institute of Technology, Haifa 32000, Israel

Received 26 July 2004; accepted 3 September 2004

Abstract

The main research objective was establishing a simple but reliable methodology for the building design stage that would yield environmentally optimal buildings. A three-step methodology is proposed: (1) design variable grouping—four distinct groups were recognized according to their stage of major influence (production and construction, operational energy, maintenance to demolition, and an Integrated Group relevant to several life cycle stages), (2) generating the within group optimization methodology, and (3) integration.

This paper presents the methodology developed for the grouping procedure, and its testing and application on a simple generic office module. Sensitivity analysis highlights the significance of electricity production fuel.

Keywords: Sustainable construction; Performance-based design; Life cycle assessment; Optimization

1. Introduction

Life cycle assessment (LCA) principles have been compiled into a well-established tool [1–4] and are applied in industry as a systematic means for evaluating the overall environmental performance of a product/process, and for their environmental optimization. LCA was applied in the chemical industry [5–7], as well as in other manufacturing industries, such as painting processes [8], photovoltaic production processes [9], nuclear fuel reprocessing technologies [10], wastewater treatment [11], and telecom products design [12].

In a suitable process for environmentally optimal building design, the objective function aims at minimizing the total environmental impact associated with all life cycle stages of the building project (from cradle to grave). However, building as a process is not as streamlined as an industrial process, and varies from one building to the other, never repeating itself identically. In addition, buildings are much more complex products, composed of a multitude of materials and components each constituting various design variables (presented in most cases by means of component dimensions or material bulk quantities) to be decided at the design stage. A variation of every design variable may affect the environment during all the building-relevant life cycle stages such as: production, construction, maintenance, service life (including operational energy usage), repair, rehabilitation, demolition, dumping, and recycling. A further complication stems from the nature of the building design process, which is highly fragmented. It consists of many separate professionals, working in different offices each engaged in providing solutions to other sets of performance criteria that are not related to the environmental impact of the building, but rather to essential requirements such as safety, health, comfort, serviceability, maintainability, and aesthetics. Coordination of these decisions is usually performed by the architect, and is based on logistics and

---

*Corresponding author. Fax: +972 4 8295697.
E-mail address: becker@tx.technion.ac.il (R. Becker).

0360-1323/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.buildenv.2004.09.004

geometrical compatibility, whereas overall environmental-impact minimization would require at this stage a non-linear optimization over the entire set of decision variables, and depend on the usage of highly sophisticated mathematical tools. The direct application of LCA to the whole building environmental optimization is thus not straightforward, and cannot be accomplished without additional modifications.

A comprehensive methodology for the design stage could not be found in the literature. It is recognized that some very simple, and thus useful, tools have been developed for assessment of a building's impact on the environment. However, some of these tools are used to grade design solutions according to a pre-assigned grading scale that was established by a prescriptive approach, without addressing the actual environmental performance (i.e., impacts) of the suggested solution (BREEM [13], LEEDS [14]), and others use only a limited set of data (BEES [15], ATHENA [16]). Therefore, they can be applied with some confidence only to cases that are very similar to those used for the establishment of the grading scales.

Consequently, it was recognized that there is a need to establish a comprehensive performance-based methodology that can easily be implemented in the design process of a building to reliably ensure the building's overall environmental performance.

The methodology presented in this paper aims at overcoming the disadvantages of the prescriptive tools while keeping the environmental optimization procedures simple and amenable to the building design process.

2. The proposed methodology

The methodology proposed in this paper is based on the following thesis: it is possible to group the multitude of building design decision variables into smaller clusters in such a manner that environmental optimization can be performed within each group separately, and then, by combining the partial decisions so derived, the overall environmentally optimal solution for the entire building would be obtained. Moreover, it is hypothesized that these groups can be aggregated from the building life cycle stages, so that the design variables within each group have their largest environmental impacts within that stage and negligible impacts in the other stages. Consequently, each of the studied variables would be optimized with respect to the relevant life cycle stage where it has largest environmental impacts.

A partially intuitive separation of impacts has been performed historically into two categories, energy usage related and manufacturing related, with different researchers investigating optimal design strategies for the design variables they assumed relevant to one of these categories. No overall optimization has been sought, and the two routes have usually been pursued separately.

A wealth of literature is available on optimal design related to energy usage, including effects of various design factors such as thermal mass, thickness of insulation, window sizing, glazing, ventilation, shading, etc. [17–25]. Within this approach the environmental impacts during the other life cycle stages have usually been neglected. Lately, a manufacturing-related approach has developed, focusing on evaluating environmental performance of building components and materials within one or more of the other life cycle stages (production, construction, maintenance, demolition, and recycling), while neglecting their impacts on the other stages and in particular on the operational energy usage. The manufacturing-related approach was applied to various building elements, such as floor covering [26,27], glazing [28], structural assemblies [29], building frames [30], and thermal insulation materials [31].

We suggest that this intuitive separation of the impacts into two categories only may not be sufficient for a complete and comprehensive environmental optimization of building impacts, while the distinct grouping of the design variables into a minimal set of four groups would enable the desired methodology.

The existing literature easily reveals that every building design variable has different environmental impact bounds within different life cycle stages. For a reliable grouping it is necessary to be sure that the set of design variables within the group has its largest environmental impact in the certain life cycle stage that constitutes that group, so that when optimized within the group, the resulting combination will also yield the unique overall optimal solution that would have been achieved if optimization had been performed on the entire population composed of all the separate sets. When this is ensured, the optimal solution for every given set can be sought separately, while neglecting the environmental impacts associated with all the other life cycle stages constituting the other groups.

Thus, the suggested overall environmental optimization methodology for building design is based on a three-step procedure: (1) grouping procedure—recognizing a number of distinct groups of the decision variables based on their impacts during the various building life cycle stages, and separating the decision variables into these groups. (2) Within group optimization—establishing the most suitable methodologies for ensuring minimization of the total environmental impact within each group. (3) Integration—integrating the partial decisions into a comprehensive whole building design procedure toward an overall optimal environmental solution.

This procedure will ensure that the combined optimal sets lead to an overall optimal environmental solution.

3. Grouping procedure methodology

The first aim was to identify the minimal set of distinct groups that enables the systematic separation of the design variables, according to the extent of their environmental impacts in the recognized groups. This has to be accomplished in a manner that is related to the entire life cycle of the building and enables the application of a unified quantitative tool for the selection of the most adequate (optimal) solution within every group.

The entire sequence of the building life cycle may be regarded as composed of two main phases: pre-occupancy and post-occupancy. The first phase consists mainly of material and component production, their transportation to the building site, and all the construction activities until the building is finished. The second phase includes regular building usage and operation (leading mainly to energy usage for appliances, acclimatization, lighting, and internal transportation), maintenance, repair, rehabilitation, demolition, dumping, and recycling.

Most of the environmental impacts of the building materials or components are directly and monotonously related to their dimensions or bulk quantities. Consequently, the environmental burdens imposed by the building during most stages of every main phase are uniquely related to the amounts of the materials or components that are relevant to that stage. A conceptual difference between the two main phases stems, however, from the fact that in the pre-occupancy stage the amounts of materials depend only on the design solution, whereas in the post-occupancy phase repetitious actions and replacement of materials take place, leading to a dependence of the material amounts and impacts on the maintenance, repair, and discarding strategies.

Operational energy for acclimatization and lighting, however, does not follow these simple rules. It depends in a non-linear manner on the simultaneous combination of thermal and bulk properties of many components, dimensions of the building spaces and glazed areas, ventilation rates, and systems' efficiencies as well as on the climatic conditions and usage patterns. An additional specific feature is that energy demand should be regarded as an interim component in the environmental analysis, with the actual environmental burdens imposed only by the part which is provided by depletive energy sources. Consequently, based on existing trends and the other arguments listed above, operational energy should be regarded as a distinct group that may require different tools than the other groups.

Eventually, we suggest separating the decision variables into four main groups: (1) Production & Construction Group (P&CG)—this group includes design variables that affect mainly the environmental impact stemming from the production and construction stages, i.e., when considering the set of alternatives for any variable in this group, the largest impact on the environment of the given set stems from the production and construction. (2) Operational Energy Group (OEG)—this group includes design variables that affect mainly the environmental impact imposed by the depletive energy sources used to provide the operational energy demand for acclimatization and lighting, i.e., when considering the set of alternatives for any variable in this group, the largest impact on the environment of the given set stems from the operational energy. (3) Maintenance to Demolition Group (MtDG)—this group includes variables that affect mainly the environmental impact in the maintenance, repair, rehabilitation, demolition, dumping, and recycling stage, i.e., when considering the set of alternatives for any variable in this group, the largest impact on the environment of the given set stems from the maintenance-to-demolition activities. (4) Integrated Group (IG)—an IG relevant to several life cycle stages, i.e., when considering the set of alternatives for any variable in this group, the largest impact on the environment of the given set stems from at least two main previous stages.

A general framework for the methodical and systematic grouping procedure is presented in Fig. 1. It is comprised of two main steps:

(1) *Analysis and investigation*: Deriving the separate environmental-impact ranges of the studied variables, as associated with the operational energy stage, the production and construction stage, and the maintenance-to-demolition stage. This step is outlined in Section 3.1.
(2) *Synthesis and grouping*: Final distribution of the design variables into the four groups according to the groups that gained the maximal environmental-impact range. This step is outlined in Section 3.2.

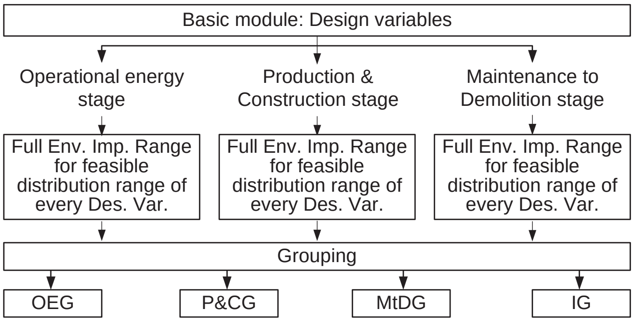

Fig. 1. Grouping procedure—schematic of basic steps.

The procedure seems to be complicated when dealing with a full size building. However, in most cases a building is composed of a limited number of basic modules that can represent the entire building (e.g., a single office or a total single floor in an office building, a single apartment in a residential building, a single class in a school building, etc.).

3.1. Analysis and investigation

The aim of this step is to identify the environmental-impact ranges for every design variable within every life cycle stage. The general methodology we suggest includes the following steps:

- Establish the optimal combination of the thermally relevant design factors, which yields the best environmental score achievable at the operational energy stage, and denote it as the 'Base Point'. Vary each design variable from its Base Point over all its feasible solutions, and establish the accompanying environmental score. For every given variable establish the total range of energy-related environmental score deviation from the optimum.
- For each design variable establish the set of feasible solutions. Establish the environmental score of every solution in each of the other two stages. In each stage establish for every given set the total range of the environmental score variation.
- Use the set of ranges in every life cycle stage as the database of design variable characteristics for the synthesis and grouping step.

There are some major differences in the detailed procedures and analyses needed for identifying the impact ranges in every stage. The methodology for the stage-specific analysis and synthesis steps is thus outlined separately in Sections 3.1.1–3.1.3. As treatment of the operational energy stage is substantially different from that of the two others, the order of these sections does not follow their order of appearance during the building life cycle.

3.1.1. Operational energy stage

Typically at this stage, environmental damage associated with the operational energy stems from consumption of electricity and other fuels for acclimatization (heating, cooling, and ventilation) and lighting, whereas operational energy supplied by natural energy resources, such as solar radiation and natural lighting, is considered as "clean". Moreover, in the assessment of environmental damage associated with the energy sources all the impacts of the technology and the production means are considered as well.

Another typical trait is that minimization of energy consumption requires simultaneous consideration of all the relevant variables in order to obtain their optimal combination. The multi-variable optimization process cannot be replaced by an additive variable-by-variable procedure.

The procedure for establishing the impact ranges of the studied design variables is thus composed of: (1) establishing the electricity and/or fuel consumption 'Base Point' by means of the optimal combination of all the design variables, (2) establishing the range of deviation from the optimal electricity and/or fuel demand for each design variable's feasible range, and (3) establishing, for each design variable, the full environmental-impact range (FEIR) that is related to the operational energy for acclimatization and lighting. This range is an indicator of the possible deviations from the desired optimum that an actual choice of a solution for the given variable may lead to.

In the first step, the optimal combination of all the design variables for the basic module is established in each of the orientations the module may face (north, west, south, and east). When only electrical power is used for thermal acclimatization, ventilation, and lighting—the objective function is the total annual electricity consumption. The electricity consumption for the optimal combination is then recognized as the Base Point. When mixed energy, such as electricity, gas or liquid fuels, is used—the objective function should be based on a fuel equivalent, such as the CO_2-equivalent or the environmental score. The numerical example presented in Section 4 was based on electrical power only. The optimization problem at this step is truly multi-variable. It thus requires the employment of a reliable but fast optimization algorithm, which enables derivation of results that do not depend on the user's level of training. Amongst the existing methods the Genetic Algorithm [32] has been identified as most appropriate for this step.

The second step consists of establishing for each design variable the possible deviations of the total annual electricity (or fuel-equivalent) consumption from the Base Points in the various orientations. This is performed separately for every orientation by keeping all design variables at their optimal level for the given orientation, except the studied variable that varies in its entire engineering-valid range. Electricity consumption increase for every design variable is obtained from the difference between its worst case and the optimal combination established in the previous step. For further analysis this value is multiplied by the design service life of the building. Eventually, with the assumption that in most cases actual design of buildings does not include orientation-dependent solutions, the minimal and maximal electricity consumption increase for each variable are identified (independent of the basic module's orientation) to establish the lower and upper bounds of the variable's impacts.

In the third step, the electricity consumption ranges are converted into environmental-impact ranges by means of LCA methods. The environmental impacts are expressed by means of the environmental score as suggested by the utilized LCA method. Since the results of environmental damage associated with electricity consumption vary with the factors of electricity production, such as fuel sources and technology options, it is suggested to convert electricity consumption into an environmental score by using the local fuel sources and technology option. In addition, the environmental score depends on the options of the chosen LCIA method, where different LCIA methods have been developed with different intra-method options and weighting schemes (such as Eco-indicator 99 [33] that includes three options and two weighting schemes, Ecopoints 97, etc.), each yielding a different score. Thus, in order to derive a general conclusion regarding the environmental-impact ranges, independent of the applied LCIA method, it is suggested to incorporate all these options in the derivation of the impact ranges. In the example presented in Section 4, we have used the Eco-indicator LCIA method options.

3.1.2. Production and construction stage

Environmental damage associated with production and construction stems from production, transportation, and construction processes related to building materials, products, and components (denoted in the sequel as Items). A three-step procedure is used for establishing the impact ranges of the studied design variables: (1) establishing the relevant database of environmental impacts for all the concerned Items, (2) deriving the environmental scores for all the relevant alternatives of the studied design variables, (3) establishing, for each design variable, the FEIR that is related to the production and construction stage.

The first step requires establishing, for every Item concerned, the impacts inventory per a representative unit of that Item (mass, volume, etc.). The basic database for many materials can be found in some of the existing LCA tools. However, these databases do not include all the needed information for many of the relevant building products and components, nor for the construction process itself. In the presented example, we have used two available databases (SimaPro 5.0 [34] and BEET [35]) and supplemented them as much as possible from local data. Therefore, using an LCA program, which enables editing of existing variables and adding new ones according to local conditions, is essential. In addition, this step requires quantification of the Items' amounts for every design variable.

The second step consists of developing the impact database per alternative. This is accomplished by applying the LCA method to the evaluated quantity of every Item. For the partial impacts associated with energy consumption during the Item's production, the choice of fuel sources and technology options for electricity production should be based on the location of material or component manufacturing. As in Section 3.1.1, all the LCIA method options should be considered here as well.

In the third step, the FEIR as related to production and construction is established for every variable. It is derived from the set of differences between the worst and best environmental scores associated with the alternatives for every variable, as derived by the various LCIA options.

3.1.3. Maintenance-to-demolition stage

Environmental damage associated with maintenance, repair, rehabilitation, demolition, dumping, and recycling stems from Items similar to those included in the production and construction stage, with the addition of repeating activities and materials relevant to the maintenance operations and to the demolition process, including discarding of materials or their recycling throughout the design life of the whole building. A four-step procedure is used for establishing the environmental-impact ranges of the studied design variables: (1) establishing the life cycle scenarios of the various routine activities relevant for each Item throughout the building's entire life; (2) establishing the relevant database of environmental impacts for all the concerned Items and activities related to building operation, maintenance and repair, such as cleaning, scrapping, replacement, painting, etc.; (3) deriving the environmental scores for all the relevant alternatives of the studied design variables; (4) establishing, for each design variable, the FEIR that is related to the maintenance-to-demolition stage.

The first step provides for every Item the most possible scenario of activities that are carried out throughout the building's life in order to ensure its proper performance. These may include short span activities such as cleaning or inspection, mid-span activities such as painting, repair and rehabilitation, and long span activities such as complete replacement of a component/system or end of life of the building itself.

The second step includes two parts. The first consists of extending the impacts inventory for every Item already listed in it, to account for all the maintenance-to-demolition activities per a representative unit of that Item (mass, volume, etc.). In addition, it may require an extension of the database's listed Items, in order to account for cleaning, maintenance and repair materials and components. The second part should provide the impacts per units of maintenance-to-demolition activities, such as cleaning, scrapping, dismantling, discarding, recycling, etc. and their quantities in the various alternatives.

The third step is similar to the second step outlined in Section 3.1.2. In addition, while deriving the environmental score for Items with a service life as long as the building's life span, consideration is given to maintenance and repair activities along their life and to the additional activities at the end of their life. The other Items, which should be replaced several times during the life span of the building due to their shorter service life (such as wall covering, floor covering, etc.), involve the repetition of production and construction impacts each time they are re-installed. Existing LCA tools provide the framework for these supplements, but lack the specific data. In the present study, we are supplementing, in the framework of SimaPro 5.0, the relevant data for some of the major activities of this stage, as outlined in Section 4.

The fourth step is identical to the third step outlined in Section 3.1.2.

3.2. Synthesis and grouping

In this step, the design variables are separated into the four groups: OEG, P&CG, MtDG, and IG. The grouping of every design variable is performed by comparing the values of its FEIR in the three life cycle stages. The following difference criterion is used in order to decide whether two ranges are similar or significantly different: only when the minimal as well as the maximal values of one range are significantly larger than the corresponding values of the two other ranges, the variable is included in the group associated with the larger values. Otherwise, it is assigned to the IG. An acceptable difference criterion may be based on a difference of more than 100% as recommended by the uncertainties theory of Eco-indicator 99 [33].

4. Application to an office-building generic module

A very simple generic basic module of a typical multi-story office building was used for the illustration and testing of the suggested methodology. Due to lack of available data, the analysis does not cover all the possible Items and design variables, but it is sufficiently comprehensive for the purpose of demonstration.

4.1. Case description

4.1.1. Basic module description

Analysis and synthesis were performed on a 3 m × 4 m and 3 m high module with three internal walls (partitions) and one external wall, located on a typical intermediate floor, between two similar modules. The module can face each of the four major orientations (north, west, south, and east). For acclimatization energy calculations, it was assumed that the building is constructed in a heating-dominated climate with a mild summer and cool winter (represented by Jerusalem's Typical Meteorological Year). Occupancy hours are 7:00–18:00 for 5 days week^{-1}. The module is occupied by one person. The air infiltration causes a $1\,\text{h}^{-1}$ air change rate. Heating and cooling are by means of a heat pump (with a coefficient of performance (COP) for heating 2.75 and for cooling 3.0), with temperature set-points 20 and 24 °C, respectively. The reference point for the daylight calculation is at the module's center at a height of 0.8 m, with a required illuminance of 500 lx. The design levels of internal heat sources are: for electric lights 360 W and for electric equipment 250 W. Analysis was performed for a building's design life of 50 years.

4.1.2. Studied variables

The following assumptions have been made in establishing the list of design variables:

- A decision regarding the main structural material is based on structural optimization. Thus, the present environmental analysis does not address the materials used for the main structural members such as columns or beams.
- Only the building fabric is addressed, whereas service systems are not part of the present demonstration.
- Only the main building elements and materials are addressed. Smaller elements such as doors, electrical wiring, and light bulbs are neglected.
- Only the prevailing local building technologies are considered.

The set of design variables addressed in the present demonstration is given in the left column of Table 1. The right column lists the set of alternatives that were considered for each variable. As described in Section 3.1, environmental impacts should be established for the entire range of possible Items and their feasible dimensions.

However, this elaborate task can be somewhat simplified for the establishment of the operational energy impacts' ranges, since many of the alternatives have very similar thermal properties and, as such, have similar effects on the operational energy. In order to establish the impacts on operational energy it is thus sufficient to consider a subset of generic variables, which covers all the relevant thermal properties without excessive redundancy. Specifically, for internal walls thermal inertia is the main variable to be considered, whereas for external walls thermal inertia and thermal resistance are significant variables. The fourth variable in Table 1, external wall type, represents thus the sole effect of thermal inertia and its distribution. It includes three wall types, which have exactly the same thermal resistance but different thermal inertia characteristics. Wall I has external thermal insulation above a large internal mass, and thus represents the effect of a large internal thermal inertia sensed at the inner surface,

Table 1
Decision variables

Variable (1)	Alternatives (2)
Partitions	Gypsum wallboard, concrete block, cellular block, gypsum block, and silicate block
Floor/ceiling	Flat reinforced concrete slab, ribbed slab with concrete blocks, ribbed slab with cellular blocks, and hollow-core pre-stressed concrete plate
Floor covering	Ceramic tile, terrazzo, marble, PVC, and carpet
External wall type	Same thermal resistance ($r = 0.865\,\mathrm{m}^2\,\mathrm{K\,W}^{-1}$) with varying thermal mass: (I) internal mass (0.15 m concrete) with external insulation (30 mm expanded polystyrene), (II) external mass (0.15 m concrete) with internal insulation (30 mm expanded polystyrene), and (III) uniformly distributed mass and insulation (0.2375 m lightweight concrete block)
External wall covering	Stone, ceramic tile, and plaster
Glazing	54 types
Window size	Width and height from 0.3 to 2.7 m at discrete steps of 0.3 m
Insulation thickness	External and internal (0.0–0.2 m with 0.01 m intervals)
Concrete mass thickness	Internal and external (0.1–0.2 m with 0.01 m intervals)
Block mass thickness	0.2–0.3 m with 0.01 m intervals

delaying response to indoor thermal changes. Wall II has internal thermal insulation above a large external mass, and thus represents the effect of a very small internal thermal inertia, with the insulation sensed immediately at the inner surface, thus enabling fast response to indoor thermal changes. Wall III has a uniformly distributed thermal insulation and mass throughout the entire wall thickness, and thus represents the effect of thermal inertia and insulation sensed simultaneously at the inner surface. The last three variables in Table 1 represent then the amounts of thermal inertia and thermal resistance.

Consequently, the required subset was generated in the following process, which coincided with the analysis carried out for establishing the optimal Base Point for total annual acclimatization and lighting electricity demands:

For every variable in Table 1 only several Items were selected from its list of alternatives, according to their ability to represent the entire range of thermal properties of this variable. For example, lightweight internal partitions are represented by the regular gypsum wallboard partition, whereas heavier partitions are represented by a silicate block wall with varying thickness. Thermal resistance is represented by the thickness of foamed polystyrene boards, and thermal inertia by the thickness of concrete.

Optimization was first performed for the seven upper variables in Table 1, in order to identify the preferred external wall type, and only then the last three variables were considered and the final Base Point was established.

4.1.3. Analysis tools

For determining the environmental-impact ranges related to each life cycle stage the following analysis tools were used:

Operational energy stage: EnergyPlus [36], GAOT [37], SimaPro [34], and Eco-indicator 99 [33].
Production and construction stage, and maintenance-to-demolition stage: SimaPro and Eco-indicator 99.

4.1.3.1. Energy evaluation. Thermal analysis was performed by EnergyPlus [36], which is a suitable tool for the cases when primary energy demand (electricity and/or other fuels) has to be evaluated rather than energy. Optimization was performed by means of the Genetic Algorithm GAOT [37]. This algorithm was chosen since it is a powerful tool when the objective function is derived from running another program (in this case, the thermal simulation program) and it does not require additional non-existing information such as derivatives. In order to automate the entire procedure for the optimization step, a link between GAOT and EnergyPlus has been created, so that a call to the simulation program is performed automatically each time the objective function has to be calculated.

4.1.3.2. Environmental inventory. Environmental inventory analysis was performed by means of the SimaPro database tool. SimaPro is known as a mature-database tool. It contains a comprehensive database of materials and processes in a variety of fields. In addition, all processes are editable and can be changed to fit different conditions, or to build new ones. This tool also contains a large number of evaluation procedures such as CML 92, CML 2 baseline 2000, Eco-indicator 95, Eco-indicator 99, Ecopoints 97, EDIP/UMIP 96, and EPS 2000. Moreover, sensitivity analysis for waste scenarios, recycling allocation methods, normalization, and weighing factors are also available in SimaPro.

4.1.3.3. Life cycle assessment impact assessment. Environmental scoring was established by means of the Eco-indicator 99 tool. This is a damage-oriented method that divides the damage into three groups: damage to human health, damage to ecosystems, and resources depletion. The data are processed into one single score using the concept of Cultural theory [38] and includes three methodological options, which use different assumptions regarding the damage time frame and the required level of damage certainty: egalitarian (E)—accounts for the very long-term effects of all possible damaging emissions, individualist (I)—accounts for the short-term effects of only those emissions whose effects have been proven as damaging, and hierarchist (H)—accounts for a balance between short- and long-term effects of emissions with consensus about their damage. In Eco-indicator 99, each of these options can be used with two existing alternative weighting sets for the relative importance of the studied main damages (damage to ecosystem quality, damage to human health, and resource depletion): an average weighting set (A), and a weighting set relevant to the specific methodology option (E, I, or H) that is based on the same cultural and socioeconomic approach. In addition, Eco-indicator enables implementation of a user-specified weighting set as well. However, we regard the issue of user defined environmental preferences as part of a required deeper sensitivity analysis that is not within the scope of this paper and would deserve special attention in the next stages of our research work. Due to its comprehensive set of currently utilized options, Eco-indicator 99 was found as the most suitable LCA tool when it is desired to derive a general and method-independent conclusion regarding the environmental-impact ranges.

In the sequel, we denote every combination of methodical option and weighting set by the two relevant symbols, e.g., the hierarchist option with an average weighting set is denoted by H/A.

4.1.4. Database development

Environmental databases were drawn from SimaPro 5.0 [34] and BEET [35]. Some material data in the two databases had first to be modified in order to represent the local materials. Components' data that were not present in these databases has been established by means of the available basic material data and the operations associated with their production. The database for the construction and demolition processes was not available and had to be established. It is based in the meantime only on the environmental impacts resulting from transportation of the building Items (materials/products/components) to the building site and from the energy required for on-site usage of equipment during the construction process. Similarly, for the demolition stage the database is based in the meantime only on the impacts resulting from transportation of building Items from the building site to disposal sites and from on-site energy demand for equipment usage during the demolition activities. Due to lack of local Israeli data, the American manual Means Man-Hour Standards for Construction [39] was used to develop the on-site construction/demolition equipment hours per alternative. This value was then multiplied by the energy consumed per hour of operation of the tools or equipment.

4.1.5. Specific additional details

In Section 3.1.1, it was suggested to convert electricity consumption into an environmental score by using the local fuel sources and technology option. Currently, most of the actual electricity production in Israel is based on coal, with two power stations producing some 80% of the country's consumption. However, due to lack of detailed data in SimaPro for the Israeli electricity production technology, the analysis is performed at this stage by the coal-based French technology.

In addition, recent policy is to convert most of Israel's power stations to natural gas until the end of this decade. Hydro power and wind turbines, as well as other highly clean sources, are also considered. It is highly probable that the large variance in the environmental impacts, which stem from these different fuels, may affect the grouping results. To obtain some initial information on the possible extent of this effect, a sensitivity analysis was performed for various fuels and production technologies as presented in Section 4.3.

Consequently, the alternatives addressed include: coal-based French technology, coal-based Spanish technology, gas-based French technology, and hydro-based French technology.

4.2. Results and discussion

4.2.1. Operational energy stage

Table 2 presents results for establishing the environmental-impact ranges that are related to operational energy, i.e., the optimal combination of variables in each of the four main orientations, which provides the optimal Base Point for total annual acclimatization and lighting electricity demands.

Using the full set of alternatives for all the decision variables in Table 1 yields a solution space of 3,936,600 points, with many redundant thermally equivalent alternatives. The reduced subset, with the limited number of alternatives, which cover the full range of relevant thermal and optical characteristics of the solution space, reduced the solution space to 118,098 points.

The next part of the first step included a refinement of the optimization process to account for the variables that have not yet been studied (namely, insulation thickness, thermal mass thickness, and block thickness).

Table 2
Optimal combination of design variables and their Base Point electricity consumption

Variable (1)	North (2)	South (3)	West (4)	East (5)
Partitions	Gypsum wallboard	Silicate block	Silicate block	Silicate block
Floor/ceiling	Massive concrete	Massive concrete	Massive concrete	Massive concrete
Floor covering	PVC	PVC	PVC	PVC
External wall type	(III) Uniform mass	(I) Internal mass	(III) Uniform mass	(III) Uniform mass
External wall covering	Stone	Plaster	Plaster	Plaster
Glazing	Low emissivity	Low emissivity	Low emissivity	Low emissivity
Window size	2.7 m × 1.5 m	2.7 m × 0.9 m	2.4 m × 1.2 m	2.7 m × 1.2 m
Annual electricity (kWh m^{-2})	36.869	34.620	45.851	39.618

Table 3
Fifty-year electricity demand deviations from optimum for the design variables' feasible ranges

Variable	Electricity demand deviation (kWh 50 yr m^{-2})				Range per m^2 (kWh 50 yr m^{-2})	Range per 12 m^2 module (kWh 50 yr $module^{-1}$)
	North	South	West	East		
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Partitions	26.9	***46.2***	21.4	**18.2**	18.2–46.2	218.4–554.4
Floor/ceiling	**218.3**	308.3	***352.0***	279.7	218.3–352.0	2619.6–4224.0
Floor covering	**16.6**	22.8	***28.6***	22.9	16.6–28.6	199.2–343.2
External wall type	**5.4**	***29.7***	24.8	9.7	5.4–29.7	64.8–356.4
External wall covering	*2.2*	1.3	***2.2***	**0.9**	0.9–2.2	10.8–26.4
Glazing	***4565.8***	4054.7	3754.0	**3181.5**	3181.5–4565.8	38178.0–54789.6
Window size	***2355.2***	1188.3	1337.6	**1101.2**	1101.2–2255.2	13214.4–27062.4
Ext. ins. thickness	**378.8**	486.6	***628.4***	471.9	378.8–628.4	4545.6–7540.8
Int. ins. thickness	**344.8**	450.8	***587.5***	437.4	344.8–587.5	4137.6–7050.0
Ext. conc. thickness	**10.4**	18.2	***20.1***	10.7	10.4–20.1	124.8–241.2
Int. conc. thickness	10.2	***17.6***	14.5	**7.9**	7.9–17.6	94.8–211.2
Block thickness	**34.6**	48.4	***62.0***	44.6	34.6—62.0	415.2–744.0

For the given climatic conditions, the minimal annual electricity was obtained for the thickest insulation thicknesses considered for walls I and II, and for the largest thickness of wall type III. With this the optimal combinations of the design variables, as well as the Base Point electricity consumption for all the variables have been established.

The second step consists of establishing the range of increase in electricity demand for every design variable in the four main orientations. The full feasible range of each variable was addressed while the other variables were kept constant in their optimal state. Columns 2–5 in Table 3 present the 50-year additional electrical energy (m^{-2}) of the worst alternative in each orientation. Column 6 presents the minimal and maximal values of this factor. These are denoted by bold and bold/italic fonts, respectively. For the sake of further analysis in the next stages, column 7 presents the 50-year additional electrical energy range for the entire 12 m^2 module.

Results in Tables 2 and 3 clearly demonstrate that, for a given design variable, module orientation may affect the optimal solution as well as the magnitude of the electricity demand deviation from the optimum. Since the actual chosen solution for a design variable is usually uniform in a given building, the associated electricity demand deviation from the optimum may generally range within the range indicated in Table 3.

In the third step, the ranges of 50-year additional electrical energy were converted to environmental-impact ranges. The entire set of six scoring options, three methodical options with two weighting sets each (see Section 4.1.3), has been applied. As mentioned previously, electricity production is assumed to be based on French technology using coal as the primary fuel. Table 4 presents an example of these results, as derived for the floor/ceiling variable. Column 8, denoted by FEIR, is composed of the minimal and maximal values that have been derived in the six options in both rows, and reflects the variability stemming from the full range of subjective methodologies and weighting sets (in this case the range thus derived is 85.1–267.0 Pt).

The final results of this step for the entire set of design variables (i.e., values of their FEIR as related to the

Table 4
Environmental-impact ranges stemming from operational energy for floor/ceiling variable

Electricity impact range (kWh 50 yr module^{-1})	Environmental-impact range (Pt)						FEIR (Pt)
	I/A[a]	I/I[b]	H/A[c]	H/H[d]	E/A[e]	E/E[f]	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
2619.6 (min)	95	124	100	**85**	165	147	85 (min)
4224.0 (max)	153	200	162	137	***267***	236	267 (max)

Note: The minimal and maximal values of the environmental impact range are denoted by bold and bold/italic fonts, respectively.

[a] Individualist methodology/average weighting set.

[b] Individualist methodology/individualist weighting set.

[c] Hierarchist methodology/average weighting set.

[d] Hierarchist methodology/hierarchist weighting set.

[e] Egalitarian methodology/average weighting set.

[f] Egalitarian methodology/egalitarian weighting set.

operational energy stage) are presented in Table 6, together with the results from the analysis in the next stages.

4.2.2. Production and construction stage

For every alternative in the design variables list presented in Table 1, the environmental-impact score, which stems from all the actions and aspects related to the production and construction stage, has been evaluated for each of the six scoring options. Table 5 demonstrates the detailed results for the floor/ceiling variable. In addition, it includes the range of scores for every scoring option. The FEIR is then established by the minimal and maximal values of the scores' range (in this case the range thus derived is 110.0–263.0 Pt).

The final results of this step for the entire set of design variables (i.e., their FEIRs as related to the production and construction stage) are presented in Table 6.

4.2.3. Maintenance-to-demolition stage

For every alternative in the design variables list presented in Table 1, the environmental-impact score, which stems from actions and aspects related to the maintenance-to-demolition stage, has been evaluated for each of the six scoring options. Presently, only the following activities and operations and their effects have been accounted for: cleaning and regular operational maintenance, replacement of Items, and energy demand for scrapping, dismantling or demolition. The following activities and operations have not been implemented yet due to insufficient data at present: discarding, dumping, recycling, landfilling, incineration, etc. The results for this life cycle stage are thus somewhat deficient when compared to those for the other stages. The final quantitative findings may be affected by this deficiency, and should thus be regarded solely as a means for demonstrating the methodology, and not as final and general recommendations for any practical purpose.

Table 5
Environmental scores for the floor/ceiling variable as related to the production and construction stage

Alternatives (1)	I/A (2)	I/I (3)	H/A (4)	H/H (5)	E/A (6)	E/E (7)
Flat reinforced concrete slab	421	565	338	277	342	270
Ribbed slab (concrete block)	500	676	407	331	407	319
Ribbed slab (cellular block)	308	413	260	217	263	209
Hollow-core pre-stressed concrete plate	346	467	281	229	284	224
Range of scores (Pt)	192	***263***	147	114	144	**110**

Note: Electricity production by coal-based French technology (Pt). The minimal and maximal values of the environmental scores are denoted by bold and bold/italic fonts, respectively.

The EFIR was then established in exactly the same manner as in Section 4.2.2.

The final results of this step for the entire set of design variables (i.e., their FEIRs as related to the maintenance-to-demolition stage) are presented in Table 6.

4.2.4. Grouping results

Table 6 presents the results of the FEIRs for all the investigated design variables, as related to the three life cycle stages: production and construction, operational energy, and maintenance to demolition.

The three ranges for every variable reflect the extent of influence of changing its solution from the relevant optimal choice within the feasible domain of engineering solutions. Consequently, the range with maximal bounding values represents the stage when a deviation of this variable from its optimum may have the largest effect on the environment. However, due to the general accuracy limitations of existing LCA analysis tools it was decided that only when the larger range's bounds

Table 6
Design variable grouping (electricity production by coal-based French technology)

Variable	Full environmental-impact ranges per life cycle stage (Pt)			Group allocation
	Production and construction (2)	Operational energy (3)	Maintenance to demolition (4)	
(1)				(5)
Partitions	81–185	7–35	4–8	P&CG
Floor/ceiling	110–263	85–267	8–16	IG
Floor covering	48–93	6–22	252–482	MtDG
External wall type	37–97	2–23	6–15	P&CG
External wall covering	18–52	0–2	14–35	IG
Glazing	0–2	1240–3460	1–4	OEG
Window size	1–5	429–1710	1–10	OEG
Ext. ins. thickness	2–11	148–476	<1	OEG
Int. ins. thickness	2–11	134—445	<1	OEG
Ext. conc. thickness	36–105	4–15	3–9	P&CG
Int. conc. thickness	36–105	3–13	3–9	P&CG
Block thickness	17–47	13–47	0–1	IG

are at least 100% larger than another range's bounds they are considered significantly different. It can be noticed that in this example the following variables: partitions, floor covering, external wall type, glazing, window size, external insulation thickness, internal insulation thickness, external concrete mass thickness, and internal concrete mass thickness have distinct largest range bounds at only one life cycle stage, thus belonging in the grouping procedure to that specific group. The other variables: floor/ceiling, wall covering, and block thickness have obvious similar range bounds in two stages, thus belonging in the grouping procedure to the IG.

The following final grouping was obtained in this analysis:

(i) *P&CG*: Partitions, external wall type, and external concrete mass thickness.
(ii) *OEG*: Glazing, window size, external insulation thickness, and internal insulation thickness.
(iii) *MtDG*: Floor covering.
(iv) *IG*: Floor/ceiling, wall covering, and block thickness.

4.3. Sensitivity analysis

Varying the electricity production technology affects the environmental score associated with the electricity consumption. This is due to the large variation in the environmental impacts of different fuels, as well as due to some differences in the impacts stemming from the different technological details of various processes even when an identical fuel is used.

In Section 3.1.1, it was thus recommended to perform the grouping procedure on a local basis, and utilize electricity production technology and fuel sources that reflect the local situation. Consequently, this implies that similar buildings, located in similar climatic conditions but in different countries, would not necessarily yield the same grouping of variables.

In order to check this hypothesis, a sensitivity analysis associated with using several options for the electricity production technology and fuel source were performed. Table 7 presents results of the grouping procedure when the previously used coal-based French technology is replaced by coal-based Spanish technology, which is somewhat more environmentally damaging than the previous. Consequently, the bounds of the FEIRs for identical electricity usage increase. The influence of the operational energy on grouping thus increases, but, the change is not sufficiently significant to alter the grouping results obtained with the coal-based French technology (presented in Table 6). Other coal-based technologies yielded the same final groupings as well. Apparently, it may be concluded that the technological differences when the same fuel is concerned do not affect the grouping.

In addition, it was noticed that for the various coal-based technologies the main impacts are associated with damage to human health and resource depletion. The maximal score was then obtained for the E/A option (which is based on the largest set of substances and assigns a significantly large weighting factor to resource depletion) whereas the minimal was obtained for the H/H option (which is based on a large set of substances but assigns the smallest weighting factor to damage to human health).

Tables 8 and 9 present the results of the grouping procedure when coal is replaced by gas and hydro as the fuel source. An asterisk (*) indicates that grouping of a given variable has changed.

A significant decrement in the FEIRs for the same electricity usage, due to the less environmentally damaging fuels, is observed. The influence of operational

Table 7
Sensitivity analysis for coal-based electricity production technology (coal-based Spanish technology)

Variable	Full environmental-impact ranges per life cycle stage (Pt)			Group allocation
	Production and construction	Operational energy	Maintenance to demolition	
(1)	(2)	(3)	(4)	(5)
Partitions	80–185	9–42	5–10	P&CG
Floor/ceiling	110–261	106–324	10–19	IG
Floor covering	47–93	8–26	251–482	MtDG
External wall type	38–98	3–27	7–18	P&CG
External wall covering	18–52	0–2	13–47	IG
Glazing	0–2	1540–4200	1–4	OEG
Window size	1–2	534–2080	1–10	OEG
Ext. ins. thickness	2–12	184–578	<1	OEG
Int. ins. thickness	2–12	167–541	<1	OEG
Ext. conc. thickness	18–53	5–19	4–10	P&CG
Int. conc. thickness	18–53	4–16	4–10	P&CG
Block thickness	17–48	17–57	0–1	IG

Table 8
Sensitivity analysis for the fuel used for electricity production (electricity production by gas-based French technology)

Variable	Full environmental-impact ranges per life cycle stage (Pt)			Group allocation
	Production and construction	Operational energy	Maintenance to demolition	
(1)	(2)	(3)	(4)	(5)
Partitions	81–184	4–14	2–3	P&CG
Floor/ceiling	112–263	47–104	4–6	P&CG *
Floor covering	49–93	4–8	252–483	MtDG
External wall type	36–98	1–9	3–6	P&CG
External wall covering	18–51	0–1	15–48	IG
Glazing	0–2	683–1355	1–4	OEG
Window size	1–5	236–699	1–10	OEG
Ext. ins. thickness	1–11	81–186	<1	OEG
Int. ins. thickness	1–11	74–174	<1	OEG
Ext. conc. thickness	36–105	2–6	2–3	P&CG
Int. conc. thickness	36–105	2–5	2–3	P&CG
Block thickness	17–47	7–18	<1	P&CG *

Table 9
Sensitivity analysis for the fuel used for electricity production (electricity production by hydro-based French technology)

Variable	Full environmental-impact ranges per life cycle stage (Pt)			Group allocation
	Production and construction	Operational energy	Maintenance to demolition	
(1)	(2)	(3)	(4)	(5)
Partitions	82–185	<1	<1	P&CG
Floor/ceiling	113–265	1–2	<1	P&CG *
Floor covering	49–94	<1	253–484	MtDG
External wall type	35–97	<1	<1	P&CG
External wall covering	17–52	<1	16–49	IG
Glazing	0–2	13–23	1–4	OEG
Window size	1–5	5–12	1–10	IG *
Ext. ins. thickness	1–11	2–3	<1	IG *
Int. ins. thickness	1–11	1–3	<1	IG *
Ext. conc. thickness	36–105	<1	<1	P&CG
Int. conc. thickness	36–105	<1	<1	P&CG
Block thickness	17–47	<1	<1	P&CG *

energy on the grouping allocation is thus diminished.

In addition, it was noticed that for the gas-based technology the main impacts are again associated with damage to human health and resource depletion, whereas for hydro-based technology the main impacts are associated with damage to ecosystems. The maximal scores for gas-based technology were then obtained for the H/H (which is based on a large set of substances and assigns the largest weighting factor to resource depletion) and the minimal ones for the I/A option (which is based on the smallest set of substances and assigns the smallest weighting factors to both: damage to human health and resource depletion), whereas the maximal scores for the hydro-based technology were obtained for the E/E option (which is based on the largest set of substances and assigns the largest weighting factor to damage to ecosystems) and the minimal ones for the I/I option (which is based on the smallest set of substances and assigns the smallest weighting factor to damage to ecosystems).

Consequently, the observed results demonstrate that for a number of variables, which had in the previous case (coal-based French technology) larger FEIR bounds for the same electricity usage, the grouping has been altered:

> *For gas-based French technology*: Floor/ceiling moved from IG to P&CG, and block thickness moved from IG to P&CG.
> *For hydro-based French technology*: Floor/ceiling moved from IG to P&CG, window size moved from OEG to IG, both, internal as well as external insulation thickness moved from OEG to IG, and block thickness moved from IG to P&CG.

5. Conclusions

It was demonstrated that the proposed procedure enables the distribution of the design variables into the four suggested groups. In the presented case study, most of the design variables were grouped into the three distinct stage-related groups, each associated solely with one main stage in the building life cycle (production and construction, operational energy, or maintenance to demolition), and only a few variables were allocated to the Integrated Group. Consequently, optimization of each set of designated variables can be performed within their host group only. This enables to split the design optimization process to four smaller procedures, each providing a solution for a small number of design variables, and a well-defined objective function that is relevant to the specific group. The four procedures replace the tremendously large one-step cradle-to-grave optimization on the entire set of design variables, while ensuring that the superposition of the four sets of optimal solutions would provide the optimal solution combination for the entire building (e.g., the sought solution with the lowest total environmental impact from cradle to grave).

The presented grouping methodology is systematic, quantitative and strongly related to the final target of environmental damage minimization. It thus overcomes shortcomings of the existing routines of intuitive separation of variables, whereby various life cycle stages are studied separately, including in the investigation the design variables assumed relevant by the specific researcher although some of them may be insignificant at the particular stage, while others, which are more relevant, have not been included. For example, optimization of the thermal mass thickness variable and external wall type variable is usually performed with respect to operational energy [22,23], while the results obtained in the present study indicate that environmentally they may actually belong to the Production & Construction Group (Tables 6–9), and should thus be optimized with respect to their environmental impacts in the production and construction stage rather than in the operational energy stage. Similarly, the thermal insulation thickness variable is traditionally optimized with respect to operational energy [19], and this seems to be justified when coal, or probably another environmentally harmful fuel, is used for electricity production (Tables 6–8). However, the results obtained in the present study indicate that when very clean fuels are used for electricity production this variable would actually belong to the Integrated Group (Table 9), and should thus be optimized with respect to its combined environmental impacts in the two stages: production and construction, and operational energy.

A further more general conclusion that seems to follow from the results of this study is that in order to apply the suggested methodology, generalized design variable grouping can be performed on representative modules of various building occupancy types. This grouping would depend, however, on climate characteristics and type of fuel used for electricity production, whereas for the same fuel the electricity production technology would probably not alter the grouping.

Future development of the methodology and tools would be devoted to: (i) improving the representation of the maintenance-to-demolition stage database to include the missing operations and activities of dumping, recycling, landfilling, and incineration, (ii) further and deeper sensitivity studies, (iii) establishing suitable methodologies for deriving the environmentally optimal solution in each of the four separate groups, and (iv) demonstrating on an actual building project how the application of the multi-stage systematic methodology, followed by a simple superposition of the partial decisions, leads to a full life cycle (cradle to grave) optimal solution for the entire building.

Acknowledgements

This research has been developed within the framework of S. Pushkar's Ph.D. dissertation under the guidance of R. Becker (Supervisor) and A. Katz (additional Supervisor).

References

[1] ISO 14040. Environmental management—life cycle assessment—principles and framework. ISO, 1997E.

[2] ISO 14041. Environmental management—life cycle assessment—goal and scope definition and inventory analysis. ISO, 1998E.

[3] ISO 14042. Environmental management—life cycle assessment—life cycle impact assessment. ISO, 2000E.

[4] ISO 14043. Environmental management—life cycle assessment—life cycle interpretation. ISO, 2000E.

[5] Alexander B, Barton G, Petrie J, Romagnoli J. Process synthesis and optimization tools foe environmental design: methodology and structure. Computers & Chemical Engineering 2000;24:1195–200.

[6] Azapagic A, Clift R. Life cycle assessment and multiobjective optimization. Journal of Cleaner Production 1999;7:135–43.

[7] Azapagic A, Clift R. The application of life cycle assessment to process optimization. Computers & Chemical Engineering 1999;23:1509–26.

[8] Dobson I. Life cycle assessment for painting processes: putting the VOC issue in perspective. Progress in Organic Coatings 1996;27(1–4):55–8.

[9] Dones R, Frischknecht R. Life-cycle assessment of photovoltaic systems: results of Swiss studies on energy chains. Progress in Photovoltaics 1998;6(2):117–25.

[10] Griffin N. A clean technology approach for nuclear fuel reprocessing. Journal of Chemical Technology and Biotechnology 1997;68(4):361–6.

[11] Roeleveld P, Klapwijk A, Eggels P, Rulkens W, vanStarkenburg W. Sustainability of municipal wastewater treatment. Water Science and Technology 1997;35(10):221–8.

[12] De Langhe P, Criel S, Ceuterick D. Green design of telecom products: the ADSL high speed modem as a case study. IEEE Transactions on Components Packaging and Manufacturing Technology Part A 1998;21(1):154–67.

[13] Prior J. Building research establishment environmental assessment method, (BREEAM), version 1/93 New Offices, 2nd ed. Building Research Establishment Report, 1993.

[14] U.S. Green Building Council. *LEED* (buildings: leadership in energy and environmental design), environmental building rating system criteria. Third Ballot Draft, 1996.

[15] Lippiatt B. Selecting cost-effective green building products: BEES approach. Journal of Construction Engineering and Management 1999:448–55.

[16] Trusty W, Meil J. ATHENA^{TM}: an LCA decision support tool application results and issues. Second international conference, Paris, 1997. p. 239–48.

[17] Becker R, Paciuk M. Upgrading energy efficiency, comfort and air quality in an Israel school. In: Carmelict J, Hens H, Vermeir G, editors. Research in building physics. Proceedings of the second international conference on building physics, Leuven, Belgium, September, 2003. p. 929–35.

[18] Al-Rabghi O, Hittle D. Energy simulation in buildings: overview and BLAST example. Energy Conversion and Management 2001;42:1623–35.

[19] Bojic M, Yik F, Leung W. Thermal insulation of cooled spaces in high rise residential buildings in Hong Kong. Energy Conversion and Management 2002;43:165–83.

[20] Bojic M, Yik F, Sat P. Energy performance of windows in high-rise residential buildings in Hong Kong. Energy and Buildings 2002;34:71–82.

[21] Bojic M, Yik F, Wan K, Burnett J. Influence of envelope and partition characteristics on the space cooling of high-rise residential buildings in Hong Kong. Building and Environment 2002;37:347–55.

[22] Kalogirou S, Florides G, Tassou S. Energy analysis of buildings employing thermal mass in Cyprus. Renewable Energy 2002; 27:353–68.

[23] Shariah A, Shalabi B, Rousan A, Tashtoush B. Effects of absorptance of external surfaces on heating and cooling loads of residential buildings in Jordan. Energy Conversion and Management 1998;39:273–84.

[24] Datta G. Effect of fixed horizontal louver shading devices on thermal performance of building by TRNSYS simulation. Renewable Energy 2001;23:497–507.

[25] Bodart M, Herde A. Global energy savings in offices buildings by the use of daylighting. Energy and Buildings 2002;34:421–9.

[26] Potting J, Blok K. Life-cycle assessment of four types of floor covering. Journal of Cleaner Production 1995;4:201–13.

[27] Jönsson Å, Tillman AM, Svensson T. Life cycle assessment of flooring materials: case study. Building and Environment 1997; 32(3):245–55.

[28] Wier G, Muneer T. Energy and environmental impact analysis of double-glazed windows. Energy Conversion and Management 1998;39(3/4):243–56.

[29] Cole R. Energy and greenhouse gas emissions associated with the construction of alternative structural systems. Building and Environment 1999;34:335–48.

[30] Jönsson Å, Björklund T, Tillman A. LCA of concrete and steel building frames. International Journal of LCA 1998;4:216–24.

[31] Erlandsson M, Levin P, Myhre L. Energy and environmental consequences of an additional wall insulation of a dwelling. Building and Environment 1997;32(2):129–36.

[32] Holland JH. Adaptation in natural and artificial systems. University of Michigan Press; 1975.

[33] Goedkoop M, Spriensma R. The Eco-indicator 99, a damage oriented method for life cycle impact assessment. Methodology report, 2000.

[34] Goedkoop M, Oele M. Introduction into LCA methodology and practice with SimaPro 5. SimaPro 5.0 User Manual, 2001.

[35] Petersen E. LCA tool for use in the building industry. International Journal of Low Energy and Sustainable Building 1999;1:1–11.

[36] Crawley D, Lawrie L, Frederic C, Winkelmann C, Buhl W, Huang Y, Curtis O, Strand R, Liesen R, Fisher D, Witte M, Glazer J. EnergyPlus: creating a new-generation building energy simulation program. Energy and Building 2001;33:319–31.

[37] Houck C, Joines J, Kay M. A genetic algorithm for function optimization: a matlab implementation. NCSU-IE TR 95–09, 1995.

[38] Thompson M, Ellis R, Wildavsky A. Cultural theory. Boulder: Westview Print; 1990.

[39] Mahoney W, Cleveland A. Means men-hour standards for construction, revised 2nd ed. R.S. Means Company Inc.; 1988.