APPLICATION OF LIFE CYCLE ASSESSMENT TO VARIOUS BUILDING LIFETIME SHEARING LAYERS: SITE, STRUCTURE, SKIN, SERVICES, SPACE, AND STUFF

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ABSTRACT

Currently, green rating systems are not directly related to environmental consequences. Moreover, rating systems score both building-related tasks with long lifetime expectancies and system-related tasks with short lifetime expectancies without separating them. Therefore, passive solar and bio-climatic architectures, which have long lifetime expectancies and thus have a strong, negative impact on the environment, are neglected. The main goal of this study is to explore differences in total environmental impact for a single "typical" building module (with the heavy wall building technology accepted in Israel) in terms of six different lifetime shearing layers, Site, Structure, Skin, Services, Space Plan, and Stuff, each of which reflects a different form of environmental damage. The objective of this study was to evaluate the six shearing layers using life cycle assessment (LCA) by applying Eco-indicator 99 (EI99). It was found that the environmental damage associated with the Building layers (Site, Structure, and Skin) was higher than that associated with the Service layers (Services, Space Plan, and Stuff). The paper may contribute to the development of a more scientific (quantitative) background for green rating systems. As a result, a greater decrease in building-related ecological impacts can be achieved, thus encouraging sustainable building activities.

KEYWORDS

green rating system, sustainable design, passive solar architecture, LCA, shearing layer concept

INTRODUCTION

Scoring is an important step in the development of rating systems (Bossel 1999). The scoring procedure is usually based on a comparison of building performance and current building regulations (Green Star 2011; BREEAM 2011; SBTool 2012) or input from a panel of experts (Green Globes 2013). A scoring range of 1 to 5 (as applied in the Green Star system) is usually suggested. The use of negative scores for buildings that have not met the minimum conventional industry standards, such as that applied in SBTool (from -2 to +5), is very questionable (Lee and Burnett 2006). Furthermore, the "determination of weightage mostly involves judgmental or conscious-based value due to the inherent complexity and the lack of objective

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basis" (Chew and Das 2008). Thus, the scoring procedures are based on a qualitative approach and are not directly related to environmental consequences.

Moreover, scores are usually assigned based on both building- and system-related characteristics without considering them separately according to their different lifetime expectancies and environmental damage (Shaviv 2008). For example, the "Optimize Energy Performance" credit (LEED 2013) is based on Appendix G of ASHRAE 90.1 (ASHRAE 2010), which considers both building- and system-related performance simultaneously. Shaviv (2011) criticizes this approach as allowing building owners and design teams to earn "cheap and easy points", emphasizing the correct sizing of mechanical and electrical systems for efficiency and overlooking truly sustainable architecture containing bio-climatic and passive solar aspects. "The relations between separate sub-systems within a building, and of the building itself with its surroundings, are rarely linear. The performance assessing method needs to reflect that complexity." (Horvat and Fazio 2005).

Green buildings already have gained momentum and become the trendy fashion and mainstream architectural practice (Young 2008; Dell'Agnese 2008; Blankin and Kenney 2010; Keeton 2010; Thomson 2010). However, to emphasize truly sustainable architecture, including bio-climatic and passive solar aspects, Shaviv (2008) suggested that energy use associated with building design should be treated separately from energy use related to mechanical and hot water system design due to their different lifetime scales, which correspond to different levels of environmental damage (e.g., the lifetime of the building is 50-100 years, but the lifetime of the systems is 15-25 years). Shaviv suggested dividing the energy category of the Israeli Green Building Standard (SI5281) into two subcategories: "building energy performance" and "building services systems." This separation procedure is already included in the recent revision of SI5281 (2011).

Furthermore, Pushkar and Shaviv (2013) considered a building in terms of six shearing layers (Site, Structure, Skin, Services, Space Plan, and Stuff) in accordance with the shearing layer concept invented by Frank Duffy (1990) and further developed by Stewart Brand (1994). In this concept, each shearing layer has a different lifetime scale and consequently a different environmental damage contribution.

Following this suggestion, the authors calculated the green points using the SI5281, Sustainable Building Tool (SBTool) (2012), and Leadership in Energy and Environmental Design (LEED) rating systems (LEED 2009). Analyzing the total percentages of the Building and System layers for all environmental categories, it was found that the SI5281, SBTool, and LEED systems use different approaches to emphasize the importance of each of six building layers. SI5281 focuses on the importance of Building layers (Site, Structure, and Skin) with a long timescale (from fifty years to eternal), with 60% of the total possible points assigned to these layers. The SBTool gives the same priority to both Building (50% of points) and Service (50% of points) layers. Finally, LEED v3 focuses on the Service layers (Services, Space Plan, and Stuff) with a short timescale (from daily to twenty years), assigning 66% of the total possible points to these layers.

In addition to SI5281, LEED v3, and SBTool, the shearing layer concept was also applied to the LEED v4 (2013), BRE Environmental Assessment Method (BREEAM 2011), and GreenStar (2011) rating systems (Pushkar and Shaviv Accepted). In this analysis, it was found that the BREEAM, Green Star, and LEED v4 rating systems also prioritize the Service layers, with short lifetime expectancies, assigning approximately 60% of the total points to these layers.

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In these studies, the aforementioned systems were simply reshaped based on the concept of the building as comprising six shearing layers. For example, the subcategory Building Energy Performance (within the Energy category of SI5281) states that satisfying the requirements of the Energy Efficiency credit (1.1.3 Energy Efficiency according to SI5282 [2011]) is worth 21 points. This credit intends to reduce the energy consumption required for the heating and cooling of the building by designing the building in an energy-conscious manner. Energy-conscious building strategies mostly depend on the design of the building skin (insulation of the envelope, window size, type of window glazing and shading, building thermal mass, and night ventilation for passive cooling), as well as the design of the building's structure (including the thermal mass of the structure, building geometry, compactness and proportions, and window orientation) (SI5282 2011). Therefore, the points corresponding to this credit were divided between Skin (13 points) and Structure (8 points) (Pushkar and Shaviv 2013; 2014, In Press).

These analyses were performed based on the suggestion that different environmental damages are associated with different shearing layers. However, this assumption requires verification. Life cycle assessment (LCA), which is already deeply embedded in construction practices (Singh et al. 2011), can be used as a quantitative methodology for the evaluation of environmental damage.

Some green building rating systems have begun to recognize the importance of LCA. For example, the Materials category in the BREEAM system includes credit for the life cycle effects of external walls, windows, the roof, upper floor slabs, and floor finishes/coverings (BREEAM 2011). LEED offers a "building life-cycle impact reduction" credit for their Materials category (LEED 2013).

However, the direct application of traditional LCA (which proves to be a problematic task under current building practices [Pushkar et al. 2005; Khasreen et al. 2009; Bin and Parker 2012; Monteiro and Freire 2012; Van Ooteghem and Xu 2012]) to green rating systems can be difficult and impractical. The reductionist approaches taken in LCA can overlook some of the emergent properties of system interactions. For example, SI5281 includes the credit 1.1.3 Energy Efficiency according to SI5282 (2011). SI5282 is an Energy code for office buildings in Israel based on a prescriptive approach (Shaviv et al. 2008). This code provides a recommended prescription for 12 decision variables. Some of these variables, such as building orientation, infiltration, and night ventilation, simply cannot be accounted for using LCA. However, in the hot-humid climate of the Mediterranean coast, the interaction of high thermal mass with night ventilation is effective for residential buildings, providing over 5°C of cooling (Capeluto et al. 2004). In addition, LCA can also obscure significant issues, such as local ecosystem disruption based on project development activities. Some points in green rating systems attempt to access this notion, which goes beyond the basics of LCA accounting. For example, the credit "LE 04 Enhancing site ecology" (BREEAM 2011) aims to preserve and increase the ecological value of the site as a result of project development.

Thus, this paper suggests an indirect approach for LCA application to green point allocation by exploring differences in total environmental impact for a single building module based on six shearing layers. The objective of this study is to apply LCA methodology to evaluate the six shearing layers: Site, Structure, Skin, Services, Space Plan, and Stuff. Unfortunately, this contribution cannot be rigorously tied to the rating systems. However, by revealing the environmental impacts of the building shearing layers, the paper can contribute to developing a more scientific background for green point scoring.

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"SHEARING" A BUILDING ACCORDING TO LIFETIME EXPECTANCY

Frank Duffy introduced the idea of presenting a building by layers according to lifetime expectancy. He argued that "A building properly conceived is several layers of longevity of built components." He distinguished four building timescale layers: Shell, Services, Scenery, and Set ("four S's"). Shell is the structure (fifty years), Services are plumbing, HVAC equipment, lifts, cables (fifteen years), Scenery is partitions, dropped ceiling (five to seven years), Set is furniture (months to weeks) (Duffy 1990). Duffy argued that: "Thinking about buildings in this time-laden way is very practical. As a designer you avoid such classical mistakes as solving a five-minute problem with a fifty-year solution, or vice versa. "Thus, Building layers are "slow" layers with long lifetime expectancy - like "a fifty-year solution", while Service layers are "speedy" layers with a short lifetime expectancy - like "a five-minute problem". Consequently, slow Building layers require more attention from an architect than speedy Service layers. Speedy Service layers are shortly replaced; thus, their design is of less importance in their "first installation" (when green certification is achieved). In contrast, slow Building layers are more static layers and not replaced frequently; thus, it is important to design correctly their "first installation".

Stewart Brand (1994) expanded Duffy's concept of "four S's" that was oriented toward interior design in commercial buildings into a more general concept of "six S's." According to Brand's concept, an entire building can be separated into six different timescale shearing layers: Site (eternal), Structure – the foundation and load-bearing elements (fifty to three hundred years), Skin – exterior surfaces (twenty to fifty years), Services – communication wiring, electrical wiring, plumbing, fire sprinkler systems, HVAC, elevators and escalators (ten to twenty years), Space plan – interior walls, ceilings, floors, and doors (three to ten years) and Stuff – chairs, desks, phones, pictures, kitchen appliances, and lamps (daily to monthly). Brand explained that: "Site dominates the Structure, which dominates the Skin, which dominates the Services, which dominates the Space Plan, which dominates the Stuff." The insight of this: Site constrains the Structure, which constrains the energy efficiency of the Skin, which relates to the efficiency of the Services. Thus, slow Building layers regulate speedy Service layers, leading to additional emphasis on the importance of environmentally correct design of Building layers.

Brand's 6-S sequence considers both the design and the construction stage. The architect and building engineers create building drawings layer-by-layer. These layers "shear" a whole building into the six shearing layers from the bottom layer to the upper layer in the following sequence: Site, Structure, Skin, Services, Space Plan, and Stuff. The bottom layers, which are fixed first in the drawings, will be part of the building for longer than the upper layers (Brand 1994). The architect begins the design phase with a site plan (Site layer). Next, the engineer designs the foundation, columns, beams, and floors, thereby creating the second layer (Structure). Next, the architect suggests an exterior wall composition, designing the third layer (Skin). HVAC and plumbing engineers design the fourth layer (Services), including elevators, escalators, HVAC, plumbing, and sprinkler systems. The architect then creates the fifth layer (Space Plan), designing partitions, ceilings, floors, and doors. Eventually, the architect of interior design creates the sixth layer, filling it with items (Stuff layer): furniture, kitchen appliances, and lamps. The construction stage also follows this sequence of layers: excavation and site preparation (Site); foundation, framing and floor construction (Structure); wall erection (Skin); services installation (Services); space plan construction (Space Plan); and furnishing (Stuff).

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More basic building materials, such as concrete and steel, are usually needed in the bottom layers. Thicker concrete walls are necessary to obtain lower thermal conductance and higher thermal inertia. A large number of large windows of high quality are needed to optimize solar heat gain. Additional internal thermal mass is sometimes required to allow for temporary storage of the increased solar heat for release at night. Although improving these properties affecting the operational energy lowers the building's heating and cooling loads, the environmental impact associated with the production, construction, maintenance and demolition stages of the Skin materials (concrete, steel, and glass) can be significant. From an environmental viewpoint, concrete and steel production processes are highly energy-intensive; therefore, the processes are associated with significant carbon dioxide (CO_2) emissions (Van den Heede and Belie 2012; Burchart-Korol 2013).

In contrast, the upper layers require much smaller quantities of building material than the bottom layers. In addition, the components of the upper layers can easily be selected to be environmentally friendly. For example, it is possible to select refrigerants and HVAC equipment that minimize or eliminate the emission of compounds that contribute to ozone depletion and climate change. To support environmentally responsible forest management, the use of flooring, sub-flooring, wood doors, and wood finishes with the Forest Stewardship Council's (FSC) certification is preferred. Thus, the bottom building layers and upper service layers have different environmental influences and should be designed separately.

Therefore, the goal of this work is to evaluate the influence of the bottom building layers, with long lifetime expectancies, separately from the influence of the upper service layers, with short lifetime expectancies. Consequently, this study groups the six shearing layers into two main layer types with different environmental loads: Building layers (i.e., Site, Structure, and Skin) and Service layers (i.e., Services, Space Plan, and Stuff). The question guiding this study, then, is the following: how does the shearing layers concept treat building and system environmental damages?

The answer to the above question is determined by analyzing the shearing layer concept when applied to a single "typical" building module with heavy wall building technology. Such a module was chosen based on the tendency of heavy structure buildings to be thermally effective in the heat-dominated Mediterranean climate of Israel (Capeluto et al. 2004). Despite the significant number of scientific articles analyzing the LCA of building components (Singh et al. 2011), investigations into the application of the shearing layer concept to the LCA of the building have not yet been performed.

MATERIALS AND METHODS

Research framework

A very simple generic basic module of a typical multi-story office building was used for the LCA evaluation of the six shearing layers. LCA evaluations were performed on a 3 m x 4 m, 3-m-high module with three internal walls (partitions) and one external wall located on a typical intermediate floor between two similar modules. The modules can face any of the four major orientations (north, west, south and east). For the acclimatization energy calculations, it was assumed that the building is constructed in a heating-dominated climate with a mild summer and cool winter. The simulation was carried according to the climatic conditions

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of Jerusalem's typical meteorological year given in the Climatic Atlas of Israel (Bitan and Rubin 1991/94). Average daily temperature variation in August: 11.7°C, daily average relative humidity (RH) in August: 63%. Average daily temperature variation in January: 7.5°C, daily average RH in January: 76%.

The occupancy hours from Sunday to Thursday are set as 7:00 to 18:00. The reference point for the daylight calculation is the module's center at a height of 0.8 m with a required illuminance of 500 lx. Air infiltration induces a 0.5 h^{-1} air change rate. Heating and cooling are achieved using a heat pump (coefficients of performance (COP): 2.75 for heating, 3.0 for cooling) with set-points of 20°C and 24°C, respectively. The design levels were 360 W for electric lights, 250 W for electric equipment, and 1 person with an activity level of 100 W for occupants. Clothing is taken as 1 Clo in winter and 0.5 Clo in summer. In addition, it should be noted that the minimum window area was 9% of the floor area (1.08 m^2). The analysis was performed for a building design life of 50 years.

Table 1 lists the components considered for each layer. Reinforced concrete technology was assumed. Table 2 lists the building materials considered for each of the building components: the foundation, columns, beams, partitions, floor/ceiling, floor coverings, wall type, and wall coverings.

TABLE 1: Components of the six shearing layers.

Building layers	Components
Site	Excavation and landfill
Structure	Foundations, columns, beams, and ceilings
Skin	External walls, external wall covering, roof, and glazing
Service layers	Components
Services	HVAC, electrical fixtures, and plumbing fixtures
Space Plan	Partitions, floor coverings, and doors
Stuff	Computers, printers, furniture, and light bulbs

TABLE 2: Description of building components.

Component	Composite materials (thickness (m)) / (section (m x m))
Foundation: concrete	Concrete length: 14 (0.4 x 0.5), steel
Columns: concrete	Concrete length: 2.6 (0.3 x 0.3), steel
Beams: concrete	Concrete length: 6 (0.2 x 0.35), steel
Partitions: gypsum board	Gypsum board (0.0125), glass wool (0.075), gypsum board (0.0125)
Roof/ceiling: concrete slab	Reinforced concrete (0.14)
Floor coverings: marble	Sand (0.06), mortar (0.02), marble (0.012)
Wall type: concrete	Concrete (0.05, polystyrene (0.03), concrete (0.15)
Wall coverings: stone	Stone (0.02), concrete (0.05), mortar (0.006)

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Analysis tools and methods

Thermal analysis was performed using EnergyPlus software. Environmental inventory analysis was performed using the SimaPro database tool. SimaPro (SimaPro 7.3.3) is a mature database tool featuring 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 build new ones. Environmental scoring was established using the EI99 tool. Due to its comprehensive set of currently utilized methodological options, EI99 is regarded as a suitable LCA tool for deriving general and methodology-independent conclusions regarding environmental damages (Pushkar 2014).

The EI99 tool was used to calculate the environmental scores (pt) associated with the six shearing building layers. As a result, six EI99 environmental scores (e/e, e/a, h/h, h/a, i/i, and i/a options) were calculated for each studied layer (Site, Structure, Skin, Service, Space Plan, and Stuff).

Data collection

Considered life cycle stages

A complete building LCA ("cradle to grave") consists of three primary stages: production and construction (P&C), operational energy (OE), and maintenance to demolition (MtoD). The analyzed LCA stages for each shearing layer are presented in Table 3. Only the area required for the erection of the studied module on the site was considered. Therefore, only the P&C stage was evaluated for the Site layer. Due to the negligible influence of the properties of the Structure-layer materials on the environmental damage associated with the thermal acclimatization, ventilation, and lighting of buildings, the OE for this layer was neglected. For buildings with sustainable architecture containing bio-climatic and passive solar aspects, the operational energy performance for thermal acclimatization, ventilation, and lighting mainly depends on the properties of the materials used in the building envelope and less on the energy efficiency of HVAC. Thus, for the OE stage, 70% of the total energy was allocated to the Skin layer. The remainder (30%) of the energy was allocated to the Services layer, which was also part of the OE stage. These allocation percentages are based on work of Pushkar and Shaviv (In Press). The OE stage was omitted as non-relevant for the Space Plan and Stuff layers.

TABLE 3: Considered LCA stages of the six shearing layers.

Layers	P&C	OE	MtoD
Site	X	-	-
Structure	X	-	X
Skin	X	X	X
Services	X	X	X
Space Plan	X	-	X
Stuff	X	-	X

P&C - production and construction;
OE - operational energy;
MtoD - maintenance to demolition

P&C stage: production database

The production stage of the building technology associated with environmental damage is subdivided into three data collection levels: raw material extraction, the production of composite

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materials, and the manufacturing of composite components. The SimaPro software database includes all of these data collection levels and their associated transport processes. Complete databases were available for all of the building components required for the studied building model, including the building and service layers.

P&C stage: construction database

The construction database contains information about the environmental damage from energy use for the transportation of the workforce/employees to and from the construction site and the construction equipment and building materials/products. It also contains damage information related to energy use for on-site equipment, solid waste, liquid waste, and water. The energy use for the transportation of building materials/products, on-site equipment, and solid waste (5% by weight) were considered in this study, while liquid waste and water were neglected due their negligible contribution in this stage.

- **Distances over which building materials/products are transported to a construction site**

The transportation distances between the supply centers and building sites depend on the building materials/products. Israel is a small country spanning 424 km from north to south and 114 km from east to west at its widest point. Thus, the average suitable transportation distances corresponded to relatively short transportation distances within the country and the number of existing building material/component supply centers. For example, a minimum transportation distance of 20 km was assumed for ready-mix concrete, which is the main building product for the Structure and Skin layers. The concrete that is usually supplied to a building site from a batching plant by mixer trucks must be constantly mixed. Thus, it remains in liquid form during transportation. The long, hot, rainless summers of the Israeli climate make this task very difficult. Thus, the ambient summer temperature is one of the most important factors affecting the setting time of ready-mix concrete. The high temperatures greatly shorten the setting time of the fresh concrete mix. Therefore, a relatively short transportation distance must be used for successful concrete casting.

- **On-site equipment use**

A variety of power-operated tools and equipment, such as compressors, drills, saws, and welders, are essential for the erection of the building components from the Structure and Skin layers. The American manual Means Man-Hour Standards for Construction (Mahoney and Cleveland 1988) was used to calculate the number of hours for which the on-site equipment was in operation per building component. The number of hours was multiplied by the energy consumption per hour of equipment operation. The equipment power data were obtained from the Tool Catalog (Southern-Tool). No detailed data were available for the Israeli electricity production in SimaPro. Therefore, the electricity consumption for power-operated equipment was converted into an environmental score based on a coal-based French approach.

Operational energy stage

By applying EnergyPlus, thermal analysis of the studied module was performed for each of major orientations (north, west, south and east). Next, the average operation consumption of the evaluated building module was converted into an environmental score based on a coal-based French approach.

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MtoD stage: maintenance database

The MtoD database contains data on the environmental damages of the cleaning, repair, complete replacement and recycling of a component. Only cleaning and replacement procedures were considered for the Services, Space Plan, and Stuff layers.

- **Cleaning**

The floor coverings (Space Plan layer) in office buildings should be cleaned every workday. Thus, a cleaning rate of 240 times per year was used as an appropriate washing rate for the building floor covering (Space Plan). The marble floor coverings were cleaned with water and soap.

- **Replacement (as conceived by Frank Duffy and as was assumed in this study)**

In Israel, the entire lifetime of a building is assumed to be 50 years. The Structure (foundation and load-bearing elements) was considered by Frank Duffy as a layer with a lifespan of 50 to 300 years. In this study, the lifetime of the Structure layer is assumed to be 50 years (equivalent to the entire lifetime of the building).

The Skin layer (exterior surfaces) was considered as having a timescale of twenty to fifty years. In this study, the lifetime of the external wall, roof, and stonewall coverings is assumed to be as long as the entire lifetime of the building (50 years). However, the lifetime of the glazing is considered to be 15 years. Thus, this component had to be replaced three times during the full lifetime of the module.

The Services layer was considered to have a timescale of ten to twenty years. In this study, a 20-year HVAC lifetime was suggested, while the service life of the electrical and plumbing fixtures was assumed to be 10 years. Consequently, the HVAC was replaced twice, and the electrical and plumbing fixtures were replaced four times, during the entire lifetime of the building module.

The Space Plan layer was considered as having a timescale of three to ten years. It was assumed that the lifetime of the partitions and marble floor coverings is equal to that of the building. Therefore, these components were only destroyed (without replacement) at the end-of-life stage of the building. However, the lifetime of the doors was assumed to be 10 years, corresponding to four replacements of this component during the lifetime of the building module.

The Stuff layer was considered as having a timescale of days to months. In contrast to the daily to monthly timescale suggested by Frank Duffy, in this study, a more reliable service life of 5 years was considered for the Stuff layer. This required the consideration of nine replacements of this component during the building lifetime.

MtoD stage: demolition database

Similar considerations have been applied to the demolition database in the MtoD stage (e.g., the transportation distances of building materials/products to a disposal site and on-site equipment use).

- **Distances over which building materials/products are transported to a disposal site**

Disposal methods (e.g., landfill disposal, recycling, and reuse) affect the distances for transporting building materials/products to a disposal site. For example, there are only three recycling plants for construction waste in Israel (Israel Ministry of Environmental Protection, Recycling Companies 2013). Therefore, a relatively long transportation distance of 200 km was used for materials/products that are typically recycled, such as concrete. However, there are 22 landfill sites in Israel (Israel Ministry of Environmental Protection, Waste Sites 2013),

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which is a relatively high number. Thus, a fairly short distance of 50 km was assumed for materials/products that are disposed of in landfills, such as polystyrene.

- **On-site equipment use**

Many types of power-operated equipment, such as compressors, drills, saws, and welders, are crucial in the demolition process. The data sources used for the P&C stage, the American manual Means Man-Hour Standards for Construction (Mahoney and Cleveland 1988) and the Tool Catalog (Southern-Tool), were used to estimate the demolition hours for on-site equipment use per building component and the equipment power data, respectively. The electricity consumption of the power-operated equipment was converted into an environmental score based on a coal-based French approach (as in the P&C stage).

Limitations: LCA assumptions and omitted issues

Matthews et al. (2000) asserted that the inventory analysis in LCA studies should take into account the full set of "supply chains" as relevant data. The authors concluded that excluding any supply chain from the analysis would lead to inaccurate analysis results.

However, the present study cannot be considered a comprehensive LCA study. Indeed, some supply chains were excluded from the analysis on reasonable grounds. The LCA limitations described in the next paragraphs can be justified by highlighting the primary goal of the study, which was to analyze the LCA of shearing layers when applied to a single building module, namely, the typical heavy wall building technology accepted in Israel. Therefore, the intent of this paper is not discuss how analyses based on this typical building module might be generalized to other buildings in a similar context or in different geographical locations but rather to investigate the environmental influence of the bottom building layers and upper service layers of the building module based on concrete technology.

Building components

In this study, only primary building module components, such as foundations, columns, beams, and ceilings (Structure); external walls, external wall covering, roof, and glazing (Skin); HVAC, electrical fixtures, and plumbing fixtures (Services); partitions, floor coverings, and doors (Space Plan); and computers, printers, furniture, and light bulbs (Stuff) were considered (Table 1). Of course, a "complete" building has many additional components, such as communication appliances, communication wiring, fire sprinkler systems, elevators and escalators, installation appliances and wiring (Services); and phones, pictures, kitchen appliances, dishwashers, clothes washers, hair driers, cleaning products, and filters (Stuff) (Table 4). However, it is difficult to link the environmental load of these whole-building-related components to the simple building module considered here. Because large uncertainties can be involved in such LCA due to different opinions about the relevance of each component to the studied simple building module.

TABLE 4: Excluded components.

Layers	Excluded components
Services	Communication appliances, communication wiring, fire sprinkler systems, elevators and escalators, installation appliances, and wiring
Stuff	Phones, pictures, kitchen appliances, dishwashers, clothes washers, hair driers, cleaning products, and filters

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Life cycle procedures

Some non-relevant life cycle procedures were excluded from the analysis (Table 5). The building module considered in this study is supposed to be located within a brownfield but not within a highly contaminated site. As a result, remediation services, such as decontamination (soil washing, biological and thermal treatment, etc.), were excluded for the Site layer.

For the Skin layer, the environmental damage from cleaning, repair, complete replacement (such as external walls, external wall covering, and roof), and recycling of components was not considered. A module with three internal walls (partitions) and only one external wall located on a typical intermediate floor and between two similar modules was analyzed. Thus, the cleaning of this single external wall was neglected. As explained previously, the lifetimes of the external walls, external wall covering, and roof are the same as those of the entire building. Therefore, these components were only destroyed (without replacement) at the end-of-life stage of the building.

For the Space Plan layer, the environmental damage from cleaning, repair, and complete replacement of a component was not considered. As mentioned previously, the lifetime of the partitions and marble floor coverings was assumed to be equal to that of the building. Therefore, these components were only destroyed (without replacement) at the end-of-life stage of the building. Cleaning, repair, and recycling practices usually vary widely from office to office, and it is difficult to make assumptions about them for a simple building module. Therefore, these elements were excluded from the analysis.

TABLE 5: Excluded life cycle procedures

Layer	Excluded life cycle procedures
Site	Remediation services, such as decontamination (soil washing, biological and thermal treatment, etc.)
Skin	Cleaning, repair, complete replacement of a component
Space Plan	Cleaning, repair, complete replacement, recycling of a component

RESULTS AND DISCUSSION

In this paper, the analyzed Building and Service layers were evaluated by EI99 for a very simple generic basic module of a representative multi-story office building based on the typical heavy wall building technology accepted in Israel, applying all of the methodological options (i/a, i/i, h/a, h /h, e/a, and e/e).

Under all methodological options (Figure 1), the Building layers have higher priority (approximately 90%) than the Service layers (approximately 10%). The results support the results presented by Pushkar and Shaviv (2013; 2014, In Press), who applied the shearing layer separation procedure to all environmental categories of SI5281 (2011), such as energy, site, water, materials, health and wellbeing, waste, management, transportation, and innovation. The authors concluded that SI5281 already accommodates the shearing layer concept very well because of the higher priority of Building layers (60%) and lower priority of Service layers (40%).

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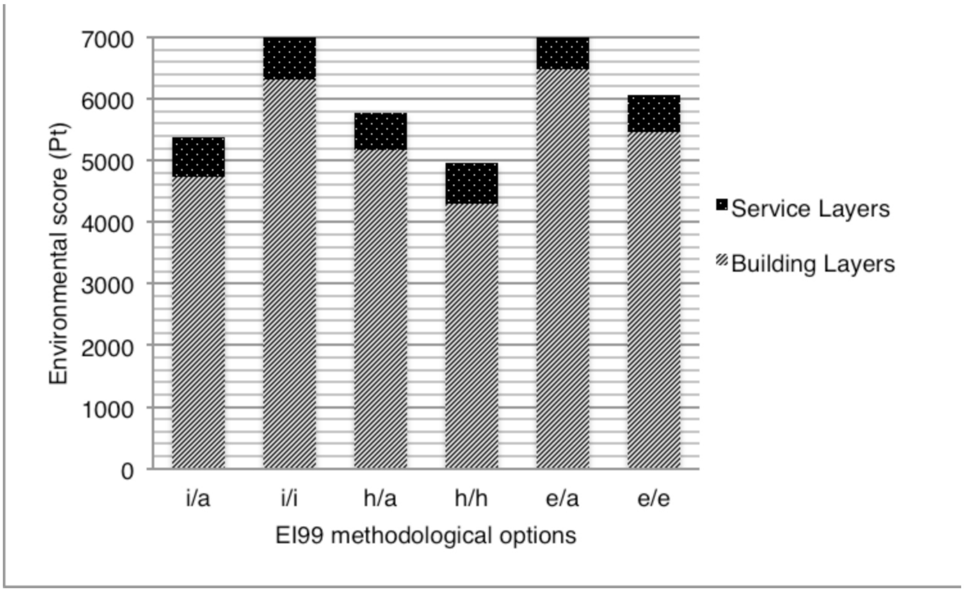
Figure 1: Environmental damage resulting from the Building and Service layers.



In this work, the ratio of the relative environmental damage of the three Building layers (Site, Structure, and Skin) was approximately 1:25:65 (Figure 2 - 4), confirming that the Skin layer is the most important. This is because the environmental evaluations of this layer were conducted for the OE stage in addition to the P&C and MtoD stages. In contrast, the Site layer has a lower priority. However, the ratio given in the current version of SI5281 is 5:1:3 for the Site, Structure, and Skin Building layers, respectively (Pushkar and Shaviv 2013; 2014, In Press). SI5281 considers all the relevant credits in the Site category, such as site selection, contaminated land, building and development density, heat island effect, maximization of the usage of built space, conservation of local fertile/top soil for use on site, and ecology on site (SI5281 2011). However, in this study, only excavation and landfill practices were considered under the Site layer because the specific case-study building module was taken to be located within a brownfield but not within a heavily contaminated area; this study was not conducted for a generic case with all possible environmental damage associated with the building site.

Menna et al. (2013) presented the LCA results for the Pre-Use phase (P&C) for the four environmental impact categories of IMPACT 2002+ (LCIA tool), namely, climate change, human health, ecosystem quality, and resource depletion, disaggregated into building components (foundation, structural elements, nonstructural components, water and electrical systems, and major appliances). The authors find that the major contributions arise from the structural (Structure layer) and nonstructural components (Skin layer) (approximately 30 - 40% each). In this study, the Structure layer contributes approximately 20 - 25% of the environmental damage, whereas the Skin layer contributes approximately twice (65-70%) (Figure 2- 4) the value reported by Menna et al. (2013) for this layer.

The high damage associated with the Skin layer found in the work is due to the attribution of 70% of the operational energy to the Skin layer, justified by the fact that it is responsible for bio-climatic and passive solar aspects of sustainable architecture. This corresponds

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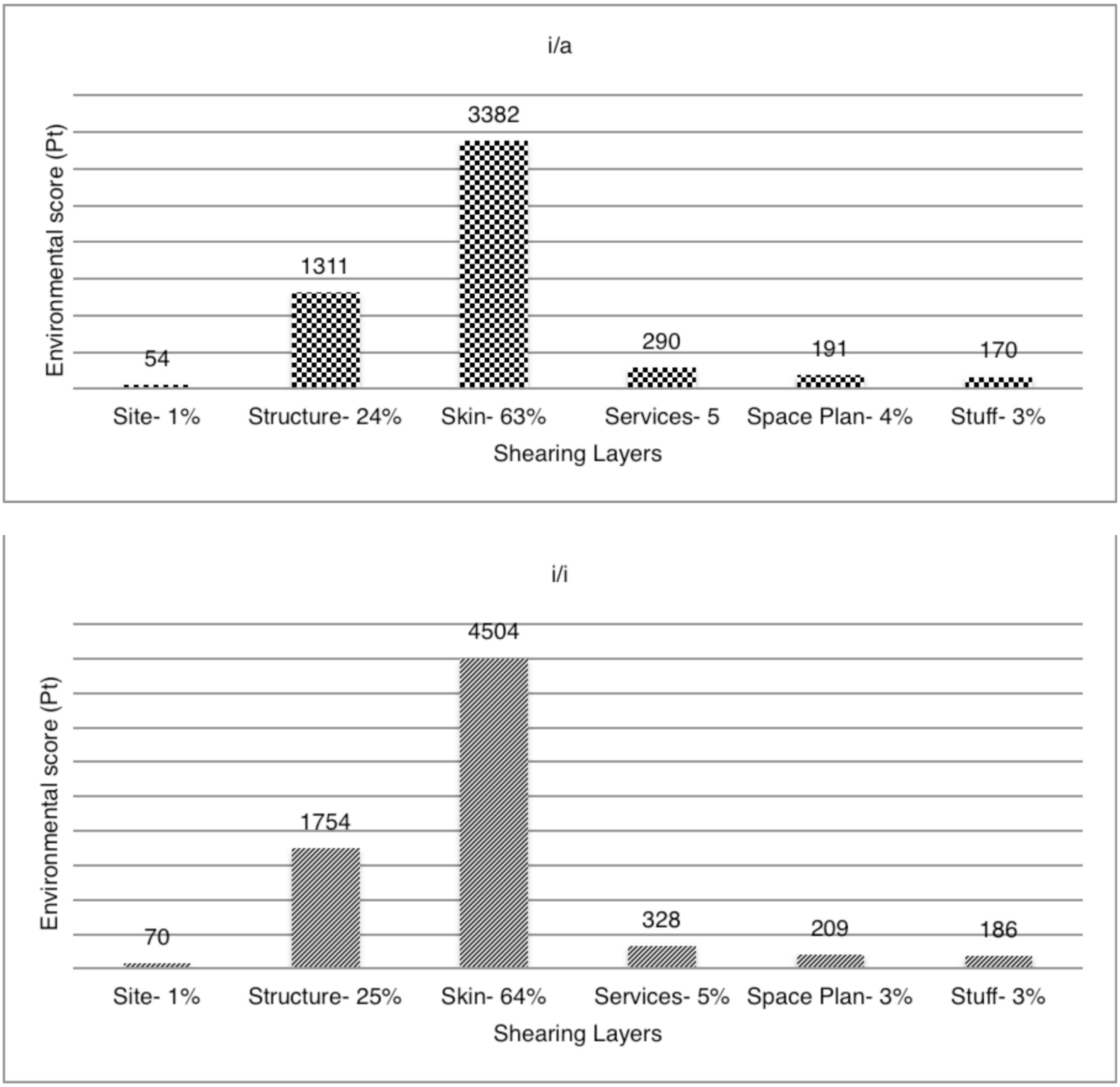
Figure 2: Environmental damage resulting from the Building layers (individualist options).



to the well-known fact that operating energy usage from appliances, acclimatization, lighting, and internal transportation is much higher (50 - 70%) than the embodied energy of the building for almost any building (Peuportier 2001; Scheuer and Keoleian 2002; Menna et al. 2013). Thus, the high damage found for the Skin layer (including a high amount of operational energy) is reasonable.

According to Menna et al. (2013), water and electrical systems (Services layer) and major appliances (Stuff layer) contribute a relatively little environmental damage (approximately 10% each). In this work, the corresponding values for these layers were only 5 - 6% per layer (Figure 2 – 4). This value is likely lower than the aforementioned result in the literature because the building module studied here was simple building module and, as was explained previously, some building components were reasonably excluded from the analysis.

In addition, SI5281 (Pushkar and Shaviv 2013; 2014, In Press) prioritizes the System layer over the Space Plan and Stuff layers, with a ratio of 6:1:1. Correspondingly, this study found a

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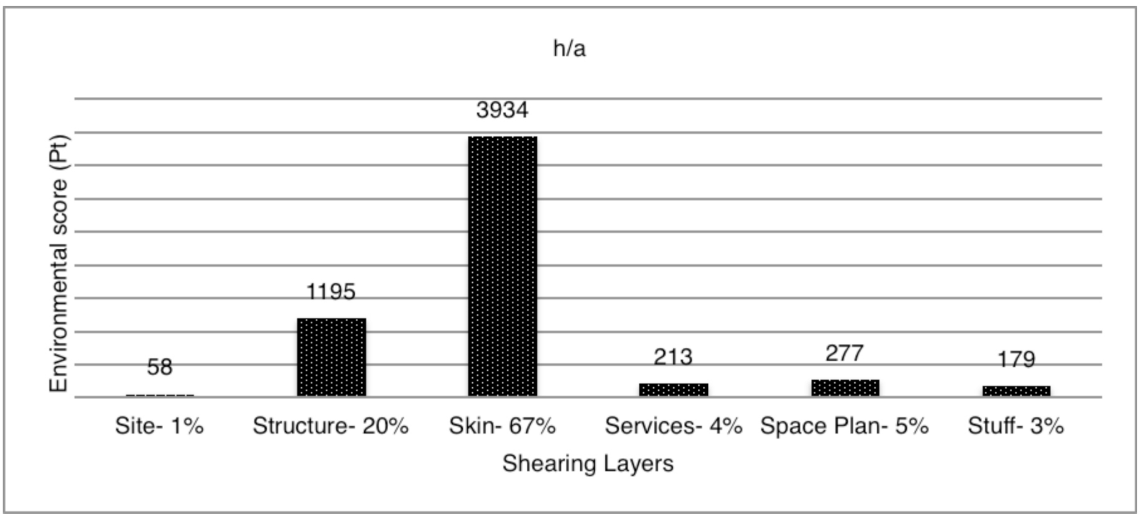
ratio of 2:1:1 for the System, Space Plan, and Stuff layers, respectively, for the i/a and i/i methodological options (Figure 2). Meanwhile, under the h/a, h/h, e/a, and e/e options, a ratio of 1:2:1 for the System, Space Plan, and Stuff layers, respectively, was obtained (Figure 3 and 4).

Inaccurate green point allocation in building rating systems can lead to the application of inappropriate sustainable strategies in subsequent projects. For example, as confirmed in this study, using the SI5281 (SI5281 2011), the Structure layer can be neglected due to the lower priority of this layer in this rating system. This result can lead to inaccurate estimates of the initial construction cost, the life-cycle cost, the embodied energy, occupants' health, and resource/habitat conservation, among other variables, of a building throughout its life cycle phases: production, construction, operation, maintenance, demolition, and rehabilitation.

Figure 3: Environmental damage resulting from the Building layers (hierarchist options).



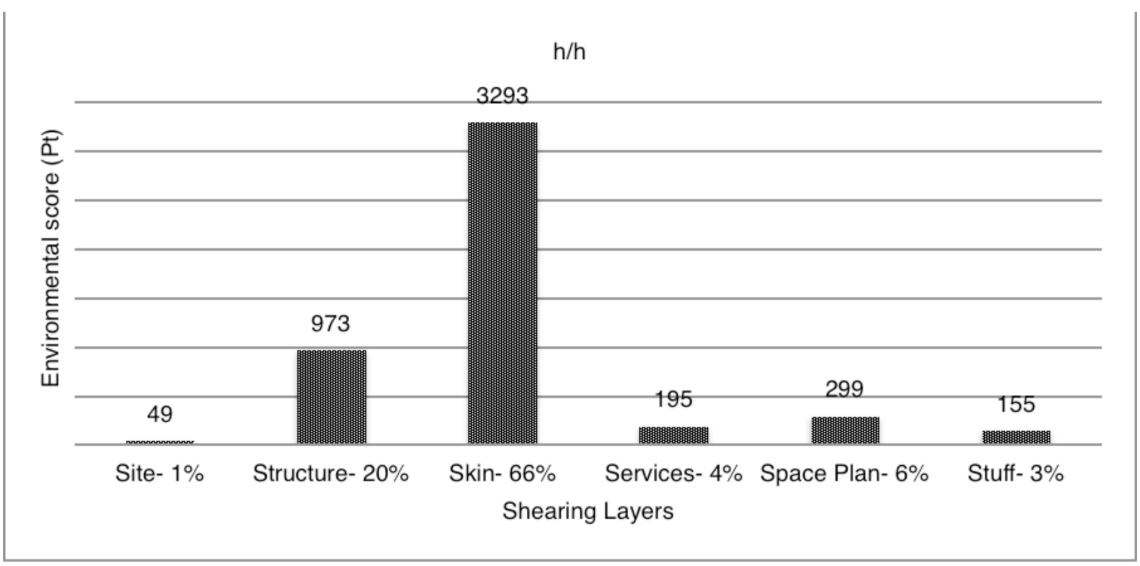


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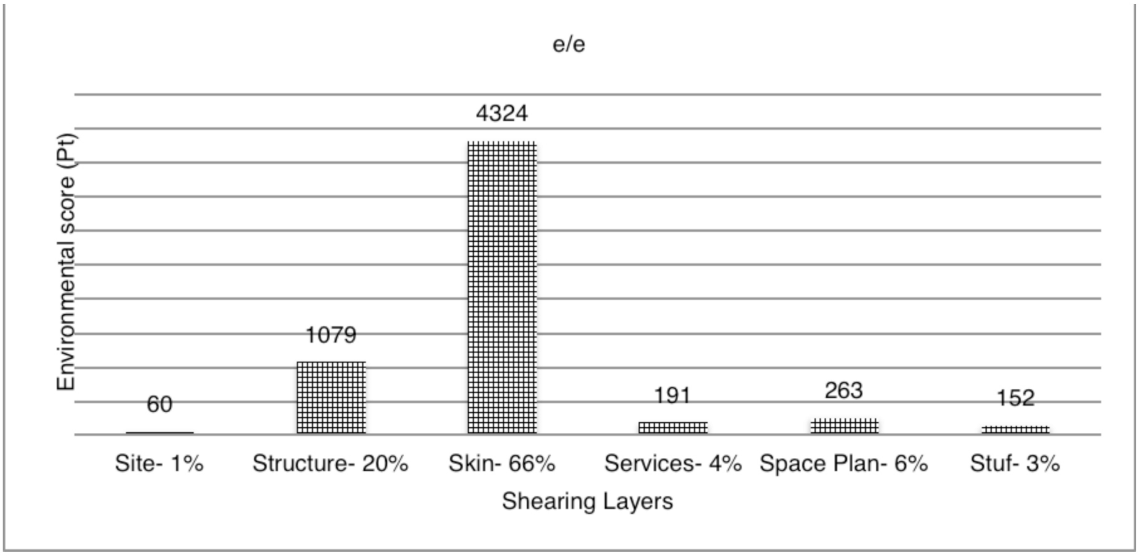
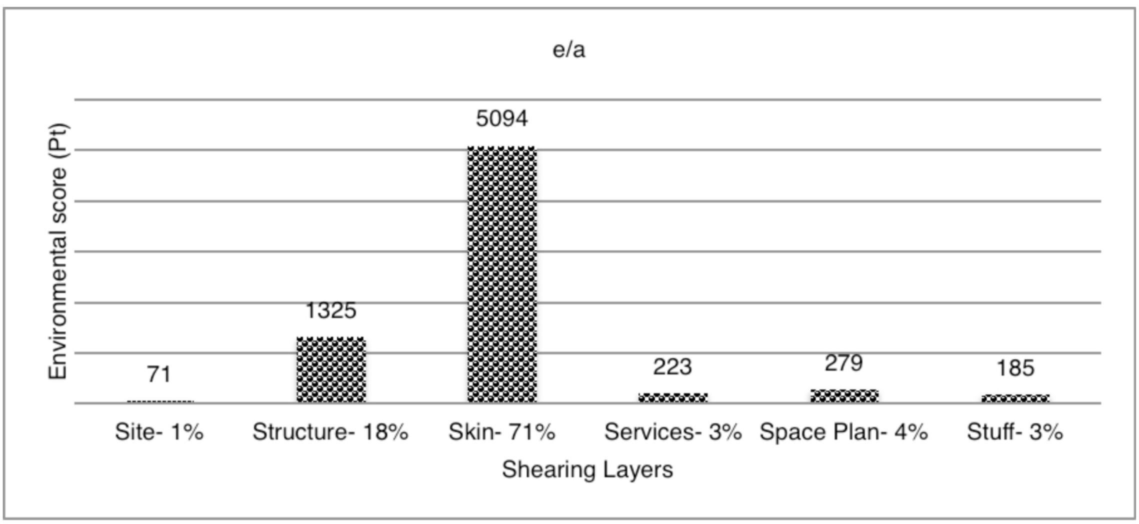
Figure 4: Environmental damage resulting from the Building layers (egalitarian options).





CONCLUSION

Scoring allocation is currently a principal problem within green rating systems (Lee and Burnett 2006; Chew and Das 2008). According to Pushkar and Shaviv (2013; 2014, In Press), a more reliable credit allocation of green points for green building standards may be achieved based on the analysis of the six shearing layers of each building, each of which has a distinct lifetime and thus a different level of environmental damage.

In this paper, this suggestion was analyzed by exploring the differences in total environmental impact for a single typical building module among shearing layers. It was found that the Building layers (Site, Structure, and Skin) contribute much more environmental damage than the Service layers (Services, Space Plan, and Stuff). By revealing the environmental impacts of the building shearing layers, this paper may contribute to developing a more scientific background for green point scoring. Due to the building-module-inherent LCA assumptions and simplifications used in this study, further environmental studies are required in this area.

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