LIFE CYCLE ASSESSMENTS OF WHITE FLAT AND RED OR WHITE PITCHED ROOFS FOR RESIDENTIAL BUILDINGS IN ISRAEL

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ABSTRACT

Historically, white flat roofs have been used in Israel due to the intense solar radiation and long, hot, rainless summers. However, red pitched roofs have also been frequently used for aesthetic reasons. It has been recently observed that red pitched roofs have been recolored white by homeowners. The goal of this study was to compare the life cycle assessments (LCAs) of white flat roofs versus red or white pitched roofs through their production (P), operational energy (OE), and maintenance to disposal (MtoD) stages. EnergyPlus software was used to evaluate the OE stage. The ReCiPe method was used to evaluate the environmental damages in all the stages. A two-stage nested ANOVA was used to determine the significant differences between the ReCiPe result of a white flat roof and the ReCiPe result of a red/white pitched roof. It was found that (i) selection of the best roof technology (flat or pitched) requires consideration of the LCA, including the P, OE, and MtoD stages; (ii) the white (flat and pitched) roof was the best technology, while the red pitched roof was the worst technology; and (iii) the combination of the ReCiPe endpoint hierarchical six methodological options method with two-stage nested hierarchical mixed ANOVA is the best approach for assessing the differences related to the LCAs of roof technologies.

KEYWORDS:

white flat roofs, red pitched roofs, LCA, ReCiPe, two-stage nested mixed ANOVA

INTRODUCTION

Based on ISO 13315-1 (2012), the "cradle to grave" life cycle assessments (LCAs) of roof technologies as well as LCAs of any other building components (wall, floor, window, etc.) include the following life cycle stages: production and construction (P&C), operational energy (OE), and maintenance to disposal (MtoD). Typically, sustainable white (cool) roofs were only evaluated through to the OE stage in terms of their thermal performance or operational energy consumption (Akbari 2003; Levinson et al. 2007, Levinson and Akbari 2010; Oleson et al. 2010; Saber et al. 2012). However, the P&C stage was found to be a significant stage (nearly 50% of the LCA) when heavy concrete roof technologies were evaluated (Huberman et al. 2015; Napolano et al. 2015; Pushkar 2016a). In addition, the MtoD stage, which highly

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depends on recycling and disposing practices, was evaluated as an important stage in the LCA of roof technologies (Sandin et al. 2014). Moreover, LCA evaluations of roofs, as well as any building-related LCA studies, are country specific because (i) their OE stage highly depends on the local climate, building type, and primary fuel source for energy production (Karimpour et al. 2014) and (ii) their P&C stage highly depends on local building technologies (Huberman and Pearlmutter 2008).

A few studies have focused specifically on the LCA of white flat roofs (Saiz et al. 2006; Susca 2012; Cubi et al. 2016). Susca (2012) and Cubi et al. (2016) studied white flat roofs installed in office buildings, whereas Saiz et al. (2006) focused on residential buildings. Despite different occupant behaviors in office and residential buildings, the climate (either cold or hot) was found to be a prevailing factor in LCA studies of white flat roofs (Saiz et al. 2006; Susca 2012; Cubi et al. 2016).

Saiz et al. (2006) evaluated white flat roofs for an eight-story residential building located in the cold semi-arid climate of Madrid. They found that by replacing the common gray gravel flat roof for a white flat roof, cooling energy decreased, and heating energy increased. Similar results were presented by Cubi et al. (2016), who considered white flat roofs installed in office buildings located in three Canadian cities: Vancouver, Calgary, and Toronto. It was found that white roofs cannot be recommended for cold climates due to an increase in heating energy from the resulting high solar reflectance (Cubi et al. 2016). However, by considering office buildings located in a humid subtropical climate (Long Island City, New York), Susca (2012) revealed that significant OE environmental impacts (up to 70% of the impact related to roof manufacture and replacement) could be avoided when a white roof was installed instead of conventional a black roof.

In four hot climates in Israel (i.e., hot Mediterranean, mild Mediterranean, hot semi-arid, and hot desert climates), the white roof has been dominant for flat-roofed buildings (SI 5282 2011). It is based on at least two climatic characteristics found in Israel: high solar radiation throughout the year (the average daily solar radiation on a horizontal surface ranges from 3.33 kWh/m^2 in winter to 7.67 kWh/m^2 in summer) and long, rainless summers (Pearlmutter et al. 2010).

Two studies that consider local Israeli roof technologies were revealed in the literature (Huberman et al. 2015; Pushkar 2016a). Huberman et al. (2015) compared two concrete-based roof technologies—a vaulted roof technology and a typical flat roof technology—installed in low-rise residential buildings located in a hot semi-arid climate (represented by Beer Sheva). In the Huberman et al. (2015) study, roof technologies were considered through the application of different configurations of segmental and parabolic vault forms of roofs, while the flat roof was considered as a reference case. It was reported that when compared to a flat roof, a vaulted roof can decrease the cumulative life cycle energy by nearly 25%. The authors evaluated the cumulative life cycle energy via life cycle energy analysis (LCEA), which was composed of an embodied energy for production (P) stage and operational energy for cooling and heating needs in the OE stage, and presented their results in GJ/m^2. In this case, the primary fuel source for energy production was disregarded (Huberman et al. 2015). Recently, however, different results were obtained when either LCEA or LCA of some building related constructions was applied (Pushkar 2016b).

Pushkar (2016a) evaluated the cradle to grave LCA of three local Israeli flat roof technologies. In the Pushkar (2016a) study, roof technologies were considered through the application of differently composed roof building materials: concrete-based, concrete block-based, and autoclaved aerated block-based roofs. The roofs were installed in office building modules located in the four climate zones of Israel. A concrete-based flat roof was recommended in the hot Mediterranean, semi-arid and hot desert climates, whereas the block-based flat roofs were found more appropriate for a mild Mediterranean climate (Pushkar 2016a).

In both Huberman et al. (2015) and Pushkar (2016a), the P and OE stages are the most influential on the LCA. The P stage is a significant stage because the building sector in Israel is based on heavy-concrete building envelopes, which provide thermal efficiency in a hot climate (Capeluto et al. 2004), and therefore, a large amount of concrete is required in these roof constructions. OE is a significant stage because non-renewable fuels, such as natural gas, are the main local energy sources for OE production (Friedman et al. 2014).

Historically, the red pitched roof has been used “to establish new aesthetic norms and conventions for the vernacular landscape” (Fu 2012). Thus, in Israel, in addition to the white flat roof, the red pitched roof has been widely used. It is possible that the main reasons for the use of red pitched roofs in Israel are aesthetic; people may prefer living in houses with beautiful red roofs. In Israel, however, residents sometimes cover their red roofs with a white coating to decrease heat loads in the summer. Such behavior demonstrates that the red pitched roof is a controversial issue in Israel (Figure 1).

Sproul et al. (2014) cited the conclusion of Akbari et al. (2009), who noted that “white roofs (compared with dark-colored roofs) on air-conditioned buildings in hot climates can cut cooling energy use by 10–20% on the floor of the building immediately beneath the roof.” Suehrcke et al. (2008) also concluded that using a white pitched roof can decrease summer heat gain by approximately 30% compared to a dark one in the hot climate of Townsville, Australia. However, the cradle to grave LCA of concrete-based local roof technologies such as red and white pitched roofs versus white flat roofs in Israeli climates has not yet been studied.

FIGURE 1. Residential house in Nesher, Israel. The roof with red tiles was covered by a white coating by a building’s residents.

The aim of this study was to evaluate the LCAs of two concrete-based roof technologies typically used for Israeli residential buildings, including (i) white flat and (ii) red and white pitched (each with slopes of 20% and 40%) roofs in four different climate zones in Israel to determine the environmental impact of each technology.

METHODS

Research framework

The LCA of a concrete-based flat roof was compared with the LCAs of concrete-based pitched roofs (hip roofs on a rectangular plan). The roofs were installed in a building module in a typical single-story residential building. The dimensions of the module were 10 m x 10 m and 3 m in height (SI 5282 2011).

The flat roof was covered with white bitumen sheets. The pitched roofs were covered with either (i) red ceramic tiles or (ii) white ceramic tiles. For each of the pitched roofs, slopes of 20% and 40% were examined. Figure 2 illustrates a white flat roof, a red pitched roof, and a white pitched roof (both pitched roofs have a slope of 40%). The building module locations were selected to represent all four climate zones in Israel, including a hot Mediterranean climate, represented by Tel-Aviv; a semi-arid climate, represented by Beer Sheva; a mild Mediterranean climate, represented by Jerusalem; and a desert climate, represented by Eilat (SI 1045 2010).

EnergyPlus v.8.3 software, a U.S. Department of Energy (DOE) building energy simulation program, was used to calculate the OE requirements (EnergyPlus). Natural gas, as one of the major fuel types used for electricity production in Israel (Friedman et al. 2014), was applied for the OE analysis. The SimaPro software platform was used to evaluate LCAs. SimaPro contains both life cycle inventory (LCI) databases, such as Ecoinvent, and life cycle impact assessment (LCIA) methods, such ReCiPe (Goedkoop et al. 2008). The LCI analysis allows the user to evaluate input and output data associated with the product production, construction, recycling, or demolition processes. In the Ecoinvent database, which is based on European scale, the LCI is collected per 1 m^3 or 1 kg of product. Thus, the Ecoinvent database was taken as the foundation and was then adapted to Israeli roof technologies. The ReCiPe endpoint hierarchical six methodological options method was used to evaluate the environmental damages associated with the LCAs of the roofs.

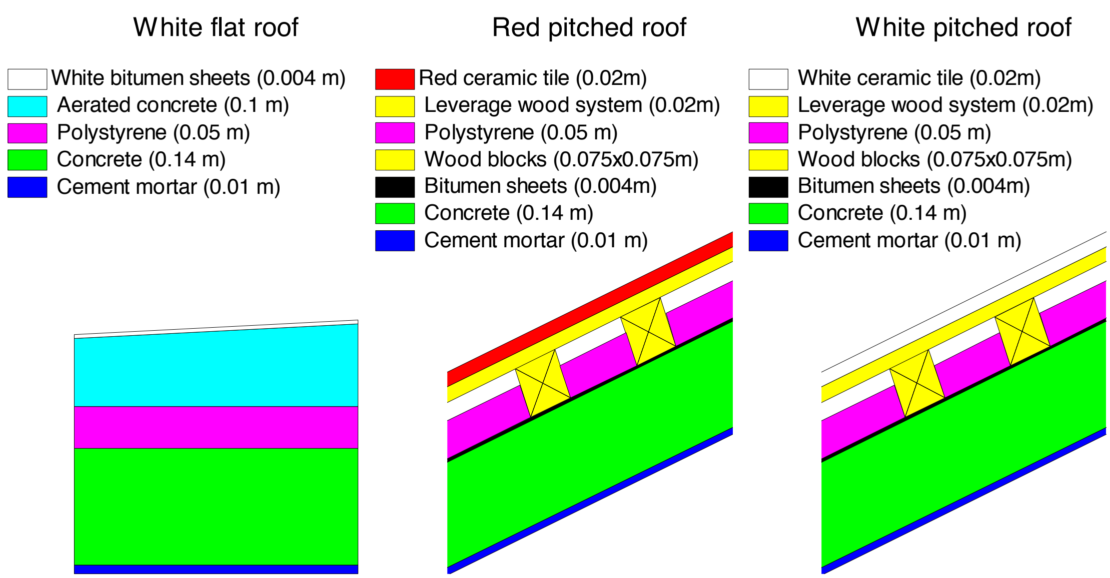
LCIA analysis allows the user to convert LCI results to the environmental impacts and then convert the impacts to the environmental damages. For such conversions, scientific models are required. In ReCiPe, such models were employed for global impacts such as climate change and ozone layer, as well as for continental/regional/local impacts such as ecotoxicity, acidification, and eutrophication. For non-global impacts ReCiPe considers a European scale. For example, for acidification, "This chapter describes the calculation of characterization factors for acidification for plant species in forest ecosystems on a European scale" (Goedkoop et al. 2008). Therefore, ReCiPe was found to be an appropriate LCIA method in an Israeli context (Pushkar 2016a). The detailed explanation about the ReCiPe LCIA method is presented below, in the chapter "LCIA: the ReCiPe endpoint hierarchical six methodological options method."

The main steps of the environmental damage evaluations of the P&C and MtoD stages of the roofs included the following: (i) the evaluation of the quantities of the local roof technologies by weight (kg/area of roof [m^2]); (ii) evaluation of the LCI results by applying the LCIs of the Ecoinvent database per 1 kg of roof materials to the quantities of the roofs; and (iii) the conversion of the LCI results to the LCIAs based on the level of environmental damages (Pt) using the ReCiPe method.

The main steps of procedure for establishing the OE environmental damage of the roofs included the following: (i) evaluation of electricity for the OE stage using EnergyPlus with consideration for local Israeli climates (kWh/roof area/50 years); (ii) converting OE electricity to the LCI results by applying LCIs of the Ecoinvent database for electricity production with natural gas source to the electricity for OE; and (iii) the conversion of the LCI results to the LCIA based on the level of environmental damages (Pt) using the ReCiPe method.

Both EnergyPlus and ReCiPe evaluations were made as deterministic models. This means that the statistics of the input data provided by SimaPro and EnergyPlus (mean, standard deviation, etc.) were not used in the study.

FIGURE 2. Layer sequence and thickness design of the two concrete-based roof technologies: (i) white flat and (ii) red and white pitched. Pitched roof slopes were both 40%.



Thermal conductivity and structural performance

The roofs were designed in compliance with local construction requirements (Pearlmutter et al. 2010) (Figure 2). The same thermal conductivity (U-value = 0.48 $W/m^2{\cdot}K$, according to the Standard of Israel (SI 1045 2010)) and the same structural performance according to SI 466 (2003) were achieved (Table 1). Steel quantity was evaluated by considering the bending moment from the dead load (roof self-weight) and live load (1.5 kN/m^2) on the concrete slab. The safety factor was assumed to be 1.4 for the dead load and 1.6 for the live load (SI 413 1995). The design strength was 340 MPa for steel and 21.5 MPa (B-42.5) for concrete, and the density of the steel was 7858 kg/m^3.

TABLE 1. The sequence, thickness, thermal conductivity, and density of layers in the two roof technologies: flat and pitched roofs.

Roof component	Component thickness (m)		Thermal conductivity (W/m·K)	Density (kg/m^3)
	Flat	Pitched		
Ceramic tiles	—	0.02	0.10	2000
Wood	—	—	0.13	460
Bitumen sheets	0.004	0.004	0.17	1200
Aerated concrete	0.10	—	0.60	800
Polystyrene	0.05	0.05	0.03	30
Concrete	0.14	0.14	2.10	2400
Cement mortar	0.01	0.01	0.86	1800

Environmental evaluations

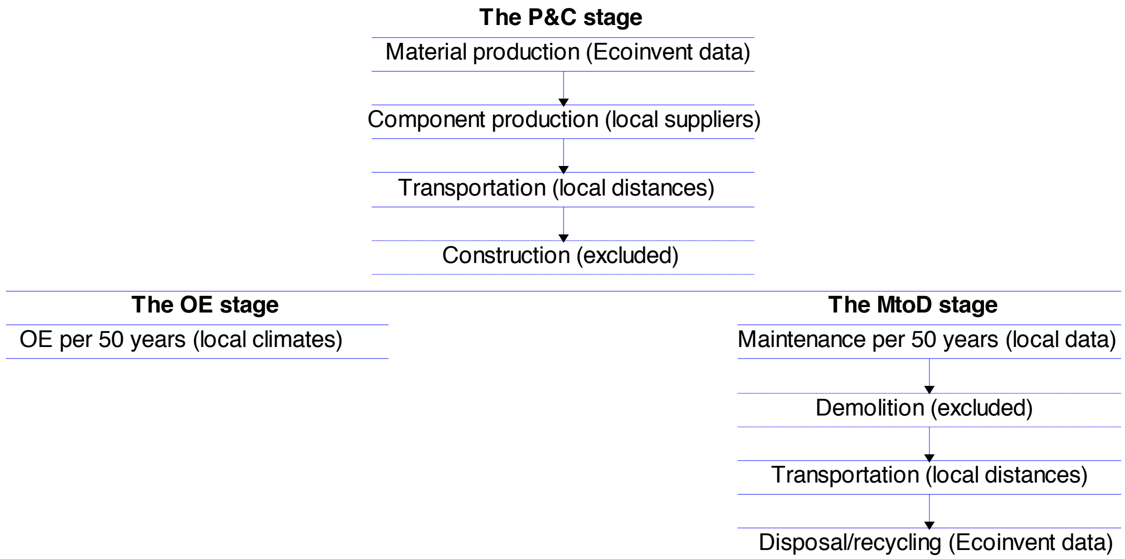
The environmental framework of the LCAs was based on the following: (1) goal and scope (definition of the functional unit [FU] and system boundaries); (2) LCI completion; (3) LCIA; and (4) interpretation (ISO 14040 2006).

Goal and scope. The specific goals of this study were the following: (i) to compare the contributions of the P, OE, and MtoD stages to the total LCA of the flat and pitched roof technologies; (ii) to determine the best roof technology by applying the six methodological options in ReCiPe; and (iii) to compare the environmental evaluations of the roof technologies via two ReCiPe methods. The two ReCiPe methods were the following: (i) the simultaneous evaluation of the six methodological options of the ReCiPe endpoint hierarchical method with a two-stage hierarchical mixed ANOVA; and (ii) the ReCiPe endpoint default h/a methodological option method. The FU was the roof area serving the single-story building module (100 m^2 of floor) with an OE of over 50 years. The P, OE, and MtoD stages were evaluated. The system boundaries are presented in Figure 3 and are discussed below in the chapters of LCIs in detail.

LCI: the P stage. On the building material production level, e.g., raw material extraction and production of the building materials, such as cement, water, rock, sand, and limestone, was completed with Ecoinvent data (SimaPro v.7.3.3 software). Due to a lack of Israeli data, this step was based on data from European countries, with the supposition that it is similar to Israeli data on this material production level (Table 2).

On the component production level, quantities of composite materials for the roofs were determined according to the relevant local Israeli product suppliers such as Readymix Industries, Ltd. (Pushkar 2014). Transportation of roof material and components from the supplier to the construction site was performed across local transportation distances. Israel is a small country; therefore, transportation distances are relatively small (Huberman and Pearlmutter 2008; Pushkar 2014). Nevertheless, the transportation distances are different for different building materials and products. Therefore, the average suitable transportation distances corresponded to the available suppliers of building materials and components were supposed. For example, ready-mix concrete needs to be delivered to the site within a relatively short time for successful concrete casting. In this case, a short transportation distance of 20 km was supposed (Pushkar

FIGURE 3. Process flowchart for the LCA of the roofs.



2014). However, the longer transportation distance of 200 km was assumed for such building products such as ceramic, polystyrene, wood, and bitumen sheets.

The construction of local flat concrete-based roofs was evaluated by Pushkar (2007), who evaluated that concrete casting and vibrating procedures with one concrete pump and two gas engine vibrators required an electricity consumption of approximately 14 kWh/1000 kg of concrete, while no local Israeli information about construction of pitched concrete-based roof was revealed. However, the flat and pitched roofs studied in this paper were both based on the same concrete casting procedure. The only difference between flat and pitched roofs is the covering layers (Figure 2). Therefore, it was suggested that the difference between the energy required for construction of aerated concrete and bitumen sheets layers in the case of flat roofs

TABLE 2. Production (P) stage: data input from Ecoinvent database (European data, Switzerland and Germany) (SimaPro v.7.3.3).

Material	Data source
Bitumen sheets	Bitumen, at refinery
Aerated concrete; cement mortar	Cement mortar, at plant
Polystyrene	Polystyrene foam slab, at plant
Concrete	Concrete, extracting, at plant
Reinforcing steel	Reinforcing steel, at plant
Wood	Wood, at plant
Ceramic tiles	Roof tiles, at plant
Transport	Transport, combination truck, average fuel mix/tkm

and for the construction of leverage wood systems and ceramic tile layers in the case of pitched roofs can be considered as relatively small. As a result, construction procedures were excluded from the LCAs of the three roofs (Figure 3).

LCI: the OE stage. The building modules with the analyzed roofs were modeled in EnergyPlus v.8.3 software (EnergyPlus). Heating and cooling were accomplished using a heat pump (coefficient of performance [COP], 3) with set points of 20°C for heating and 24°C for cooling. A four-person occupancy with an activity level at 100 W, electric lights at 600 W, electrical equipment at 800 W, and clothing at 1 Clo (winter) and 0.5 Clo (summer), was supposed. Detailed weather data for the four climate zones were collected through the EnergyPlus Weather Data for Israel website (weather data by region for Israel). According to Napolano et al. (2015), the transmission heat loss (in winter) and heat gain (in summer) were computed only based on the roof. The environmental evaluation of OE was conducted with SimaPro v7.3.3 software using electricity production by natural gas from a Spanish power plant, as Israeli electricity production data, which is also based on natural gas, were not available in the SimaPro databases.

LCI: the MtoD stage. Maintenance is involved in the bitumen sheet replacement rate during the 50 year-life cycle of the building module. The bitumen sheet replacement was accounted only for white flat roofs and was assumed as 5-year replacement rate based on a study performed for a hot Mediterranean climate (Napolano et al. 2015) and personal communication with local Israeli contractors.

Demolition of local flat concrete-based roofs was evaluated by Pushkar (2007), who evaluated that bar-reinforced concrete demolition with an air compressor requires an electricity consumption of approximately 106 kWh/1000 kg of concrete, while no local Israeli information about the demolition of pitched concrete based roofs was revealed. However, as was mentioned early in the P stage, the only difference between flat and pitched roofs is the covering layers (Figure 2). Thus, the difference between the energy required for the demolition of aerated concrete and bitumen sheets layers (flat roof) and the demolition of leverage wood systems and ceramic tile layers (pitched roofs) was supposed to be relatively small. As a result, the demolition procedure was excluded from the LCAs of the three roofs (Figure 3).

Disposal/recycling procedures were completed with Ecoinvent data (SimaPro v.7.3.3 software). Due to a lack of Israeli data, these procedures were based on data from European countries (Table 3). Disposal methods (e.g., landfill disposal, recycling, and municipal incineration) influenced the distances required for transportation of building materials and components to a disposal site. A relatively short distance to disposal sites, 50 km, was assumed for the disposal of bitumen sheets, aerated concrete, cement mortar, wood, ceramic tiles and polystyrene, while a transportation distance of 200 km was assumed for the recycling of reinforcing steel and concrete. This is because in Israel, landfill sites are numerous compared to the small number of recycling plants (Israel Ministry of Environmental Protection 2015).

LCIA: the ReCiPe endpoint hierarchical six methodological options method. The LCI was converted to an LCIA using the ReCiPe method (Goedkoop et al. 2008). ReCiPe considers uncertainties of the models that convert inventory (for example of CO_2, CH_4, and N_2O [greenhouse gases] or SO_x and NO_x [acidic gases], etc.) results to the 18 midpoint environmental impacts (such as ozone depletion, human toxicity, radiation, P. C. ozone formation, particulate formation, climate change, terrestrial ecotoxicity, terrestrial acidification, agriculture land occupation, urban land occupation, national land transfer, marine ecotoxicity, marine eutrophication, fresh water eutrophication, fresh water ecotoxicity, fossil fuel consumption, minerals consumption, and water consumption) taking into account different perspectives on

TABLE 3. MtoD stage: data input from Ecoinvent database (European data, Switzerland and Germany) (SimaPro v.7.3.3).

Material	Data source
Bitumen sheets	Disposal, building, bitumen sheet, to final disposal
Aerated concrete; cement mortar	Disposal, building, cement (in concrete) and mortar, to final disposal
Polystyrene	Disposal, building, polystyrene isolation, flame-retardant, to final disposal
Reinforcing steel	Disposal, building, reinforcement steel, to recycling
Concrete	Disposal, building, reinforced concrete, to recycling
Wood	Disposal, building, wood, to municipal incineration
Ceramic tiles	Disposal, municipal solid waste, to municipal incineration
Transport	Transport, combination truck, average fuel mix/tkm

the causes of environmental impacts. This uncertainty depends on the level of scientific proof of the environmental effects and their possible timeframe for damages (Goedkoop et al. 2008).

To address the different assumptions on these issues, ReCiPe suggests three environmental perspectives: egalitarian, individualistic, and hierarchical. The egalitarian perspective allows for considering all possible damages for a long timeframe. Individualistic perspective allows for counting damages with only proven effects for a short timeframe, e.g., during 100 years or less. Hierarchical perspective allows for a balance between the egalitarian and individualistic perspectives, where damages are based on a consensus about their effects for balance in an intermediate timeframe.

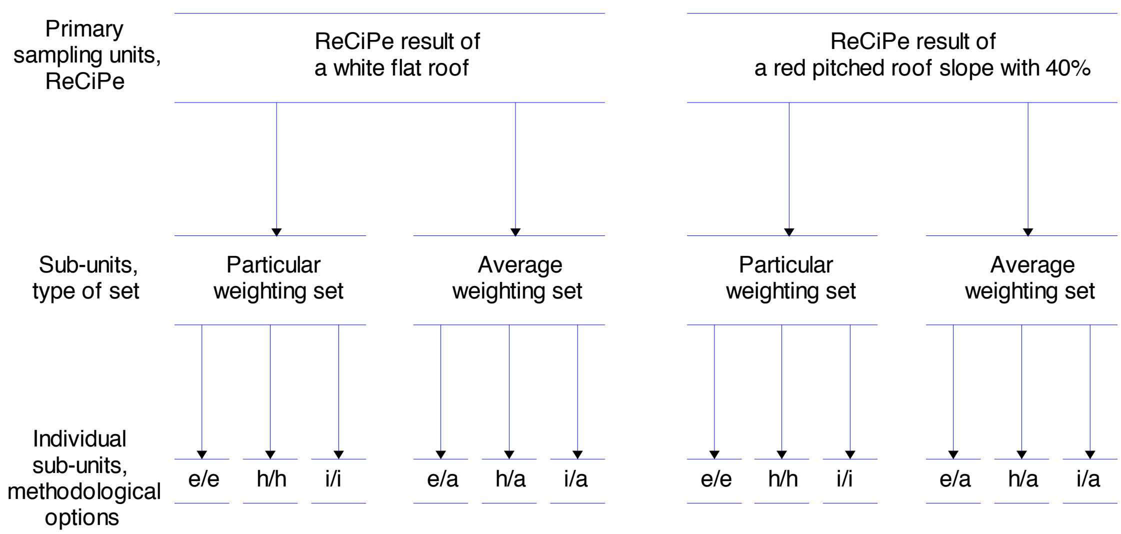
After evaluation of the 18 midpoint environmental impacts at each of the three perspectives, the impacts can be grouped to the three endpoint environmental damages: human health, ecosystems, and resources. Eventually, the weighting sets can be applied to these damages to evaluate a single score (Pt) of environmental damages. The ReCiPe method includes two different endpoint weighting sets: (i) a set of weighs for the given methodological perspective (e.g., the egalitarian, individualistic, and hierarchical weighting data sets); and (ii) an average set. As a result, ReCiPe consists of six methodological options with different combinations of perspective/weighting: egalitarian/egalitarian (e/e), egalitarian/average (e/a), hierarchical/hierarchical (h/h), hierarchical/average (h/a), individualistic/individualistic (i/i), and individualistic/average (i/a) (Goedkoop et al. 2008).

Typically, the ReCiPe endpoint h/a method is used for environmental evaluation (Burchart-Korol et al. 2016). In addition, 10–20% of the difference in h/a scores is usually sufficient to decide that the compared alternatives are different (Goedkoop and Spriensma 2001). However, the simultaneous use of the six methodological options can aid in mitigating the uncertainty of the LCIA method (Pushkar 2014). In this context, the three perspectives in ReCiPe can be considered as two weighting sets, the average weighting set (e/a, h/a, and i/a) and the particular weighting set (e/e, h/h, and i/i), and as a consequence, their design structure was defined as a hierarchical design structure (Pushkar 2014). Therefore, in this study, the six methodological options of ReCiPe in conjunction with hierarchical ANOVA were used, allowing the simultaneous evaluation of the six methodological options in ReCiPe. In this way, all different views on environmental evaluations can be taken into account (Pushkar 2016a).

The design structure and statistical analysis of the ReCiPe results

The design structure of the two-stage ANOVA model. To correctly use a two-stage ANOVA test, the hierarchical design structure should be previously determined (Picquelle and Mier 2011). Figure 4 illustrates, for example, two primary sampling units: the ReCiPe result of a white flat roof and the ReCiPe result of a red pitched roof. The primary sampling unit contains two sub-units: the particular weighting set and the average weighting set. Each sub-unit contains the three individual sub-units (two sub-units contain six methodological options in total). Measurements are performed on the individual sub-units. Recently, a similar design structure was used to evaluate environmental damage from five concrete mixtures with cement types accepted in Israel (Pushkar and Verbitsky 2016a).

FIGURE 4. A two-stage nested hierarchical design structure with the six methodological options in ReCiPe results: egalitarian/egalitarian (e/e), egalitarian/average (e/a), hierarchical/hierarchical (h/h), hierarchical/average (h/a), individualistic/individualistic (i/i), and individualistic/average (i/a).



Statistical analysis. The LCIA (ReCiPe endpoint) results were log transformed prior to analysis. The deterministic model for the ReCiPe results was used (Goedkoop et al. 2008). The differences between the two ReCiPe values were evaluated as follows: (i) using a two-stage, nested (hierarchical), mixed ANOVA with degrees of freedom (df) $df_1 = 1$ $df_2 = 2$; and (ii) based on the percent change of the ReCiPe default h/a option results, which is calculated using the relationship ReCiPemax*ReCiPemin-100.

P-values were evaluated according to three-valued logic: "it seems to be positive," "it seems to be negative," and "judgment is suspended" (Hurlbert and Lombardi 2009); that is, there seems to be a roof difference, there does not seem to be a roof difference, or judgment is suspended with respect to the roof difference, respectively.

RESULTS AND DISCUSSION

Preparatory events

The evaluated quantities of the roof components for the flat and pitched roofs are presented in Table 4. The impacts of the selected roof on the OE requirements of the building modules located in Tel Aviv, Beer Sheva, Jerusalem, and Eilat are presented in Table 5.

TABLE 4. Quantities of the roof components designed for the flat and pitched roofs.

Roof component	Flat (kg/100 m^2)	Pitched20 (kg/103 m^2)	Pitched40 (kg/111 m^2)
Ceramic tile	—	4120	4440
Wood	—	2120	2300
Bitumen sheets	480	495	530
Aerated concrete	8000	—	—
Polystyrene	150	155	170
Concrete	33600	34600	37300
Cement mortar	1800	1850	2000
Steel	980	870	550

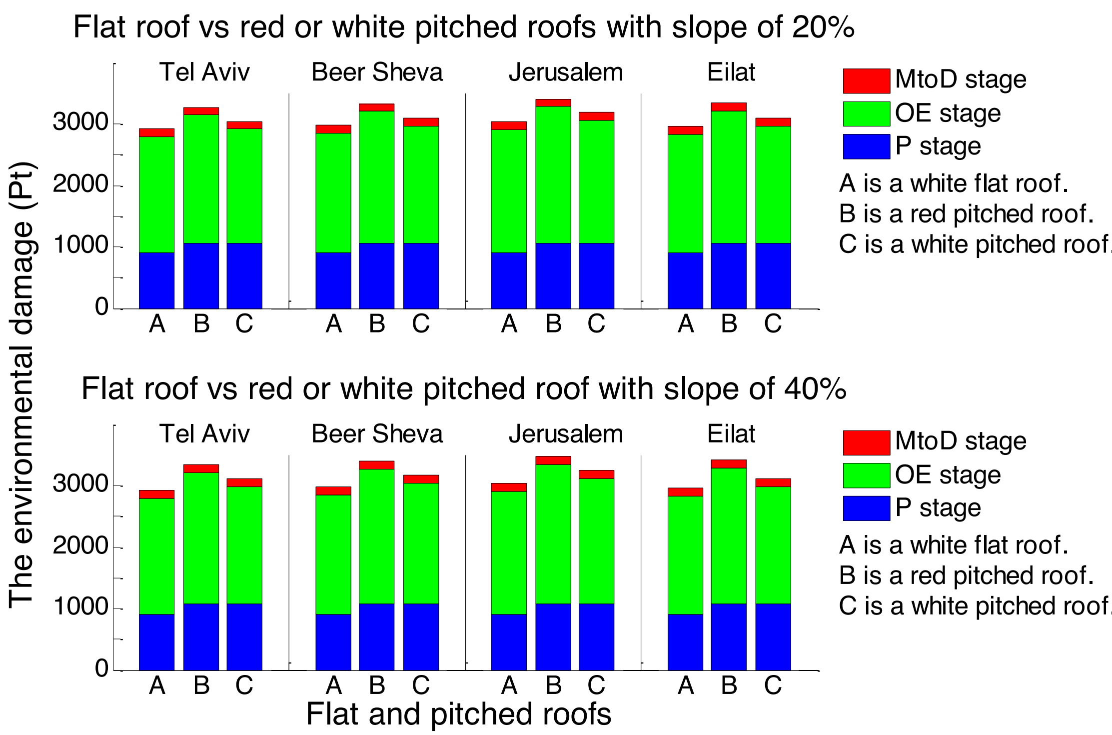
TABLE 5. Operational energy (OE) requirements for space conditioning (heating and cooling) of the building module, caused by the selected roof technology. The deterministic model was used (EnergyPlus).

Roof Technology	OE energy (kWh/roof area/50 years)			
	Tel Aviv	Beer Sheva	Jerusalem	Eilat
Flat (white)	136028	140014	144167	138278
Pitched20 (red)	151097	155445	160681	156208
Pitched20 (white)	134792	138486	144861	138236
Pitched40 (red)	154278	158986	163736	160083
Pitched40 (white)	137375	141431	147500	138278

The ranges of P, OE, and MtoD stages

The P, OE, and MtoD stages of the flat and pitched roofs show the same ranges in the four climate zones in Israel, as shown in Figure 5. Both the P and OE were revealed as the most significant stages. The ranges of the P and OE stage were approximately 30–35% and 60–65% (for white flat roofs), 30–35% and 60–65% (for red pitched roofs with both slopes, 20% and 40%), and 35–40% and 55–60% (for white pitched roofs with both slopes, 20% and 40%). The range of the MtoD stage was approximately 5% of the LCA of each of the three types of roof: white flat, red pitched, and white pitched. This can be explained by the fact that approximately the same OE is required for residential buildings in all climate zones in Israel (Pushkar and Verbitsky 2016b). The OE stage differences between red and white pitched roofs are based on the fact that the solar absorbance for red pitched roofs is 0.9, while the solar absorbance for white pitched roofs is 0.45 (SI 5282 2011). Therefore, the ranges of the P, OE, and MtoD stages were not affected by either climate or the slope of the roofs. However, the stages were significantly influenced by the roof color.

FIGURE 5. Environmental damages in the production (P), operational energy (OE), maintenance to disposal (MtoD) stages of flat and pitched roofs (using natural gas for OE needs) in Tel-Aviv, Beer-Sheva, Jerusalem, and Eilat. The three evaluated roofs were a white flat roof (A), a red pitched roof (B), and a white pitched roof (C). The environmental damage (Pt) is evaluated based on the default h/a option in ReCiPe.



Selection of the best roof technology

Ranking and pairing of the statistical comparative analyses of the white flat, red pitched, and white pitched roofs were performed separately in the P, OE, and MtoD stages and in the LCA (i.e., P + OE + MtoD). Only the 40% slope was considered for the pitched roofs. The results of the rankings are illustrated in Figure 6, and the results of the comparative analyses are presented in Table 6.

FIGURE 6. Production (P), operational energy (OE), maintenance to disposal (MtoD), and LCA (i.e., P + OE + MtoD) of the flat and pitched roofs of a residential building using natural gas for OE needs in Tel Aviv. The three evaluated roofs were white flat (A), red pitched (B), and white pitched (C). The pitched roofs had a 40% slope. The environmental damage (Pt) was evaluated with the two sets of methodological options, the average weighting set (e/a, h/a, and i/a) and the particular weighting set (e/e, h/h, and i/i) in ReCiPe.

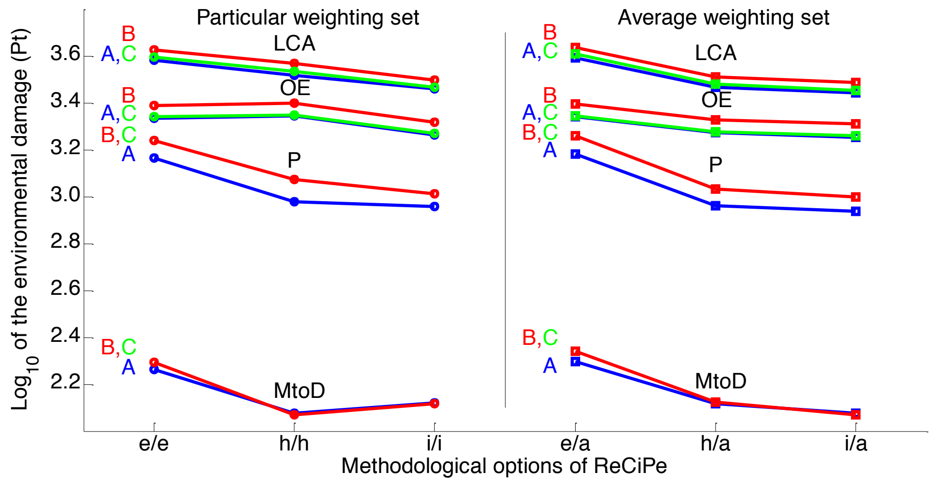


TABLE 6. A residential building using natural gas for the operational energy (OE) stage in Tel Aviv. P-value (P) and percent differences (%) are presented in the table as P (%) of the pairing differences in the two roof technologies, flat and pitched (slope 40%), as a function of production (P), OE, maintenance and disposal (MtoD), and LCA (i.e., P + OE + MtoD) environmental damage evaluated with ReCiPe, two-stage nested mixed ANOVA, degrees of freedom (*df*) $df_1 = 1$ $df_2 = 2$, and probability resulting from a significance test (P).

LCA stage	Roof technology	White flat	Red pitched	White pitched
P	White flat	X	**0.0087 (18)**	**0.0087 (18)**
	Red pitched		X	X
	White pitched			X
OE	White flat	X	*0.0885 (13)*	0.8294 (1)
	Red pitched		X	0.1018 (12)
	White pitched			X
MtoD	White flat	X	0.3792 (2)	0.3792 (2)
	Red pitched		X	X
	White pitched			X
LCA (P + OE + MtoD)	White flat	X	**0.0374 (14)**	0.1401 (6)
	Red pitched		X	0.1415 (7)
	White pitched			X

Note: Font style is bold—seems to be positive; Font size is ordinal—seems to be negative; Font style is italic—judgment is suspended.

The P stage. The ranking, based on all methodological options in ReCiPe, in ascending order of environmental damage, is as follows: 1st—white flat roof and 2nd—red and white pitched roofs. The differences between the white flat roof and each of the pitched roofs (red or white) seem to be positive (P = 0.0087), and the percent difference (h/a) is 18% (Table 6). The roofs have different areas: flat—100 m^2; pitched—111 m^2 (Table 4). Therefore, according to the P stage, the flat roof is the best roof technology.

The OE stage. The ranking based on all methodological options in ReCiPe, in ascending order of environmental damage, is as follows: 1st–2nd—white flat roof, 1st–2nd—white pitched roof, and 3rd—red pitched roof. The differences between the white flat roof and the white pitched roof seem to be negative (P = 0.8294), and the percent difference (h/a) is 1%. Judgment is suspended regarding the differences between the white flat and red pitched roofs (P = 0.0885); the percent change (h/a) is 13%. (Table 6) Therefore, according to the OE stage, additional studies are needed to identify the best roof color and technology.

The MtoD stage. The white flat roof and red and white pitched roofs altered their positions from first to second under different methodological options: i/i, h/a, e/e, and e/a—white flat roof in the first position and red and white pitched roofs in the second position; i/a and h/h—red and white pitched roofs in the first position and white flat roof in the second position. However, according to the simultaneously evaluated six methodological options of ReCiPe, the differences between the white flat roof and the red and white pitched roofs seem to be negative (P = 0.3792), and the percent difference (h/a) is 2% (Table 6).

The LCA. The ranking of the roofs according to the LCA, based on all methodological options in ReCiPe, was the same as for the OE stage. However, the results of statistical evaluations according to the LCA were not the same as for the OE stage. In contrast, in the OE stage results the difference between the white flat roof and the red pitched roof seems to be positive (P = 0.0374), and the percent difference is 14%. The difference between the white flat roof and the white pitched roof seems to be negative (P = 0.1401), and the percent difference is 6% (Table 6). Therefore, if choice of roof color (e.g., white versus red) is based only on the OE stage, then the less optimal roof may be chosen. To choose the optimal roof color, the LCA must be used. In the Israeli context, the red pitched roof is the worst decision compared to a white flat roof or a white pitched roof.

Preferred methods

The h/a methodological option in Eco-indicator 99 (EI99, h/s) was recommended as the default option (Goedkoop and Spriensma 2001). In 2008, ReCiPe (Goedkoop et al. 2008) (based on EI99) was developed. However, the default option was not changed (Vadenbo et al. 2014).

It was recently demonstrated that if building technologies, such as flat roof technologies (Pushkar 2016a) and wall technologies (Pushkar and Verbitsky 2016b), were environmentally evaluated via ReCiPe (h/a), then environmental damages would be incorrectly evaluated. One of the reasons for the erroneous use of h/a is a disordinal interaction between the methodological options with the average weighting set (e/a, h/a, and i/a) and the methodological options with particular weighting sets (e/e, h/h, and i/i) of ReCiPe or EI99 (Pushkar 2014, Figure 1). In this study, when the white flat roof was compared to a red pitched roof at the OE stage, ReCiPe (h/a) showed a 13% difference (Table 6). According to Goedkoop and Spriensma (2001), if similar technologies and materials were compared, then a difference of 10–20% would be significant. However, using ReCiPe with a two-stage, mixed ANOVA, which allows us to simultaneously evaluate the six methodological options of ReCiPe, reveals that judgment regarding the choice between a white flat roof and a red pitched roof should be suspended (P = 0.0885) (Table 6).

CONCLUSION

The following conclusions were drawn from this study of flat and pitched roofs for residential buildings in Israel:

The ranges of P, OE, and MtoD stages. The ranges of the P, OE, and MtoD stages (i) did not change under either varying climate (Tel Aviv, Beer Sheva, Jerusalem, and Eilat) or roof slope (20–40%) and were (ii) different based on roof color (white or red). Thus, in the Israeli context, the climate and roof slope factors were not significant. However, roof color was a significant factor.

Selection of the best roof technologies. It was found that different solutions stem from consideration of the P, OE, and MtoD stages, and the LCA of the roofs. Considering only the P stage, the white flat roof was the best solution. Considering the OE stage, a decision should be suspended when the white flat roof and the white pitched roof are compared environmentally. Considering the MtoD stage, there is no difference among the white flat roof, red pitched roof, and white pitched roof. Considering the LCAs of the roofs, it is clear that only white flat and white pitched roofs offer optimal environmental solutions. In contrast, the red pitched roof is the worst environmental solution. Thus, it is concluded that to correctly evaluate environmental damage in the building sector, LCAs must be used.

Contribution of this paper

Currently, the Israeli Standard SI 5282 (2011) for buildings contains several levels of OE certification. An increase in the level of certification is typically associated with the P&C and MtoD stages of additional building materials. As was demonstrated in this paper, in an Israeli context, the consideration of these two stages (in addition to the OE stage) can influence the selection of the best roof alternative. Therefore, exploring the possibility of expanding SI 5282 (2011) to all other building envelope components, such as external walls and external shading devices, from the currently evaluated OE stage to at least the P stage is recommended due to its significant share in the LCAs of concrete-based local Israeli building technologies.

Limitation of this paper

In addition, analyses of the sensitivity of flat and pitched roof technologies to different clean renewable fuel sources such as PV (used for the OE stage) need to be conducted.

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