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# ECO-INDICATOR 99, ReCiPe AND ANOVA FOR EVALUATING BUILDING TECHNOLOGIES UNDER LCA UNCERTAINTIES

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**Abstract**

The Eco-Indicator 99 (EI99) method and the ReCiPe method are used to determine the fundamental uncertainties in the life cycle impact assessment (LCIA) model through the configurations of the following six methodological options: egalitarian/egalitarian (e/e), egalitarian/average (e/a), hierarchist/hierarchist (h/h), hierarchist/average (h/a), individualist/individualist (i/i), and individualist/average (i/a). In this study, the aforementioned options were presented as (i) a set of methodological options with their particular weighting set (e/e, h/h, and i/i) and (ii) a set of methodological options with the average weighting set (e/a, h/a, and i/a), thereby creating a hierarchical design of both the EI99 and ReCiPe methods. The first goal of this study is to provide the appropriate statistical test as a supplemental method to EI99 and ReCiPe for the evaluation of the different environmental damage caused by four building technologies. The second goal is to compare the two damage oriented methods of EI99 and ReCiPe when the same building technologies are compared. Two-stage nested mixed ANOVA rather than a t-test is recommended as a supplemental method in both evaluations of EI99 and ReCiPe due the hierarchical structure of the methodological options. ReCiPe rather than EI99 is suggested as a damage oriented method of building technologies due to its extended list of impacts of the ecosystems damage category and its accounting for more reliable cost parameters in the resources damage category instead of the vague supplement of the energy requirement in a distant future that is applied in EI99.

*Keywords:* hierarchical design structure, LCIA uncertainty, sampling design

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## 1. Introduction

As building sustainability is now an important issue, many environmental assessment methods have been developed and widely applied in the building and construction industry (Anand and Amor, 2017; Boros et al., 2017; Finnveden and Moberg, 2005). According to recent comprehensive reviews presented by Buyle et al. (2013) and Cabeza et al. (2014), the most practiced methods are Life cycle energy assessment (LCEA) and Life cycle assessment (LCA). Additional methods used include Life cycle cost (LCC) (Cabeza et al., 2014; Boros et al., 2017), Material Flow Analysis (MFA) (Rincón et al., 2013), and Economic input–output analysis-based LCA (EIO-LCA) (Kofoworola and Gheewala, 2009).

In LCEA studies in the production stage, the embodied energy coefficients of the building materials are usually considered (Kofoworola and Gheewala, 2009; Ramech et al., 2012). For the operational energy stage in which electricity consumption for heating, cooling, and lighting are measured, energy bills are used (Adalberth, 1997a, 1997b; Radhi, 2008; Winistorfer et al., 2005), actual energy consumption is recorded (Balciunas et al., 2016; Kofoworola and Gheewala, 2009), or energy simulations are performed (Perez and Capeluto, 2009; Shaviv et al., 2008).

Accordant to Trusty and Horst (2005), LCA methods can be divided into three groups: whole-building assessment rating systems, whole-building decision tools, and product comparison methods. Whole-building assessment rating systems, such as

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Leadership in Energy and Environmental Design (LEED) (2013), BRE environmental assessment method (BRE Group, 2011), and Green Star (2011), are widely recognized. Notable examples of whole-building decision tools are Athena Eco-Calculator (Trusty and Meil, 1997), Eco-Quantum (Mak et al., 1997), and BEET 2000 (Petersen, 1999). For performing product comparison process-based Life cycle impact assessment (LCIA), methods such as Eco-Indicator 99 (EI99) (Goedkoop and Spriensma, 2001) and ReCiPe (Goedkoop et al., 2009) can be used. The typical process-based methods use detailed extensive Life cycle inventory (LCI) databases, such as Ecoinvent presented in SimaPro (PRé Consultants, 2010); these databases allow for detailed analysis of the environmental impact and damage (Lasvaux et al., 2014). As a consequence, many researchers are now using process-based LCA for analyzing building environmental measures (Kosareo and Ries, 2007; Laleman et al., 2011; Lamnatou and Chemisana, 2014; Mithraratne and Vale, 2004; Peri et al., 2012; Pushkar, 2014; Pushkar et al., 2005; Saiz et al., 2006).

The main problem of current LCA practices is that the use of different LCIA methods produces different LCA results; the variety of results is due the fact that the different LCIA methods assign different levels of importance to the different impacts (Buyle et al., 2013). In addition, building LCA, unlike standard manufacturing product LCA, has many uncertainties regarding the site specific impacts, model complexity, life-time assumption, indoor environments, and inclusion of recycled material data (Cabeza et al., 2014). In addition, limitations exist with respect to the availability of LCIA models for assessing environmental impacts (LCIA model configuration) (Dong and Ng, 2014), accessibility of relevant data, and data quality (ISO 14040, 1997).

Recently, Pieragostini et al. (2012) reviewed optimization techniques and tools based on LCA, under the process engineering field. According to Pieragostini et al. (2012), “Among the LCIA methods, the eco-indicator 99, which is based on the endpoint category and the panel method, is the most used in practice.” To handle uncertainties in the LCIA model configuration, EI99 uses three perspectives (adopted from Cultural Theory) with different attitudes to environmental problems: egalitarian (e), hierarchist (h), and individualist (i). Egalitarian considers all of the potential long-term issues, while individualist only considers the short-term proven issues (i.e., 100 years or less). Hierarchist is a balance perspective between the egalitarian and individualist perspectives. (Goedkoop and Spriensma, 2001). ReCiPe is based on both the CML 2002 developed by the Center of Environmental science of Leiden University (Guinée et al., 2002) and the EI99 methods; therefore, ReCiPe continues to apply these three perspectives (e.g., egalitarian, hierarchist, and individualist) (Goedkoop et al., 2009). CML is a midpoint approach tool, in which evaluation of the level of the environmental impacts, such as abiotic depletion, acidification, eutrophication, global warming, and so on, can be achieved. EI99 is an endpoint approach tool that evaluates environmental damage, such as human health, ecosystem quality, and resources. ReCiPe can be applied on both the midpoint approach (ReCiPe midpoint) and the endpoint approach (ReCiPe endpoint). The methodological perspectives (individualist, hierarchist, and egalitarian) differ according to several factors, including the number of substances considered, the normalization data set, and the weighting data set. The environmental score evaluation is complex due to different effects of each of the aforementioned factors.

The normalization set is based on a damage calculation of all of the relevant European emissions, extractions, and land-uses. There are three damage models for human health, ecosystem quality, and resources. There are also three normalization sets (Table 1). In both EI99 and ReCiPe, each of the three methodological perspectives has a different normalization set (SimaPro v7.2).

To perform single score evaluation, both EI99 and ReCiPe use the same weighting data sets (Table 2). “There are two ways to interpret the results of the weighting result. The three damage models can be combined with their particular weighting set. The three damage models can be combined with the default weighting set” (Goedkoop and Spriensma, 2001). Thus, both EI99 and ReCiPe consist of six methodological options with the following perspective/weighting methodological options: egalitarian/egalitarian (e/e), egalitarian/average (e/a), hierarchist/hierarchist (h/h), hierarchist/average (h/a), individualist/individualist (i/i), and individualist/average (i/a).

**Table 1.** EI99 (ReCiPe) normalization sets based on European data from 1997 (2000) year (SimaPro v7.2)

| ***Damage categories*** | ***Methodological option*** | | |
|---|---|---|---|
| | i/i and i/a | h/h and h/a | e/e and e/a |
| **Human Health** | 8.25E-03 (47.6) | 1.54E-02 (49.5) | 1.55E-02 (47.6) |
| **Ecosystem Quality** | 4.51E+03 (5.53+0.3) | 5.13E+03(5.72E+03) | 5.13E+03 (3.73E+03) |
| **Resources** | 1.50E+02 (7.2E-0.5) | 8.41E+03 (3.27E-05) | 5.94E+03 (3.27E-05) |

**Table 2.** Weighting data sets using European data (Goedkoop and Spriensma, 2001)

| ***Damage category*** | ***Methodological options*** | | | | | |
|---|---|---|---|---|---|---|
| | ***i/i*** | ***i/a*** | ***h/h*** | ***h/a*** | ***e/e*** | ***e/a*** |
| **Human health** | 550 | 400 | 300 | 400 | 300 | 400 |
| **Ecosystem quality** | 250 | 400 | 400 | 400 | 500 | 400 |
| **Resources** | 200 | 200 | 300 | 200 | 200 | 200 |

To reduce the problems associated with weighting, EI99 suggests the use of the mixing triangle developed by Hofstetter et al. (1999). The mixing triangle allows for the visual presentation of the product evaluations for all possible weighting sets, while each point within the triangle is presented as a combination of weights that adds up to 100% (Goedkoop et al., 2010). The mixing triangle technique is sometimes used in EI99 evaluations (Lassaux, 2000).

To reduce the problems associated with perspectives, Goedkoop and Spriensma (2001) recommended using the hierarchist version as a default and using the other two perspectives, egalitarian and individualist, as sensitivity analyses. The authors argued that this sensitivity analysis allows for the validation of the answer within all of the assumptions of the time frame and the required level of proof of environmental damage to human health, ecosystem quality, and resources. Thus, all of the methodological options that were specifically developed to address EI99 fundamental uncertainties must be used with EI99 (Laleman et al., 2011; Pushkar, 2014). In this study, the aforementioned options were presented as (i) a set of the methodological options with their particular weighting set (e/e, h/h, and i/i) and (ii) a set of the methodological options with the average weighting set (e/a, h/a, and i/a), thereby creating the hierarchical design of EI99 and ReCiPe.

When the decision-maker must compare a LCA of products (services) using the EI99 options, EI99 suggests considering the relative and absolute uncertainties. According to EI99, if two similarly produced materials are compared, even small differences, such as 10 to 20% of the compared EI99 scores, indicate that the materials differ (relative uncertainty). However, when two completely different materials are compared, only a much larger difference, for example, 100%, is adequate to conclude that these materials differ significantly (absolute uncertainty) (Goedkoop and Spriensma, 2001). However, there are some difficulties in applying the EI99 comparison method for determining the difference between the building components. Occasionally, it is very difficult to determine whether the building components that are compared are produced from completely different materials or whether they are produced using similar materials. For example, let us compare two alternatives involving floor/ceiling components: a ribbed slab with a concrete block and a ribbed slab with a cellular block. In both alternatives, we have the same building material (concrete) and two different building materials (concrete block and cellular block). Moreover, when the building technologies are compared, the situation is more complicated when both the relative and absolute uncertainties are involved.

The first goal of this study is to provide an appropriate statistical test as a supplemental method to EI99 and ReCiPe evaluations that addresses the uncertainties in the fundamental LCIA model configurations while considering the problematic combinations of similar and dissimilar components that are usually found in building technologies. The second goal is to analyze the results of the two applied damage oriented methods, that is, EI99 and ReCiPe, when evaluating the same building technologies.

Two statistical tests, an unpaired two-tailed t-test and a two-stage nested mixed balanced analysis of variance (ANOVA), were validated, comparing the environmental performance of the building technologies. The main advantage of using unpaired two-tailed t-test or two-stage nested mixed balanced ANOVA to supplement the EI99 and ReCiPe evaluations is the possibility for all basically dissimilar views on environmental problems to be simultaneously considered.

## 2. Material and methods

Four different construction technologies were considered (Table 3): Cellular Block (CLB), Hollow-Core Prestressed Concrete Plate (HCPP), Reinforced Concrete (RC) slab, and Concrete Block (CNB). The building materials considered for each building component are presented in Table 4. A three-story building with the dimensions 34 m × 34 m × 9 m was used in this study. In total, the building included: 2511 $m^2$ of wall, 14304 $m^2$ of floor/ceiling, and 20592 $m^2$ of partitions.

Environmental evaluation and statistical analyses were performed using a two-step calculation procedure. Initially, the EI99 and ReCiPe methods were used to calculate the environmental scores (Pt) associated with the building technologies.

**Table 3.** Building Technologies

| ***Building component*** | ***Cellular block (CLB)*** | ***Hollow-core pre-stressed concrete plate (HCPP)*** | ***Reinforced concrete slab (RC)*** | ***Concrete block (CNB)*** |
|---|---|---|---|---|
| **Wall type** | cellular block | concrete | concrete | concrete block |
| **Wall covering** | plaster | plaster | plaster | plaster |
| **Floor/ceiling** | ribbed slab (cellular block) | hollow-core pre-stressed concrete plate | flat reinforced concrete slab | ribbed slab (concrete block) |
| **Floor covering** | marble | marble | marble | marble |
| **Partitions** | cellular block | gypsum board | gypsum board | concrete block |

**Table 4.** Description of the building components

| ***Building component*** | ***Composite materials (thickness (m))*** |
|---|---|
| | ***Wall type*** |
| Concrete | stone (0.02), concrete (0.05), polystyrene (0.03), concrete (0.15), plaster (0.01) |
| Concrete block | plaster (0.02), concrete block (0.25), plaster (0.01) |
| Cellular block | plaster (0.02), cellular block (0.25), plaster (0.01) |
| | ***Wall covering*** |
| Plaster | plaster (0.02) |
| | ***Floor/ceiling*** |
| Hollow-core pre-stressed concrete plate | concrete (0.05), hollow pre-stressed plates (0.1) |
| Flat reinforced concrete slab | reinforced concrete (0.14) |
| Ribbed slab (concrete block) | reinforced concrete (0.05), concrete block (0.2); thermal bridges: reinforced concrete (0.25) |
| Ribbed slab (cellular block) | reinforced concrete (0.05), cellular block (0.2); thermal bridges: reinforced concrete (0.25) |
| | ***Floor covering*** |
| Marble | sand (0.06), mortar (0.02), marble (0.012) |
| | ***Partitions*** |
| Gypsum board | gypsum board (0.0125), glass wool (0.075), gypsum board (0.0125) |
| Concrete block | plaster (0.01), concrete block (0.08), plaster (0.01) |
| Cellular block | plaster (0.01), cellular block (0.08), plaster (0.01) |

As a result, six EI99 and six ReCiPe environmental scores (e/e, e/a, h/h, h/a, i/i, and i/a options) were calculated for each technology studied (CLB, HCPP, RC, and CNB). These technologies were then compared by applying the following: (i) an unpaired two-tailed t-test and (ii) two-stage nested mixed balanced ANOVA.

## 3. Experimental

An environmental assessment was performed for the CLB, HCPP, RC, and CNB technologies by examining two life cycle stages, production and construction (P&C) and maintenance to demolition (MtoD). The production database for the building technology considered the environmental damage that was associated with raw material extraction, the production of composite materials, and the manufacturing of composite components. The SimaPro software version 7.1 (PRé Consultants, 2010) database includes all of these data collection levels and their associated transport processes for the building components studied.

The construction database contained information regarding environmental damage from the following: energy use for the transportation of the work force or employees to and from the construction site and of construction equipment and building materials/products, energy use for on-site equipment, and solid waste, liquid wastes, and water. The energy use for the transportation of building materials/products, on-site equipment, and liquid and solid waste (5% by weight) was considered in this study. The transportation distances between the supply centers and the building sites depend on the building materials/products. For example, a minimum transportation distance of 20 km was assumed for building products, such as ready-mix concrete. The transportation distances for P&C stage used in the study are presented in Table 5.

**Table 5.** Transportation distances (construction stage)

| ***Building material/component*** | ***Distance (km)*** |
|---|---|
| Mixed concrete | 20 |
| Concrete block | 100 |
| Cellular block, marble, gypsum board, and polystyrene | 200 |

The MtoD database contained data on the environmental damage from cleaning, repair, complete replacement of a component, and demolition. Only demolition was considered in the present study. The entire building lifetime was assumed to be 50 years. The timescale of marble coverings is as long as the entire lifetime of the building; therefore, this component was only destroyed (without replacement) at the end-of-life stage of the building. Components such as partitions, floors/ceilings, and wall types last as long as the entire lifetime of the building; therefore, they are also only destroyed at the end-of-life stage of the building.

Similar considerations were applied to the demolition database, for example, in the MtoD stage (e.g., the transportation distances for building materials/products to a disposal site and on-site equipment use). Disposal methods (e.g., landfill disposal, recycling, and reuse) affect the distances for transporting building materials/products to a disposal site. There are only three recycling plants for construction waste in Israel (IMEP, 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 a relatively large number (22) of landfill sites in Israel (IMEP, 2013). Thus, a relatively short distance of 50 km was assumed for materials/products that are placed in landfills, such as polystyrene (Table 6). By comparison, concrete blocks can be partially reused on site; therefore, their transportation was not considered. Transportation distances for MtoD stage used in the study are presented in Table 6.

A variety of power-operated tools and equipment, such as compressors, drills, saws, and welders, should be considered for both the construction and demolition of the building components. The American manual "Means Man-Hour Standards for Construction" (Mahoney and Cleveland, 1988) was used to calculate the number of hours during which the on-site equipment was in operation per building component. The equipment power data were obtained from the Tool Catalog (http://www.southern-tool.com). In Table 7, detailed analyses of the energy equipment consumption (kWh) for P&C and MtoD stages for concrete wall component (as an example of the equipment energy consumption accounting used in this study) is presented. The electricity consumption for power-operated equipment was converted into an environmental score (Pt) based on a coal-based French technology (Israeli electricity production data were not available in SimaPro).

In the present study, some statistical terminology (i.e., a "sampling frame", a "primary unit", "sub-units", and "individual sub-units") presented by Picquelle and Mier (2011) was used. The sampling frame is defined as a "collection of all elements (primary sampling units) accessible for sampling in the population of interest". The primary unit is defined as an "element within the sampling frame that is sampled and is statistically independent of other sampling units within frame". The primary unit contains the "sub-units". The sub-unit contains the "individual sub-units" (Picquelle and Mier, 2011).

In the one-stage sampling design, the building industry is defined as two sampling frames. The first sampling frame includes the three primary sampling units, that is, the e/e, i/i, and h/h methodological options of EI99 or ReCiPe (the methodological options with their particular weighting set). The second sampling frame includes the other three primary sampling units, that is, the e/a, i/a, and h/a methodological options of EI99 or ReCiPe (the methodological options with the average weighting set). Consequently, the difference in the environmental damage (i.e., the factor of interest) between the two building technologies can be evaluated within each of the sampling frames. A statistical analysis can be performed in two sampling frames, but not simultaneously, because the three methodological options from one set were computed via one model, whereas the three methodological options from another set were computed via another model. In both sampling frames, the three primary sampling units are random. In this context, the appropriate statistical test is an unpaired two-tailed t-test.

In the two-stage sampling design, the building industry "is defined as a single sampling frame" (Pushkar and Verbitsky, 2016a). Both the EI99 and ReCiPe result of four building technologies "are defined as the primary sampling units" (Pushkar and Verbitsky, 2016a). "Each primary sampling unit contains two sets: the particular weighting set and the average weighting set, which are defined as sub-units" (Pushkar and Verbitsky 2016a). The two sub-units of the EI 99 and ReCiPe results of the building technologies "contain three methodological options for each of the weighting sets (e/e, h/h, i/i) and average weighting sets (e/a, h/a, and i/a), defining a total of six individual sub-units" (Pushkar and Verbitsky, 2016a). "Measurements are performed on the individual sub-units" (Pushkar and Verbitsky, 2016a). Therefore, the difference between the two clusters (i.e., two building technologies) can be assessed within the single sampling frame, where the six methodological options of both EI99 and ReCiPe are statistically analyzed (Pushkar and Verbitsky, 2016b). In this case, the correct statistical test is two-stage nested mixed (i.e., fixed, random) balanced ANOVA (Quinn and Keough, 2002).

**Table 6.** Transportation distances (demolition stage)

| ***Method of disposal*** | ***Building material/components*** | ***Distance (km)*** |
|---|---|---|
| Recycling | concrete, marble, gypsum board | 200 |
| Land filling | polystyrene, plaster, cellular block | 50 |
| Reusing | concrete block | 0 (performed in place) |

**Table 7.** Equipment energy consumption (kWh) for concrete wall construction (P&C stage) and demolition (MtoD stage) procedures

| ***Equipment**** | ***Equipment hours (hr/unit)*** | | ***Equipment power (kW)*** | ***Equipment consumption (kWh)*** |
|---|---|---|---|---|
| | ***P&C*** | ***MtoD*** | | |
| 033 172 4950 concrete placing and vibrating (1000 kg) | | | | |
| 2 gas engine vibrators | 0.19 | - | 3.73 | 0.8 |
| 1 concrete pump | 0.09 | - | 18.7 | 1.7 |
| 020 704 0600 concrete wall demolition (1 $m^3$) | | | | |
| 1 air compressor, 250 C. F. M. | - | 0.13 | 44.8 | 5.8 |

**Formwork performance – not included (quantity and type of power tools related to formwork are not presented); reinforcing in place performance – not included (it is not significant for wall type variable).*

If the data set can be presented as a hierarchical (nested) balanced structure, then using two-stage ANOVA in comparison with the unpaired two tailed t-test is associated with the increased power of the statistical test, i.e., the ability to reject a false null hypothesis correctly, because the six methodological options of EI99 or ReCiPe are taken into account simultaneously in the case of two-stage ANOVA test.

There are three null hypotheses:

- there are no differences in the effects between the primary sampling units in a one-stage sampling design when only the set of e/e, i/i, and h/h methodological options is used;
- there are no differences in the effects between the primary sampling units in a one-stage sampling design when only the set of e/a, i/a, and h/a methodological options is used;
- there are no differences in the effects between the primary sampling units in a two-stage sampling design when the two sets of e/e, i/i, and h/h and e/a, i/a, and h/a are used simultaneously.

The data sets were multiplied by $10^6$ and log-transformed prior to analysis if necessary. Four concrete building technologies were compared using both an unpaired two-tailed t-test and a two-stage nested mixed balanced ANOVA test. An unpaired two-tailed t-test was used to compute the difference between all pairings of the building technologies within the two separate sampling frames, applying the methodological options with their particular weighting set (e/e, i/i, and h/h) and applying the methodological options with the average weighting set (e/a, i/a, and h/a). Two-stage nested mixed balanced ANOVA was used to compute the difference between all pairings of building technologies within the primary sampling units (including evaluation with the six methodological options of EI99 or ReCiPe).

For analysis of the signs and magnitudes of the statistical effects, Neo-Fisherian significance assessments were used. In accordance with three-valued logic P values were evaluated: “it seems to be positive”, “it seems to be negative”, and “judgment is suspended” (Hurlbert and Lombardi, 2009, 2012).

## 4. Results and discussion

The environmental impact results for the h/a methodological option are presented in Figs. 1 and 2 (EI99 and ReCiPe evaluations, respectively), while Tables 8 and 9 present the six EI99 and six ReCiPe environmental scores (e/e, e/a, h/h, h/a, i/i, and i/a options), respectively, that were calculated for each technology studied (CLB, HCPP, RC, and CNB).

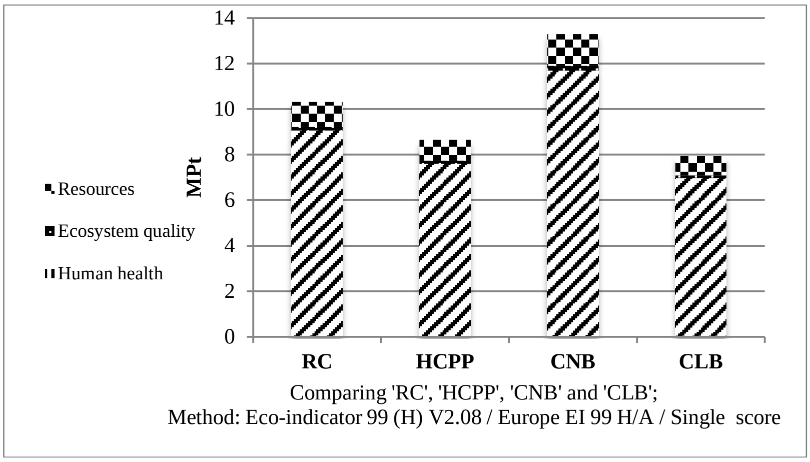


**Fig. 1.** EI99 H/A scores (Pt × $10^6$) of the building technologies

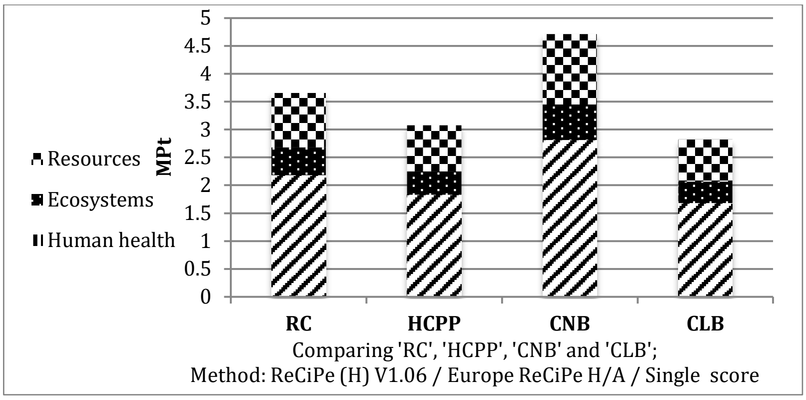


**Fig. 2.** ReCiPe H/A scores (Pt x $10^6$) of the building technologies

**Table 8.** EI99 scores (Pt × $10^6$) of the building technologies

| ***Building technology*** | ***Methodological options of EI99*** | | | | | | |
|---|---|---|---|---|---|---|---|
| | ***i/i*** | ***h/h*** | ***e/e*** | ***i/a*** | ***h/a*** | ***e/a*** | ***Mean*** |
| **CLB** | 10.27 | 7.05 | 17.28 | 8.04 | 7.93 | 12.73 | 10.55 |
| **CHPP** | 11.88 | 8.20 | 20.80 | 9.19 | 8.65 | 15.16 | 12.31 |
| **RC** | 13.77 | 9.22 | 23.81 | 10.67 | 10.30 | 17.28 | 14.18 |
| **CNB** | 19.26 | 11.35 | 29.77 | 14.73 | 13.32 | 21.95 | 18.40 |

**Table 9.** ReCiPe scores (Pt x $10^6$) of the building technologies

| ***Building technology*** | ***Methodological options of ReCiPe*** | | | | | | |
|---|---|---|---|---|---|---|---|
| | ***i/i*** | ***h/h*** | ***e/e*** | ***i/a*** | ***h/a*** | ***e/a*** | ***Mean*** |
| **CLB** | 3.83 | 2.78 | 4.73 | 2.63 | 2.82 | 5.15 | 3.66 |
| **CHPP** | 3.31 | 3.03 | 5.15 | 2.86 | 3.07 | 5.61 | 3.84 |
| **RC** | 3.94 | 3.60 | 6.12 | 3.40 | 3.65 | 6.68 | 4.57 |
| **CNB** | 5.08 | 4.64 | 7.90 | 4.38 | 4.71 | 8.61 | 5.89 |

Comparing absolute numbers, the single score evaluation in EI99 (Fig. 1 and Table 8) is approximately two times higher than the single score in ReCiPe (Fig. 2 and Table 9). The weighing factors are the same in both EI99 and ReCiPe (Table 1) (Goedkoop and Spriensma, 2001; Goedkoop et al., 2009); therefore, the weighing factors do not influence the difference in the results. However, the normalization factors applied in ReCiPe are higher than the normalization factors applied in EI99 (Table 2); the different reference years used for accounting (EI99: 1997 year and ReCiPe: 2008 year) were taken into account, considering the European population (Goedkoop and Spriensma, 2001; Goedkoop et al., 2009).

In addition, for the ecosystems damage category in ReCiPe, more midpoint categories are taken into account; therefore, this damage category has a greater contribution to a single score than in the EI99 evaluation. Additionally, the resources damage category has a different treatment in ReCiPe compared to the EI99 approach: "Unlike the model of Müller Wenk used in Eco-indicator 99, ReCiPe does not assess the increased energy requirement in a distant future; rather, we base our model on the marginal increase in costs due to the extraction of a resource" (Goedkoop et al., 2009). Therefore, in ReCiPe, the ecosystems and resources damage categories have greater contributions to the single score evaluation than in the EI99 evaluation (Fig. 1 and 2).

Tables 10 (EI99 evaluation) and 11 (ReCiPe evaluation) present the mean and SD for the methodological options with their particular weighting set (i.e., e/e, i/i, and h/h) and the mean and SD for the methodological options with the average weighting set (i.e., e/a, i/a, and h/a) of the environmental damage of the four concrete building technologies. Although the changes among the four building technologies were similar in both weighting sets, minimal environmental damage is revealed for the CLB technology, and maximal environmental damage is revealed for the CNB technology for both of the EI99 and ReCiPe evaluations. However, applying two different statistical tests, an unpaired two-tailed t-test and two-stage nested mixed balanced ANOVA test, there are different statistical evaluations for the EI99 and ReCiPe methods. Tables 10 and 11 present the P-values corresponding to the environmental damage (EI99 and ReCiPe evaluation, respectively) in any of the pairings from the four building technologies evaluated with the t-test. Using the methodological options of EI99 with their particular weighting set (Table 10), the P-values reveal that any differences between all pairings seem to be negative. Therefore, in this case, the null hypothesis that there was no difference in environment damage between CLB and CNB was not rejected.

Using the methodological options of EI99 with the average weighting set (Table 10), for any of the comparisons between building technologies (except the comparison between the CLB and CNB technologies), the differences seem to be negative. However, the P-value ($P = 0.063$) reveals that judgment should be suspended regarding the difference between CLB and CNB. Therefore, in the case of the null hypothesis stating that there was no difference in environmental damage between CLB and CNB, the judgment regarding this null hypothesis should be suspended. Using the methodological options of ReCiPe with the particular and average weighting sets (Table 11), the P-values reveal that any differences between all pairings seem to be negative. Therefore, in this case, the null hypothesis stating that there was no difference in the environmental damage between CLB and CNB was not rejected.

Tables 12 and 13 show the P-values as a result of the environmental damage (EI99 and ReCiPe evaluation, respectively) in any of the pairings from the four building technologies evaluated using two-stage nested mixed balanced ANOVA. Considering the EI99 evaluations (Table 12), the differences between the pairings CLB and CHPP, CLB and RC, CHPP and RC, and RC and CNB seem to be negative ($P = 0.324$, $P = 0.112$, $P = 0.345$, and $P = 0.126$, respectively). Regarding the difference between CHPP and CNB ($P = 0.067$), judgment is suspended. However, the difference between CLB and CNB seems to be positive ($P = 0.031$).

**Table 10.** Average of the two sets of EI99 and P-values (P) for four concrete building technologies as a function of the environmental damage, in $10^6$ Pt. The mean ± standard deviation (SD), an unpaired t-test, degree of freedom (df) df = 4, and the probability resulting from a significant testing (P)

| ***Building technology*** | ***CLB*** | ***HCPP*** | ***RC*** | ***CNB*** |
|---|---|---|---|---|
| **Mean ±SD of e/e, i/i, and h/h** | 11.53 ± 5.23 | 13.62 ± 6.48 | 15.60 ± 7.46 | 20.13 ± 9.24 |
| **CLB** | X | P = 0.690 | P = 0.480 | P = 0.223 |
| **HCPP** | | X | P = 0.747 | P = 0.373 |
| **RC** | | | X | P = 0.550 |
| **CNB** | | | | X |
| **Building technology** | CLB | HCPP | RC | CNB |
| **Mean ±SD of e/a, i/a, and h/a** | 9.57 ± 2.74 | 11.00 ± 3.61 | 12.75 ± 3.93 | 16.66 ± 4.63 |
| **CLB** | X | P = 0.610 | P = 0.282 | P = 0.063 |
| **HCPP** | | X | P = 0.567 | P = 0.144 |
| **RC** | | | X | P = 0.294 |
| **CNB** | | | | X |

**Table 11.** Average of the two sets of ReCiPe and P-values (P) for four concrete building technologies as a function of the environmental damage, in $10^6$ Pt. The mean ± standard deviation (SD), an unpaired t-test, degree of freedom (df) df = 4, and the probability resulting from a significant testing (P)

| ***Building technology*** | ***CLB*** | ***HCPP*** | ***RC*** | ***CNB*** |
|---|---|---|---|---|
| **Mean ±SD of e/e, i/i, and h/h** | 3.78 ± 0.98 | 3.83 ± 1.15 | 4.55 ± 1.37 | 5.87 ± 1.77 |
| **CLB** | X | P = 0.835 | P = 0.470 | P = 0.147 |
| **HCPP** | | X | P = 0.522 | P = 0.169 |
| **RC** | | | X | P = 0.364 |
| **CNB** | | | | X |
| **Building technology** | CLB | HCPP | RC | CNB |
| **Mean ±SD of e/a, i/a, and h/a** | 3.53 ± 1.40 | 3.85 ± 1.53 | 4.58 ± 1.83 | 5.90 ± 2.35 |
| **CLB** | X | P = 0.807 | P =0.477 | P = 0.209 |
| **HCPP** | | X | P =0.624 | P =0.274 |
| **RC** | | | X | P = 0.484 |
| **CNB** | | | | X |

**Table 12.** P-value (P) of the pairings difference in four concrete building technologies as a function of the environmental damage evaluated with EI99. Two-stage nested mixed balanced ANOVA, degree of freedom (df) $df_1 = 1$ $df_2 = 2$, and probability resulting from a significance test (P)

| ***Building Technology*** | ***CLB*** | ***HCPP*** | ***RC*** | ***CNB*** |
|---|---|---|---|---|
| **CLB** | X | P = 0.324 | P = 0.112 | P = 0.031 |
| **HCPP** | | X | P = 0.345 | P = 0.067 |
| **RC** | | | X | P = 0.126 |
| **CNB** | | | | X |

**Table 13.** P-value (P) of the pairings difference in four concrete building technologies as a function of the environmental damage evaluated with ReCiPe. Two-stage nested mixed balanced ANOVA, degree of freedom (df) $df_1 = 1$ $df_2 = 2$, and probability resulting from a significance test (P)

| ***Building Technology*** | ***CLB*** | ***HCPP*** | ***RC*** | ***CNB*** |
|---|---|---|---|---|
| **CLB** | X | P = 0.279 | P = 0.018 | P = 0.003 |
| **HCPP** | | X | P = 0.0004 | P = 0.0001 |
| **RC** | | | X | P = 0.0002 |
| **CNB** | | | | X |

Considering the ReCiPe evaluations (Table 13), the differences between the pairings CLB and RC, CLB and CNB, HCPP and RC, HCPP and CNB, and RC and CNB seem to be positive ($P \leq 0.018$). However, the difference between CLB and HCPP seems to be negative (P = 0.279).

The first null hypothesis was tested by an unpaired two tailed t-test when three e/e, i/i, and h/h methodological options were analyzed. This null hypothesis, that is, there was no difference in the environmental damage between CLB and CNB, was not rejected (EI99 and ReCiPe evaluations). The second null hypothesis was tested by the unpaired two tailed t-test when three e/a, i/a, and h/a methodological options were analyzed. This null hypothesis, that is, there was no difference in environmental damage between CLB and CNB, was not accepted (judgment is suspended) for the EI99 evaluations; it was accepted for the ReCiPe evaluations. The third null hypothesis was tested by two-stage nested mixed balanced ANOVA test when six methodological options were analyzed. This null hypothesis, that is, there was no difference in the environmental damage between CLB and CNB, was rejected using EI99 evaluations; using the ReCiPe evaluations, this null hypothesis was rejected for five paring comparisons: CLB and RC, CLB and CNB, HCPP and RC, HCPP and CNB, and RC and CNB.

The main benefit presented by both the EI99 and ReCiPe methodologies is that environmental damage can be calculated using six methodological options. In such a way, all of the methodological options of these LCIA methods can be taken into account, considering the fundamental uncertainties in the EI99 and ReCiPe methodological configurations. These options were designed on the basis of different assumptions regarding the seriousness of the environmental effects and the level of scientific proof of the environmental effects (Goedkoop and Spriensma, 2001; Goedkoop et al., 2009; Goedkoop et al., 2010); therefore, the different options provide different results (Cordella et al., 2008; Laleman et al., 2011; Pushkar, 2007; Pushkar, 2014).

For all of these studies, different options provided different results. For such cases, Goedkoop and Spriensma (2001) recommend the following: "If the conclusions change, we can conclude that the answer depends on the perspective. This is also very important information." However, this recommendation is not helpful for choosing the best alternative. Incorrectly choosing the best alternative can result in estimation of a different amount of environmental damage than expected, thereby requiring distinctly different cost-effective solutions.

Moreover, using the EI99 recommendations regarding the application of absolute and relative uncertainties while making decisions regarding the differences between alternatives in the building sector appears to be impractical when comparing building technologies for which both similar and dissimilar building materials are involved.

Unpaired two-tailed t-tests are widely used in building construction (for example, Ahmed et al., 2012; Ibáñez-Forés et al., 2011; Kikuchi and Hirao, 2010; Zobel, 2013). A two-stage nested ANOVA method was used in at least four experimental studies to avoid uncertainty in the control of building materials (Ackerman et al., 1996; Al-Khateeb et al., 2013; Kim, 2006; Videla and Imbarack, 2010).

The present study validated the use of an unpaired two-tailed t-test and two-stage nested mixed balanced ANOVA as possible supplemental tests for the EI99 and ReCiPe evaluations. An unpaired two-tailed t-test was used to compute the difference between all of the pairings of building technologies within two separate sets of methodological options: (i) the options with their particular weighting set (e/e, h/h, and i/i) and (ii) the options with the average weighting set (e/a, h/a, and i/a). Applying only the set of e/e, h/h, and i/i methodological options does not allow for the best alternative to be selected, e.g., all building technologies will lead to the same environmental damage.

For the EI99 evaluation and the ReCiPe evaluation, when the t-test was used, the suggestion that the CLB technology cannot be identified as the best alternative. Thus, using only three of six methodological options can lead to incorrect results.

For damage oriented LCIA methods, such as EI99 and ReCiPe, six methodological options were specially established to address the fundamental uncertainties of the methods. Therefore, all of these options that are designed for the fundamentally different assumptions about the time frame and the required level of proof of environmental damage must be taken into account (Laleman et al., 2011; Pushkar, 2014). The hierarchical design of the EI99 and ReCiPe evaluations allowed for a two-stage sampling design to be implemented. Thus, it was possible to use two-stage nested mixed balanced ANOVA to compute all of the pairings of building technologies, including simultaneous evaluation with the six methodological options of EI99 and ReCiPe. In both evaluations, CLB technology can be confirmed as the best alternative. For ReCiPe, each technology studied (CLB, HCPP, RC, and CNB) has different environmental damage. The only exception is the pair of CLB and HCPP technologies, which both have the same environmental damage.

## 5. Conclusions

Two-stage nested mixed ANOVA instead of the t-test can be suggested as a supplemental method in both the EI99 and ReCiPe evaluations due the hierarchical structure of their methodological options. ReCiPe rather than EI99 can be recommended as a more appropriate damage oriented method for the evaluation of building technologies. ReCiPe, in contrast to EI99, has an extended list of impacts for the ecosystems damage category. In addition, the ReCiPe method uses more reliable cost evaluation parameters compared to the EI99 method, which uses vague supplemental energy requirements of the distant future.

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