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# Life-Cycle Assessment as a decision-support tool for early phases of urban planning: evaluating applicability through a comparative approach

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**Abstract**. While ambitious environmental objectives are being set for new constructions in Switzerland, the assessment of urban-scale projects and comparison of their performance to national targets are made possible by a growing number of life-cycle assessment (LCA) tools. However, previous research emphasizes the lack of existing tools to support the decision-making process at the early design stage, characterized by a low level of project details. This paper presents a comparison between three LCA tools. The first, stemming from a research and development project (SETUP), is an exploration tool relying on a database of urban-level scenarios and their environmental performance, able to convert district targets (e.g. 2000-Watt society objectives) into specific sub-targets at the building or component levels. The other two are online LCA tools currently available to practitioners (Sméo and Calculation tool for 2000-Watt-society-sites RH II ), that allow assessing the project and verifying its compliance with a given target. Each tool was applied to a low-carbon case study, the blueFactory district in Fribourg (Switzerland), in two hypothetical contexts corresponding to the schematic and detailed project development phases, characterized by different levels of details. When used for the assessment of a project at a more advanced development stage with a high resolution of detail, findings indicate that Smeo and RH II provide similar environmental performance results. However, in early planning stages, SETUP shows better abilities to support decision-making by providing ranges of results and highlighting uncertainties and the influence of design parameters that have not yet been fixed.

## 1. Introduction

On the global level, the building sector has a major impact on the environment, being responsible for approximately 32% of final energy consumption and 19% of related CO2 emissions [1]. In the context of climate change mitigation reinforced by the Paris Agreement [2], countries have been developing, implementing and strengthening national plans and targets for decreasing the environmental impact of the built environment. Switzerland introduced the 2000-Watt Society vision, that sets the pathway to limiting the total primary energy use to 2000 Watts per person and greenhouse gas emissions to 1 ton per person by the year 2100 [3], with intermediate goals for the year 2050 [4]. Accordingly, the Swiss

Society of Engineers and Architects (SIA) defined targets for the building sector, with non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP) as the main assessment metrics [4].

Life-cycle assessment (LCA) is a well-recognized method for estimation of the environmental impacts from the product phases, over the construction process and use, and up to the end-of-life [5]. Even though LCA is widely used for benchmarking the finalized construction project to environmental targets, its application is essential for guiding the practitioners during the design process at early planning stages. As notably stated by the SIA, "*important decisions for the achievement of the target values are made in the early planning phases (strategic planning, preliminary studies and preliminary project)"* [4]. Moreover, the application of LCA is extending beyond the scale of individual buildings (building labels such as Minergie-ECO [6] or new concepts such as Life Cycle-Zero Energy Building LC-ZEB [7]), to considerations at larger scales such as neighborhoods and cities [1,8–10].

LCA-based tools for urban level projects need to fulfill numerous requirements [11], and their application at early design stages faces several challenges [12]. Tools are needed for exploration of interrelations between specific design choices and their influence on the project performance as early as the beginning of the project, in the context of high uncertainty, lack of information and low resolution of project details. The objective of this study is to assess the ability of LCA tools to support the decision-making process for urban–level projects, and to better understand the type of results they are able to provide.

Testing LCA tools is hardly possible by referring to empirical evidence from the real life context (e.g. analysis of energy bills within Building Energy Simulation Test (BESTEST) [13]), due to the system, spatial and temporal boundaries for life-cycle impact assessment of urban-level constructions. Therefore, the study compares LCA-based tools that are currently available to practitioners in Switzerland.

## 2. LCA-based tools

Three LCA-based urban-level tools developed for the Swiss built environment context are identified: SETUP, which stands for Specific Environmentally-conscious Targets for Urban Planning, Smeo Red thread for sustainable construction (Fr. Sméo Fil rouge pour la construction durable) [14], and Tool for 2000-Watt-Society-sites (Ger. Rechenhilfe II für 2000-Watt-Areale, RH II) [15]. The comparisons are possible because the environmental evaluation relies on national databases of life-cycle impact values and SIA standards and norms. The three tools are characterized and compared according to eight categories identified by Bach and Hildebrand [16]. Most important features of the tools are presented in Table 1.

The main purpose of SETUP is to decompose environmental targets from district- to building-, domain- (construction, operation, mobility) and component (e.g., windows) levels, and to facilitate exploration of databases of project alternatives and relating environmental impacts of individual plots within the district at early-planning phases [17]. A proof-of-concept was developed for the blueFactory district in Fribourg, which aims to be low carbon (Figure 1). Project alternatives for each plot were created by varying 17 building parameters (e.g. building shape, depth, height etc.), and assessing operational, embodied impacts and building-induced mobility. The database thus generated includes a large number of project alternatives, sampled through the Sobol low discrepancy method (for more information see: [17]). An Excel-based VBA prototype tool allows exploring these pre-simulated databases. Input-data comprises values for construction areas per plot and building use, and the selection of a reference target for the whole site (from a certification system or building label). Outputs include: decomposed site-level performance targets (CEDtot, CEDnr and GWP) into differentiated sub-targets per plot, building program, domain and component, frequency (number of occurrences) of scenarios that are meeting different target values, influence of variable parameters (geometry, components, technical installations, etc.), and graphical presentation of (un)favorable options through a decision tree.

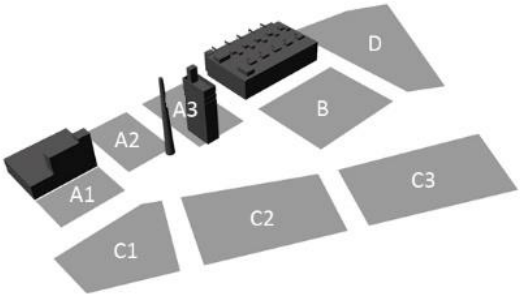


**Figure 1.** Existing buildings and plots on the blueFactory site, as defined for the SETUP tool.

Smeo assesses the sustainability of a project by addressing its environmental, economic and social domains and applying the Hermione method, which aggregates a number of quantitative and qualitative criteria [18]. Through a preliminary section of the internet platform, the project is characterized by selecting its scale (building or site), main program (residential, administration, etc.), type (new constructions, renovations, use, and transformation), phase (initiation, masterplan, district plan, realization, and use) and stakeholder. Accordingly, the suitable interface with input fields opens in the first out of several tool sections. For the purposes of this study, i.e. district-level new construction project at early and advanced planning phases, the interface offers three main sections. The General Data section is the same for both phases and it comprises input fields regarding urban-level parameters, embodied, operational impacts, mobility, etc. Beside dropdown lists with predefined data, required inputs often include aggregated parameter values, for all buildings within the studied district (e.g. floor space index, land use index, total footprint of assessed buildings, etc.), as well as adaptable default values. After entering the number of buildings within the district, the tool hypothesizes that all buildings have identical characteristics, thus not allowing the comparison of building alternatives and related impacts. The Detailed Results section is identically structured for both studied planning phases, and provides site-level results of the qualitative social and economic sustainability criteria, and the quantitative evaluation of environmental impacts (CEDnr, GWP and ecological scarcity points UBP for the entire site and per domain, illustrated in charts).

The main purpose of the third tool, RH II, is benchmarking the site-level project to 2000-Watt-Society targets. The data input begins with specifying the main project features, e.g. project type (new constructions, renovations, buildings in use), reference year for norms and targeted impacts (2030, 2050), project phase (according to SIA 112) and other data which determines the format of the user interface, requested input, software workflow, etc. Data is entered separately for each building. For the preliminary study phase, input is simple and intuitive with a lot of adaptable default values and dropdown lists, which requires only general knowledge from the user. In contrast, the module for the project execution phase requires more detailed input of numerical values for embodied and operational impacts, transferred from independent software, which might require expert skills. In this case, boundaries of LCA depend on the external software. The type of data outputs for both project phases is identical: on site and building scales, numeric values per impact category (CED, CEDnr and GWP) per domain and in total, with corresponding graphs for the site level indicating compliance or not with the 2000-Watt-Society targets.

**Table 1.** Comparison of three LCA-based tools according to [16].

| | **SETUP** (prototype) | **Smeo** | **RH II** |
|---|---|---|---|
| Origin | EPFL Fribourg, Switzerland, 2019 | City of Lausanne and Canton of Vaud, Switzerland (www.smeo.ch), 2009 | Federal office of Energy OFEN, Zurich, Switzerland (www.local-energy.swiss), 2018 |

| | | | |
|---|---|---|---|
| Data source | CEN EN 15978, KBOB 2009/1:2016, SIA 380/1:2016, etc. | SIA 112, KBOB 2009/1:2012, SIA 380/1:2009, etc. | SIA 112, KBOB 2009/1:2014, etc. |
| Required user's knowledge | No prior knowledge | Basic knowledge | Expert knowledge |
| Accessibility | Conditional access (project stakeholders) | Free access (registration needed) | Free access (registration needed) |
| Entry format | Spreadsheet | Input fields and dropdown lists | Input fields and dropdown lists |
| Level (scale) | District-, plot- and component-levels | District-level | District- and building-levels |
| Default settings | Default settings | Default settings partly available | Default settings partly available |
| Life cycle phases | According to CEN EN 15978: Product (A1-3), Use (B6), End-of-life (C1-4) | According to SIA 112 project phase; project planning construction and use phases | According to SIA 112 project phase, but also dependant of system boundaries of external software |

## 3. Comparability of the tools

In order to better understand differences among workflows and discrepancies between impact assessment results, the tools are applied to the urban-level project in the advanced stage, characterized by a high resolution of project detail. The comparison is focused on embodied and operational impacts, without considerations of building-induced mobility, because these impacts do not influence the design process. The case study is the hypothetical project illustrated in Figure 2 for the blueFactory site introduced earlier.

Impact assessment of the blueFactory site focuses on ten administrative buildings, three of which also have residential use (plots C1 and C2, see Figure 1), with total area of approx. 126 000 m$^2$. Buildings have rectangular floorplans and north-south orientation of the longer facades. Buildings' depth is 18-30m and height 3-15 floors. Window-to-wall ratio on all facades is 0.65 for the office buildings and 0.5 for the apartment buildings. Triple glazed windows (U-value: 0.5 W/m$^2$K) have wooden frames (U-value: 1.3 W/m$^2$K), and the thermal transmittance of external walls and roof is of 0.1 W/m$^2$K. Construction of roof, interior floors and external walls are defined according to the Swiss construction catalogue (concrete slab [E0 B01] and wall [W W04]) [19]. Thermal insulation is polystyrene, covering slab material linoleum and covering material of external walls is cement panels. 90% of the total roof surface is covered with PV systems. The HVAC system is a heat pump, with coefficient of performance COP=2.43.

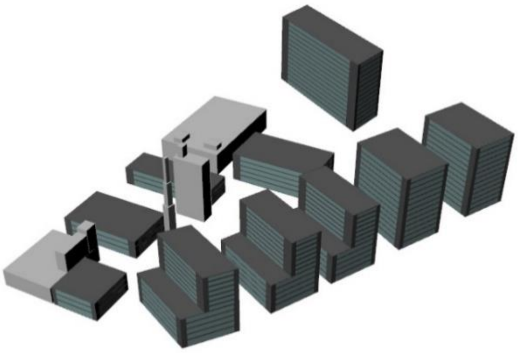
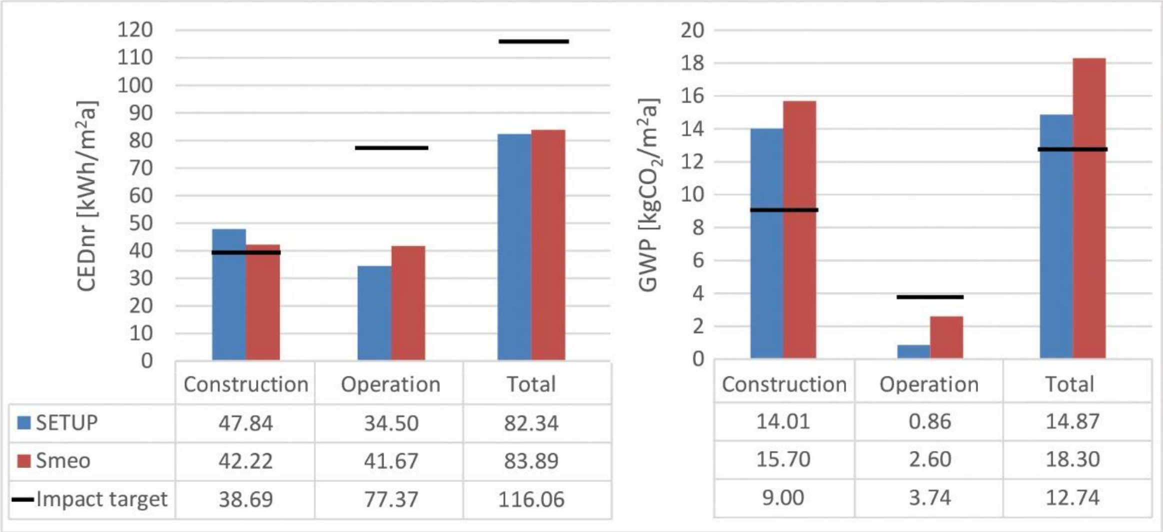


**Figure 2.** Urban massing volumes of the hypothetical project (blueFactory site case study) in the advanced planning phase.

The assessment of the environmental impacts of the hypothetical project in its advanced planning stage is performed in SETUP and Smeo, and the results are shown in Figure 3. RH II is excluded from this first experiment, as it requires inputs deriving from external simulation software.



| | Construction | Operation | Total |
|---|---|---|---|
| 🟦 SETUP | 47.84 | 34.50 | 82.34 |
| 🟥 Smeo | 42.22 | 41.67 | 83.89 |
| — Impact target | 38.69 | 77.37 | 116.06 |

| | Construction | Operation | Total |
|---|---|---|---|
| 🟦 SETUP | 14.01 | 0.86 | 14.87 |
| 🟥 Smeo | 15.70 | 2.60 | 18.30 |
| — Impact target | 9.00 | 3.74 | 12.74 |

**Figure 3.** Results in terms of CEDnr (left) and GWP (right) impacts computed with SETUP and Smeo, compared to environmental targets defined by SIA [4].

The construction CEDnr impacts computed with Smeo is 5.6 kWh/m$^2$a lower than the value obtained with SETUP, which corresponds to a relative change of 11.7% (compared to SETUP). In terms of GWP impacts, the Smeo result is higher by 1.7 kgCO$_2$/m$^2$a, which is equivalent to a relative change of 12% compared to the SETUP result. Discrepancy of embodied impacts of construction might be explained by the mismatch between component options offered in Smeo (e.g. external walls, floor slabs, roof, etc.) and those set for the case study, which were based on options available in SETUP. Therefore, the selection in Smeo was done to match the desired components as close as possible, in terms of types and thermal properties of materials.

Compared to SETUP, absolute increase of CEDnr operational impacts computed with Smeo is 7.2 kWh/m$^2$a, which is in terms of relative change 20.8%. Considering GWP impacts, the 1.74 kgCO$_2$/m$^2$a difference represents as much as a 202% increase from the Smeo to the SETUP result. This gap might be explained by different energy conversion coefficients derived from distinct versions of KBOB databases (data sources, see Figure 1), and different boundaries for the impact assessment of the electricity produced by the PV systems. Indeed, Smeo does not take into account positive impacts of electricity exported to the grid, in comparison to SETUP where the calculation is based on [20], which states that this positive impact should be accounted for.

Environmental impact assessment of the project in its advanced phase is possible, despite methodological differences and heterogeneous inputs and outputs between SETUP and Smeo. It should also be noted that impact results in SETUP are obtained by identifying a specific project alternative from the database of pre-simulated projects (see: [17]). However, due to the extent of the database (limited sample size), it is not always possible to identify the desired project alternative, because this particular scenario might not exist in the database.

## 4. Application of tools in early planning phase

At the beginning of the planning process, urbanists need to make decisions regarding the design parameters on building scales, and understand the implications of their design choices on the environmental performance of the site in later phases of its life cycle. The ability of the LCA tools SETUP, Smeo and RH II to facilitate the decision-making process is tested by answering a design question, formulated according the findings of a survey on the current use of LCA tools in building design [21]. More than 80% of survey respondents (out of 263 practitioners) are considering building shape and orientation as design parameters during the early project phase. Accordingly, our design question is: "Which design choices relating to building shape and orientation would increase the feasibility of the construction project and contribute to meeting environmental targets?" Tested variable parameters include bar-shaped buildings with north-south orientation of longer facades (I N-S), same shape with east-west orientation of longer façades (I E-W), "L" shape (L), "U" shape (U) and atrium shape (O).

To be able to answer the design question, the assessment in Smeo and RH II must be performed through an iterative process, in which only the tested parameter is changed while all other parameters are kept constant. Therefore, the hypothetical project for the blueFactory site in its early planning phase is defined by a set of assumptions. Impact assessment of the site level project comprises administrative buildings, with varying area according to the building shape. Other hypotheses correspond to those set for the project in the advanced design stage, excluding the PV systems, as the calculation of operational impacts between SETUP and Smeo significantly differs (see Section 3). Relating parameters are adapted according to the input format of each tool (e.g. Smeo requires inputs such as floor space index, length of buildings perimeters, etc., while RH II needs data regarding each building such as building footprint and thermal envelope factor). On the other hand, SETUP relies on the database of project alternatives (Section 2) and requires input of building program and area for each plot, which is in total 104 000 m$^2$.

## 5. Answer to the design question

The illustration of the impacts of masterplan alternatives with equally shaped buildings (Figure 4), shows an incoherence between selecting a building shape according to the mean and median (SETUP) and minimum (RH II and Smeo) impacts. Indeed, the shape with the lowest GWP differs according to the tool: it is I E-W for RH II, and I N-S for Smeo and SETUP (although there is an overlap with other distributions such as I E-W). A more detailed illustration of impacts related to project alternatives on individual plots (Figure 5) indicates more consistency among the three tools. Mean and median (SETUP) and minimum impact results (RH II and Smeo), presented in Table 2, indicate that the bar shape is most favorable for accomplishing compliance with the impact target. However, there is a mismatch in terms of selecting the building orientation (except on plots A2 and D).

Mean and median impacts are calculated in SETUP based on a high number of project alternatives, which are taking into consideration effects of the variation of other not yet defined design choices, and thus capturing the uncertainty aspect in early design. In contrast, the impacts computed with traditional tools derive from more definite range of results obtained from a manual iterative process in which only one parameter is varied. Therefore, higher reliability of making a decision on most favorable building shape and orientation according to SETUP results is argued by the representativeness of a distribution range of results.

SETUP indicates increase in feasibility indices from I N-S shape (FI = 8.1%) to O shape (FI = 10.1%) on the site level, and from plot A1 (FI = 4%) to plot D (FI = 64%) on the plot level (see Table 2). The compliant part of the distribution range of results includes variability of uncertain design parameters, and thus indicates a high number of feasible project alternatives. On the other hand, RH II results demonstrate that none of the considered project alternatives is feasible, while Smeo assumes uniformity between the buildings and demonstrates compliance in one project alternative with I N-S shape.

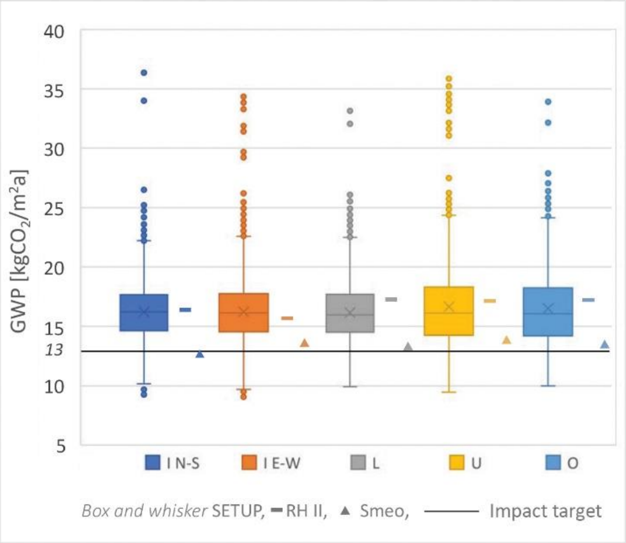


**Figure 4.** Site-level GWP impacts of master plan alternatives composed of buildings with uniform shape, compared to environmental targets defined by SIA [4].

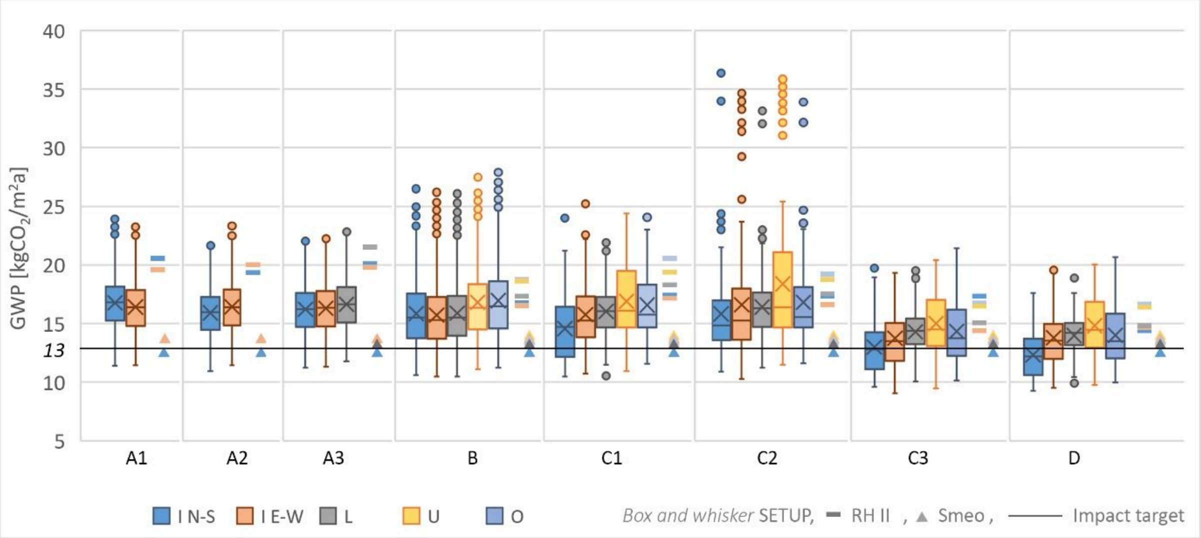


**Figure 5.** Plot-level GWP impacts of project alternatives with variable shapes.

**Table 2.** Building shapes and orientations, GWP impacts and feasibility indices for individual plots.

| | | A1 | A2 | A3 | B | C1 | C2 | C3 | D |
|---|---|---|---|---|---|---|---|---|---|
| Setup | Shape and orientation | I E-W | I N-S | I N-S | I E-W | I N-S | I N-S | I N-S | I N-S |
| | Mean GWP [$kgCO_2/m^2a$] | 16.44 | 15.99 | 16.21 | 15.90 | 14.71 | 15.85 | 13.24 | 12.64 |
| | Median GWP [$kgCO_2/m^2a$] | 16.41 | 15.98 | 16.23 | 15.31 | 14.71 | 14.88 | 12.82 | 12.18 |
| | Feasibility index [%] | 3.95 | 8.11 | 5.46 | 18.49 | 36.65 | 20.37 | 54.32 | 64.20 |
| RH II | Building shape | I E-W | I N-S | I E-W | I E-W | I E-W | I E-W | I E-W | I N-S |
| | Lowest GWP [$kgCO_2/m^2a$] | 19.80 | 19.30 | 19.80 | 16.70 | 17.30 | 16.70 | 14.50 | 14.50 |
| Smeo | Building shape | I N-S | I N-S | I N-S | I N-S | I N-S | I N-S | I N-S | I N-S |
| | Lowest GWP [$kgCO_2/m^2a$] | 12.70 | 12.70 | 12.70 | 12.70 | 12.70 | 12.70 | 12.70 | 12.70 |

## 6. Discussion. Decision-support and ability to lead the design process

Difference between lowest (L) and highest (I N-S) median GWP values is 0.26 $kgCO2/m^2a$, and between lowest (L) and highest (U) mean GWP values is 0.5 $kgCO2/m^2a$. As SETUP results are more representative, they can be used for demonstrating the low sensitivity of building shape to GWP impacts, which can direct the attention of practitioners to another parameter in following steps of design process.

Increase in feasibility indices from simple bar shape to more complex atrium shape relating to the site level, and from smaller plot A1 to larger plot D, relating to the plot level, can be explained by embodied impacts normalized by m$^2$ which are disproportionate to size and complexity of constructible volumes. For instance, smaller plot A1 cannot facilitate construction of L, U and O shaped, but only bar buildings with maximum 5 floors, while larger plot D is suitable for all building shapes, with maximum height of 18 floors. SETUP reveals a wider approach to assessing the project compliance by exploring a series of project alternatives that are incorporating unknown design parameters. This uncertainty is opening the possibility for exploration of scenarios and identification of design parameter values that all feasible scenarios have in common.

Ranking of impacts calculated with traditional tools is matching the ranking of mean and median values within distribution range, however they do not fall into the interquartile range, for most of the alternatives. Limited insight to slightly differentiated or totally uncompliant project alternatives, might direct the design process to incorrectly defined assumptions regarding yet unknown parameters, and also point to the differences among contextual characteristics of plots (e.g. shading effects across the site).

Graphical representation of impact results with box and whisker plots illustrates a probabilistic approach in early design and reveals the richness of considering uncertainty. Compared to the limited number of results computed with traditional tools according to one variable parameter, mean and median, maximum and minimum impacts and interquartile range are integrating the effects of the design choices that have to be made in the following steps of the design process. Outliers theoretically represent false results that should be removed from the database. If we however assume that outliers here correspond to scenarios that are valid and not erroneous, this emphasizes that we might be misled by the initial assumptions about the project.

## 7. Conclusion. Importance of uncertainty in decision-support

LCA at early planning stages exposes several challenges. It is difficult for urbanists to fully anticipate the links between their design decisions and the later project performance when the resolution of project detail is low and the scale extends beyond a single building. In order to perform life cycle assessment, they need to define a high number of hypotheses regarding the unknown parameters. Even with project assumptions, it is not yet possible to demonstrate the robustness of impact results on life cycle scale, as the reference for validation of LCA method is missing (e.g. BESTTEST). Therefore, three methods developed to provide decision support in early stages (among other purposes) are tested in this study.

Traditional LCA-based tools used in Switzerland are applicable for the impact assessment of the urban-level project at advanced stages of design, with the main purpose to benchmark the project against environmental targets. In early design stages, testing the comparativeness of outputs reveals the value of distribution range of results and the importance of integrating the uncertainty aspect. Since we are unable to confirm that LCA results are absolutely correct, it is still challenging at this point to compare the project with the target. SETUP provides a broader view on project compliance with ranges of results representative of many design choices. The risk of making incorrect conclusions is decreased, as we are able to explore common design choices within feasible project alternatives. Wide space for exploration of the project is available precisely due to the presence of uncertainty linked to the project. In contrast, results from traditional tools are straightforward, as they derive from an iterative process that mainly focuses on the adaptation of input parameters in relation to the outputs (one-step at the time method which defines only several points in the planning process). Results may vary from totally compliant to totally uncompliant, therefore it might be premature to take decisions based on LCA at early design stages. Without the uncertainty aspect, traditional tools might be referred to as compliance or confirmation tools, rather than decision-support tools.

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