# Track 8: Innovative Processes and Methodologies to Transform SBE

## Session 1.11: Processes, Design, Tools and Methodologies in SBE (1)

# Does the Sequence Matter? - Investigating the Impact of the Order of Design Decisions on the Life Cycle Performance

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**ABSTRACT**

Life Cycle Assessment (LCA) is increasingly gaining importance in regards to building sustainability evaluation. Life Cycle Performance (LCP) describes the sum of all expenses for the production, operation and deconstruction in relation to the use and lifespan of a building. Considering LCP at the very early stages of the design process can have a significant impact on the overall LCP of the building. Thereby a multi-stage decision-making (MD) process allows the generation of a wide range of designs without eliminating the variants which seem to have comparatively low LCP in the beginning. Within this process all design variants are being developed until the final LCP calculation. By means of the MD tree, the planner can easily compare the different designs. This paper is questioning the order of the design stages used in the MD process for optimizing the LCP: Starting with the building volume and finishing with the construction type can be regarded as a typical sequence for arriving at a solution. But what consequences would a change of this order have? In practice planners can mix up the design order intuitively e.g. by having an idea for a specific construction type and start to develop the building volume based on that. In the following paper this process of switching the sequence of design stages is mimicked by a computational parametric tool. The aim is to investigate the impact of the stage order on the LCP and the geometry of building variants. Findings from the case study can be utilized in practice for the creation of generative tools based on MD processes.

***Keywords:*** *multi-stage decision-making process, Life Cycle Performance, design process, design automation*

## 1. INTRODUCTION

Life Cycle Assessment (LCA) is increasingly gaining importance in regards to building sustainability evaluation, mostly in the form of building certification labels utilized in architectural practice. The application of LCA at a late stage of the design process to evaluate the environmental impact is not sufficient on its own if the results are not used to improve the design (Wittstock et al., 2009). The highest optimization potential lies within the early design stages where the decisions made have the biggest influence on energy demand (Hegger et al., 2007) and environmental impact (Schneider, 2011) while featuring the smallest costs for changes to the design (Paulson, 1976). However, in practice most fundamental decisions concerning the building geometry are made with little or no involvement of simulation software (Picco, 2014). Regarding the design process as a search process, where variants are generated, evaluated, selected and improved in an iterative manner (Newell & Simon, 1972) suggests the aid of computational tools to minimize the time for arriving at a solution. Referring to Rittel (1992), there are several methods to search for solutions: these range from a linear approach, where one single solution is produced in each design stage and no alternatives are created (Figure 1a); to a simplified multi-stage decision making approach, where for each stage of a design multiple variants are created, and the best one is developed further in the subsequent stages (Figure 1b); to a multi-stage decision-making (MD) process, where in each stage all design variants are considered (Figure 1c). The latter strategy generates a much higher number of designs than the other two methods what reduces the risk of missing out good solutions. Additionally, it holds the potential of discovering design variants which have comparatively worse performance in the early stages, although in combination with aspects from the following stages, their performance can improve significantly. By means of the MD tree (Figure 1c), the planner can easily compare the different designs and decide which geometry to choose.

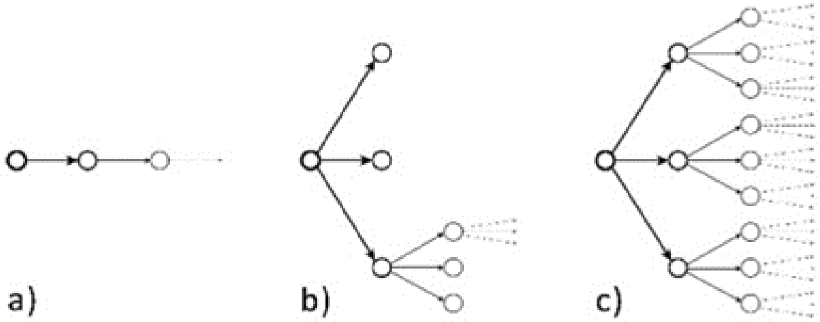


*Figure 1: (a) Linear process (b) Simplified multi-stage decision-making process (c) Multi-stage decision-making (MD) process (Rittel, 1970)*

The following paper is questioning the order of the design stages used in an MD process for finding optimized design variants according to the desired Life Cycle Performance (LCP). The LCP is a measure for the environmental performance of a building during the whole life cycle and in this context, it is used as an assessment value for the different designs. For arriving at a design solution it may seem logical to proceed from the general to the detail (Lawson, 2005), however, does that strategy lead to best solutions or is changing the sequence an option for achieving even better results?

## 2. METHODOLOGY

Is a computational tool which operates based on the MD process to be developed for the implementation in architectural practice, fundamental as well as detailed theoretical knowledge of this design process becomes necessary. In architectural theory, the topic of sequence, also referred to as stage order, in the MD process is widely unexplored. The following paper addresses this issue by means of a case study. For that matter, a parametric computational tool which is able to generate, analyze, optimize and visualize design variants in an MD tree has been programmed using the software Grasshopper3D (Rutten, 2015) for Rhinoceros3D.

Starting with the building volume plus the circulation core and concluding with the construction type can be regarded as a typical sequence for arriving at a solution. That stage order is the basis for the first MD process of the case study. Although, in practice planners can mix up the design order e.g. by having an idea concerning the construction type and develop the building volume from there. This sequence is the theory behind the second MD process explored in the case study. Both sequences are compared by regarding the design variants of the two resulting MD trees. That method should provide knowledge on the influence of stage order on the design outcomes in MD processes. Implementing those findings in future MD processes can lead to better designs with higher LCP values. The setup of the case study is explained in the following.

### 2.1 Parametric model generation

Generating numerous design variants in a short amount of time requires parametrically defined models which can easily be altered by changing the parameter values. In the following case study, two to four residential buildings are located on a rectangular site which is shaded at three sides. For study purposes the floor area ratio (FAR) is kept very low at 0.6, ensuring a high solution space (high FAR leads to geometrically fairly similar solutions). Each design variant has a total floor area of 2500m$^2$ which is divided into subareas for the individual buildings on the site. Minimum and maximum dimensions are set to ensure reasonable sizing of the building volumes. The buildings can have two to four floors and the glazing area is constantly 30% of the exterior wall area. Due to the parametric positioning of the buildings on the site it is likely that these initially intersect. Therefore, an algorithm, which resolves the intersections plus maintains a pre-set minimum distance between the buildings, has been developed. Additionally, building cores which include the main circulation spaces within the buildings are inserted. In order to enable natural lighting and ventilation, they solely can be positioned at exterior walls, preferably in shaded areas to keep the solar gains to the usable floor spaces. If a building exceeds a defined building size, further circulation cores are added. All of those model features are parametrically controlled and each combination of the parameter values generates different design variants. The analysis starts automatically after the creation of every single design variant.

## 2.2 Building model analysis

### 2.2.1 Solar analysis

Solar radiation analysis is a fast way of evaluating the solar radiation on the building exterior considering shading from surrounding buildings for the time frame of one year. Visualized on the building façade, the results display to which extend the building is exposed to sunlight and indicate the potential amount of daylight in the interior.

### 2.2.2 Energy analysis

In order to quickly calculate the operational energy demand, we implemented a quasi-steady state method with monthly energy balances within Grasshopper. The implemented algorithms are based on DIN V 18599-2:2011 (DIN, 2011) and have been verified in Lichtenheld et al. (2015). The developed parametric energy calculation tool is able to provide results in real time (< 0.1s).

### 2.2.3 LCP analysis

In this paper, a previously developed parametric Life Cycle Assessment method (PLCA) is used (Hollberg & Ruth, 2016). Based on the 3D model generated in Grasshopper, the surface areas are extracted to automatically establish a bill of quantities needed for the calculation of embodied energy and environmental impacts (life cycle modules A1-A3, C and D). The environmental indicators for the individual materials are taken from ökobau.dat (BBSR, 2011) which complies with EN 15804 (CEN/TC 350, 2012). For the calculation of the LCP, we used the weighting process included in the DGNB certification. The procedure is explained in Hollberg et al. (2016).

## 2.3 Optimization process

Optimization serves the finding of design variants according to a design goal, which in this case study is the maximal LCP. These optimization processes operate based on evolutionary Algorithms (Rechenberg, 1994) conducted by Galapagos (Rutten, 2011) which is an inbuilt component in Grasshopper.

For starting an optimization, a parametric model, an assessment formula called the fitness and a fitness goal are required. The optimization of the first stage in the first MD process aims to find the best sizing of the building volumes, their location on the site plus the position of the cores at the exterior walls of the buildings. Here the fitness takes into account multiple performance criteria such as the average building surface area to volume ratio (S/V), the average solar radiation of the façade and the average shading value of the cores. The latter describes the difference of the solar radiation actually reaching the cores to the desired shaded condition and is purely based on an assumption of the authors. According to this assumption, the LCP might increase by arranging the buildings in a shorter distance to each other to create small but highly shaded areas on the façades. In those areas the circulation cores should be placed. Since the areas of the exterior walls where the cores are attached are excluded from the average solar radiation value of the façades, this value might increase what leads to a higher LCP. This assumption represents ideas that planners may have for improving the design. After all performance criteria are defined, their values are remapped to a domain which goes from 0 to 1 to ensure that all values stay in the same number range for them to have approximately equal impact on the fitness. In the following mathematical equation those performance criteria are combined:

Fitness = average S/V – average solar radiation + average shading factor.

The goal of this fitness is minimization and it expresses, that the average S/V as well as the average shading factor aim for minimization, whereas the average solar radiation should be increased. In the second stage of the first sequence, the resulting optimized design variant is combined with six different construction types and accordingly six LCP values are calculated.

In contrast, for the optimization in the second MD process where the construction types are defined in the first stage and the volumes plus cores in the following, the fitness is the LCP itself which should be maximized.

## 3. RESULTS

As the first MD tree displays, for each configuration of two, three and four buildings, three variants for building volumes plus cores are generated by means of optimization (Figure 2, left). The fitness used for the optimizations in the first stage of sequence 1 considers the average S/V of the building, the average solar radiation on the façade and the average shading value of the cores. It is not possible to take the LCP as the fitness at that point because one more stage is following which holds multiple aspects, in this case the six pre-selected construction types. Determining the construction type is essential for the LCP calculation. Since the construction types are only included in the second stage of this sequence, defining a custom fitness equation for the optimization in the first stage becomes inevitably.

Regarding the LCP values for the different construction types, a repeating pattern becomes apparent. For every design variant the order of the LCP from best to worst is the same, which indicates, that every single construction type has a specific influence on the LCP. For example, the worst LCP comes with the concrete construction and the best with the wood construction type. For enabling a better comparison between the different design variants, distances from each building to the closest building nearby are calculated. The average distance for every individual design variant is assigned. The overall average distance of all designs in the first MD tree is 4.52m, which means that most of the buildings are positioned relatively close to each other.

In the second MD tree the order of generating the volumes plus cores and applying the construction types is switched around. Hence, the first stage in that MD tree includes the six construction types (Figure 2, right). From there in stage two, for each construction type three design variants are generated with two, three and four buildings. Since no more stages with multiple aspects are following, the fitness for the optimization of the volumes plus cores in the second stage is the LCP, which needs to be maximized. The LCP values of the second MD tree show the same pattern as described for the first MD tree. Comparing the two MD trees reveals that the LCP values are quite similar with a slight deviation from 0.7% to a maximum of 6.2%. In 83% of the calculations the second MD tree delivered the best LCP. The average distance of all design variants is roughly doubled with 10.27m.

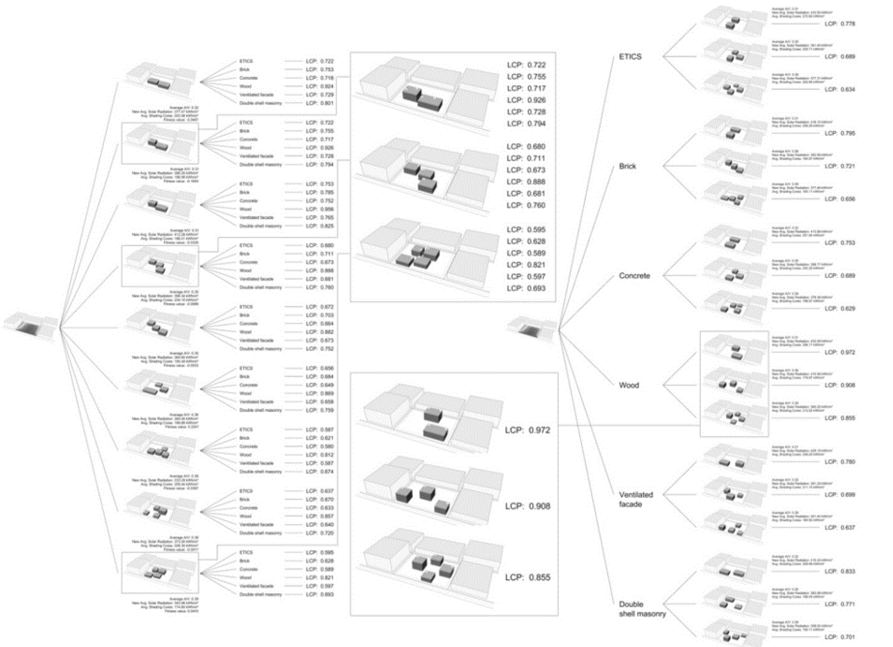


*Figure 2: First MD tree (left), second MD tree (right), for each tree three variants are enlarged for readability.*

## 4. DISCUSSION

From the results of the case study it can be concluded, that sequence has an influence on the resulting LCP and on the geometries of the design variants. However, the pattern amongst the LCP values reasoning in the influence of the different properties of each individual construction type is constantly the same for both MD trees. That shows, that the pattern-like behaviour of the LCP is not connected to the stage order. Although both, the first and the second MD tree deliver similar LCP results, there is a deviation of a maximum of 6.2% in the LCP values. In 83% of the cases, the best LCP results come from sequence 2, where first the construction type is determined and from there the volumes plus cores are developed. The reason for that, are the different fitness equations used for optimization in the two sequences (due to the missing construction types in the first stage of sequence 1). The fitness of the first stage in sequence 1 combines the three seemingly main performance criteria which influence the LCP. Those are the average S/V, the average solar radiation on the façade and the average shading value of the cores. Maintaining the number ranges of all performance criteria without scaling them to the range of 0 to 1 could result in an overly dominant influence of the criterion with the highest number range. In contrast, the one with the smallest number range would have relatively low impact. Therefore, all three performance criteria got assigned an equal influence on the fitness based on the planner's own judgement. Assigning appropriate weighting to each performance criterion is a difficult task. The weighting is indicating to which extent the LCP is influenced by the different performance criteria, but this information is mostly unavailable. Therefore, the planner has to not only decide which performance criteria to include in the fitness equation but also which weighting to apply.

In contrast, the weighting in the second fitness which is the LCP itself, is different. That influence is reflected by the average building distance of both sequences. In sequence 1, the buildings have an average distance of 4.52 m, which means they are located relatively close to each other. This is the consequence of the high influence of the average shading value of the cores on the fitness equation. For achieving a certain amount of shading for the cores at some parts of the building façades, the optimization algorithm creates shaded areas by arranging the buildings close to each other. That however, results in a lower average solar radiation on the building façades which leads to worse LCP values in comparison to sequence 2. It can be concluded, that the custom fitness equation was not completely appropriate in regards to the final goal of achieving maximal LCP. The author's assumption of improving the design outcomes by including an average shading value of the cores in the fitness equation was proven wrong and should be excluded from the fitness.

In contrast to sequence 1, the average building distance of 10.27 m of sequence 2 is resulting from the LCP as the fitness. For maximizing the LCP, the optimization algorithm is aiming for the maximum solar radiation on the building facades. This leads to the minimization of shading by arranging the buildings relatively far apart. The LCP values of sequence 2 were higher than of sequence 1 because the most efficient way of establishing a fitness equation is to take directly the final assessment method as the fitness which was the LCP in this case study.

The case study proofs that it is of importance to pay special attention to the fitness equation and to the weighting used for optimization. It can be concluded, that the optimization delivers best results when the fitness is oriented towards the final assessment method as much as possible. That means, the performance criteria included in the fitness equation plus their weighting should have a similar influence on the final result (LCP) as on the fitness. An even better option is to take the final result as the fitness, which was the case in the second sequence. For that reason, the order of the second MD process was more effective in finding optimized design variants in regards to the LCP.

## 5. CONCLUSION

As the case study shows, the sequence matters when it comes to MD processes. Highly dependent on the stage order, the fitness for optimizations has a major influence on the resulting design variants as well as on the final assessment value. Best optimization results can be achieved by applying the least possible amount of different fitness equations in one sequence and by using the design goal as the fitness. Findings from the case study can be regarded as theoretical background for the creation of generative tools based on MD processes. By means of MD trees planners can get a better understanding of how different construction types influence the LCP as well as the geometry of the design variants. MD trees can help designers to explore a wide range of designs according to the desired performance and choose one for further development. The processes can be programmed to function highly automated, what minimizes the calculation time and makes it more likely to be applied in architectural practice.

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