A Matter of Sequence

Investigating the Impact of the Order of Design Decisions in Multi-stage Design Processes

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Abstract. The design as a process is not a new topic in architecture, yet some theories are widely unexplored, such as the multi-stage decision-making (MD) process. This design method provides multiple solutions for one design problem and is characterized by design stages. By adding new building components in every stage, multiple solutions are created for each design solution from the previous stage. If the MD process is to be applied in architectural practice, fundamental and theoretical knowledge about it becomes necessary. This paper investigates the impact of sequence of design stages on the design solutions in the MD process. A basic case study provides the necessary data for comparing different sequences and gaining fundamental knowledge of the MD process. The study contains a parametric model for building generation, a parametric Life Cycle Assessment tool and an optimization mechanism based on Evolutionary Algorithms.

Keywords: Multi-stage decision-making process · Design process · Life Cycle Performance · Design automation

1 Introduction

Over the course of time, numerous design strategies for finding design solutions according to architectural design problems have been developed by theorists like Gero [1], Markus [2], Maver [3], and Rittel [4]. Those strategies aim to structure the design process into manageable chunks which are easier to process for the human mind as design problems can be extremely complex. “The common idea behind all these ‘maps’ [strategies] of the design process is that it consists of a sequence of distinct and identifiable activities which occur in some predictable and identifiably logical order.” [5]. Rittel introduced different methods for solution-finding which are characterized by multiple design stages. In every stage, new features are added to the design, such as windows, circulation cores, etc. The strategies proposed by Rittel range from a linear approach, where one single solution is produced in each design stage and no alternatives are created (Fig. 1a); to a simplified multi-stage decision making approach, where for

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each stage of a design multiple variants are created, and the best one selected for the development in subsequent stages (Fig. 1b); to a multi-stage decision-making (MD) process, where in each stage all design variants are considered for further development (Fig. 1c). The latter method generates a much higher number of designs than the other two strategies. This benefits the solution space exploration and therefore, increases the chance of finding the best performing designs. The solution space contains all possible solutions for a design problem [6]. Additionally, the MD process 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. Regarding these advantages, the application of the MD process in architectural practice can have a positive impact on the design performance. With this however, fundamental as well as detailed theoretical knowledge of the MD process becomes necessary.

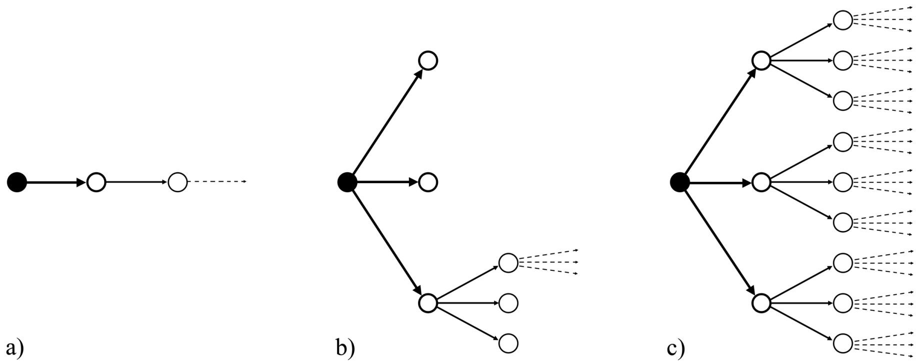

Fig. 1. Linear process (a), simplified multi-stage decision-making process (b), multi-stage decision-making (MD) process (c) [4]

Although Rittel provides the theoretical framework for the design process, he does not make any specific statements concerning the division of a design problem into multiple design stages. Consequently, no guidelines exist for determining the number of design stages and assigning their order in the MD process. In the following, both the stage number and the stage order are summarized under the term ‘sequence’. The topic of sequence in the MD process is widely unexplored. This paper investigates the impact of sequence on design solutions in the MD process, in particular on their geometries and performance values. According to the two aspects which make up a sequence, the research is divided into two parts with the following core questions:

(1) How does the fragmentation of a design problem into design stages affect the resulting design solutions?
(2) What impact does the stage order have on design solutions? For arriving at a design solution, it may seem logical to proceed from the general to the detail [5], yet does this strategy lead to the best solutions, or is changing the stage order a useful option for achieving even better results?

These questions are addressed by means of a case study. Findings from the case study should serve as basic theoretical knowledge of MD processes. Conducting an MD process manually can easily become a very time-consuming process due to the numerous design variants that need to be created in every design stage. Therefore, a computational method is required to speed up the process. The application of computational simulation reduces the architectural design process to an optimization process. By integrating optimization into the workflow, the chances of finding design solutions with the highest performance values increase. As a computer-aided application of the MD process that operates completely automatic does not exist yet, a research tool was developed by the authors which enables one to conduct MD processes automatically.

2 Methodology

A case study focuses on the investigation of the impact of sequence on design solutions in MD processes from a theoretical point of view. Therefore, a basic design problem with a low number of parameters and evaluation criteria is sufficient. The used design problem was constructed by the authors and does not refer to a real case scenario.

The study is structured into two parts according to the research questions posed in the introduction. Each part contains two MD processes which involve the same three design components (building volumes, circulation cores, construction types), yet in different sequences. Only three design components, which is a fraction of the number of components involved in practice-oriented design, are included in the study. A major reason for this minimalistic approach is to make the change of sequence reasonably simple. Furthermore, incorporating a low number of performance influencing components facilitates the discovery of the reasons for possible differences in design solutions between the MD processes. The chosen components represent increasing levels of detail in design. The building volumes and their position on the site embody the least detailed level of the three, followed by the circulation cores which contain the main vertical circulation spaces, and six predefined construction types, such as wood construction, concrete construction, etc. The latter have the highest level of detail because they contain information about the materials and how those are assembled. As one example for possible evaluation criteria of buildings the Life Cycle Performance (LCP) was picked for this case study. The performance goal of the case study is the generation of design solutions with the maximum LCP.

2.1 Parametric Model Generation

The design process is reduced to an optimization process. Optimization requires the creation of variety which can be achieved by generating dissimilar design variants. Therefore, a parametrically defined generative model is necessary. Developed from the design problem, this model incorporates multiple design components.[1]

[1] For this case study, the model has been visually programmed using the software Grasshopper for Rhinoceros3D.

The design problem outline of this case study is as follows: On a rectangular site which is shaded at three sides, a configuration of two to four residential buildings with an optimal Life Cycle Performance (LCP) is to be designed. For study purposes the floor area ratio (FAR) is kept very low at 0.6, ensuring a broad solution space (high FAR leads to geometrically similar solutions). Every configuration of buildings provides a gross floor area of 2500 m^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. Natural lighting within the building is provided by ribbon windows. Due to the parametric positioning of the buildings on the site it is likely that these initially overlap. Therefore, an algorithm, which resolves the overlaps plus maintains a pre-set minimum distance between the buildings, has been developed. Circulation cores, preferably located in the shaded areas to keep the solar gains to the usable floor spaces, are included. To enable natural lighting and ventilation, they solely can be positioned at exterior walls of the buildings. The circulation cores contain the main vertical circulation spaces within the buildings. If a building exceeds a defined building size, further circulation cores are added. Figure 2 shows the parametric building model generation process which includes all the features mentioned in the design problem outline. Every combination of parameter values generates different design variants. The building analysis starts automatically after the creation of a design variant.

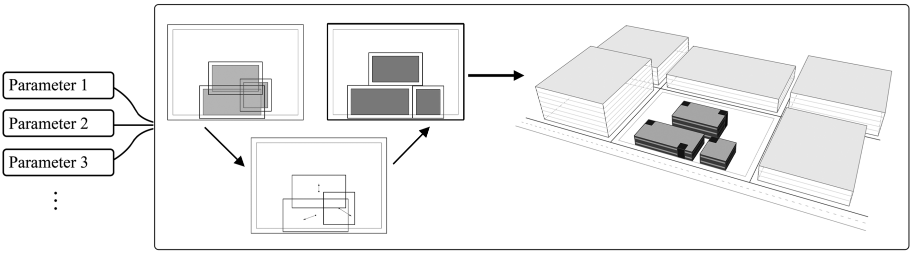

Fig. 2. Parametric building model generation with an inbuilt algorithm for resolving building footprint overlaps (left)

This design problem involves making optimal use of available daylight by taking into account the shading conditions on site, plus the overshadowing that buildings create by themselves. Furthermore, the shape, volume, and position of the buildings need to be considered in order to achieve best LCP results. A set of six potential construction types is provided.

2.2 Building Model Analysis

Life Cycle Assessment (LCA) is increasingly gaining importance in regards to building sustainability evaluation [7]. It takes into consideration both the operational and the embodied energy over the building's whole life cycle. LCA can be defined as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" [8]. Considering LCA at the very early stages of design process can have a significantly positive impact on the LCP of the building. However, the evaluation of the design through LCA is not sufficient on its own, if it does not improve the design [9]. Moreover, the calculation results should be used as feedback about the design variant in order to support decision-making during the design process. A measure of the resulting environmental performance of variants during their whole life cycle is the Life Cycle Performance (LCP). By means of the LCP, different design variants can be compared, which is used within the case study of this paper.

A previously developed parametric LCA method is used for the calculation of the LCP [7]. This method is fully integrated into a programming software allowing the calculation of operational energy demand and embodied environmental impact of design variants. Since both, the LCA method and the parametric model, are programmed in the same software, exporting and re-importing of data is not necessary thus enables the application of optimization processes. Furthermore, the parametric LCA tool is able to provide results in real-time (<0.1 s). That facilitates finding optimal design solutions in a reasonable amount of time. The LCA method divides all necessary input into three categories, namely geometric information, non-geometric information and surrounding conditions. All of those are defined parametrically to permit quick adaptation to changing parameters.

As geometric information, surface areas are automatically extracted from a design variant. These areas are sorted by zones, in which one zone corresponds to one building floor. The circulation cores are not taken into consideration as they are not part of the building's heating area. Hence, these are subtracted from the building volumes. Non-geometric parameters such as material properties, the thickness of building components (e.g. exterior walls, insulation), HVAC systems, etc., are defined numerically. In this case study, six common construction types are chosen for the LCP calculation. These are: External Thermal Insulation Composite System (ETICS), Brick construction, Concrete construction, Wood construction, Ventilated façade system and Double shell masonry system. Surrounding conditions, such as climate or user data, are taken from standards. The shading value that indicates to which extent the windows are shaded by surrounding buildings is derived from the solar radiation analysis.

Since one building configuration in the case study contains two to four buildings, an LCP value is calculated for each of the buildings. However, the buildings need to be assessed as one complete configuration for optimization. Hence, a weighted average is calculated from the individual LCPs. The weighting is determined by the gross area of each building.

2.3 Optimization Process

Every design stage can contain either an enormously large number of possible variants or an identifiable number of variants. In the latter case, an exhaustive search can be applied. An example for an exhaustive search within the case study is the six selected construction types. However, the number of potential variants very large, a heuristic search becomes necessary in order to find solutions for the design problem within a reasonable time frame. In the case study, Evolutionary Algorithms (EA), also referred to as optimization strategies, are used for that matter. EA mimic biological evolution, namely, the process of natural selection and the 'survival of the fittest' principle [10]. The application of EA cannot guarantee to find an optimal solution, yet it might find one or multiple solutions which can be regarded as good enough from the planner's point of view.

EA require genomes and a fitness with an assigned goal in order to start operating.[2] Genomes are all parameters which can be varied during the optimization to generate design variants. The fitness is a numeric mathematical function which can include one or multiple performance criteria, such as average solar radiation and Surface Area to Volume Ratio (S/V). These criteria are combined by means of addition. Depending on the optimization goal, a positive or negative prefix is assigned to each criterion. The optimization goal can either aim to maximize or minimize the performance results calculated by the fitness function. Consequently, if the optimization goal of the complete function is set to maximization, each criterion which is to be maximized has a positive prefix. In contrast, each criterion that should be minimized gets a negative prefix. The opposite is the case if the optimization goal aims for minimization. Often negative and positive prefix are included in one fitness function. That means one criterion cannot be improved without having a negative impact on at least one other criterion. Furthermore, all criteria need to be scaled to the same numeric range to avoid overly dominant behavior of some criteria towards the other criteria. In the case study, a range from 0 to 1 is applied. Additionally, these criteria can be weighted according to their significance to the performance. However, the difficulty of the weighting processes is to identify how these criteria influence the performance. For example, it is known that the S/V impacts the LCP, but it is not clear how it should be weighed against other criteria like solar radiation in the fitness function in order to represent its significance to the LCP. The fitness function delivers a performance value for each generated design variant which is crucial for optimization processes.

Usually, an optimization stops when a termination condition is reached. In the case study, the optimization process was stopped after the 40th generation. Every generation contained 50 design variants.

2.4 Multi-stage Decision-Making Trees

Rittel's [4] theory of the MD process implies the need of visualizing produced design solutions according to the design stages used for the process. MD trees serve this need as they provide a clear overview of the generated data by arranging it in a tree-like structure. This makes comparing results easy for the planner. The design phases are represented by stages and the alternative design solutions in these stages are organized by branches. As MD trees are controlled parametrically, a vast amount of data can be

[2] Galapagos which is a component included in Grasshopper, was used for conducting all optimizations within the case study.

visualized with least effort. Saving the data of the design solutions according to a defined file name structure, and including the resulting file paths in the algorithm, enables automated data input. Moreover, the MD trees are updated in real time as soon as new results are saved or changes are applied to the already existing ones. The average, minimum and maximum values, etc. can be computed automatically, providing fast numeric evaluation methods for the planner. Figure 3 displays the optimization process plus the saving of graphical and numeric data of the optimized design solution for the automated creation of MD Trees.

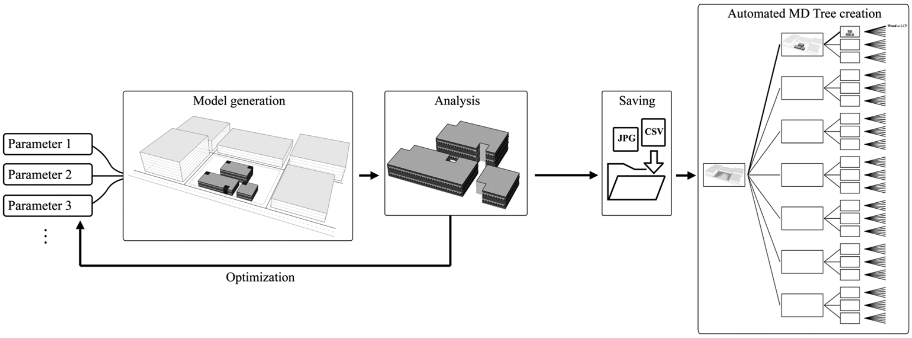

Fig. 3. Optimization process and automated MD Tree creation

2.5 Design Sequences

Part (1) of the study addresses the fragmentation of a design problem into design stages for the application of MD processes. It focuses on the influence of defining separate stages for design components in comparison to combining certain components in one stage in regards to resulting design solutions. Therefore, two MD processes with two different sequences are compared by considering the geometries and the performance values of their design solutions. In sequence 1 (MD process 1), all three design components (building volumes, circulation cores, construction types) are separated into three stages (see Fig. 5 left). Starting with the building volumes and their locations on the site in stage 1, continuing with the positioning of the circulation cores in stage 2, and concluding with assigning the construction types in stage 3, is the stage order of sequence 1. This order corresponds to the level of detail of the components as described above. However, this stage order is not solely determined by the level of detail. Logical constraints need to be considered in this example since the cores can only be placed within the building volumes. That makes it impossible to optimize core positioning without the building volumes. Because of the connection of the cores to the building volumes, the latter must be defined first in this sequence.

In sequence 2 (MD process 2), the building volumes and the cores are combined in stage 1 (see Fig. 5 middle). The six construction types are subject of stage 2. This sequence is based on a hypothesis of the authors and represents typical assumptions that planners may make of design solutions. The hypothesis refers to the solar radiation accessibility on the building façades. Generally, it can be assumed that in order to achieve acceptable solar radiation on all façades, the buildings may tend to maintain high distances to all shadow casting objects such as other buildings of the configuration and the surrounding buildings (see Fig. 4 left). This would be the case for sequence 1 where the volumes and their positions are defined in the first stage. After the volumes are placed on the site, the cores would be positioned in the areas where least solar radiation is identified in order to leave the spaces with good daylight accessibility to the apartment areas. In contrast, the hypothesis states that purposely created shaded areas on the building façades for the core placement can improve the solar radiation. A higher solar radiation may lead to better LCP values. The idea behind this assumption is to decrease the distance of some buildings on the site to achieve highly shaded, yet small areas. In these areas, the cores can be positioned (see Fig. 4 right). By decreasing the distances between the buildings on the site, the distances to the surrounding buildings increase. This can reduce the shading on the building façades caused by surrounding buildings which simultaneously improves their average solar radiation values. This hypothesis can only be considered if the building volumes, their positions, and the cores are optimized in the same stage. If they are divided into separate stages, the influence of the cores cannot be taken into account during the formation and positioning of the building volumes.

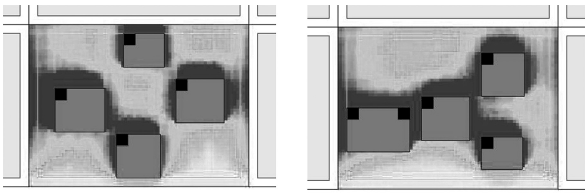

Fig. 4. Author's hypothesis: large building distances (left); small building distances (right)

Resulting from this hypothesis, a fitness function is developed. Sequence 2 requires only one fitness function since both criteria which are to be optimized are included in a single stage. The six construction types in stage 2 are already predefined and do not need to be optimized in this case study. Generating design solutions with high LCPs is the aim of the optimization. However, it is not possible to take the LCP as the fitness function and its maximization as the fitness goal in stage 1 of sequence 2. The reason for that is the missing information about the construction type which is content of the subsequent stage. Therefore, the planner needs to assign a fitness function for stage 1 of sequence 2 which does not contain the LCP but aims for optimization oriented towards the LCP.

The first step for creating such a fitness function is to define important performance criteria which influence the LCP. Moreover, it has to be possible to analyze the design variants of the regarded stage according to those performance criteria. One major performance criterion is the Surface Area to Volume Ratio (S/V) which is an indicator for the compactness of a building volume. It is calculated by dividing the area of the building envelope by the volume of the building. The S/V is an important criterion for determining a building's heat gain and heat loss. That means, a bigger surface area induces more heat gain in warm weather conditions and increased heat loss in cold conditions. Consequently, a minimized S/V is of great benefit to the LCP as it reduces the energy demand of the building. To provide one S/V value for the fitness function, an average of all S/V in a building configuration is calculated.

Another LCP influencing criterion is the solar radiation. It shows to which extent the building façades are exposed to sunlight and indicates the potential amount of daylight in the interior. Daylight accessibility of the building interior is of significance as it impacts the solar heat gains in cold weather conditions, and energy consumption in regards to artificial lighting. Thus, a reasonable amount of daylight in the buildings improves the LCP. As a solar radiation value is calculated for each analysis point on the façades, an average solar radiation value needs to be identified for the complete configuration of the buildings in order to create one value which can be included in the fitness function. However, the areas where the cores attach to the building façades are excluded from the average solar radiation value since they are not part of the heated apartment areas. That implies, that by placing the cores in shaded areas the average solar radiation of the remaining façade areas increases.

In regards to the earlier explained hypothesis of the authors, a shading factor for the cores is added. This factor is included to facilitate the creation of shaded areas where the cores should be positioned for improving the average solar radiation of the buildings. In order to achieve that, it aims to decrease some distances between the buildings on the site by trying to find core positions in semi-shaded areas. Choosing semi-shaded areas instead of fully shaded ones should aid positioning the cores not necessarily at the most shaded areas of the façades (primarily located at the north façades), but at those which are created between the buildings.

Weighting is always included in a fitness function, even when the planner only scales the values to the same numeric range. All criteria involved in a fitness function have a certain influence on the LCP depending on their values, i.e. a higher value has a higher impact on the performance. Additional weighting can be applied if the planner assumes that some criteria are more important than others. In this case study, all three criteria included in the fitness function are not additionally weighted. The weighting resulting from the scaling process seems appropriate enough from the author's point of view. Adding all criteria delivers the fitness function for sequence 2.

Next, the fitness goal needs to be assigned which determines the prefixes of the criteria in the fitness function. In this case, it is set to minimization. The adjusted fitness function for sequence 2 is the following:

$$\text{Fitness}_{\text{Seq.2}} = \text{S/V} - \text{average solar radiation} + \text{shading factor} \tag{1}$$

This function expresses, that the S/V and the shading factor aim for minimization, whereas the average solar radiation should be increased.

To enable comparison of the design solutions resulting from sequence 1 and sequence 2, the fitness functions involve partially the same performance criteria. Since sequence 1 includes two optimization stages, accordingly two fitness functions are required. The first stage of sequence 1 where the building volumes and their positions on the site are optimized, aims for minimization and has the fitness function of:

$$\text{Fitness}_{\text{Seq.1.1}} = \text{S/V} - \text{average solar radiation of building volumes} \quad (2)$$

The average solar radiation in this function is calculated from all solar radiation values on the façade because the cores are not included in this stage. For the second optimization in sequence 1 which aims for maximization, the following fitness function is used:

$$\text{Fitness}_{\text{Seq.1.2}} = \text{average solar radiation} \quad (3)$$

At this point, the volumes and their positions are already optimized and therefore, the S/V is not included in the fitness $_{\text{Seq. 1.2}}$. The average solar radiation of the façade can be improved by positioning the cores in shaded areas. The shading factor is not relevant at this stage of the sequence because the building volumes and their positions are already determined and their distances cannot be changed. Therefore, the shading factor is not included in both fitness functions of sequence 1.

The (2) part of the case study serves the investigation of the impact of stage order on design solutions in an MD process. The initial sequence for this approach is sequence 2 from part (1) of the case study. Choosing this sequence facilitates the change of stage order as this MD process has only two stages. In stage 1 the building volumes, their positions on the site, and the cores are optimized. Stage 2 contains six different construction types which do not require optimization. By swapping these two stages, sequence 3 (MD process 3) is created (see Fig. 5 right). Its first stage holds the six construction types, whereas the optimization of the building volumes, their positions on the site, and the cores is conducted in the second stage. As the optimization in this sequence is content of the last stage, it is possible to take the LCP as the sole performance criterion in the fitness function and its maximization as the fitness goal.

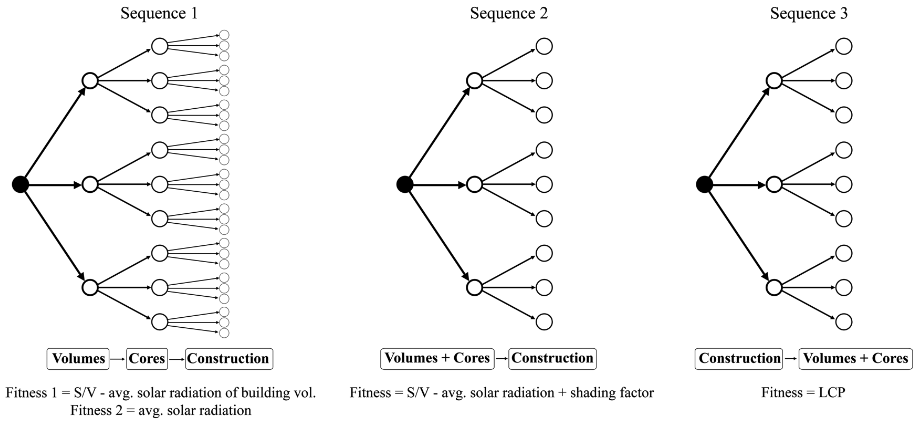

Fig. 5. MD Tree 1 for sequence 1 (left), MD Tree 2 for sequence 2 (middle), MD Tree 3 for sequence 3 (right)

Consequently, the main difference of the solution generation in these two sequences lies in their fitness functions. The fitness function of sequence 2 is determined by the author's assumptions about the design solutions. In contrast, the fitness function of sequence 3 is fully determined by the LCP calculation which simultaneously is the final assessment method of the generated design solutions.

3 Results

In order to ensure systematic comparison between the sequences, several evaluation factors are established.[3] They sum up the design solution data of each individual MD process by creating average values. The first evaluation factor in this case study is the average LCP of a complete sequence. A higher LCP indicates better environmental performance of a design solution. The average of the S/V and the solar radiation on the façades are further evaluation factors for design solutions. By means of the average building distance the geometries of the design solutions can be differentiated. It is calculated by measuring the distance from each building to all the other buildings of a design solution. In the next step, the shortest distance for each building is identified (see Fig. 6). Based on the shortest distance values, the average building distance is calculated for each design solution. The average of these values again, is the average building distance for a complete sequence.

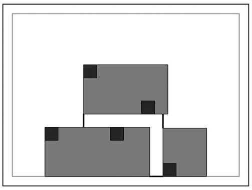

Fig. 6. Identifying the building distances

(1) For sequence 1, nine design solutions for the building volumes and their positioning on the site are generated in the first stage, which corresponds to three solutions for each configuration of two, three and four buildings. The next stage contains three design solutions for core positioning for each of the nine designs from the previous stage. In the last stage, each of the solutions from stage two is paired with six different construction types. This makes a total of 162 design solutions in this sequence (Fig. 7). Even by starting with a low number of items in the first stage, the multiplications with the items of the following stages result in a high number of design solutions. This on the one hand can be regarded as extremely beneficial for having a

[3] Another important information to keep in mind when evaluating design solutions is that slight deviations in the results are common for optimization processes which operate based on EA. These deviations are to be considered before making conclusions about the different sequences.

variety of design options to choose from for the planner. On the other hand, this process can easily become very time-consuming if a high number of optimizations has to be conducted within an MD process. That should be kept in mind when determining the number of desired design solutions.

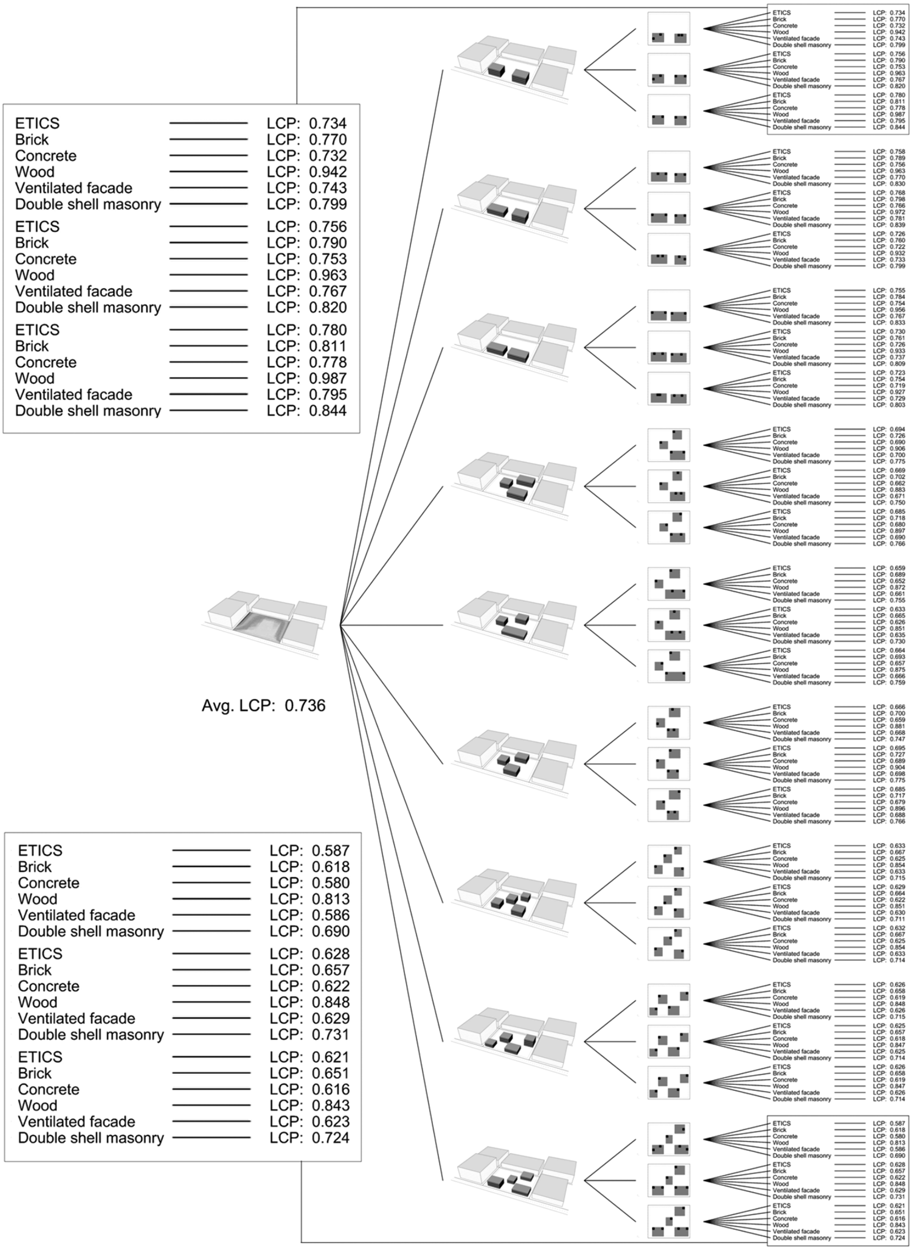

Fig. 7. MD process with sequence 1 with zoom-in parts for better readability

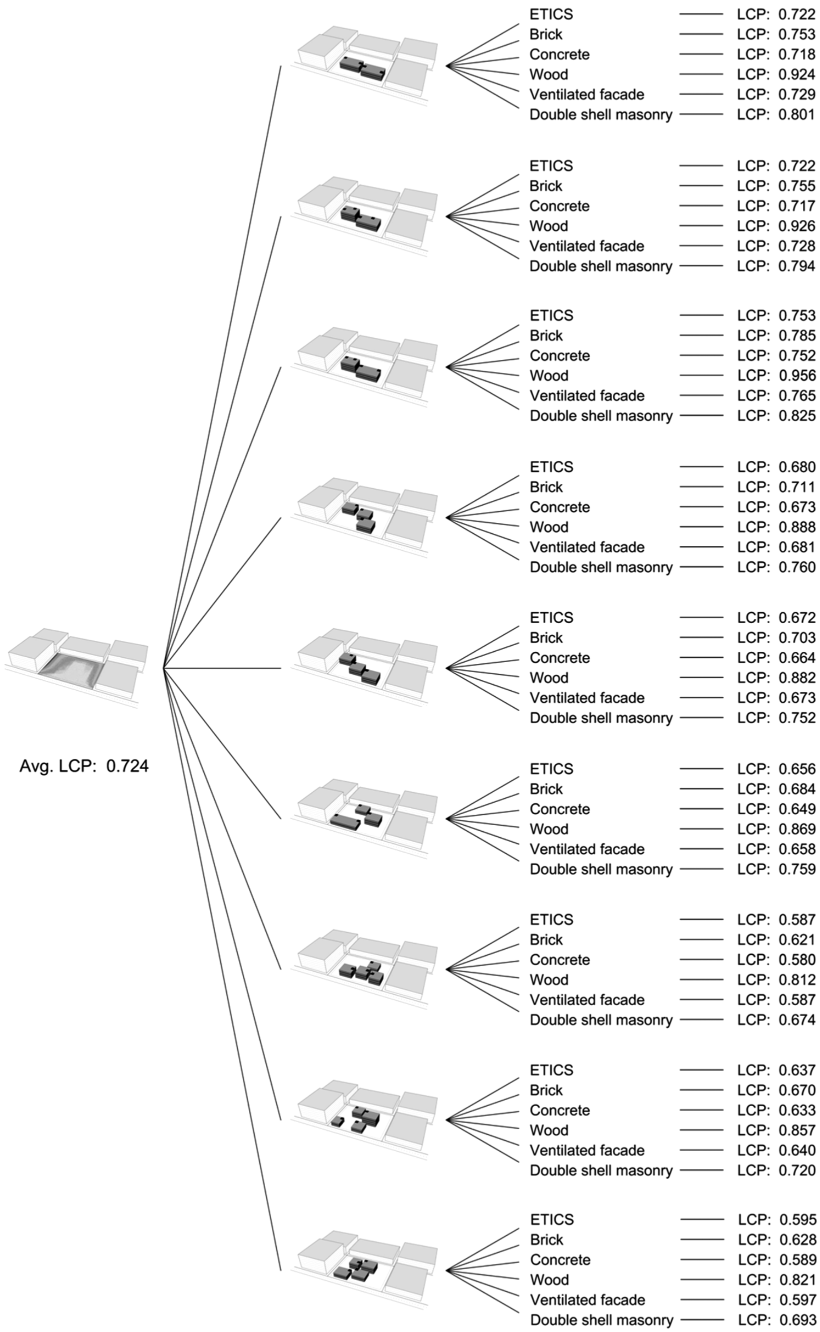

Fig. 8. MD process with sequence 2

The number of design solutions in sequence 2 is significantly lower than in sequence 1 due to the combination of two optimization stages in one. In the first stage of sequence 2, nine design solutions are produced, three for each configuration. They involve the building volumes, their positioning on the site and the core positioning. In combination with the six construction types in the subsequent stage, a total of 54 design solutions is produced in MD process 2 (Fig. 8).

Table 1. Evaluation values of sequence 1 and sequence 2

Average	Sequence 1	Sequence 2	Difference
LCP [WBP]	0.736	0.724	−1.7%
Distance [m]	8.50	4.52	−53.2%
S/V [m^{-1}]	0.352	0.352	±0%
Solar radiation [kWh/m^2]	403.027	370.477	−8.8%

The evaluation values of both sequences are summarized in Table 1. It can be observed that the average LCP of 0.736 resulting from sequence 1 is slightly higher than the average LCP of 0.724 from sequence 2. An enormous difference can be noted in the average building distances where the value of sequence 1 is almost twice that of sequence 2. In contrast, the average S/V values of both sequences are the same.

The MD trees of both sequences (Figs. 7 and 8) show a pattern in the individual LCP values which is caused by the different construction types. If for each individual design solution all LCPs resulting from the six construction types are sorted from the best to the worst, a specific order can be observed: wood construction, double shell masonry, brick construction, ventilated façade, ETICS and concrete. This order is constantly the same for both sequences. This indicates, that it is not dependent on the sequences. Instead, each construction type has a specific influence on the LCP.

The results from part (2) of the case study can be regarded in Figs. 8 and 9. As described above, in the first stage of sequence 2, nine design solutions are generated which makes three for each configuration of two, three and four building. The second stage of this sequence holds six construction types, which makes a total of 54 design solutions (Fig. 8).

Changing the stage order leads to a different number of design solutions. In sequence 3, the six construction types are content of the first design stage. The second stage of this sequence provides three design solutions for each of the construction types

Table 2. Evaluation values of sequence 2 and sequence 3

Average	Sequence 2	Sequence 3	Difference
LCP [WBP]	0.724	0.750	+3.6%
Distance [m]	4.52	10.27	+127.2%
S/V [m^{-1}]	0.352	0.352	±0%
Solar radiation [kWh/m^2]	370.477	399.170	+7.7%

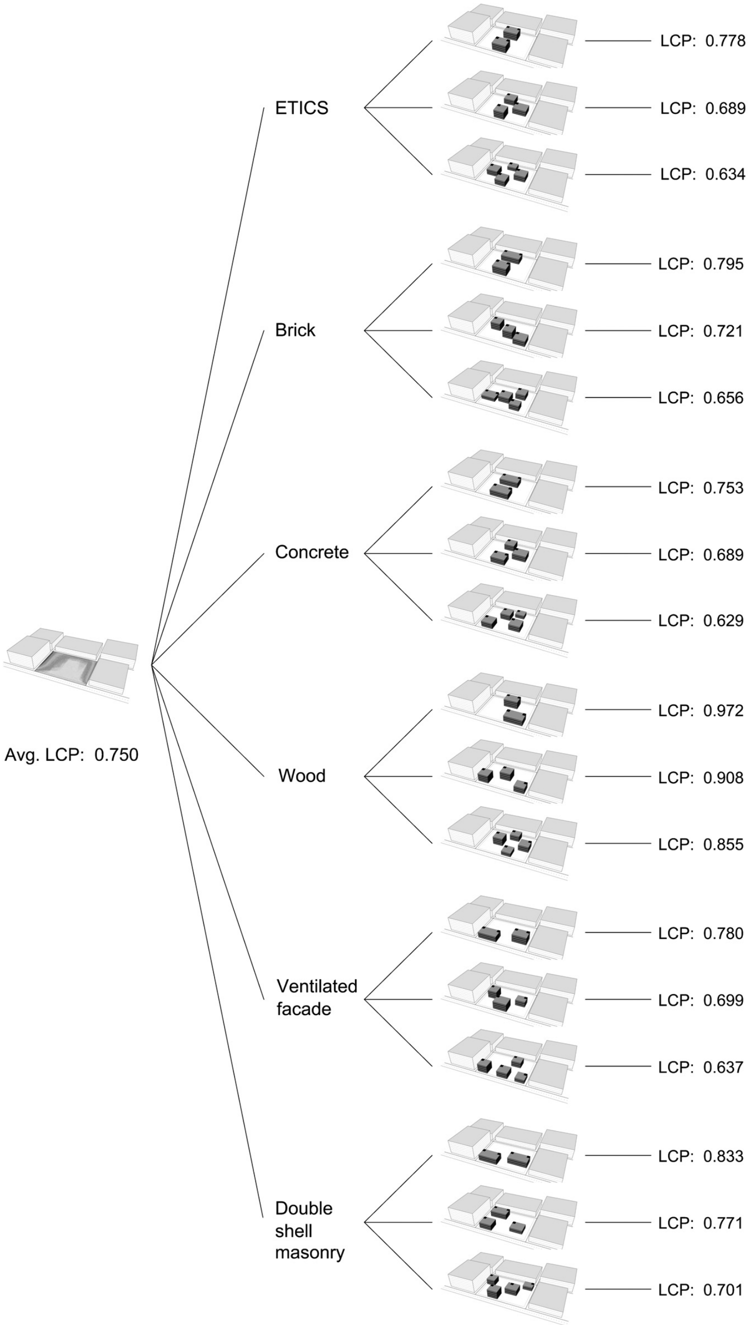

Fig. 9. MD process with sequence 3

from the previous stage. This corresponds to one design solution per building configuration. In total, 18 design solutions are generated for sequence 3. The outcomes of sequence 3 can be regarded in MD tree 3 (Fig. 9).

Both sequences differ significantly in the computation time they required to generate all design solutions. This can be explained by the number of optimizations they include. Sequence 3 has double the number of optimizations in comparison to sequence 2.

Table 2 displays the evaluation values of sequence 2 and sequence 3. Comparing the average LCP values of both sequences, it can be noted that sequence 3 delivers a higher value than sequence 2. Furthermore, the average building distance in sequence 3 is more than a double in comparison to sequence 2. This can be regarded in relation to the average solar radiation on the façades which accordingly, is higher in sequence 3 than in sequence 2. The building volumes in both sequences are of the same compactness.

4 Discussion

The comparison of sequence 1 and sequence 2 shows that both deliver different performances and geometries. As the LCP is the main focus of the comparison, it is crucial to explore the reasons for the difference in the results. Sequence 1 provides a better average LCP than sequence 2 which does not match with the expectations of the authors to create better performing design solutions by combining two design stages in one. In order to investigate the reasons for this discrepancy, it is necessary to take a closer look at the geometry evaluation values. As the average S/V of both sequences is nearly identical, it can be assumed that the solar radiation on the façades is the reason for the difference. The average solar radiation of sequence 1 is higher than that of sequence 2. Regarding these values in conjunction with the building distances, a direct numeric relationship becomes apparent, i.e. the higher the building distance, the higher the solar radiation. By maintaining a high distance, the shading on the façades gets reduced, hence leading to higher solar radiation values. The reason for such a difference in the building distances are the fitness functions used in both sequences for optimization. In sequence 1, the building volumes and their positions on the site are optimized in the first stage by applying a fitness function which contains the S/V and the solar radiation. Both performance criteria are directly related to the aspects which are to be optimized. The S/V influences the formation of building shapes and volumes, whereas the solar radiation aims for a placement of buildings in high distances to minimize shading. This fitness function is based on fundamental knowledge of building forms. Same applies to the second optimization stage of sequence 1 where the average solar radiation is to be maximized by placing building cores in shaded areas. These two fitness functions of sequence 1 are established without further assumptions from the author's side. In contrast, the fitness function of sequence 2 additionally incorporates a hypothesis stated by the authors. According to the hypothesis, a shading factor is added to the fitness function which already involves the S/V and the solar radiation. Since the shading factor is the only difference between the first fitness in sequence 1 and the fitness in sequence 2, it is obvious that this must be the reason for the different average building distances. The EA aims to find core positions with the desired shading condition. It, therefore, places buildings in smaller distances to each other to increase shading in some areas and then position the cores in these shaded zones. However, the idea of the hypothesis does not match with the outcome because the created shaded areas are too big in relation to the area which can be covered by the cores. This causes even more shading than in sequence 1 and consequently lowers the LCP values. By adding the performance criteria in one fitness function after scaling them to the same numeric range, all of them have a similar value since no further weighting is involved. This means, the author's assumption is of similar significance as the S/V and the solar radiation to the LCP. After conducting the case study, it can be concluded that this weighting is not appropriate in regards to the overall goal to generate design solutions with maximal LCP. This outcome represents the difficulty that comes with fragmenting a design problem into design stages.

If the assessment method which is used for the final evaluation of the complete design (LCA) cannot be taken for optimization purposes in all stages of the MD process, other fitness functions need to be established. The design solutions are highly dependent on these as the case study has shown. Consequently, it is the planner's task to define appropriate fitness functions. An ideal fitness function should include all performance criteria relevant to the LCP which can be applied to the design variants in the selected design stage. Additionally, appropriate weighting that matches with the weighting in the final design assessment method should be assigned to the performance criteria. In regards to the example of the case study, that implies that the weighting of the three performance criteria in the fitness function of sequence 2 should be adjusted according to the impact each criterion has on the LCP. Since the shading factor was introduced by the authors but is not included in the LCP, it should be removed from this fitness function.

Another example for a problem that can occur when establishing fitness functions is the following: Performance criteria which are relevant to the LCP and can be applied to design variants at the selected stage are not included simply because the planner is either completely unaware of them, or he does not know how these might influence the LCP. Such a case is exemplified in the second fitness function of sequence 1 where the solar radiation is taken as the sole performance criterion for the core positioning optimization. A second criterion which is relevant but not included at this stage is the S/V. Since the building volumes are already formed in the first stage of sequence 1, it may seem that the S/V does not change anymore by positioning the building cores. However, in regards to the LCP calculation, it is of relevance. As previously explained, in the energy demand calculation, the volumes of the cores are excluded from the building volumes as they are not part of the heated building volume. Consequently, their position is relevant for the S/V. Two positions can be identified, the sides and the corners (see Fig. 10). Positioning a core at a corner creates a different surface area than positioning it at a side. The latter causes a bigger envelope area in comparison to the core located at the corner. This difference influences the energy demand, especially

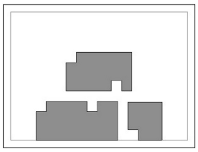

Fig. 10. Different positions of the circulation cores subtracted from the footprints

when a higher number of cores is involved. If the planner is not highly familiar with the way the LCP is calculated, he might miss out certain criteria in the fitness function as this example demonstrates.

Regarding the difficulties of establishing fitness functions described above, three main problems are shown in this first topic of the case study:

(1) The shading factor which is based on the author's hypothesis represents ideas planners may have in regards to design solutions, but do not exactly know how these might affect the LCP. By trying to incorporate such ideas, it is likely that the created fitness function is much more oriented towards the hypothesis than towards the LCP. That can lead to design solutions with worse LCP values as the case study shows.

(2) Even when the planner relies on fundamental knowledge to determine performance criteria, the problem of the weighting occurs. In order to assign weighting values, specific knowledge about the influence of different performance criteria on the LCP is required. This knowledge is highly dependent on the design problem and on the set of performance criteria involved. Therefore, high effort is necessary to determine weighting tailored to the LCP. The more components are involved in one design stage, the more complicated it becomes to define performance criteria and especially, their weighting in the fitness function.

(3) Furthermore, the planner should have high knowledge of the LCA method in order to incorporate relevant performance criteria and identify appropriate weighting factors. Therefore, the task of formulating fitness functions according to the LCP is difficult to incorporate for planners in practice, mostly due to very limited time for design exploration.

In regards to the research questions of the (1) part of the case study, it can be concluded that the fragmentation of a design problem into design stages affects the design solutions in multiple ways. Assigning design stages can lead to sequences which require fitness functions formulated by the planner. The problems he is most likely to experience with this task are described above. These problems can lead to worse LCP values as the case study shows. Furthermore, it can be noted that it is important to consider possible relationships between the design components before separating them into different stages. However, combining multiple design components in one stage where the LCP cannot be taken as the fitness function, can make establishing a fitness function very complicated. Therefore, the approach of separate design stages can be beneficial in terms of formulating fitness functions oriented towards the LCP.

In part (2) of the case study, both sequences differ in their LCP values. The reason for that lies in their fitness functions as these determine the optimization processes. Due to the stage order of sequence 2, the optimization processes are conducted in stage one. In stage two, their outcomes are combined with different construction types. The LCP can only be calculated after the last design stage of this MD process. Consequently, in order to calculate the LCP of a design variant from stage one, it needs to be paired with a construction type. Therefore, the planner needs to assign a fitness function which does not contain the LCP, but is highly oriented towards the LCP. Formulating such a fitness function is a task of high complexity if multiple performance criteria have to be involved in the function. The two main difficulties in this process are identifying performance criteria which are relevant to the LCP plus can be applied at the selected design stage, and assigning their weighting according to the impact they have on the LCP. Establishing appropriate fitness functions requires specific knowledge of the design assessment method (LCA), the design components and the performance criteria. As the results of sequence 2 show, formulating fitness functions, especially if assumptions of the planner are involved, does not necessarily lead to satisfying design solutions in regards to the performance goal.

By changing design stages, the problem of formulating additional fitness functions can be avoided as demonstrated in sequence 3. Stage one of sequence 3 contains the six construction types. For each of them, three designs are optimized. In contrast to sequence 2, here the LCP can directly be used as the fitness function. That is possible because the optimizations are conducted in the last stage of the sequence where the construction types are already determined. This provides the necessary information for calculating the LCP. The most efficient way of finding design solutions according to a performance goal is to use the same design assessment method for optimization and for the final evaluation of the design solution. That is the reason why sequence 3 delivers better performing design solutions.

It can be concluded, that stage order in MD processes can significantly affect design solutions as the case study shows. As fitness functions determine the direction of the optimization process, their formulation is of major importance for the outcome. The establishment of fitness functions is highly dependent on the position of the stages where optimization is conducted in MD processes. If not all information for the LCP calculation is available at a stage, a fitness function which does not contain the LCP has to be established. Since that is a very complex task, especially if several performance criteria have to be involved, it is possible that this fitness function does not lead to satisfying design solutions in regards to the overall performance goal of the design. Using the assessment criterion for the final solutions as the fitness function for optimization is the most effective way of generating design solutions according to the performance goal, because no further fitness function has to be formulated by the planner. That ensures, that the optimization is directly oriented towards the performance goal and is not manipulated by other fitness functions. Furthermore, the case study shows that the strategy of following the level of detail from the least to the most detailed for assigning design stages to the design components is not necessarily the best way to generate design solutions with high performances.

5 Conclusion and Outlook

To investigate the impact of stage order on design solutions in MD processes, a case study was conducted by the authors. In this case study, multiple different sequences were applied for solution generation. The results were displayed in corresponding MD trees to enable a visual comparison of the design outcomes. Additional evaluation values were used to provide a numeric comparison of the design solutions in each individual sequence. By means of this workflow, theoretical knowledge of the MD process was gained. It is worth mentioning, that all statements concerning the research questions are made solely based on this case study and do not claim general validity for all design scenarios. It is possible, that other examples of architectural design problems deliver different results in regards to the posed research questions. In regards to all findings of the case study, it can be concluded that defining an appropriate sequence for the MD process is highly dependent on the individual design problem. The sequence needs to be tailored towards the performance goal while considering all components and their relationships. It is important to consider possible relationships between the design components before separating them into different stages to avoid neglection of possibly better performing compromise solutions.

Consequently, in an ideal scenario, all components would be optimized in one stage. That may be an effective sequence for small design problems which involve a very small number of parameters. However, that does not apply to design problems with a higher number of parameters. The reason for that is the variant space which expands with each added parameter which decreases the chance of finding satisfying design solutions in a reasonable timeframe. Therefore, it can be stated that compromises have to be made between the number of stages in a sequence and the size of the variant space of each stage. Conducting optimization in the last stage of the sequence is beneficial because at this point, the performance goal can be selected as the fitness function. In this way, the optimization is directly oriented towards the performance goal which is most efficient for finding design solutions according to this goal. Additionally, the stage order may induce the need of formulating fitness functions which do not contain the performance goal as a performance criterion, but aim for optimization oriented towards it. If the design problem is very complex, case studies may be needed in order to investigate how design components affect each other and what impact they have on the performance goal. The lack of such knowledge can lead to worse design solutions. However, in practice, deadlines are short and designers cannot afford to undertake research for each design problem. This makes the investigation of fundamental aspects of MD processes such as the sequence an important task to provide basic guidelines which ideally, are applicable to many design problems.

Another approach for further studies can be a higher level of detail in the design that comes with a higher number of components. Furthermore, studies of exploring how the LCP can be influenced by certain building components may be helpful for developing a better understanding of the weighting factor. Further research on MD processes is highly recommended by the authors in order to provide the necessary knowledge for a computational application of the MD process. For the implementation in practice especially, further recommendations for assigning design stages and formulating fitness functions would be beneficial to planners who use the MD process for solution space exploration.

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