The Evolutionary Adaptation of Urban Tissues through Computational Analysis

Mohammed Makki[1], Ali Farzaneh[2], Diego Navarro[3]
[1,2]Architectural Association [3]Universitat Internacional de Catalunya
[1,2]{mohammed.makki|ali.farzaneh}@aaschool.ac.uk
[3]navarro@uic.es

The use of evolutionary solvers in design has introduced the potential of dealing with multiple conflicting objectives under a single design model. The experiments presented in this paper employ an evolutionary solver towards the generation of a 4x4 urban superblock in the city of Barcelona, one of the highest population density cities in Europe. The superblock is based on Cerda's iconic 8-sided block and takes three conflicting objectives into account, aiming not only to achieve a high density proposal but one that considers block relations, as well as green space throughout the city. The design is based on principles of evolutionary science, generating a population of solutions, whose individuals are ranked and selected based on a fitness criteria. Rather than aiming to reach a single 'optimal' solution, the model produces a population of solutions that are optimized in relation to the design environment.

Keywords: *Evolution, Computation, Algorithms, Biology*

INTRODUCTION:

Evolutionary algorithms have been used extensively in recent years to solve real world problems through a 'search and optimization' procedure. The algorithm, which is based on principles of evolutionary science, searches through a set of solutions and selects the fittest based on a preferred design criteria. The use of evolutionary algorithms can be found in various disciplines from economics to politics to music and even architecture. While the applicability of evolutionary algorithms has been common in solving single objective problems, they have proven to be an efficient problem solving technique for multiple objective problems as well, finding trade-off solutions for problems that possess multiple 'fitness criteria' that are commonly in conflict with one another.

Within the field of architecture and design, the emergence of several CAD-based evolutionary solvers has increased the utilization of evolutionary computation as a design strategy; a development that has bridged the gap between the domains of biology, computer science and the field of architecture and design. Although the former domains may seem unrelated to many within the field of design (considering their complexity and rich history), the evolutionary solvers developed have attempted to translate the algorithmic computation of natural evolution through a relatively user friendly environment.

An efficient implementation of evolutionary tools within a CAD-based environment is facilitated with a practical understanding of the underlying algorithms that drive the solver, as well as a clear explanation of the evolutionary principles implemented within the algorithm - both of which are clearly lacking in the domain of architecture and design. As such, the application of the evolutionary solver as well as a description of its underlying principles will be expanded upon in the experiments presented within this paper. The evolutionary solver - Octopus 3D, is utilized to develop an urban patch in the city of Barcelona; a design problem that consists of multiple conflicting objectives whose solution cannot be considered to be a single optimal solution, rather a set of optimal solutions that take into account all of the objective criteria without the need to employ a trade-off strategy to arrive at a given solution set.

A brief account of Barcelona's urban growth and its current implications on the population residing within will be explained, as they play a pivotal role in defining the objectives that drive the experiments. In addition, a brief summary of the developments in the field of evolutionary computation will also be engaged, as its key principles play a significant role in providing the proper foundation for an understanding of the methods employed by the evolutionary solver.

BARCELONA
Urban Growth
The city of Barcelona's development into one of the highest population density cities in Europe has been propelled in part by the Example (2). The Eixample (figure 1) is an urban plan proposed by Ildefons Cerda that addressed issues of population growth, building density, unsanitary conditions, illnesses and high mortality rates that had inflicted the city of Barcelona during the 19th century, necessitating an expansion of the city beyond its walls.

Cerda's plan for the city engaged three primary domains:

- Sanitation (Cerda, 1856) - Addressed through a predominantly statistical-driven approach (Figuerola, 1849) that was the result of an in depth field analysis of Barcelona as well as other prominent cities (Boston, Buenos Aires, New York, etc.), the consideration of block orientation, climatology and sun exposure were considered to be decisive in developing a sanitary urban expansion.
- Circulation (Cerda, 1863) - A hierarchical street network aimed to create efficient transportation throughout the city to accommodate both pedestrians and vehicles within the same network while generating greater efficiency in visual connectivity through the implementation of chamfered intersections (figure 2).
- Social Equality - The design attempted to generate the possibility of an 'endless' urban expansion of the city, establishing social equality through urban homogeneity.

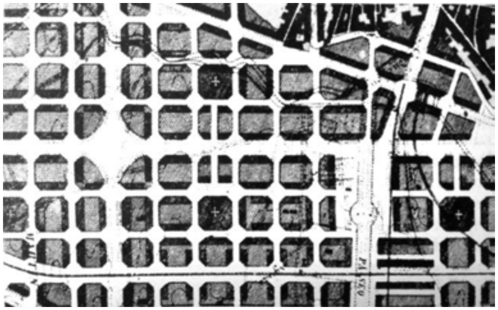

Figure 1
Fragment of Cerdá Plan, block types and orientations. (5)

Figure 2
Hierarchy of street network and green vs built area occupation. (6)

The Existing Setting

During its implementation, the lack of infrastructure and its remoteness from the city center resulted in several alterations to Cerda's original plan, mainly in the form of increased density within the Eixample's iconic eight sided block. Rather than conforming to the original plan which attempted to maintain a high percentage of open spaces and visual connectivity throughout the city (Busquets, 2004) (which intended to avoid a repeat of the unsanitary conditions that inflicted the walled city), political and investment opportunities transformed the original two sided block with an open courtyard, to a four sided block with an enclosed courtyard (3). More recently however, the 'internal courtyard' has been rendered obsolete as it has been reclaimed by the city as a storage facility (figure 3). Currently, the green-area/inhabitant ratio in Barcelona is 6.5m2, compared to the 15m2 green-area/inhabitant ratio recommended by the World Health Organization (1).

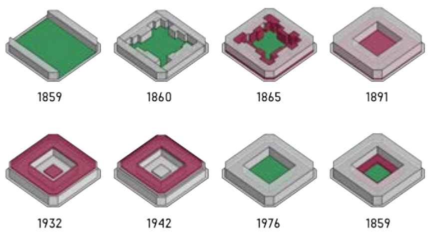

Figure 3
Development of a typical block in the Eixample.

As a result of the modifications to Cerda's original plan, the city of Barcelona has been in a continuous state of change and adaptation in an attempt to address diverse issues that have challenged the quality of life within the city. Most prominently, the city's relationship to its geography (sierra Cornella, riu Besos, riu Llobregat) the hierarchical and relational changes in specific areas such as Barcelona's future center (Les Glories) and the restructuring of the Eixample - which is engaged in this article - have been the driving factors of change within the city.

In an attempt to restore Cerda's intent of a city that encompasses sustainable mobility, public space rehabilitation, biodiversity and green areas, accessibility, social cohesion and energetic self-sufficiency, the city has followed a strategy of restructuring the superblock (a unit smaller than a neighborhood but larger than a block) in an attempt to create relationships between different blocks as well as between the block and the street (4). However, due to the existing density of Barcelona, attempts at restructuring the Eixample are notably constrained to minor changes to the existing urban condition. Thus, rather than attempt to restructure the existing city, the experiments carried out in the following chapters apply an evolutionary design strategy to generate an urban patch that incorporate Cerda's original design objectives as well as take into account Barcelona's current population density.

THE EVOLUTIONARY STRATEGY

The experiments in the following chapter employ an evolutionary solver as the underlying principle for the design process. By the mid 20-th century, several computational evolutionary models had been developed, the most prominent of these algorithms were Rechenberg and Schwefel's 'evolutionary strategies', Fogel's 'evolutionary programing' and Holland's 'genetic algorithm' (De Jong, 2006). Although each of these models had been developed almost independent from one another, the establishment of several evolutionary algorithm conferences in the 1990's resulted in highly beneficial interactions between the domains of evolutionary computation. De Jong (2006) clarifies that "the result of these first interactions was a better understanding of the similarities and differences of the various paradigms, a broadening of the perspectives of the various viewpoints, and a feeling that, in order to continue to develop, the field as a whole needed to adopt a unified view of these evolutionary problem solvers". Figure 4 illustrates the basic principles associated with evolutionary algorithms.

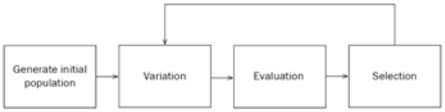

Figure 4
The principal flow of evolutionary algorithms

The 'integration' of different evolutionary paradigms, as well as the challenge associated with finding a solution to multiple conflicting objectives, led to an upsurge in different evolutionary algorithms. Each employed a different evolutionary strategy driven by a different interpretation of evolutionary principles with the ultimate objective of achieving the most optimal solution-set to a problem in an efficient timeframe. However, the two basic evolutionary principles of selection and variation remain the main driving force behind most evolutionary algorithms. Zitzler (1999) explains that:

"In evolutionary algorithms, natural selection is simulated by a stochastic selection process. Each solution is given a chance to reproduce a certain number of times, dependent on their quality. Thereby, quality is assessed by evaluating the individuals and assigning them scalar fitness values. The other principle, variation, imitates natural capability of creating "new" living beings by means of recombination and mutation."

The progression of different evolutionary strategies over the past few decades has revolved around the efficiency of an algorithm to apply these two basic principles in order to achieve the two most fundamental objectives of multi-objective optimization (Zitzler, 1999):

- Application of the most efficient assessment and selection methods to achieve the optimal set of trade-off solutions - the Pareto optimal set.
- Maintain a diverse population throughout the simulation run in order to diminish the probability of premature convergence as well as maintain a dispersed Pareto optimal set.

Thus, the methods by which different evolutionary strategies apply the principles of selection and variation are notably diverse in different evolutionary algorithms. However, the most progressive evolutionary algorithms (e.g. NSGA-2, SPEA-2) excelled through their ability to achieve the most diverse Pareto optimal set in both an efficient timeframe as well as a reasonable computational environment (Luke, 2014). As such, the algorithm associated with Octopus 3D is the Strength Pareto Evolutionary Algorithm 2 (SPEA-2) (figure 5).

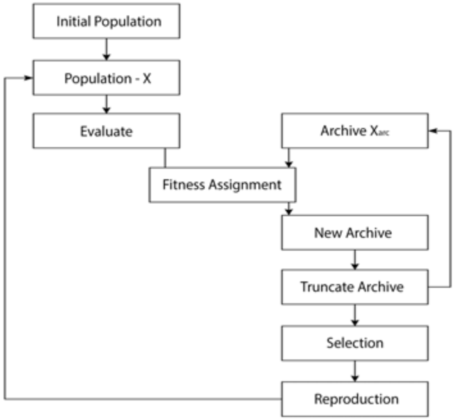

Figure 5
SPEA2 Algorithm - to increase the efficiency of reaching a diverse optimal set, algorithms incorporated different techniques and variations to the basic interpretation of the principles of natural evolution. The evolutionary solver employed in the experiment implements the algorithmic flow above. (Reproduced from Weise, 2008)

THE EVOLUTIONARY STRATEGY FOR BARCELONA

Cerda's initial plans attempted to provide a solution to a problem with multiple conflicting criteria (some of which were implemented at a later date). The primary conflicting criteria during the implementation of Cerda's plan was the requirement for the city to accommodate a high density ratio yet maintain a high number of street-accessible green spaces. However, rather than generate a solution that accommodated both criteria, a trade-off strategy directed the city towards one that prioritized population density over green spaces.

Although unknown at the time, Barcelona was following a preference-based approach that found it necessary to "convert the task of finding multiple trade-off solutions in a multi-objective optimization (problem) to one of finding a single solution of a transformed single-objective optimization problem" (Deb, 2001, p.7). The use of evolutionary population based solvers empowers the possibility to modify, evaluate and select a set of candidate solutions per each iteration, rather than a single optimal solution. Such a process allows all objectives to be considered without the requisite of employing a trade-off strategy during the simulation.

Terminology

As the biological paradigm may be perceived as foreign to many designers, a brief description of the terminology interpreted within the Octopus 3D solver is crucial for a comprehensive understanding of the experiment (table 1).

Experiment

Experiment Setup. Considering the multiple objectives and goals aimed by Cerda's original plan, the experiment objectives set out to generate an urban patch that optimizes for a high population density, greater block connectivity and a high courtyard area/density ratio. The primary element of the experiment is Eixample's iconic 8-sided block; however, to ensure greater homogeneity between neighboring blocks, the phenotype is comprised from a 4x4 superblock of 16 individuals. Each block within the phenotype is governed by a gene pool of parameters that transform the block's morphology through changes to the number of units within the block, the size of the ground floor area, the size of both the main block courtyard as well as inner unit courtyards, the number of floors within each unit of the block and the number of sides that comprise the block (table 2).

The density factor, connectivity factor (figure 6) and courtyard area/density ratio serve as the fitness criteria by which each phenotype is evaluated and assigned a fitness value. However, contrary to classical search and optimization methods, where all objectives are merged as a single objective to generate a single solution, within a population-based evolutionary solver every individual is evaluated to each fitness criterion independent of the other criteria.

Table 1
Definition of terminology within the evolutionary solver. The definitions correspond to their relevance within the CAD software and therefore are not to be interpreted as the biological definitions of the terminology.

Term	Description
Generations	*The number of iterations per simulation run.*
Population	*The number of individuals per generation.*
Phenotype	*The geometry onto which the simulation will run.*
Gene	*Single parameter that controls the intensity by which the phenotype is modified.*
Fitness Criteria	*The criteria by which the phenotype will be evaluated and selected.*
Mutation	*Random modifications to the gene pool.*
Mutation Rate	*The intensity of mutation.*
Mutation Prob.	*The probability of a gene to be mutated.*
Crossover	*Exchange of genes of different phenotypes.*
Elitism	*The number of dominant solutions selected to generate the next population.*
Pareto Front	*The most optimal solutions in the population.*

Therefore, it is plausible that the Pareto optimal solutions comprise individuals that achieve a high fitness value in relation to one criterion, while attaining a low fitness value in relation to another criterion, resulting in "multiple optimal solutions in its final population"(Deb, 2001, p.8) (figure 7).

Table 2
Summary of the experiment set up.

Goal	*Generate an urban patch that addresses Barcelona's current population density yet maintains Cerda's original goals of incorporating more green space within the city and a greater homogeneity between the blocks that comprise the urban fabric.*
Objectives	• *High population density* • *Greater block connectivity* • *High courtyard area / density ratio*
Phenotype	*4x4 superblock of 16 individual blocks*
Gene Pool	• *Number of building units within the block* • *Size of ground floor area* • *Size of main block courtyard* • *Size of inner unit courtyards* • *Number of floors per unit* • *Number of sides per block*
Fitness Criteria	• *Density factor* • *Connectivity factor* • *Courtyard / density ratio*

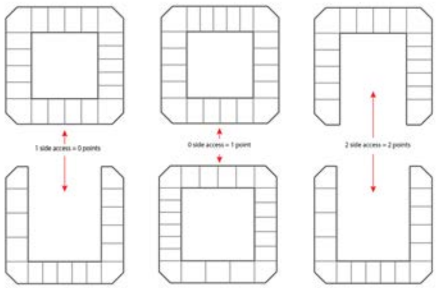

Figure 6
Courtyard connectivity is ranked to encourage larger courtyards between blocks and generate wide fields of view. A low ranking discourages blocks that have courtyards with one-sided access.

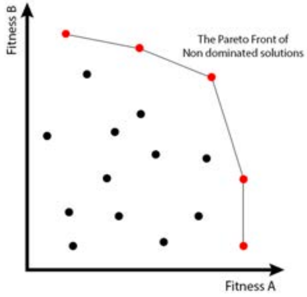

Figure 7
Every individual within a population is ranked according to the number of individuals that dominate it. In the diagram above, the Pareto front solutions are not dominated by any other individuals therefore they are considered as the optimal solutions within the population. (Reproduced from Luke, 2014).

Solver Parameters. Although the algorithm mimics natural evolution by incorporating variation and selection strategies to evolve the population towards an optimal solution set, the intensity of their application is also essential in generating a diverse solution set within an efficient timeframe. Ideally, the algorithm setup should balance a search and optimization strategy that is both explorative - adequate mutation and crossover to allow for a diverse population of candidate solutions, as well as exploitative - employ an efficient selection and variation strategy that directs the algorithm towards an optimal solution set within a feasible number of generations (Luke, 2014).

To achieve the 'ideal' balance between exploration vs. exploitation, the population is limited to 100 individuals, while the simulation target is set to 100 generations. At every iteration of the simulation run, the 100 individuals are evaluated according to the fitness criteria (stated above) and prescribed a fitness value. To evolve the population towards one that is both diverse as well as optimal, an elitism value of 50% is implemented which ensures half the population is bred from the most optimal solutions while the other half is randomly bred from the remaining solution candidates. Finally, a high mutation rate coupled with a low mutation probability, complimented with a moderate crossover rate ensures adequate variation is applied to the individuals in the population to generate diversity while simultaneously evolving the population towards 'fitter' individuals (table 3).

Experiment Results

Unlike a single-objective design experiment, the evolutionary solver does not tend to converge towards a single optimal solution, rather it aims at evolving multiple optimal solutions driven by multiple objectives. The conflicting objectives defined in the experiment led to significant geometric variety in the Pareto solution set within each population, however, objectives that did not conflict evolved individuals that shared similar geometric traits (figures 8a-c). The variety of phenotypes throughout the simulation reflected an appropriate balance of exploration vs. exploitation within the algorithm, thus reducing the probability of premature convergence of the population towards a local optimum (figure 8d).

Throughout the experiment, four different generations were selected for analysis and comparison: generations 1, 30, 60 and 100. The application of an evolutionary solver as a design strategy generates an exponential number of design solutions within each iteration, making it inefficient and unnecessary to visually analyze each individual in the simulation (in the case of this experiment, a total of 10,000 solutions) (figure 9). Thus statistical analysis of the generated solutions plays a pivotal role in the selection and modification of the optimal solutions. A comparison of the results of each generation stated above proved higher fitness factors of population density, greater courtyard relationships and higher courtyard area/density ratios (which in turn translates to larger courtyard areas). The results presented a noticeable uniform increase in the average fitness per population throughout the simulation (figure 10).

Parameter	Intensity
Population Size	*100*
Generation Size	*100*
Elitism	*50%*
Mutation Probability	*10%*
Mutation Rate	*80%*
Crossover Rate	*60%*

Table 3
Summary of the solver parameters implemented in the simulation

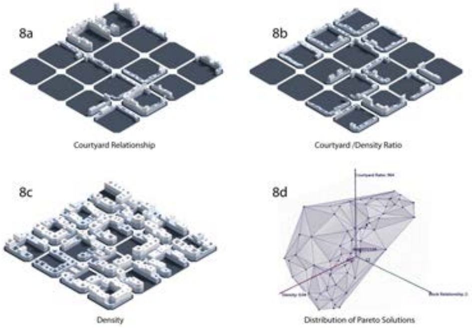

Figure 8
Pareto front individuals ranking high in each fitness criterion. The similarity between 8a and 8b is a result of the objectives complimenting each other, while the geometric differences to 8c is a result of the objectives conflicting one another. The distribution of the Pareto front solutions presented in 8d reflects the variety of different optimal solutions within a single population.

Eixample, Cerda and the Pareto Front

The experiment aimed to generate an urban tissue that exhibited high density ratios while simultaneously increasing green space areas and promoting greater courtyard relationships. Thus, a comprehensive analysis of the results require the comparison of several Pareto front superblocks from the final generation of the simulation to an existing Eixample superblock in Barcelona, as well as a comparisson to the proposed Eixample superblock put forward by Ildefons Cerda (table 4). The solutions were selected according to a balanced fitness value that accommodated the three objectives of the algorithm (figure 11).

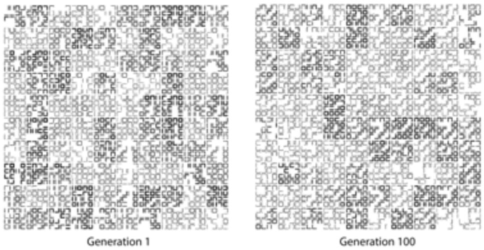

Figure 9
Visual comparison of all individuals from different generations is an almost impossible task. General patterns may be observed, however an efficient examination of the solutions must incorporate statistical methods of analysis.

The Pareto solutions selected could not achieve the density of the existing Eixample superblock without sacrificing the fitness values of the other criteria, as was the case for the courtyard areas of Cerda's proposed Eixample. However, all of the Pareto individuals selected achieved a larger population density compared to Cerda's proposal, as well as greater courtyard relationships and larger courtyard areas when compared to the existing Eixample superblock. The Pareto individuals provided a largely successful and diverse set of solutions, each excelling in a different criterion, equipping the designer with the choice of selecting the solution (or solutions) that best fit the design objectives.

CONCLUSION

Back, Hammel and Shwefel (1997) argue that "the most significant advantage of using evolutionary search lies in the gain of flexibility and adaptability to the task at hand", and while the optimal solution for a single objective problem is clearly defined, multiple objective problems require the "robust and powerful search mechanisms" (p.13, Zitzler, 1999) of evolutionary algorithms to find the fittest solution candidates that take into consideration all of the assigned objectives. The experiments proved successful by breeding a diverse set of individuals across generations that continued to perform better towards their fitness criteria. While the experiment did not provide a single optimized solution, something that is often sought after in design, it did respond to the multiple design objectives of the design model, providing a diverse set of optimal solutions.

The computational environment plays a significant role in the application of an evolutionary model as a design strategy. The experiments carried out were limited to 100 individuals and 100 generations, a limit imposed by the computational load and time required to carry out the experiments. However, a larger population and generation count would generate greater diversity as well as allow more optimization of the fitness criteria.

While the field of evolutionary science has continued to develop and progress, the field of evolutionary computation has been stagnant on Darwinian principles synthesized in the mid-20th century. Significant advancements in the fields of genetics, and more prominently, evolutionary devel-

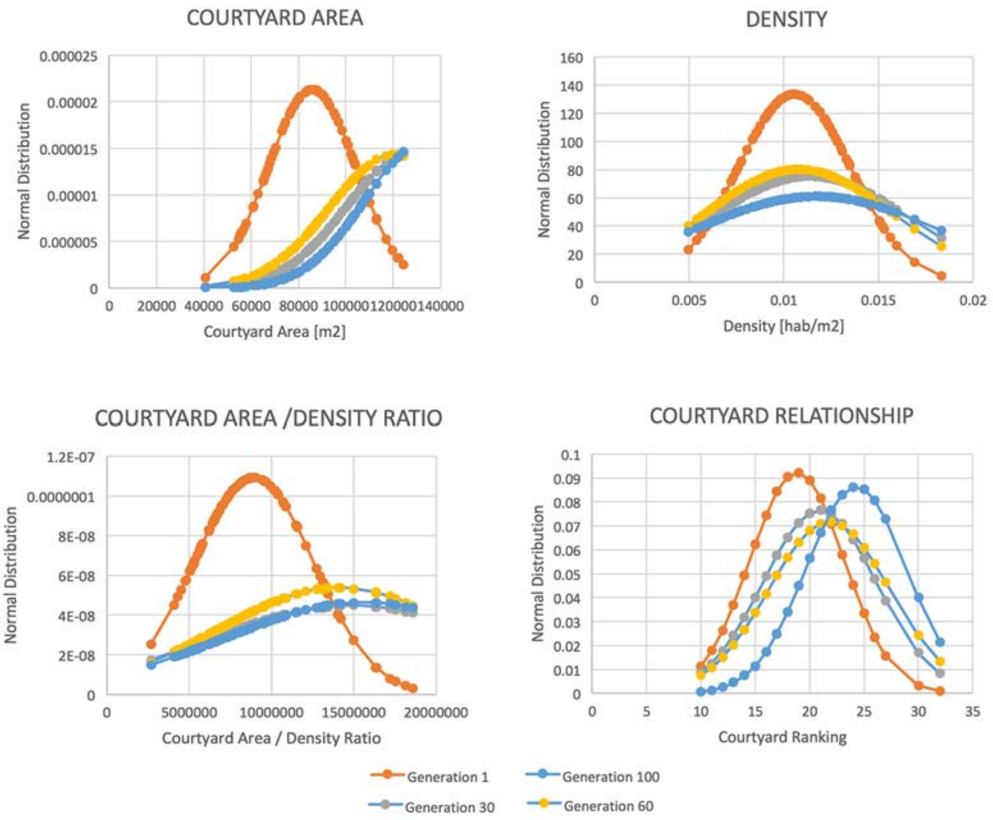

Figure 10
Comparison of the objective fitness values of different generations. The results present an almost uniform increase in fitness for all objectives between generation 0 and generation 100

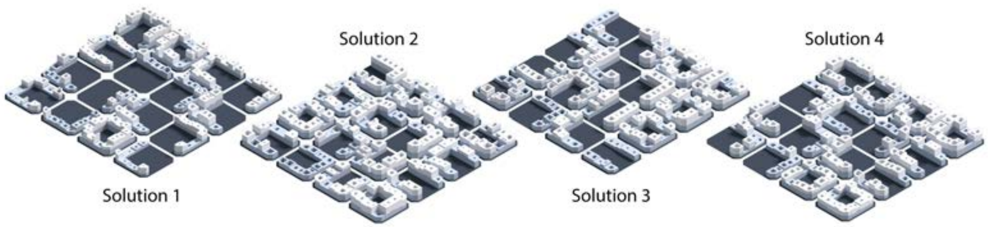

Figure 11
Four Pareto solutions selected from generation 100 that exhibited balanced fitness values in relation to all objectives.

Table 4
Fitness comparison between four Pareto solutions from generation 100 to a typical Eixample block and the Eixamle block proposed by Cerda. Factor values are not indicative of actual figures, the factor values presented in the table are remapped to a domain between 0 and 1, where 0 is the smallest possible fitness factor and 1 is the largest possible fitness factor.

Criteria	*Existing Eixample*	*Cerda Plan*	*Solution 1*	*Solution 2*	*Solution 3*	*Solution 4*
Density	*0.88*	*0.3*	*0.37*	*0.67*	*0.51*	*0.49*
Courtyard Connectivity	*0.5*	*0.6*	*0.69*	*0.52*	*0.60*	*0.56*
Courtyard Area	*0.21*	*0.47*	*0.38*	*0.32*	*0.39*	*0.40*

opment have reformulated evolutionary principles, however, they are yet to be incorporated within evolutionary algorithms. Preliminary experiments carried out by the authors incorporating key concepts of evolutionary development as a design strategy have yielded successful results in generating a significantly diverse population of solutions within a shorter timeframe. However, a thorough application of modern evolutionary principles within the field of evolutionary computation is yet to be achieved.

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