International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:6, No:7, 2012

Evolutionary Multi-objective Optimization for Positioning of Residential Houses

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Abstract—The current study describes a multi-objective optimization technique for positioning of houses in a residential neighborhood. The main task is the placement of residential houses in a favorable configuration satisfying a number of objectives. Solving the house layout problem is a challenging task. It requires an iterative approach to satisfy design requirements (e.g. energy efficiency, skyview, daylight, roads network, visual privacy, and clear access to favorite views). These design requirements vary from one project to another based on location and client preferences. In the Gulf region, the most important socio-cultural factor is the visual privacy in indoor space. Hence, most of the residential houses in this region are surrounded by high fences to provide privacy, which has a direct impact on other requirements (e.g. daylight and direction to favorite views). This investigation introduces a novel technique to optimally locate and orient residential buildings to satisfy a set of design requirements. The developed technique explores the search space for possible solutions. This study considers two dimensional house planning problems. However, it can be extended to solve three dimensional cases.

Keywords—Evolutionary optimization, Houses planning, Urban modeling, Daylight, Visual Privacy, Residential compounds.

I. INTRODUCTION

HOUSES layout problem aims on placing the clusters of dwellings in a defined area of land in such way that achieve design requirements. The houses layout planning is a complex architectural design problem. It comprises a large variety of factors (e.g. sustainability, aesthetics, and visual privacy). Planners face challenges to satisfy all these factors especially in the lack of an automated approach. The planning process mainly depends on planners' experience and common sense. The project manager or planner usually performs the task of preparing thelayout based on his/her own knowledge and expertise. Apparently, this could result in layouts that differ significantly from one person to another. To put this task into more perspective, researchers have introduced different approaches to systematically plan the layout of construction sites [1], [2], [3]. These approaches differ from one another in the level of detail they provide. Some of these approaches [1], [2] focused on arranging a set of predetermined facilities (e.g. warehouses, job offices, and various workshops) on a set of predetermined sites. Also a previous investigation [4], presented an integration between computer-aided design (CAD) platforms and optimization capabilities of genetic algorithms (GAs) to minimize the total transportation costs between facilities. Others [5], [6], presented multi-objective optimization models coupled with an energy simulation program to optimize building shape and building envelope features in green buildings. These models considered building envelope features in the optimization analysis including wall and roof constructions, insulation levels, and window types and areas. A Multi-objective-optimization was also utilized in a previous study [7] for the positioning of houses in a residential neighborhood. The main objective of this study was to place buildings in a favorable configuration constrained by two objectives, which are the performance of the garden in the south direction of each house and the visual privacy experienced for the south facade of a house. To the best of the authors' knowledge, the optimum building orientation and location, which affects the performance of a sustainable building is not investigated. In addition, all these previous approaches didn't provide a level of detailing to solve the problem of visual privacy between neighboring dwellings, which is considered as the utmost requirement in the Gulf Region.

In Gulf Cooperation Council (GCC) countries, which include the Kingdom of Saudi Arabia, nearly 80% of household electricity is used for air conditioning purposes [8]. Moreover, it is unfortunate to note that electricity generation in Saudi Arabia is completely dependent on the unsustainable practice of burning fossil fuels, which causes major environmental impacts on air, climate, water and land [9]. Given recent energy concerns, there has been a considerable interest in recent years with regard to the concept of sustainable architecture. This places an emphasis upon natural energy sources and systems with the aim of achieving building comfort through interactions between the dynamic conditions of the building's environment [10]. For example, the placement of a window in a sustainable building is of the greatest importance as it could provide effective natural light, comfort cooling and ventilation. On the other hand, such placement plays a major rule in the visual privacy of neighboring dwellings.

Historically, the issue of visual privacy for residents in indoor living space often had a decisive impact on the urban built form during the development of traditional settlements. Unfortunately, aesthetics, construction cost and new technology is usually highly considered in design on account of visual privacy. In fact, visual privacy is considered as a constraint restricting design. It is often left to clients to make modifications in the building already constructed to meet their visual privacy requirements.

Due to the improvement of economy in the Gulf region, several construction projects have been started. Many of these projects are directed towards another type of housing known

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as the compound. These compounds are varying in size from small clusters of dwellings to a population of a small town. The planning layout of these compounds needs to provide both sustainability and visual privacy as an important socio-cultural factor.

The main objective of the current study is to provide these factors by developing a numerical tool that is capable of selecting the set of design variables, which leads to the desired optimum site layout. This numerical tool integrates the object oriented features of MATLAB, and a genetic algorithm optimization technique built in-house. The outline of the remainder of this paper is as follows. In the next section, the problem is described in detail including a simple example showing how the authors got motivated to conduct the current research. This is followed by Section III, where the optimization technique and the assumptions included in the analysis are discussed. Section IV provides a detailed presentation and discussion of the results. Finally, in Section V, the main conclusions drawn from the study are presented.

II. PROBLEM DESCRIPTION AND RESEARCH MOTIVATION

In most large residential compounds that are newly constructed in Saudi Arabia, the main goal is to place the clusters of dwellings in a defined area of land in such way that provides maximum visual privacy for each settlement. In addition, due to the desert climate in this region, it is desired to locate most of the windows in the North direction to avoid intense solar radiations. Fig. 1(left) presents a simple sketch of a piece of land defined by a polygon L. Each building within this specified land is defined according to the location of its center and the in-plan orientation. These parameters are considered in the current study as the optimization design variables. To handle such type of problems, a mathematical model to express both visibility between neighboring settlements and direction to a favorite view has been developed. This model is described in detail in the following two subsections.

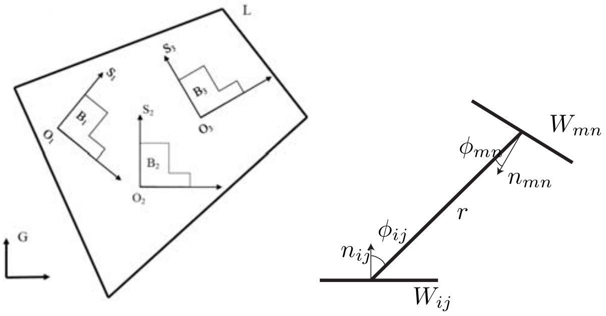

Fig. 1: Sketch of site layout (left), and Visibility between two windows (right)

A. Visibility

In order to provide visual privacy between neighboring houses, a certain visibility function V^p should be defined and included in the optimization objective function. This function can be modeled using the 2D form factor formulation [11]. As shown in Fig. 1(right), the visibility function $V^p_{W_{ij},W_{mn}}$ between two windows W_{ij} and W_{mn} can be defined by Eq.(1), where i, m and j, n represent the buildings and windows indices, respectively.

$$V^p_{W_{ij},W_{mn}} = \frac{\cos\phi_{ij}\cos\phi_{mn}}{2r} H_{ij,mn} \tag{1}$$

It should be noted in Eq.(1) that $H_{ij,mn} = 1$ if W_{ij} and W_{mn} are mutually visible and 0 otherwise.

The visual privacy $V^p_{W_{ij}}$ for a window W_{ij} is the summation of the visibility functions between W_{ij} and all neighboring windows W_{mn}

$$V^p_{W_{ij}} = \sum_m \sum_n V^p_{W_{ij},W_{mn}} \quad m \neq i \tag{2}$$

The visual privacy $V^p_{B_i}$ for a building B_i is the sum of $V^p_{W_{ij}}$ for all windows $W_{ij} \in B_i$.

$$V^p_{B_i} = \sum_j V^p_{W_{ij}} \tag{3}$$

Summing up over all buildings, one can get the overall visual privacy V^p as follows:

$$V^p = \sum_i V^p_{B_i} \tag{4}$$

Eq.(4) depends on a number of variables. These variables are utilized to specify the location and orientation of each building. The user has the flexibility to either fix the location of each building while introducing the orientation as the optimization design variable or to implement both location and orientation as the problem design variables. Such flexibility provides the user a chance to study the effect of each parameter and design variable on the change of the site layout.

B. Direction to a favorite view

A clear access to a favorite view is considered as one of the design and client preferences. During the initial stage of any site layout planning, the planner tries to arrange settlements such that facades are directed towards specific direction to avoid intense solar radiations or to maximize view to green areas, sea view, ...etc. Such a direction can be modeled by a specific vector d. The visibility function V^d to a favorite direction d can be easily calculated by evaluating the dot product of d and the perpendicular bisector vector n_{ij} of the window W_{ij}. The summation over all windows provides the overall visibility to the favorite direction as shown in Eq. 5

$$V^d = \sum_i \sum_j d \cdot n_{ij} \tag{5}$$

Weights can be introduced in the above equation in order to provide the user with design flexibility. In order to apply this concept in the proposed numerical tool, while taking into account both visual privacy and direction to a favorite view, a multi-objective-optimization is used. In this multi-objective function, specific weights for both visual privacy V^p and favorite direction V^d should be defined by the user. The user can easily change these weights based on design and client requirements. In Section IV, different examples with different weights are presented.

C. *Research motivation*

The current investigation is motivated by the idea of providing a technique to facilitate the planners' decision-making process for site layout planning problems. In such type of problems, comparisons between alternatives should be conducted to provide a reliable assessment result. As such, in order to direct the current research to what practitioners need, a feedback from experts on a simple problem is needed. A number of experienced planners with different years of planning experience have been selected to develop a site layout planning of a typical residential house as shown in Fig. 2.

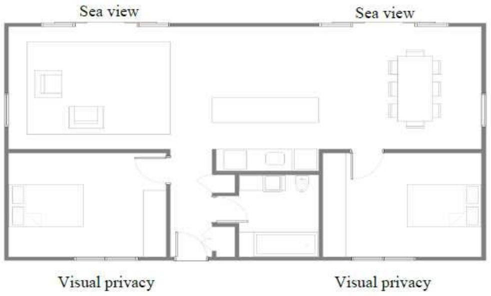

Fig. 2: Sketch plan of a typical residential house

They have been asked to provide a site layout of four typical units in a specific piece of land in order to achieve maximum visual privacy for bedrooms and maximum sea view for house facade. The area of the specified land was chosen such that the planners should face difficulties to achieve design requirements. Fig. 3 shows the best practical layout chosen from all layouts proposed by the experienced planners. It appears clearly from this layout that both visual privacy of bedrooms and direction of facade towards sea view are achieved.

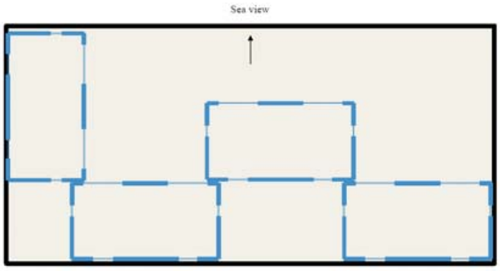

Fig. 3: Layout proposed by practitioners

By applying the proposed numerical tool to the same sample problem, an optimum solution is achieved as shown in Fig. 4 (left). It can be noticed that the optimum layout is close to what experienced planners proposed. However, visual privacy in one of the dwellings is violated because in this sample a constraint on the distance between dwellings is implemented in the numerical model in the form of a dynamic penalty function. By neglecting this constraint and resolving the same problem, the optimum solution yields to highly match the planner layout, as shown in Fig. 4 (right). Such results prove the applicability of the proposed technique especially at the initial site layout planning stage.

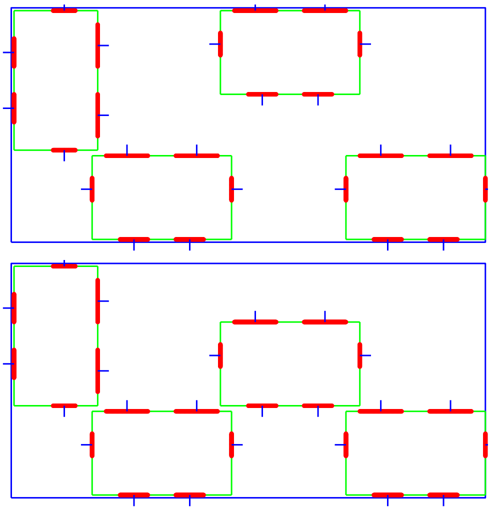

Fig. 4: Optimum solution with constraint (top) and without constraint(bottom)

III. OPTIMIZATION TECHNIQUE

Most optimization techniques available in the literature for solving general optimization problems could be classified into two groups known as *local* and *global* search techniques. Local optimization techniques are local minimize in nature because they begin the search procedure with a guess solution, which is often chosen randomly in the search space. The drawback of these techniques is that if the guess solution is not chosen close enough to the global minimum solution, the optimization technique will be trapped in a local minimum.

In the problem in hand, the estimation of the position of the guess solution is not an easy task. In addition, multiple optima are expected due to the intersection of the constraints with the objective function. As such, global search optimization techniques, like Genetic Algorithms (GAs) are found to be very promising global optimizers. Genetic Algorithms belong to a group of techniques which are generally described by the collective term evolutionary computation. The defining features of this group can be summarized in the following points:

- Their usage of a stochastic search process employing a population of solutions rather than one point at a time
- Their requirement for relatively little information about the nature of the problem being solved
- Their ability to avoid premature convergence on local optima
- Their ability to cope with constraints
- Their ability to cope with problems involving many objectives

In general, Genetic Algorithms are robust and applicable to a wide range of problems. However, one must always bear in mind the findings of Wolpert and MacReady [12] that there is no single algorithm that will perform well on all problems. In the current study, genetic algorithms are thought of as an optimization technique for their ability to explore a search space (the space of all possible solutions) rather than locating the best solution. For site layout planning problems, this is considered as a powerful feature, as rather than locating the best solution, the practitioner can find it useful to learn about the range of possibilities. In such circumstances, a single solution is undesirable and indeed, there is rarely a best solution to multi-objective problems because of the trade offs between the various objectives. Genetic algorithms are an excellent technique for helping designers to find areas within the search space that contain good solutions and additionally, the interaction between the designer and the algorithm can be highly beneficial [13].

In typical genetic algorithms, the design variables are encoded as strings of alphabets zero and one. The performance of binary (GAs) is found to be satisfactory only in case of small and moderate size problems requiring less precision in the solution, while for high dimensional problems, in which higher degree of precision is desired, binary (GAs) require huge computational time and memory [14]. To overcome these difficulties, a real coded genetic algorithm (RCGA), in which design variables are encoded as real numbers, is used as the optimization technique in the current study.

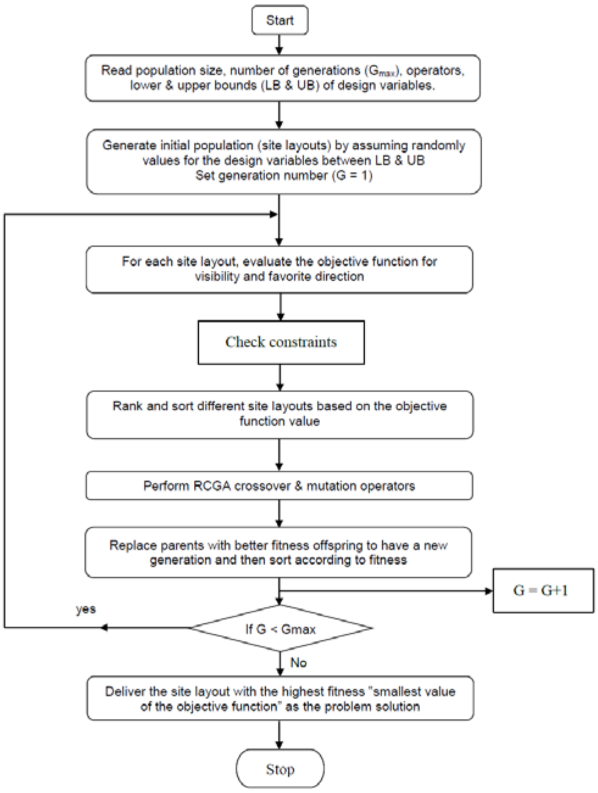

Fig. 5: Flow chart of the optimization technique

A. Genetic operators

In a simple genetic algorithm technique, genetic operators namely,"selection, crossover and mutation", should be applied, in order to reach the optimum solution. In the current investigation, the formulation of the initial population with a size of 100 candidates is based on a random selection of dwellings having different locations and orientations. Crossover and mutation operators are applied to selected pairs of dwellings in each population in order to generate new ones with better location and orientation with respect to privacy between neighboring dwellings and direction to a favorite view.

B. Constraints

Three constraints are considered in the analysis of the first case of optimization, where the objective function is set to minimize visibility between buildings. An additional fourth constraint is added in the second case, where the objective function is set to be a combination between minimizing visibility between buildings and maximizing direction to a favorite view. The constraints implemented in both cases can be summarized as follows:

1) Buildings should be located inside the borders of the land specified by the user.
2) Buildings should not intersect.
3) Distance between buildings should not be less than a minimum distance defined by the user according to design requirements.
4) Windows that are specified by the user to have a direction to a favorite view should not be blocked by other units (provide clear view to the specified windows).

In the proposed technique, the infeasible solutions are penalized by applying certain penalty functions that can be categorized into stationary penalty functions that use a fixed penalty value throughout the optimization process and non-stationary penalty functions, where the penalty values are dynamically modified. The first category is applied to the first two and the fourth constraint, while the second category is applied to the third constraint. The penalized objective function of the problem in hand is defined as follows:

$$f_{i_p}(B_i) = f_i(B_i) + \sum_{j=1}^{n} \phi_j \delta_j \tag{6}$$

where $\delta_j = 1$, if constraint j is violated, and $\delta_j = 0$, if constraint j is satisfied. In Eq.(6), n is the number of constraints implemented in the optimization process, i is the number of the introduced building from the population, $f_i(B_i)$ is the unpenalized objective function, $f_{i_p}(B_i)$ is the penalized objective function, and ϕ_j is a certain suitable constant imposed for violation of constraint j. The flow chart shown in Fig. 5 summarizes all optimization steps conducted in the current study in order to achieve an optimum site layout.

IV. RESULTS AND DISCUSSIONS

In this section, the results of the proposed optimization technique are presented. In order to provide more flexibility to the designer, a weighted multi-objective function f is used. This objective function is a linear combination between the visibility function V_p and the function V_d representing direction to a favorite view. The weights ω_p and ω_d vary between 0 and 1. These weights allow the designer to have a number of good feasible solutions to choose from.

$$f = \omega_p \, V_p + \omega_d \, V_d \tag{7}$$

Fig. 6 shows a sketch plan of a typical rectangular unit which is used to model the dwellings. This model has 4 windows A, B, C, and D. In reality, visual privacy in bedrooms are utmost while in living rooms direction to a favorite view is highly appreciated. This motivates the authors to assign higher weights for the favorite view to windows A and B (representing living rooms). On the other hand, windows C and D (representing bedrooms) have more weight for visual privacy.

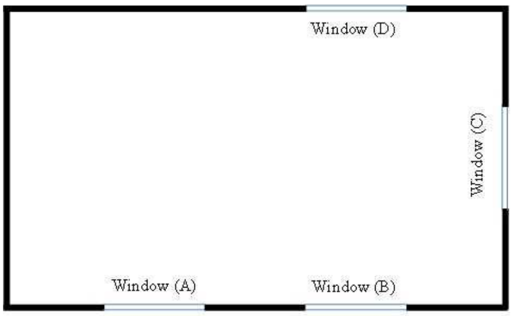

Fig. 6: Sketch plan of a typical unit

The layout shown in Fig. 7 represents one of the solutions that might be suggested by the site planner. The proposed layout provides equi-spaced dwellings distribution and a good road networking. However, this distribution doesn't guarantee minimum visibility between neighboring settlements. In order to assess this layout, the visual privacy has been calculated. Table 1 provides the visibility values of the proposed layout. It can be noticed that window C has a complete visual privacy (zero visibility) in all dwellings. On the other hand, building (5) shows the highest visibility value because of its central location.

In order to compare the layout proposed by the planner as shown above, analysis is conducted for two different cases. The first case considers visual privacy only, while a linear combination between visual privacy and direction to a favorite view is investigated in the second one.

A. Case (1)-visual privacy results

Analysis is conducted in this section based on visual privacy only (i.e. by setting $\omega_p = 1$ and $\omega_d = 0$ in Eq. 7). Figs. 8 and 9 show two possible layouts based on the proposed numerical tool. It can be noticed that both layouts provide visual privacy to most of the units.

Building	Visibility value of window				Total	Normalized
	A	B	C	D		
1	0.85	0.93	0.00	0.00	1.78	0.51
2	0.75	0.82	0.00	1.17	2.74	0.79
3	0.00	0.00	0.00	1.18	1.18	0.34
4	1.09	1.17	0.00	0.00	2.26	0.65
5	1.31	1.00	0.00	1.17	**3.48**	**1.00**
6	0.00	0.00	0.00	1.38	1.38	0.40
7	0.85	0.93	0.00	0.00	1.78	0.51
8	0.75	0.82	0.00	1.17	2.74	0.79
9	0.00	0.00	0.00	1.18	1.18	0.34

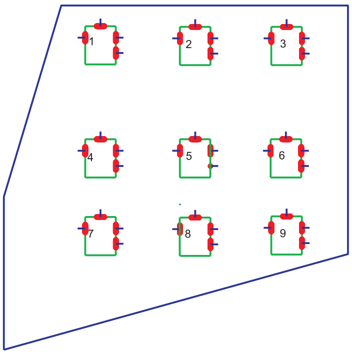

Fig. 7: Initial site layout (No optimization)

Building	Visibility value of window				Total	Normalized
	A	B	C	D		
1	0.00	0.00	0.00	0.95	0.95	0.54
2	0.00	0.00	0.00	0.49	0.49	0.28
3	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	1.00	1.00	0.57
5	0.00	0.00	0.24	0.23	0.47	0.27
6	0.34	0.38	0.00	0.00	0.72	0.41
7	0.00	0.00	0.00	0.00	0.00	0.00
8	0.59	0.46	0.00	0.70	**1.75**	**1.00**
9	0.38	0.35	0.00	0.00	0.73	0.42

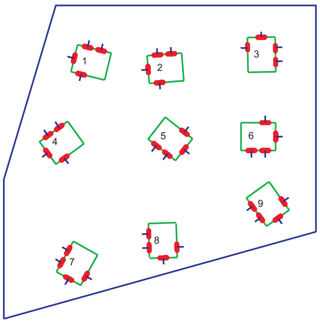

Fig. 8: Optimum solution based on visual privacy: layout(1)

In Fig. 8, the optimum layout provides the user with approximately equi-spaced dwellings. However, Fig. 9 presents another optimum configuration, which provides the architect with areas suitable for landscaping between buildings. As mentioned earlier, the ability of this technique in exploring the space of all possible solutions, gives the user a number of possibilities to choose from. For comparison purposes, the visibility is evaluated for each layout, where Tables 2 & 3 show the results of layout(1) and layout(2), respectively.

In addition, Fig. 10 shows a comparison between the initial layout, layout(1), and layout(2) based on the visibility value of each building in each layout. This figure shows that the layouts proposed by the numerical tool show less visibility values compared to the initial layout. Based on all reported results of this set, layout(2) represents the best layout from

Building	Visibility value of window				Total	Normalized
	A	B	C	D		
1	0.00	0.00	0.00	0.05	0.05	0.06
2	0.15	0.14	0.00	0.00	0.29	0.38
3	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.43	0.00	0.43	0.56
5	0.00	0.00	0.00	0.00	0.00	0.00
6	0.29	0.32	0.00	0.00	0.61	0.79
7	0.23	0.20	0.00	0.00	0.43	0.56
8	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.77	**0.77**	**1.00**

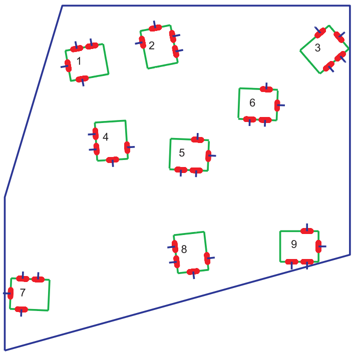

Fig. 9: Optimum solution based on visual privacy layout(2)

the perspective of visual privacy (minimum visibility between neighboring settlements).

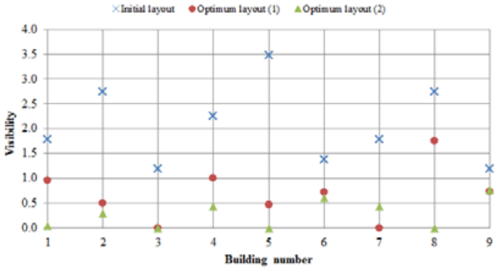

Fig. 10: Comparing results for case of visual privacy

B. *Case(2)-visual privacy and favorite view results*

In this case, a multi-objective function using the weighted sum method is used to achieve minimum visibility and maximum direction to a favorite view. For presentation purposes, only three cases are presented as a sample in order to assess the adequacy of the proposed technique. In the first case as shown in Fig. 11, less weight is assigned to visual privacy, where the constants ω_p and ω_d are assigned the values of 0.25 and 0.75, respectively.

Equal weights of 0.5 are assigned to the constants ω_p and ω_d in the second case as shown in Fig. 12. Finally, in the third case, more weight is assigned to visual privacy as presented in Fig. 13, where ω_p and ω_d are assigned the values of 0.75 and 0.25, respectively.

In the three cases, the favorite direction (e.g avoiding intense solar radiation or direction to sea view) is assumed to be the North direction.

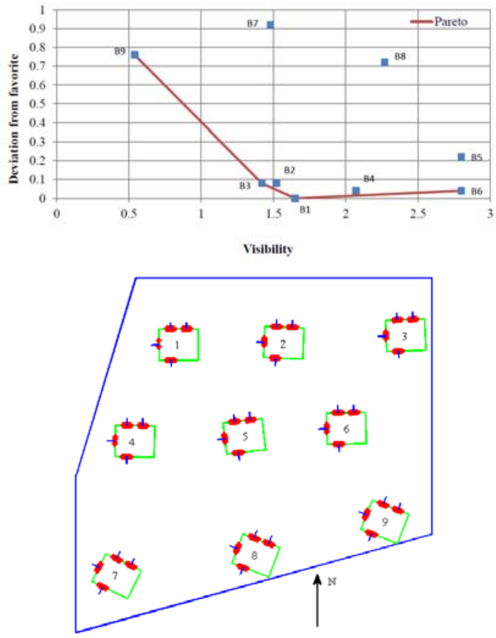

Fig. 11: Optimum layout based on $\omega_p = 0.25$ and $\omega_d = 0.75$

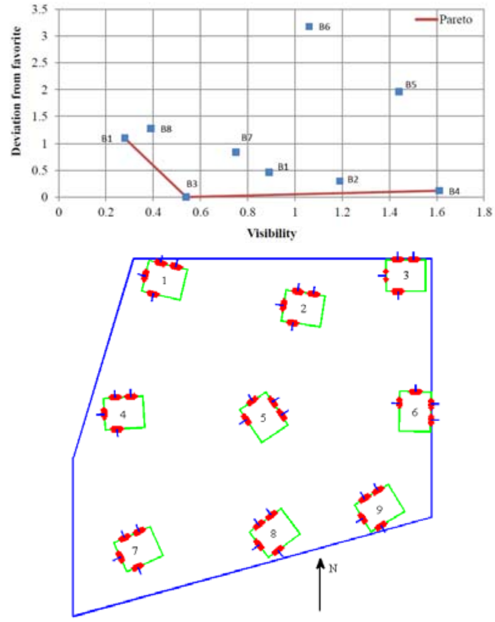

Fig. 12: Optimum layout based on $\omega_p = 0.5$ and $\omega_d = 0.5$

It can be noticed from the results, the effect of increasing the weight of the visual privacy on the change of the site layout. It appears clearly in Fig. 11 that the favorite direction is dominant over the visual privacy. In addition, all windows lying on the facade have a clear view (no obstacles) to the favorite direction. Fig. 12 provides a layout with higher degree of visual privacy on account of the direction to the favorite view. However, this layout is still acceptable as most of the

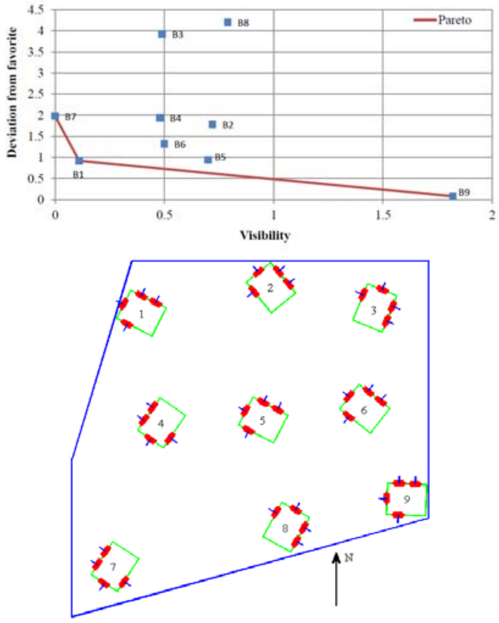

Fig. 13: Optimum layout based on $\omega_p = 0.75$ and $\omega_d = 0.25$

dwellings are directed North with respect to the reference side. On the other hand, Fig. 13 shows the case of visual privacy dominating the solution. It appears clearly from this figure that only one cluster (B9) has an exact direction towards the favorite view and most of the other clusters deviate from the required direction in order to satisfy visual privacy.

The benefit of this multi-objective technique is that it offers numerical results that can be utilized easily to differentiate between best and worst settlements. For example, by plotting the relation between the visibility value and the deviation from a favorite direction for each settlement for the three different cases as shown in Figs. 11, 12, and 13, the user can easily identify the best settlements in each case. The multi-objective genetic algorithm can identify multiple Pareto solutions in each case. The obtained Pareto front is important in helping designers to understand the trade-off relationship between the visibility and the direction to a favorite view.

V. CONCLUSIONS

The paper presents a novel hybrid technique for layout planning of residential houses. This approach benefits from the optimization capabilities of GAs in performing the task of optimally locating and orienting residential houses to achieve a number of design requirements. The multi-objective function is modeled to minimize the visibility between neighboring settlements and to maximize the direction of facades to a favorite view. The proposed technique couples the object oriented features of MATLAB, and a genetic algorithm optimization technique built in-house. The developed technique explores the search space for possible solutions, which is considered as a powerful feature for site planning problems. In addition, designers and architects can easily interact with this numerical tool in order to generate alternative sketch plans.

VI. ACKNOWLEDGMENTS

The authors would like to thank Helmut Pottmann for his advice. Also, the authors would like to express their gratitude to Khaled Nassar from the American University in Cairo and George Turkiyyah from the American university of Beirut for their valuable discussions.

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